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Tropical ice core records: evidence for asynchronous glaciation on Milankovitch timescales

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ABSTRACT: Over the last 28 years ice core records have been systematically recovered from ten high-elevation ice fields, nine of which are located in the low latitudes. Each core has provided new information about the regional climate and environmental change, and together their records challenge existing paradigms about the Earth's climate system. 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, both between the hemispheres and with high latitude glaciation that occurs on Milankovitch timescales. Although stable isotopic records suggest that global-scale cooling occurred during the Last Glacial Stage (LGS), we contend that precipitation is the primary driver of glaciation in the low latitudes. This is consistent with the time-transgressive nature of precession-driven changes in insolation (and hence precipitation) such that glaciers advance/retreat in the tropics north of the equator while glaciers retreat/advance in the tropics south of the equator. Thus, the coeval inter-hemispheric retreat of glaciers in the 20th century and the beginning of the 21st century is atypical. Copyright © 2005 John Wiley & Sons, Ltd.

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KEYWORDS: insolation; glaciation; orbital forcing; interhemispheric synchroneity.

Introduction

Half of the Earth's surface lies between 30° N and 30° S, where ca. 70% of the world's inhabitants live. Much of the climatic activity of significance to humanity (i.e. monsoons, El Niño) occurs in lower latitudes. Thus, it is imperative to expand our knowledge of past tropical climate variability to facilitate our understanding of contemporary regional, as well as global, climate changes. 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 (IPCC, 2001). 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 (Fig. 1).

The retreat of tropical glaciers such as the Quelccaya ice cap in the Andes of Peru is well documented (Thompson *et al.*, 2000a, 2003). Quelccaya's largest outlet glacier, Qori Kalis, is currently retreating 40 times faster than during the first measurement period from 1963 to 1978. A similar acceleration of glacier melting began in the mid-1980s throughout Peru (Ames, 1998) as well as on a global scale (Meier and Dyurgerov, 2002). For example, the total ice cover on Mount Kenya has decreased by 40% between 1963 and 1987 (Hastenrath and Kruss, 1992) and continues to diminish today. The Speke glacier in the Ruwenzori Range of Uganda has retreated substantially since it was first observed in 1958 (Kaser and Noggler, 1991; Kaser and Osmaston, 2002). The ice fields on Kilimanjaro have lost 75% of their area between 1912 and 1989 (Hastenrath and Greischar, 1997) and over 80% by 2000 (Thompson *et al.*, 2002). Oerlemans (2005) recently extracted a temperature history for different parts of the world from 169 records of glacier length. These data were used to reconstruct a warming of 0.5 K in the first half of the 20th century. However, most of these observations are limited to the last century, while assessing the severity of the current glacier retreat (Fig. 1) requires much longer climate histories.

Continental ice sheets generally form in higher latitudes (>40°) where the evidence for repeated growth and decay of Quaternary ice sheets is abundant (Broecker and Denton, 1990; Lowell *et al.*, 1995). In low latitudes, glaciers are restricted to the high mountain peaks in the Andes, the Tibetan Plateau and a few other isolated locations such as east Africa and New Guinea. The idea of asynchronous glaciation between the hemispheres dates back to Adhémar's calculation in 1842, shortly after Agassiz hypothesized the existence of ice

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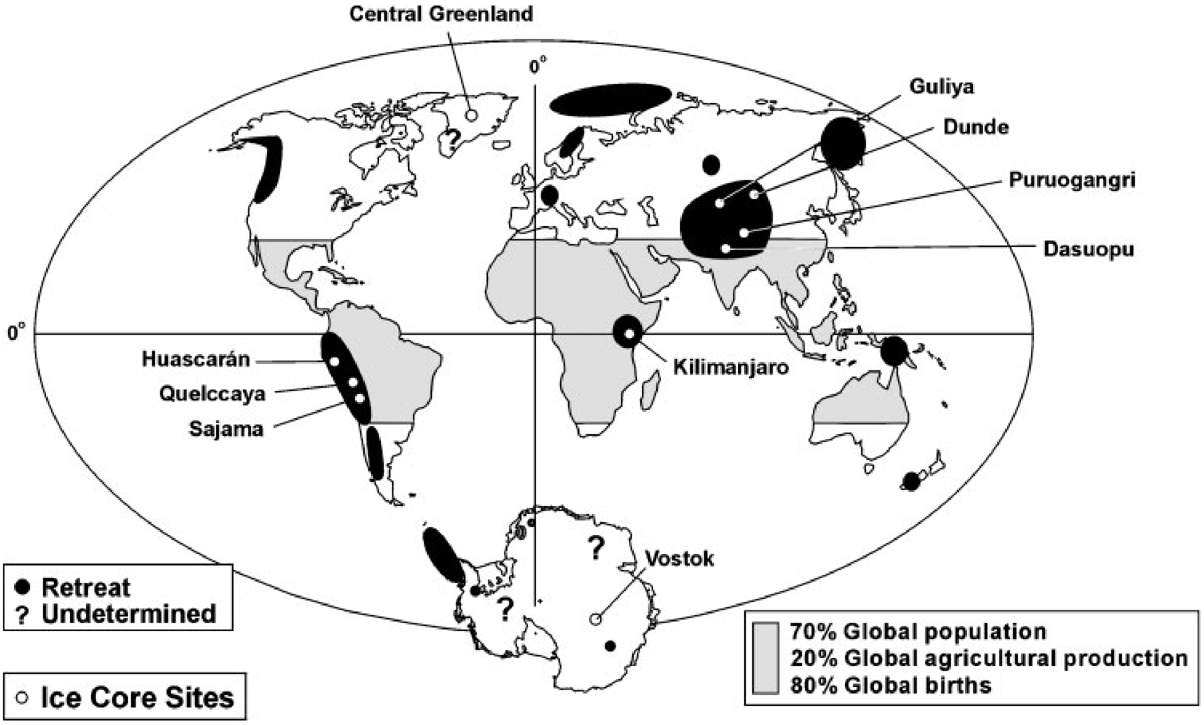

Figure 1 Global map showing ice core sites and areas of documented glacier retreat and advance during the 20th and the beginning of the 21st centuries

ages. Their hypotheses 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; Macdougall, 2004). More recently, glacial geologic evidence has suggested asynchronous glaciation between mountain glaciers and the high-latitude ice sheets (Heine, 1975, 1993; Gillespie and Molnar, 1995; Benn and Owen, 1998), while others (Lowell *et al.*, 1995; Clapperton, 1993) argue for synchronous glaciation. A primary obstacle to addressing this issue has been the lack of solid dates in the tropics. Phillips *et al.* (2000), using cosmogenic nuclide dating, suggested that maximum ice advances in the Himalayas of Pakistan occurred at 60 000 yr BP, 30 000 yr BP, and 5000–7000 yr BP. For the western Himalayas, Owen *et al.* (1997, 2001, 2002) also used cosmogenic nuclide dating to determine that on millennial timescales 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. Rigorous investigation of this idea is now possible with long, well-dated climate histories from ice cores drilled on carefully selected low-latitude ice caps and glaciers.

The ice core records

The ice-core-derived climate records discussed here represent three low-latitude regions (Fig. 1). The cores on the Tibetan Plateau were recovered from the Dasuopu glacier (28° N, 7200 m a.s.l.), the Puruogangri ice cap (34° N, 6072 m a.s.l.), the Guliya ice cap, (35° N; 6200 m a.s.l.) and the Dunde ice cap (38° N, 5325 m a.s.l.). In the South American Andes, cores were recovered from Huascarán, Peru (9° S, 6050 m a.s.l.) and Sajama, Bolivia (18° S, 6550 m a.s.l.), while in Africa cores were drilled on the top of Mt Kilimanjaro, Tanzania (3° S, 5895 m a.s.l.).

Existing ice core records of variations in $\delta^{18}O$, or the ratio of oxygen-18 (^{18}O) to oxygen-16 (^{16}O), from central Greenland through the tropics to Antarctica for the last 125 000 yr are plotted in Fig. 2. Some of the low-latitude ice cores contained sufficient organic material near the ice–bedrock contact to provide AMS ^{14}C dates that independently confirm a minimum age for the ice at that depth. All the ice core records that extend back to the Last Glacial Stage (LGS) show similar isotopic depletion, reflecting significant global cooling during the Last Glacial Maximum (LGM). Figure 3 depicts the same $\delta^{18}O$ records with the emphasis on the last 25 000 years. The $\delta^{18}O$ shift from the LGM to the early Holocene in the ice core from Byrd Station, Antarctica, is 6.6‰ (Johnsen *et al.*, 1972), in the Vostok, Antarctica, ice core it is 5.4‰ (Jouzel *et al.*, 1987) and in central Greenland it is 5.4‰ to 5.1‰ (Grootes *et al.*, 1993). Similar isotopic shifts occur in tropical ice core records, such as 5.4‰ in the Sajama record (Thompson *et al.*, 1998), 6.3‰ in Huascarán (Thompson *et al.*, 1995), and 5.4‰ in the subtropical Guliya core (Thompson *et al.*, 1997). The climate histories from these ice core $\delta^{18}O$ data contribute to a growing body of evidence that the LGM cooling was a global-scale event (Guilderson *et al.*, 1994; Beck *et al.*, 1997; Stute *et al.*, 1995; Schrag *et al.*, 1996; Broecker and Denton, 1990; Herd and Naeser, 1974; Klein *et al.*, 1995; Osmaston, 1965; Porter, 1979; Rodbell, 1992; Colinvaux *et al.*, 1996).

Asian/African monsoon region Holocene ice core records

The Dasuopu ice cap in the central Himalayas is the coldest non-polar site from which an ice core has been recovered. The ice temperature at 10 m depth in 1997 was −16 °C and the ice/bedrock temperature was −13.8 °C. Thus the ice cores archive the climate and environmental history from the time

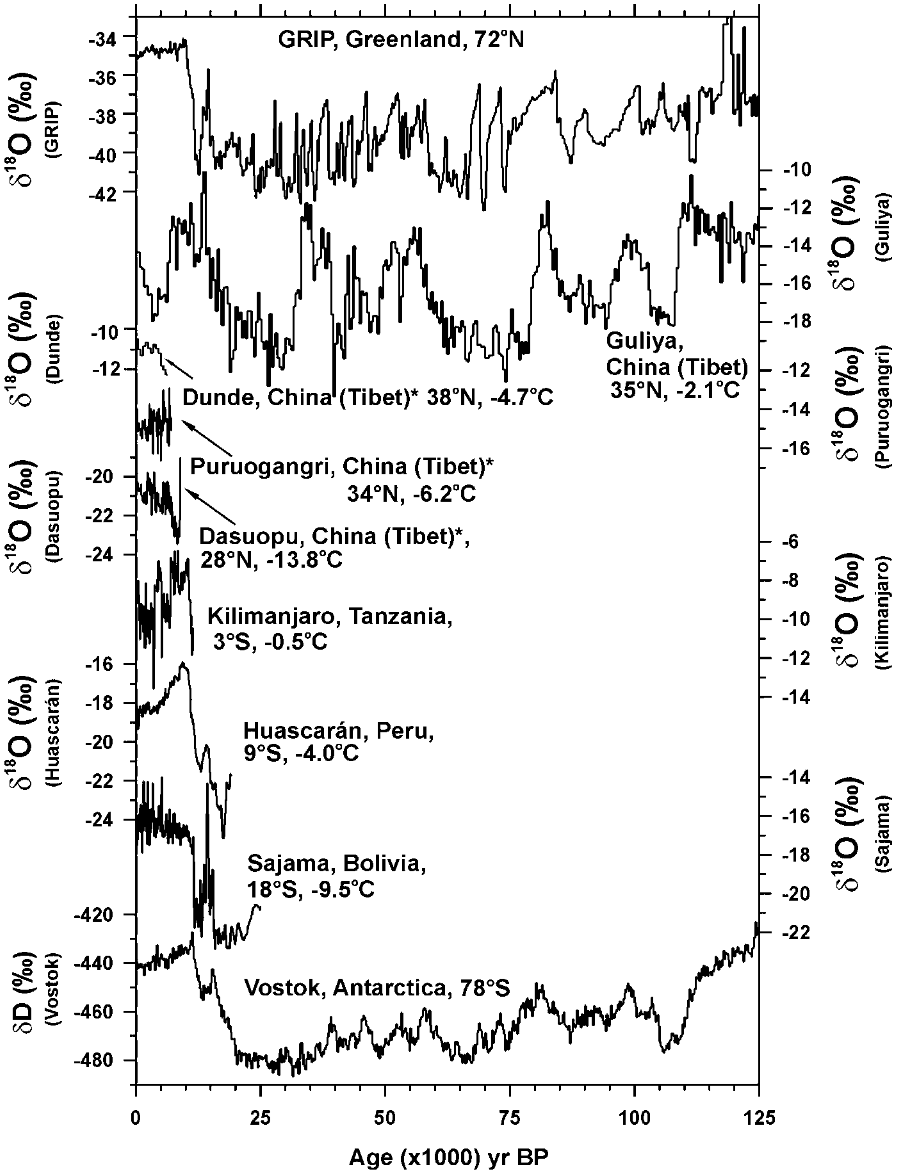

Figure 2 The δ^{18}O records are plotted from 125 000 yr BP to the present from Greenland to Antarctica. All cores except GRIP (Johnsen *et al.*, 1997) and Vostok (Jouzel *et al.*, 1987) were recovered by the OSU team and the references are cited in the text. Also included are the latitudes for all the sites and, where available, the ice/bedrock temperatures. The timescales for the Dunde, Puruogangri, and Dasuopu records, marked with asterisks (*), may be subject to future refinement

that the ice field began to grow on the summit of the Himalayas. The complete records of δ^{18}O (Thompson *et al.*, 2000b; Thompson, 2004) and methane, or CH_4 (Yao *et al.*, 2002) from two cores drilled to bedrock at the ice divide confirm the absence of glacial stage ice (Fig. 4). The δ^{18}O record lacks the 5 to 6‰ depletion in ^{18}O (indicated by more negative δ^{18}O values) that characterises glacial stage ice from the tropics to the polar regions (Figs 2 and 3). Furthermore, Dasuopu's basal ice does not contain the low (0.4 parts per million by volume, or ppmv) methane levels that characterise LGM ice in polar ice cores (Raynaud *et al.*, 2000). Thus, it is evident that this ice field at the top of the Himalayas accumulated entirely during the Holocene.

Two other ice cores obtained from the Tibetan Plateau also appear to be Holocene in origin. In 2000, cores were drilled at the summit of the Puruogangri ice cap in the Tanggula Mountains in the center of the Plateau (Fig. 1). Unlike Dasuopu, the vertical relief between the summit of Puruogangri and the surrounding terrain is low, making it easier for fragments of the sparse vegetation in the vicinity to be transported by local winds to the top of the ice field (Thompson, 2004). AMS ^{14}C dating of several plant fragments from near the bottom of the cores indicates that this ice cap started growing shortly before ca. 6000 cal. yr BP. Thus, like the Dasuopu ice field to the south, Puruogangri accumulated during the warm (moist) Holocene period and is thus a neoglacial feature (Figs 2 and 3).

Northeast of Dasuopu and Puruogangri, on the northern edge of the Tibetan Plateau, is the Dunde ice cap where cores were drilled in 1987. Dunde was the first long ice core record recovered from outside the polar regions. Based on the evidence available at the time the ice was analysed (e.g. CLIMAP Project Members, 1981; Thompson and Mosley-Thompson, 1981; Hammer *et al.*, 1985; Petit *et al.*, 1981, 1990), we interpreted the 2‰ shift in δ^{18}O, concurrent with a sudden increase in dust concentration 14 m from the bottom of the core, as evidence of glacial-stage ice (Thompson *et al.*, 1989). Re-examination of the Dunde δ^{18}O record in light of the recent δ^{18}O histories from Dasuopu and Puruogangri, coupled with a single ^{14}C AMS date of 6240 ± 330 cal. yr BP from near the ice–bedrock contact, raises the possibility that this glacier may also be a Holocene deposit. More data, especially additional ^{14}C AMS dates, are required to resolve this issue.

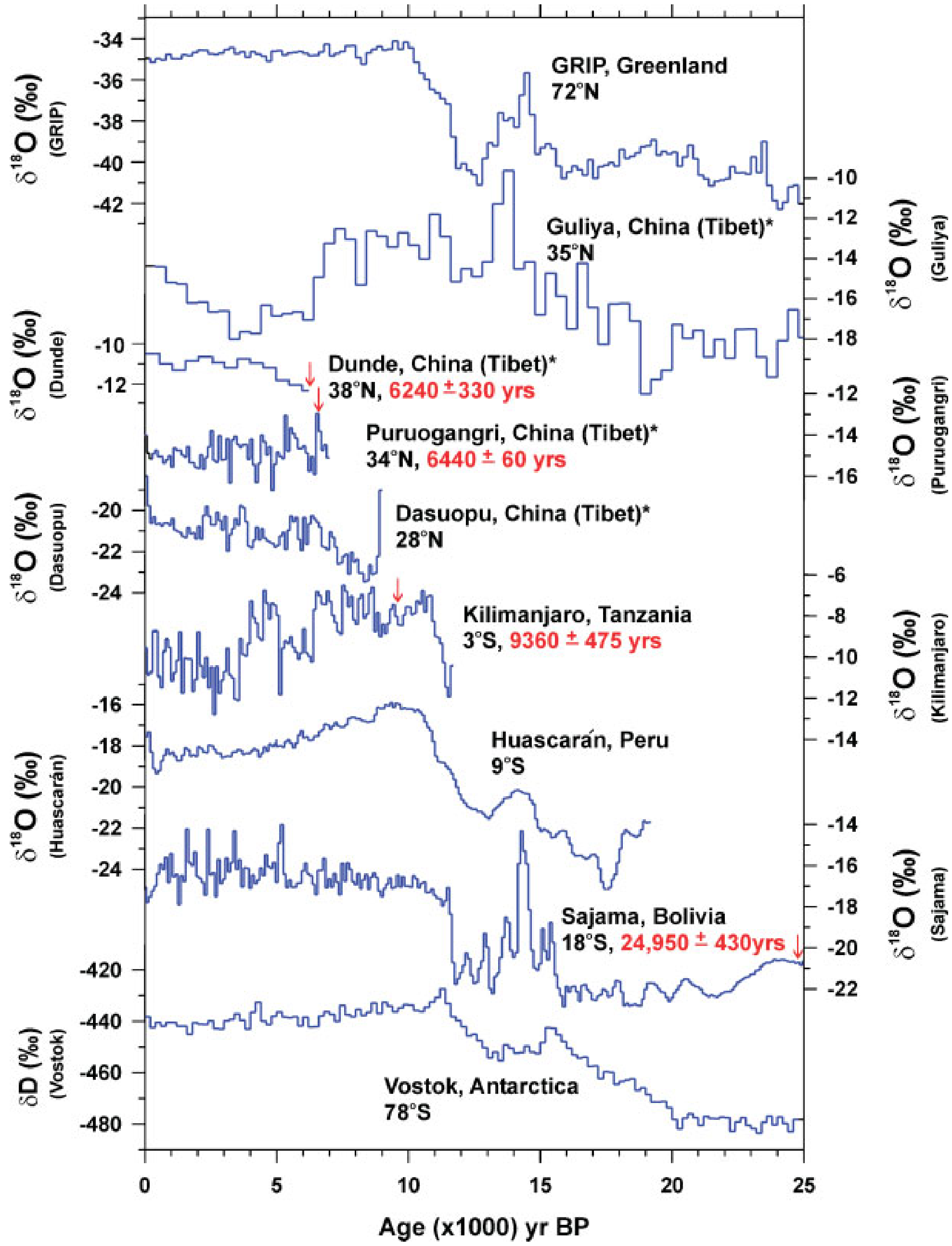

Figure 3 The δ^{18}O records are plotted from Greenland to Antarctica with emphasis on the most recent 25 000 yr. This illustrates the timescales of the climate records from the low and mid-latitude glaciers from south to north. Also included are the latitudes for all the sites and, where available, the earliest calibrated AMS ^{14}C dates. These radiocarbon-dated horizons, which are marked by downward-pointing arrows, occur close to or at the bottoms of their respective ice core records. The timescales for the Dunde, Puruogangri, and Dasuopu records, marked with asterisks (*), are possibly subject to future refinement

An additional tropical site located in equatorial East Africa provides evidence that the ice fields there are also Holocene in age. Ice cores drilled to bedrock in 2000 from the northern ice field of Kilimanjaro, Tanzania (3 ° S), extend back to an ice-modelled age of 11 700 yr BP (Figs 2 and 3). With an AMS date of 9360 cal. yr BP near the ice/bedrock contact, Kilimanjaro's basal ice is older than that on Dasuopu, Dunde and Puruogangri in Tibet, suggesting that its largest ice field accumulated very early in the Holocene (Thompson *et al.*, 2002).

Asynchronous glaciation

Ice core evidence for past changes in the tropical hydrological cycle, as well as evidence for recent warming at high elevations in the tropics, suggests that changes in water vapour inventories are a significant contributor to climate variability. Moreover, precipitation is essential for glacier development on high elevation, low- and mid-latitude mountain ranges. Figure 5 illustrates the modern average monthly precipitation distribution across the Tibetan Plateau along north–south and east–west transects. Similarly, Fig. 6 illustrates modern average monthly precipitation distribution within a north–south transect along the Andes of Peru and east–west across the Altiplano of Peru and Bolivia. Seventy to eighty per cent of the annual precipitation falls in the boreal summer from June to August (JJA) over much of the eastern and southern Tibetan Plateau and in the austral summer from December to February (DJF) in the Andes. Over the Plateau, both the total annual precipitation and the seasonality decrease abruptly from south to north and from east to west. Along the Andes the annual precipitation

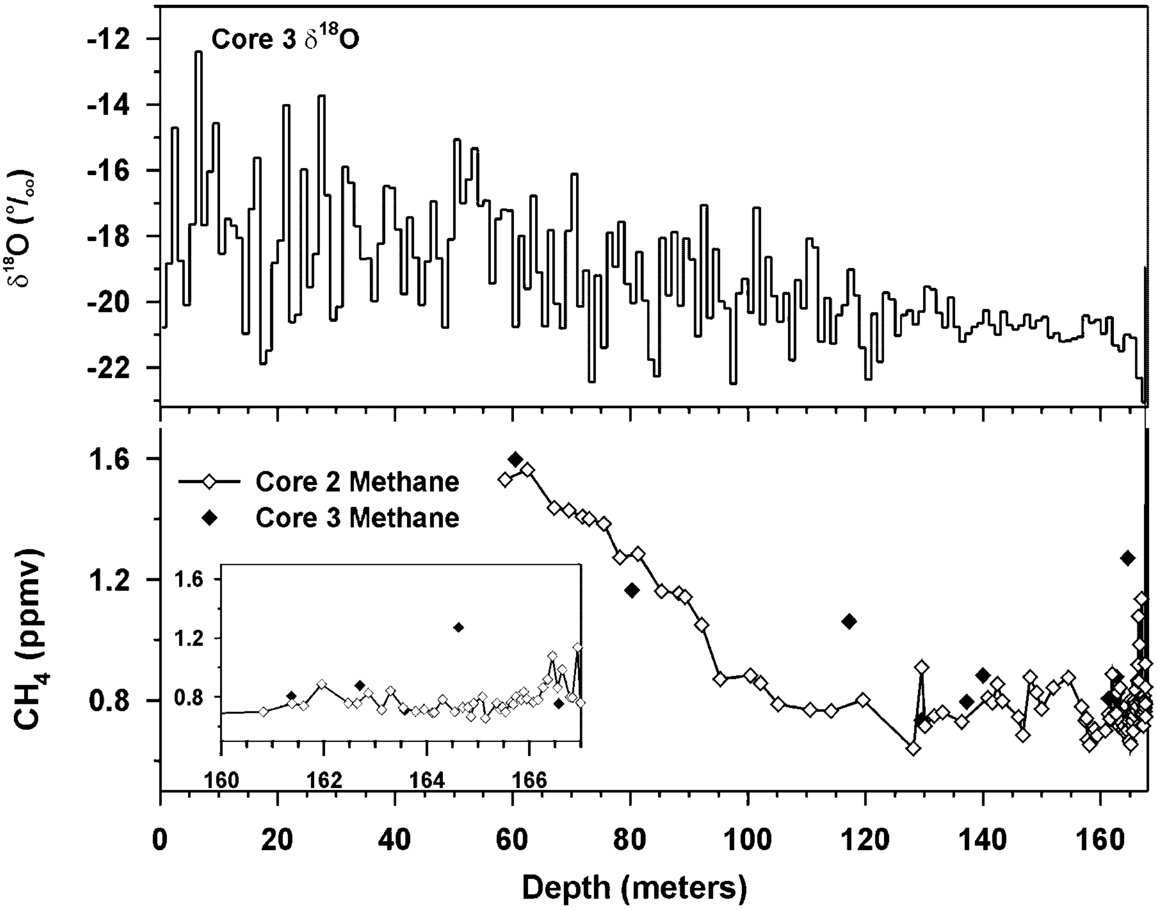

Figure 4 The $\delta^{18}O$ and CH_4 records are shown for the Dasuopu cores recovered from the 7200 m a.s.l. ice divide at the top of the Himalayas

also decreases with distance from the equator as well as from east to west across the Altiplano.

Figures 5 and 6 schematically demonstrate the results of the northward and southward migration of the major moisture supply, the rising branch of the Hadley cell. This large amorphous centre of convection determines the position of wet and dry climatic zones over much of the tropics and thus controls the location of glaciated mountain ranges today. However, in mountain ranges throughout the world, and across these plateaus, there is considerable local to regional variability in precipitation depending on dominant moisture flow trajectories and/or how storm systems move into, around and across complex terrain. For example, Lang and Barros (2002, 2004) argue that strong monsoon depressions that bring most of the snowfall to the rain shadow of the central Himalayas (where Dasuopu is located) seem to be associated with a few discrete events of convective activity that originate in the Bay of Bengal and then collide with the mountain range.

As the Earth is thermodynamically non-linear, tropical glaciers can be very sensitive to climate change. Cooler tropical temperatures during the LGM lead to a decrease in ablation rates, thereby increasing the mass of the glaciers. At high altitudes in the tropics, there is an additional amplification of this cooling due to the effects of atmospheric moisture. As global surface temperatures decrease, atmospheric humidity also generally decreases (Webster and Streten, 1978; Rind and Peteet, 1985; Broecker, 1997). The combination of cooler sea-surface temperatures and cooler trade winds, plus the effect of lower sea level and more exposed land in the lower latitudes, would all contribute to drier conditions (Webster and Streten, 1978). This reduction in moisture is crucial for increasing the lapse rate of temperature, causing additional cooling higher in the atmosphere and high-altitude glacier expansion. Under a warming Earth scenario, the situation would be reversed and glaciers might retreat rapidly. Such changes between dry and moist adiabatic lapse rates should lead to high-altitude tropical amplification of either warming or cooling temperatures.

Porter (2001) conducted a thorough review of tropical snowline depression during the last glaciation, and found an average altitudinal depression of ca. 900 m (although varying from region to region). This suggests a temperature depression at glacial maximum of 4.7 ± 0.8 °C after adjusting for a sea-level fall of 120 m. However, Porter noted that these calculations do not include the influence of precipitation changes on the glacier mass balances and they assume synchronous snowline depression at the LGM. A more recent review of tropical snowline depressions (Harrison, 2005) suggests large spatial variability with modest equilibrium line altitude (ELA) depression in the Himalayas (ca. 100 m), and the greatest depression in the southern Andes and in Papua New Guinea (ca. 800–920 m) and thus indicate that LGM temperature changes derived from ELA depressions remain controversial. The location of the ELA, where accumulation and ablation are in balance, depends upon a combination of many inputs and outputs to the glacier mass balance (for details see Paterson, 1994). Moreover, in mountain regions, the altitude and aspect of a glacier relative to moisture sources are the primary controls on the factors that determine glacier mass balance, such as temperature, precipitation, wind, and radiation receipt. Meteorological studies on numerous glaciers suggest that melting is most strongly controlled by receipt of solar radiation (Oerlemans, 2001).

The physics of glaciers is such that the length and quality of the preserved archive depend upon net accumulation (which also affects annual resolution), ice thickness, ice temperature,

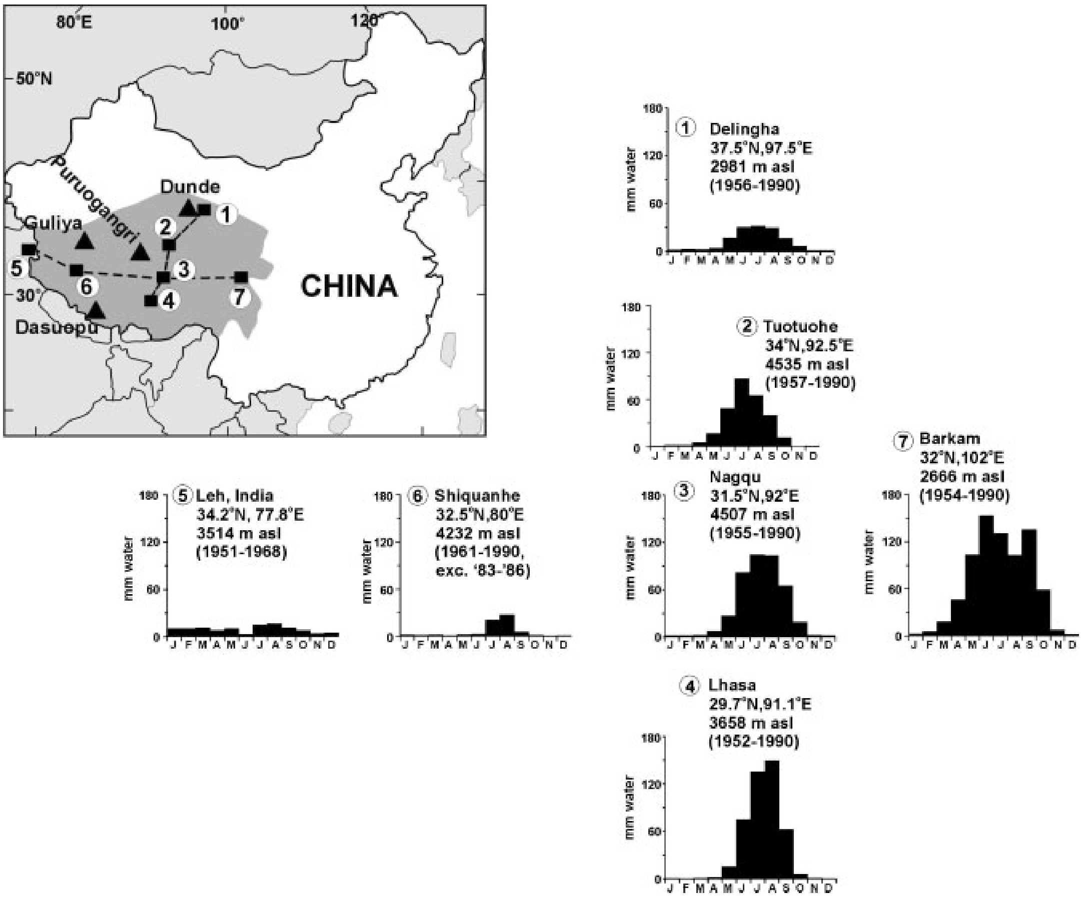

Figure 5 Meteorological station records along north–south and east–west transects on the Tibetan Plateau show the monthly distribution of precipitation under current climate conditions where 70% to 80% falls in the boreal summer (JJA). The years included in each record are shown in parentheses. Precipitation data are from the Global Historical Climate Network and can be accessed at: http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.GHCN/.v2beta/.prcp/

and geothermal gradient. Ice temperature is a particularly important control on both the quality of the preservation and the age of the record at the ice–bedrock contact. If the temperature at the ice–bedrock contact has remained below freezing throughout the glacier's history, then the record will not be removed from the bottom (Paterson, 1994). At low latitudes, very cold basal temperatures occur only on the highest glaciers.

The Huascarán and Sajama records are continuous and extend back into the LGS, thus both glaciers survived the early Holocene warm period (ca. 9000 to 6000 yr BP), yet neither record extends through the last glacial cycle to the previous interglacial (Fig. 3). This suggests that both mountain tops, among the highest in South America, were ice-free during a time when the climate was significantly colder than today. This observation poses a conundrum. What would account for the absence of these high ice fields during much of the glacial stage when temperatures were much cooler and why did they survive the early Holocene when the climate was warmer and drier than today? The answer is logically related to the relative amount of precipitation during glacial and interglacial periods. This hypothesis can be adequately tested now that a suite of ice cores, all drilled to bedrock, has been recovered between 18° S and 38° N. The temperature at the ice–bedrock contact in each of these boreholes (Fig. 2) confirms that these glaciers are indeed still frozen to their beds.

The ice core sites across the Tibetan Plateau are affected seasonally by air masses from different sources. The influences of these air masses may have varied over the Plateau through time (Davis *et al.*, 2005). Guliya in the far west, which contains a climate record that extends through the last glacial cycle, receives precipitation from the southwest (SW) Indian monsoon in the summer and the continental westerly disturbances in the winter. Although Dunde in the northeast is located at 38° N, currently 70% to 80% of its snowfall comes from the southeast (SE) monsoon during the summer. Similarly, Puruogangri and Dasuopu currently receive modest winter precipitation from prevailing westerlies, but more than 80% of their annual snowfall is monsoon-derived, although the moisture is recycled over thousands of kilometres of land mass.

The basal ages of the three Holocene Tibetan ice fields (Figs 2 and 3) suggest that they began to accumulate subsequent to the Northern Hemisphere insolation maximum (ca. 9000 to 10 000 yr BP) when the intensified Asian Monsoon system carried more precipitation over the Plateau. Previous studies (e.g. Clemens and Prell, 2003) argue that the strongest summer monsoons occurred 2000 to 3000 years after maximum Northern Hemisphere summer insolation. As discussed above, glacier mass balance depends upon the combined effects of numerous factors, including temperature, solar radiation, and precipitation. It is possible that the gradual Holocene cooling and reduced radiation receipt, coupled with enhanced snowfall from the extensive early Holocene lake systems on the Plateau, were sufficient to offset the slowly diminishing summer precipitation as monsoonal intensity slackened, thereby allowing the high mountain ice fields to expand. The Guliya ice cap was less affected by early Holocene insolation changes as its more continental location exposed it to the winter continental westerlies, resulting in the receipt of precipitation year-round.

Across the equator at 3° S, the Kilimanjaro ice core record is longer than the Tibetan records (with the exception of Guliya),

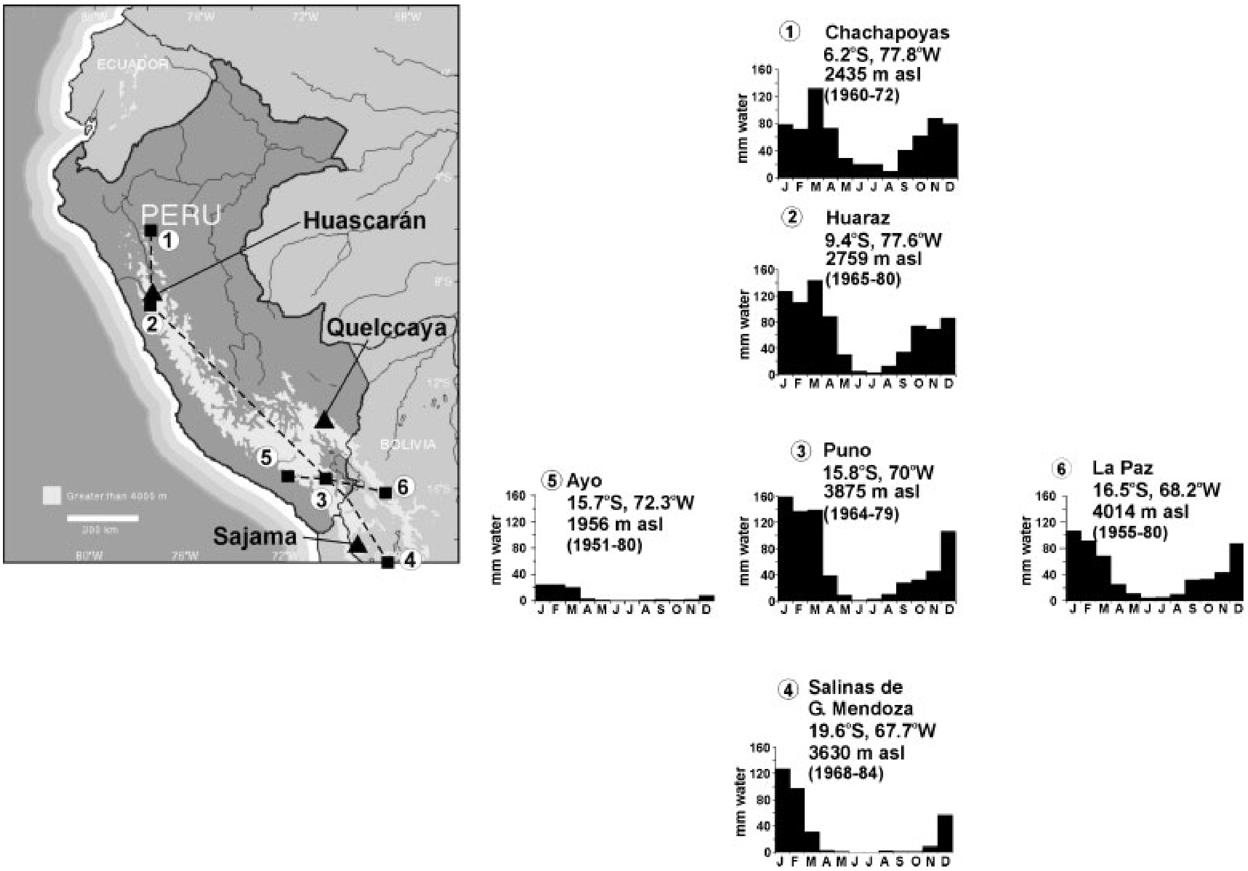

Figure 6 Meteorological station records along north–south and east–west transects across the Andes of Peru and the Altiplano show the monthly distribution of precipitation under current climate conditions where 70% to 80% falls in the austral summer (DJF). The years included in each record are shown in parentheses. Precipitation data are from the Global Historical Climate Network and can be accessed at: http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.GHCN/.v2beta/.prcp/

while in the Southern Hemisphere the Huascarán and Sajama ice cores are progressively older, respectively. The bottom ages for these sites (Fig. 3) suggest an interesting scenario for the formation of permanent ice fields on these high-elevation, low-latitude mountains. Moving from 18° S to 38° N, the glaciers appear to have successively younger basal ages (ca. 25 000, 19 000, 11 700, 8000 and 6000 yr BP on Sajama, Huascarán, Kilimanjaro, southern Tibet and northern Tibet, respectively). Our hypothesis is that this south to north trend in glacier formation was a direct response to the precession-driven northward migration of the ascending arm of the Hadley cell, which determines the timing of glacier growth and reduction. In fact, the precession cycle reached its Southern Hemisphere maximum ca. 23 000 yr BP and its Northern Hemisphere maximum ca. 11 000 yr BP (Berger and Loutre, 1991), consistent with the latitudinal pattern of glacier formation suggested by the suite of tropical ice cores presented in Fig. 7. The SPECMAP stack is also shown to illustrate the orbitally tuned record of ice sheet growth and decay. One might expect from the insolation curves in Fig. 7 that Huascarán and Sajama should have disappeared ca. 11 000 to 10 000 yr BP under low-insolation dry conditions. However, the precessional forcing is superimposed on a climate driven by changing internal boundary conditions, such as reduced ice sheet cover, increasing sea levels, reduced exposure of continental shelf area, and major increases in greenhouse gases (e.g. CO_2, CH_4). This warmer global climate might imply greater availability of water vapour throughout the world, and thus on the very high, cold mountain tops of Huascarán and Sajama glaciers could survive. However, there is ample evidence from Andean lakes such as Lake Junin (Seltzer *et al.*, 2000) and Lake Titicaca (Baker *et al.*, 2001), and a variety of geological evidence (Rodbell and Seltzer, 2000), as well as the isotope and dust records from the Huascarán ice core (Thompson *et al.*, 2000a) to indicate both warmer and drier conditions in early Holocene throughout the tropical Andes. The ice core data argue that glaciation of the Earth's tropical mountain regions depends not just on temperature, but is equally (or even more) dependent on precession-driven moisture sources that are transitory in space and time and thus are often asynchronous. One might expect this result, given that the June (boreal or Northern Hemisphere wet season) insolation curve at 30° N is out of phase with that of the January (austral or Southern Hemisphere wet season) insolation curve at 30° S over the last 140 000 years (Fig. 8). With precession-driven changes in insolation and hence precipitation, glaciers should advance/retreat in the tropics north of the equator while they retreat/advance in the tropics south of the equator. In fact, the current accelerating retreat of glaciers both north and south of the equator (Fig. 1) may be atypical and would suggest that other forcing mechanisms are driving the current global-scale glacier retreat (Thompson *et al.*, 2002, 2003).

This collection of ice core data supports the contention that (1) temperature changes cannot be the sole control on tropical glaciation and (2) precipitation changes associated with late Quaternary climate forcing are asynchronous between the northern and southern tropics. The latter is required to explain the overall pattern that emerges from the ice core data. Clearly, further investigation of the relationship between the timing of glaciation and precession-driven insolation requires careful assessment of glacier mass balances and energy budgets.

As discussed earlier, air flow on, around and across mountains and plateaus can be very complex and thus with better

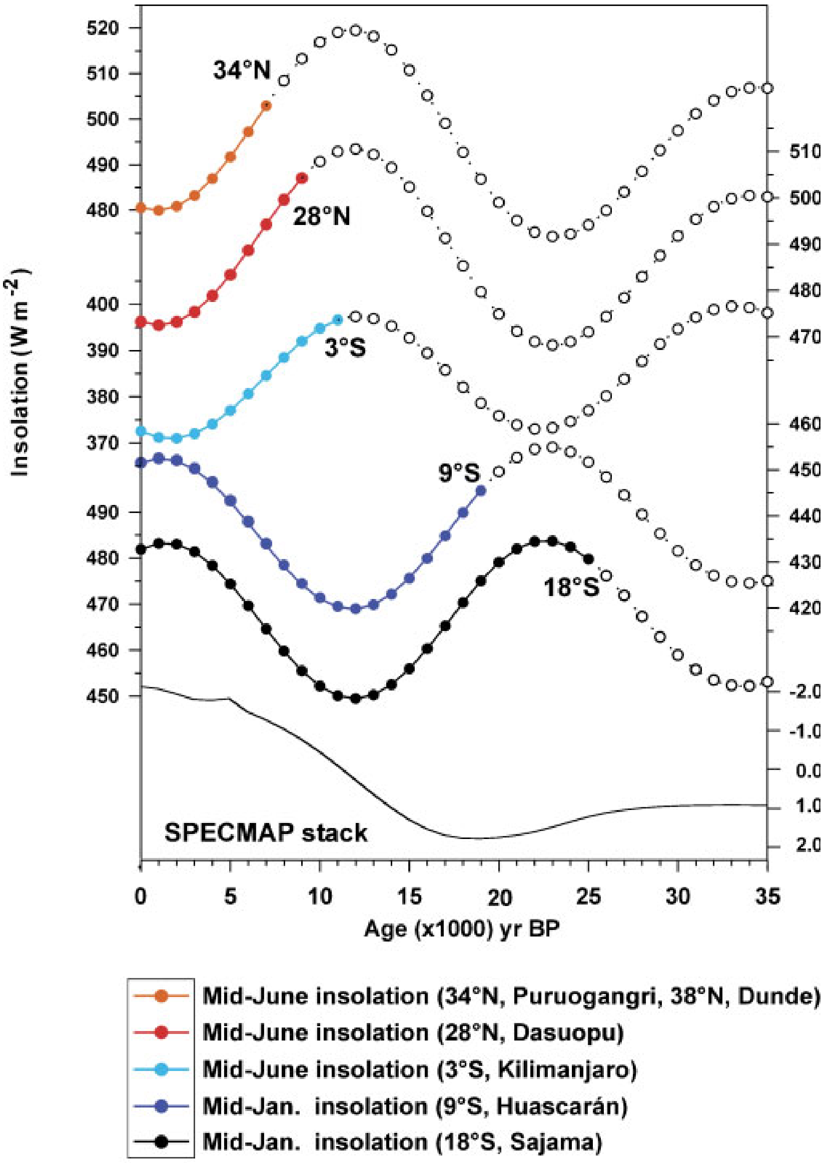

Figure 7 Wet season insolation is shown for the latitudes of five ice core sites. The solid dots indicate the apparent onset of the most recent glaciation for each site. Included at the bottom is the Specmap Archive #1 data set (ftp//ftp.ngdc.noaa.gov/paleo/paleocean/specmap/specmap1/ specmap.017). This figure is available in colour online at www.wiley.interscience.com/journal/jqs

spatial coverage we would expect to see considerable local and regional variability in the onset of glaciation relative to moisture sources through time. This is illustrated by recent discoveries of wetland plants around the Quelccaya ice cap, where 25 specimens were collected between 2002 and 2005. These perfectly preserved plants, most of which are ^{14}C AMS-dated at ca. 5000 cal. yr BP, were continuously encased in ice and only recently exposed by the retreat of the ice margin. Their condition and ages suggest that the early Holocene was warmer and/or drier than the present. Thus the conclusion can be drawn that this ice cap has existed in some form for over 5000 years. Quelccaya, Earth's largest tropical ice cap, sits on the eastern margin of the Altiplano at the point where moist easterly air flow from the tropical Atlantic via the Amazon Basin first intersects the Andes. It has probably received moisture from this source throughout its existence, and thus may well have survived while more moisture-starved glaciers such as Sajama in the centre of the Altiplano, would have been more sensitive to precession-driven changes in the moisture supply.

Understanding the relative importance of sublimation and melting on high-elevation glaciers is extremely important as the dominance of one over the other could result in threshold responses of these glacier systems during either warming or cooling climate conditions. Today tropical glaciers in the humid tropics between 20° to 25° N and S are sensitive to air temperature changes (Sobel and Bretherton, 2000; Chiang and Sobel, 2002), while dry subtropical glaciers are considered most sensitive to changes in humidity (Kaser, 2001). As these zones move north and south with precessional forcing, the relative importance of temperature, accumulation, melting and sublimation on any glacier will change, thereby leading to asynchronous glaciation on Milankovitch timescales.

Suggestions for future research and conclusions

To confirm the asynchroneity of glacier growth, recovery and reliable dating of more ice-core based climate histories archived in the present ice fields are necessary. In addition, it is important to model the relative impacts of sublimation and melting on net balance reconstruction, and to assess the

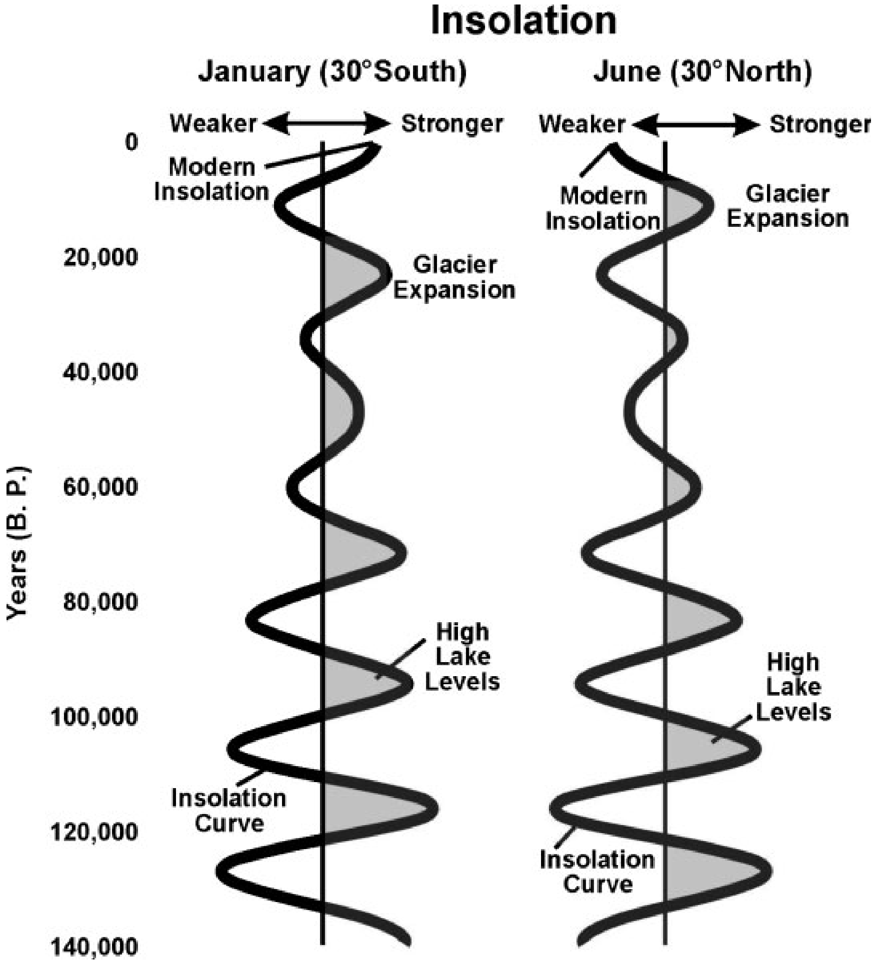

Figure 8 Insolation curves for the wet season at 30° S (January) and 30° N (June) over the last 140 000 yr show the times at these latitudes when increased precipitation would lead to glacier expansion and high lake levels (modified from Ruddiman (2001))

variations of climate with altitude in the atmosphere as the Earth moves from cold glacial to warm interglacial conditions. Further back in the Pleistocene prior to the growth of the modern glaciers, periods of greater June insolation at 30° N (ca. 130 000 yr BP) and at 30° S (ca. 115 000 yr BP) should have been nearly coincident with maximum glacier expansion and higher lake levels (Fig. 8), after adjustment for lag times in the climate system. Since glacial moraines exist across the Tibetan Plateau north of the equator as well as throughout the tropical Andes of South America, the hypothesis of asynchronous glaciation further back in time can be tested. This requires the application of new dating techniques such as exposure dating to better constrain the timing of past glacier advances and retreats.

Presently many mid- and low-latitude glaciers around the world are retreating, and since the 1980s the rate of retreat has accelerated at many locations, both south and north of the equator. Two examples of interhemispheric retreat are the glaciers in the Peruvian Andes (Ames, 1998; Thompson *et al.*, 2003) and those in Alaska (Meier and Dyurgerov, 2002; Fig. 1). The primary control driving this large-scale contemporary glacier retreat is most likely the increase in the Earth's globally averaged temperature (Hansen *et al.*, 2001; Thompson *et al.*, 2003; Oerlemans, 2005). Thus, precession with its large impact on precipitation may have controlled glacier variations in the past, leading to asynchronous changes, while enhanced greenhouse gas-related warming may presently be the dominant driver, thereby resulting in possibly unprecedented synchronous changes.

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