Journal of the Geological Society, London, Vol. **155,** 1998, pp. 353–363. Printed in Great Britain.

The role of the Indian summer monsoon and the mid-latitude westerlies in Himalayan glaciation: review and speculative discussion

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Abstract: New dates for late Quaternary glaciations in the Himalayas show that, during the last glacial cycle, glaciations were not synchronous throughout the region. Rather, in some areas glaciers reached their maxima at the global glacial maximum of *c.* 18–20 ka BP, whereas in others glaciers were most extensive at *c.* 60–30 ka BP. Comparison of these data with palaeoclimatic records from adjacent regions suggest that, on millennial timescales, Himalayan glacier fluctuations are controlled by variations in both the South Asian monsoon and the mid-latitude westerlies.

Keywords: Himalayas, Quaternary, monsoons, glaciation, palaeoclimatology.

The Himalayas and Tibetan Plateau form the largest mountain mass on earth, stretching over 2000 km east–west from Burma to Afghanistan and over 1000 km north–south from the deserts of Central China to the Indo-Gangetic Plain, and with an average elevation of 6000 m (Fig. 1). This vast area of high ground exerts an important influence on regional and global climate, in several ways (Murakami 1987). First, it has mechanical effects on atmospheric circulation, particularly in winter when it splits the surface westerly winds into northern and southern branches and prevents the southward flow of cold continental air towards the Indian Subcontinent. The mechanical effects also extend farther afield due to the enhancement of the northern westerly jet stream in the lee of the plateau. Second, heating of the plateau in summer raises air temperatures above the zonal mean for the free atmosphere at the same height, thus enhancing the pressure gradient that drives the South Asian summer monsoon. Third, uplift of the Himalayas and Tibetan Plateau is argued to have had profound effects on global climate throughout late Cenozoic times due to mechanical, thermal, and weathering effects (Ruddiman & Kutzbach 1989; Raymo & Ruddiman 1992; Prell & Kutzbach 1992). General circulation modelling predicts that the continental interior of Asia is one of the regions of the world most likely to experience large temperature increases as a result of anthropogenic climate change (Houghton *et al.* 1990, 1996), and this in turn may influence the intensity of the summer monsoon and the associated precipitation and runoff in South and East-central Asia. Approximately 75% of the world's population live in the regions adjacent to the Himalayas and Tibet, and economic activity in the region is strongly influenced by prevailing climatic conditions. It is therefore important to understand past and present climatic condition in this region as a means of improving global climate models.

Throughout the Himalayan region, extensive evidence for past glaciations is provided by well developed moraines and valley fills that exceed several tens of metres in thickness. Although relative chronologies have been established for several parts of the Himalayas, the timing of glaciation is poorly understood because of the paucity of suitable dating material. Researchers have often assumed that Himalayan glaciations were synchronous with global ice-volume maxima (e.g. Zheng 1989*a*; Burbank & Kang 1991; Anderson & Prell 1993; Emeis *et al.* 1995), implying that climatic change in the Himalaya is tied to temperature cycles in the northern mid-latitudes. However, new dates do not support this assumption (Gillespie & Molnar 1995; Sharma & Owen 1996; Owen *et al.* 1997), suggesting that the influences on climatic change in the Himalayas are more complex that previously thought. This paper will review the currently available dating evidence for the timing of Himalayan glaciations, and palaeoclimatic records from adjacent regions, and examine the possible implications for climate dynamics in the region.

Timing of Himalayan glaciations

The present dating evidence for Himalayan glaciations in summarized in Figs 2 and 3. In the north of the region, ^{14}C dates have been obtained from organic material found in moraines in the Kunlun Mountains (Fig. 3) (Derbyshire *et al.* 1991). These provide an age range of between 22 904 ± 950 to 16 151 ± 553 radiocarbon years BP (Derbyshire *et al.* 1991). Dates that are compatible with the ^{14}C dates from West Kunlun have been obtained from organic material in lacustrine deposits below moraines. These yielded a date of 30 935 ± 1700 radiocarbon years BP, while organic material in lacustrine deposits formed in a lake dammed by the same moraine gave a ^{14}C date of 14 930 ± 320 radiocarbon years BP (Derbyshire *et al.* 1991). Similar dates were obtained for moraines above the Keleqin River in the northern Karakoram Mountains (19 045 ± 365 to 24 420 ± 310 radiocarbon years BP) (Derbyshire *et al.* 1991); and for material included in moraines on the Keriya Pass (15 790 ± 384 to 18 140 ± 319 radiocarbon years BP: Li & Shi 1992) (Fig. 2b).

The glacial history of Swat in northern Pakistan is partially constrained by thermoluminescence (TL) dates from loessic deposits that overlie moraines (Owen *et al.* 1992). Owen *et al.* (1992) showed that these loessic deposits were reworked and therefore care must be taken when interpreting these dates. Nevertheless, they provide minimum ages, such that the last glaciation (Kalam Glacial Stage) must have occurred after at least 22 ka BP and terminated by about 6.7 ka BP (Owen *et al.* 1992). The timing of glaciations in the Hunza valley is also partly constrained by TL dates of glaciolacustrine and aeolian

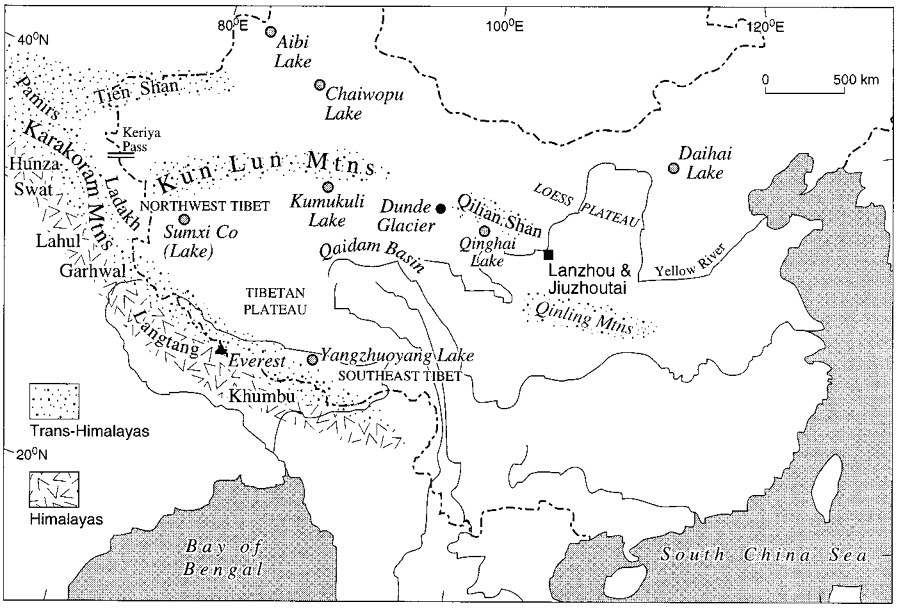

Fig. 1. The extent of the Himalayas and Tibetan Plateau, and locations mentioned in the text.

sediments (Derbyshire *et al.* 1984). The procedures used in dating analysis were not clear so it is difficult to evaluate the results. However, the dates indicate that the older glaciation in the Hunza valley represents the last glacial maximum and occurred around 50 ka BP, with subsequent glacial events being less extensive (Fig. 2d).

In the Lahul Himalaya in northern India, optically stimulated luminescence (OSL) dating strongly suggests that an extensive valley glaciation (the Batal Stage) culminated prior to 43.4 ± 10.3 ka BP. A less extensive glacial event (the Kulti Glaciation) occurred after approximately 36.9 ± 8.4 ka BP (Owen *et al.* 1996, 1997). A basal radiocarbon date from peat at Chandra Tal indicates that peat growth began about 9160 ± 70 radiocarbon years BP (Owen *et al.* 1997), suggesting an increase in either temperature or precipitation in Lahul at that time.

In the Garhwal Himalaya, northern India, glaciofluvial and aeolian sediments have been dated using OSL, showing that the maximum extent of ice occurred approximately 63 ka BP (Sharma & Owen 1996). Furthermore, Sharma & Owen (1996) showed that the main valley glaciers probably began to retreat between about 20 ka and 16 ka years BP and reached more or less their present positions by about 5 ka BP. Two younger advances were identified, the older during mid Holocene times (<5 ka BP), and the younger at about 200 to 300 years BP (Sharma & Owen 1996).

Farther east, Derbyshire *et al.* (1991) provided a minimum ^{14}C age of 41.1 ka ± 1 ka BP for moraines in the region around Namunani Peak, near the border with India and Nepal (30°30′ N, 81° E). In the Khumbu Region of Nepal, our recent work has provided an age estimate for the Periche Stage of the Khumbu Glacier recognized by Müller (1958), Fushimi (1978) and Williams (1983). Two preliminary infra-red stimulated luminescence date (additive dose method) of 18.3 ± 4.5 ka BP and 18.7 ± 2.4 ka BP were obtained from sand lenses in a major end moraine complex, and apparently represent the last glacial maximum in this area.

Dating of Pleistocene glaciations in eastern Tibet is very poor, although Lehmkuhl & Lui (1994) provided TL ages of 54 ka BP and >200 ka BP for two sets of glacial moraines in northeast Tibet.

Clearly, the timing of Pleistocene glaciations in the Himalayas and Tibetan Plateau region is very poorly constrained. Nevertheless, the dating evidence summarized in Fig. 2 suggests an emerging pattern. During the last glacial cycle, glaciers in the north of the region (Kunlun, Keriya Pass) and in the southeast (Khumbu) reached their maximum positions at 18–22 ka, approximately synchronously with the global glaciation maximum of 20–18 ka BP. In the Karakoram and northern India (Swat, Hunza, Lahul, Garhwal, Namunani), however, the last glacial maximum appears to have been earlier, in the region of 60–40 ka BP, although there is evidence that glaciers in Garhwal still occupied expanded positions at *c.* 18 ka BP. The poorly constrained Kulti Glaciation in Lahul may also have reached its maximum extent at this late date.

There is also evidence for asynchronous glacier fluctuations in the Holocene. In Swat (Fig. 2c) and northwest China (Fig. 3b), glaciers advanced during early and mid Holocene times, whereas glaciers in southwestern China and the Langtang valley, Nepal (Fig. 3b and d) underwent more extensive advances during late Holocene times (Zhou *et al.* 1991; Shiraiwa 1993).

On decadal timescales, glacier fluctuations are also asynchronous in different parts of the Himalayan region. Mayewski & Jeschke (1979) and Mayewski *et al.* (1980) considered the fluctuations of 112 glaciers in Pakistan, India and Nepal for the period between 1810 and 1970. Their data are summarized in Fig. 4, and show that, since 1850, high percentages of Himalayan glaciers have been in retreat, in contrast with the Trans–Himalayan glaciers which have undergone periods when advance was the dominant mode. More than 50% of Trans-Himalayan were in advance during the periods 1860–1869 and 1890–1909. Mayewski *et al.* (1980) compared the data shown in Fig. 4 with records of the strength of the South Asian monsoon circulation (sea-level pressure difference between 10° and 20° N at 75° E) and precipitation (average rainfall for all India). The 1900–1909 period of glacier advance in the Trans-Himalayas coincides with a peak in the monsoon circulation index, but overall there is no consistent pattern and the results are inconclusive. This is due to the crudity of the climatic record, which may bear little resemblance to the actual climatic conditions experienced on the glaciers. Indian rainfall

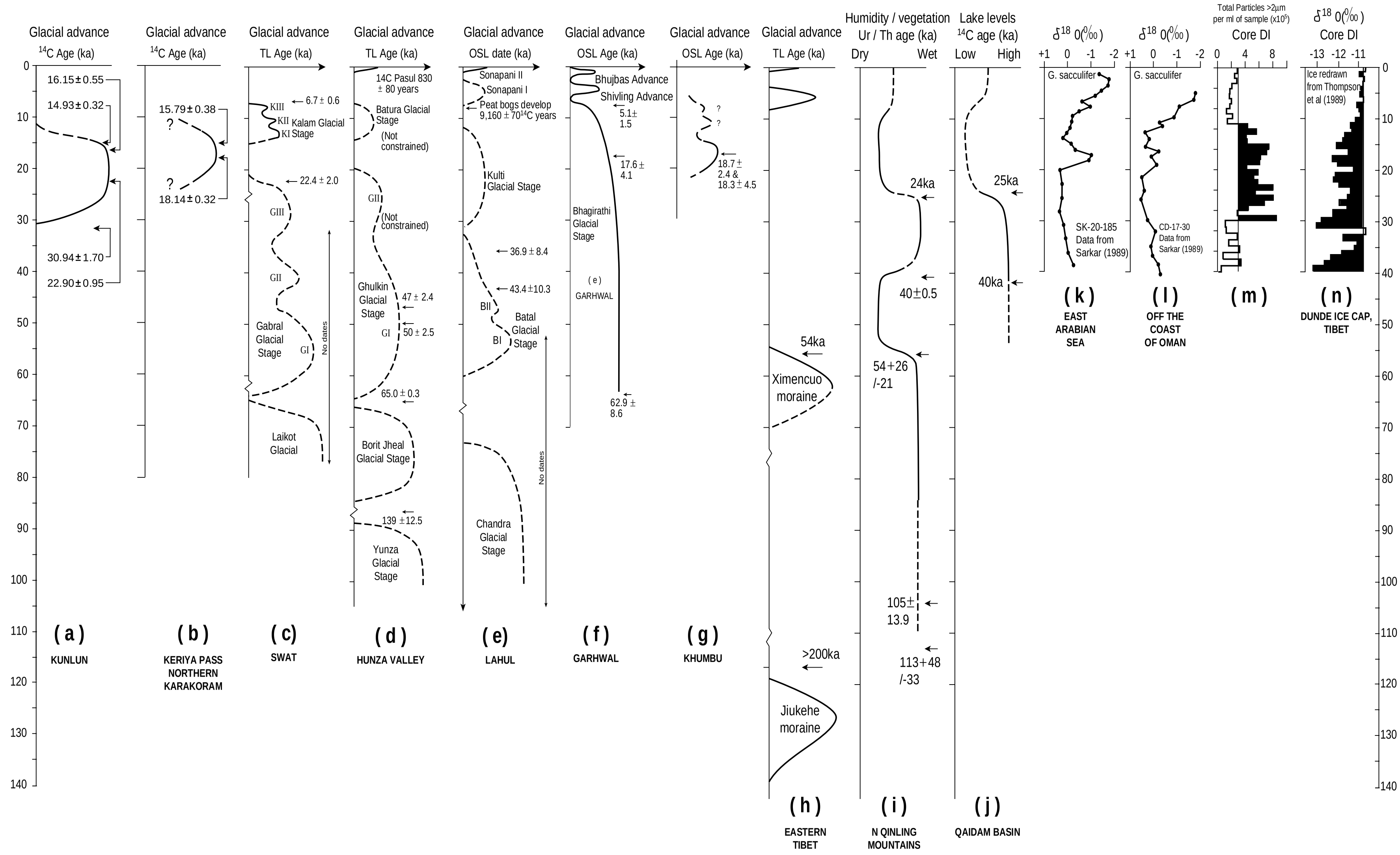

Fig. 2. Correlations of climatic proxies that may be used to infer changes in glaciation in the Himalayas and Tibet during late Quaternary times showing the comparison of the extent and timing of glaciation. (a), (b), (c), (d), (e), (f), (g) and (h) compare the timing and relative extent of glaciation for: (**a**) the Kunlun Mountains (data from Derbyshire *et al.* 1991); (**b**) Keriya Pass, Northern Karakoram Mountains (data from Derbyshire *et al.* 1991); (**c**) the Swat Himalaya (data from Owen *et al.* 1992); (**d**) the Hunza valley (data from Derbyshire *et al.* 1984); (**e**) the Lahul Himalaya (after Owen *et al.* 1996, 1997); (**f**) the Garhwal Himalaya (after Sharma & Owen 1996); (**g**) the Khumbu Himal, Nepal (J. Spencer, unpublished); (**h**) Eastern Tibet (Lehmkuhl & Lui 1994). (**i**) Relative humidity in the Northern Qinling Mountains based on palaeobotanical evidence (data from Pachur *et al.* 1994); (**j**) Lake level changes in the Qaidam Basin (data from Chen & Bowler 1986); (**k**) δ^{18}O record from *Globigerina sacculifer*, East Arabian Sea (Sarkar *et al.* 1990); (**l**) % *Juniperus* at Tsokar Lake, Ladakh (Bhattacharyya 1989); (**m**) and (**n**) δ^{18}O values and dust content from the Dunde Ice Cap core, Tibet (Thompson *et al.* 1989). Please note that all the ^{14}C dates are uncalibrated radiocarbon years as quoted in the original sources.

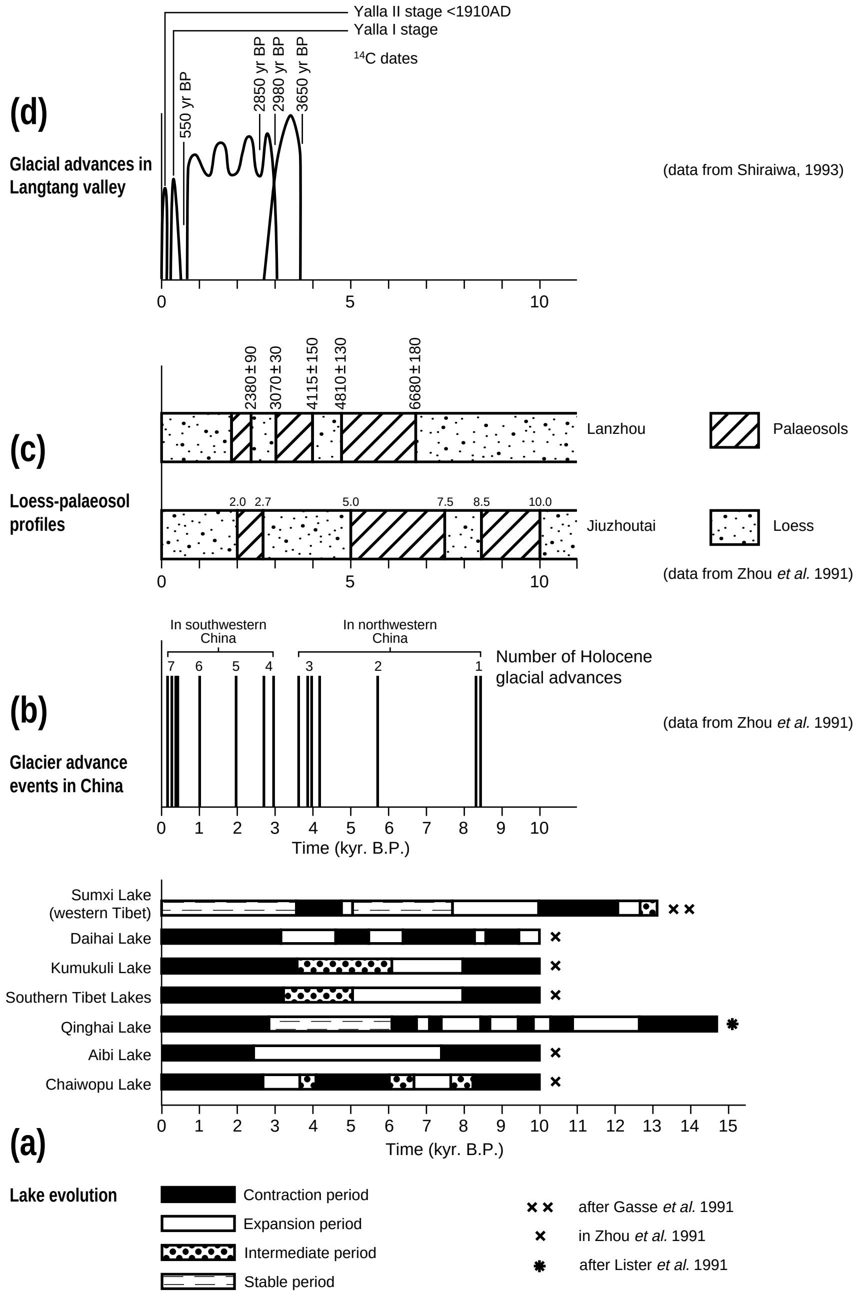

Fig. 3. Environmental changes throughout Holocene and late Pleistocene times for selected areas in Tibet and the Himalayas. (**a**) Lake level fluctuations (modified after Zhou *et al.* 1991 with data from Lister *et al.* 1991 and Gasse *et al.* 1996); (**b**) Glacier fluctuations in northwestern and southwestern China (after Zhou *et al.* 1991); (**c**) Loess–palaesol profiles from Lanzhou and Juizhoutai (data from Zhou *et al.* 1991); and (**d**) Glacial advances in the Langtang valley (data from Shiraiwa 1993; Shiraiwa & Watanabe 1991).

displays large inter-regional variability, and records in many areas are not significantly correlated with all-India rainfall (Shukla 1987). Nevertheless, the data show that glacier fluctuations can be strikingly out of phase in different parts of the Himalayas and Trans-Himalayas on decadal timescales, which likely echoes the dating evidence for asynchroneity of glacier fluctuations on longer timescales during the Pleistocene and Holocene.

Mass-balance regime of modern Himalayan Glaciers

To understand the climatic significance of past glacier fluctuations in the Himalaya it is useful to examine the current relationship between glaciers and climate in the region. Most of the region experiences a pronounced summer precipitation maximum, reflecting moisture advected northwards from the Indian Ocean by the southwest monsoon (Murakami 1987; Figs 5 and 6). Summer precipitation, however, declines sharply from south to north across the main Himalayan chain, and is much higher in Nepal and Garhwal than in Lahul and the Karakoram, and is very low over the western Tibetan Plateau. Only in the extreme west of the region is there a winter precipitation maximum, due to the influence of winter westerly winds bringing moisture from the Mediterranean, Black, and Caspian Seas. Snow and ice accumulation may also vary across the Himalayas and Tibet as a consequence of changing adiabatic lapse rates that are related to a reduction in the moisture content of air masses are forced over the Himalayas and Tibet. The result of such orographic forcing is the production of drier warm air that eventually descends from the northern slopes of the Trans-Himalayan peaks and the northern edge of the Tibetan Plateau. Such winds may have a major

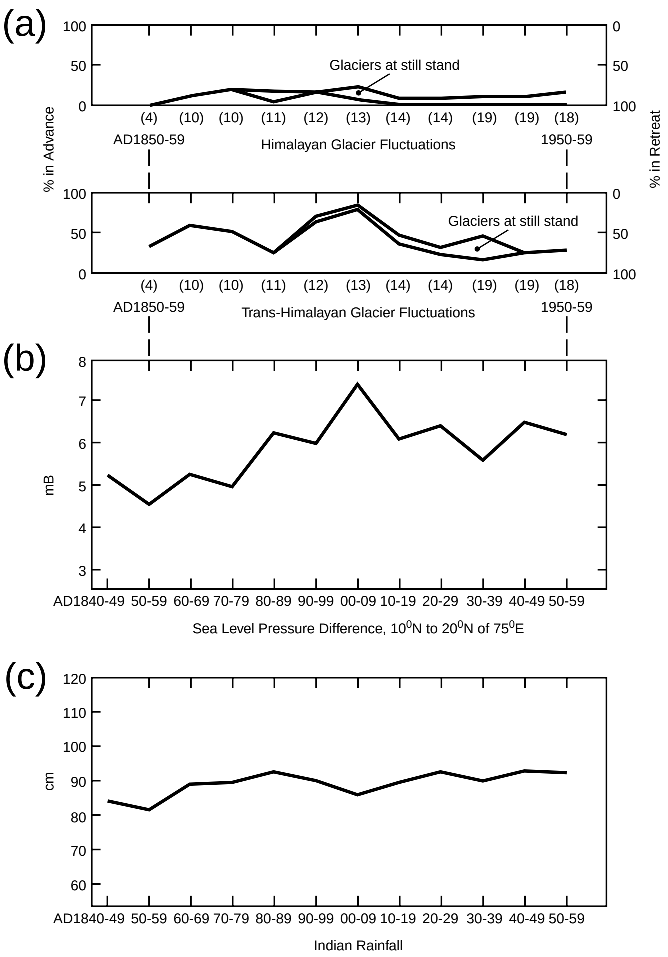

Fig. 4. (**a**) Glacier fluctuations for the Himalayas and Trans-Himalayas from 1810 to 1959 (the numbers in parenthesis refer to the number of glaciers in the sample for each ten year period); (**b**) Sea level pressure difference between 10°N to 20°N of 75°E for each ten year period; and (**c**) average of all-India rainfall for each ten year period. Redrawn after Mayewski & Jeschke (1979).

control on glacier formation both regionally and on a local scale. However, these effects have yet to be considered in any depth. A combination of the above factors results in the snowlines that vary from 4300 m in southeast Tibet to over 6000 m in western Tibet (Fig. 6c).

Due to the seasonal distribution of precipitation, glaciers in most of the Himalayan region are of the summer accumulation type, in which maxima in accumulation and ablation occur more or less simultaneously during the summer (Ageta & Higuchi 1984; Ageta & Kadota 1992; Kulkarni 1992; Nijampurkar & Rao 1992; Owen & Derbyshire 1989; Kulkarni 1992). The summer accumulation maximum reflects high precipitation during the summer monsoon, when moisture-bearing air masses originating over the Indian Ocean bring snow to high altitudes in the Himalaya (Yasunari & Inoue 1978; Higuchi *et al.* 1982; Ageta & Higuchi 1984). Glacier ablation is also at a maximum during the summer, when high temperatures result from direct solar heating, advected sensible heat, and latent heat released by condensation during deep atmospheric convection (Webster 1987*a*,*b*). In contrast, winters are cold and relatively dry, although heavy snowfalls can occur in association with westerly winds, particularly in the western parts of the Himalayan chain in India and Pakistan (Inoue 1978; Owen 1989; Owen *et al.* 1995). Ageta & Higuchi (1984) estimate that in eastern Nepal around 80% of the annual precipitation falls during June to September.

Glacier accumulation occurs by direct snowfall, blowing snow and avalanching. The relative importance of these three processes varies from glacier to glacier, although avalanching plays an important role in many catchments due to the widespread occurrence of high, steep mountain sides which intercept, but cannot retain snowfall. For example, Inoue (1977) estimated that the Khumbu Glacier, Nepal, gains approximately 2.8 times as much mass by avalanching as by direct snowfall. Steep valley walls also deliver large amounts of rockfall debris on to many glacier surfaces, resulting in extensive debris cover in their ablation zones (Fujii & Higuchi 1977; Owen & Derbyshire 1989; Owen *et al.* 1995). This is particularly true on the longer trunk glaciers that drain large, complex catchments (Moribayashi & Higuchi 1977). Continuous, thick debris cover insulates the underlying ice, and can significantly reduce ablation. Indeed, on thickly debris-covered glaciers, ablation rates can be highest in the upper part of the ablation zone, where debris cover is patchy and less extensive, rather than at the snout (Inoue 1977).

Palaeoclimatic records

As discussed above, the Himalaya and Tibetan Plateau is influenced by the South Asian monsoon in summer and the mid-latitude westerlies in winter. Thus, in order to interpret the evidence for millennial-scale glacier fluctuations in the region, it is useful to consider proxy palaeoclimatic data from the region alongside records from Indian subcontinent and Indian Ocean to the south, and high Asia to the north.

Data on long-term variations in the intensity of the South Asian summer monsoon are available from several sources, including ocean cores from the Arabian Sea, Gulf of Aden, and Bay of Bengal, and lake cores from Rajasthan, India (Bryson & Swain 1981; van Campo *et al.* 1982; Swain *et al.* 1983; Prell & van Campo 1986; Prell & Kutzbach 1987; Sirocko *et al.* 1991). The longest and most comprehensive records are from the Arabian Sea, and yield detailed information on past oceanic and atmospheric circulation patterns, in addition to sea-surface temperatures. Summer southwesterly monsoon winds blowing over the western Arabian Sea cause coastal upwelling of cool, deep, nutrient-rich waters, encouraging high biogenic productivity. Productivity indicators, notably *Globigerina bulloides*, biogenic opal (from radiolaria and diatoms) and barium (concentrated in the tests of diatoms and other marine plankton), preserved in sea-floor sediments provide proxy records of former upwelling and, therefore, intensity and/or seasonal duration of the summer monsoon (Prell 1984; Prell & Kutzbach 1987; Clemens *et al.* 1991; Emeis *et al.* 1995). In addition, ocean cores also contain windblown clastic grains, traceable to sources in Somalia, Arabia, and the Persian Gulf, and far-travelled pollen, which permit the reconstruction of former dominant wind directions (van Campo *et al.* 1982; Prell & van Campo 1986; Prell & Kutzbach 1987; Sirocko *et al.* 1991, 1993). Collectively, this evidence indicates that upwelling in the Arabian Sea was weak during the Last Glacial Maximum (LGM), and was at a minimum at the time of Termination 1a (18 ka to 17 ka BP) (van Campo *et al.* 1982; Prell & van Campo 1986; Prell & Kutzbach 1987; Sirocko *et al.* 1991, 1993). Upwelling did not cease altogether, however,

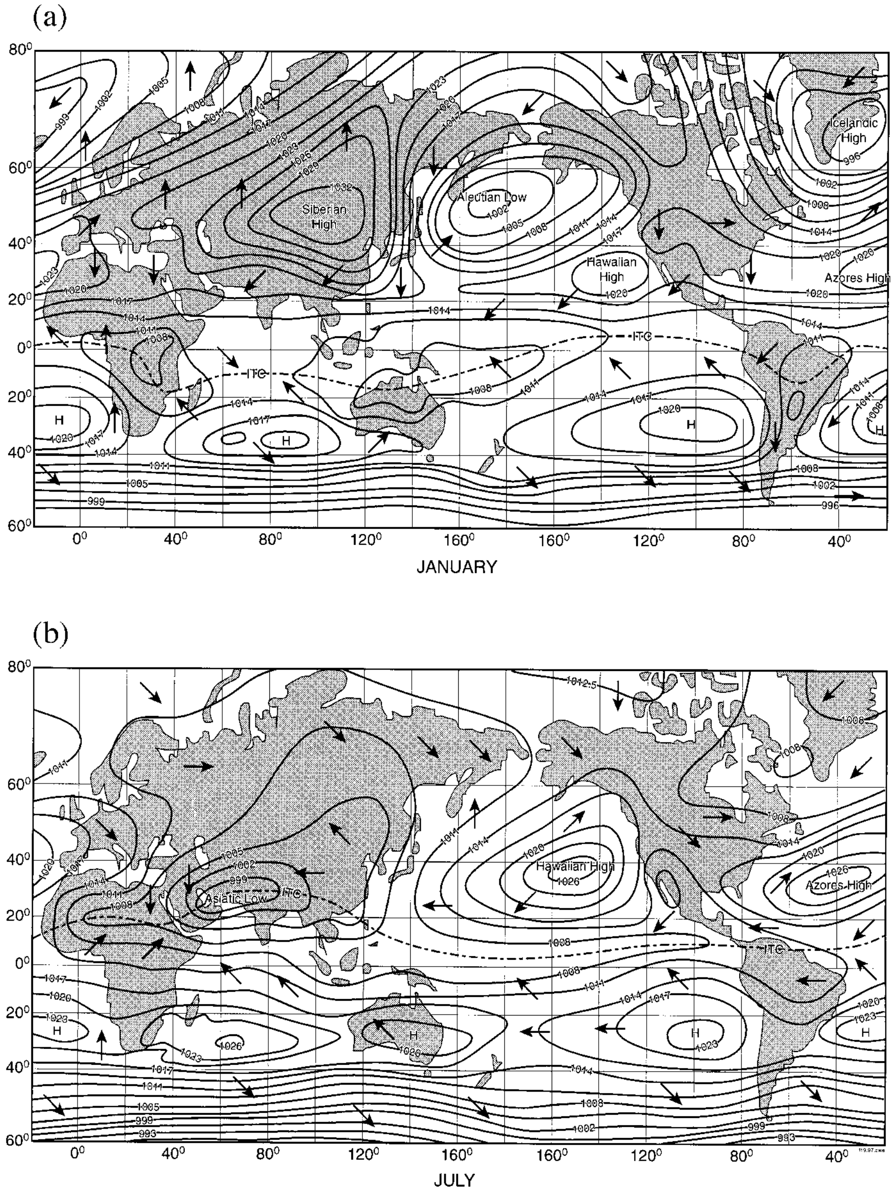

Fig. 5. (**a**) and (**b**).

indicating that the summer monsoon circulation persisted at that time. This evidence, together with reconstructed aeolian dust transport patterns, led Sirocko *et al.* (1993) to argue that the northernmost frontal position of southwest monsoon winds during Termination 1a was similar to that of today, but persisted for a shorter seasonal timespan. Summer monsoon intensity and/or seasonal duration increased at the end of the Younger Dryas (approximately 11.5 ka BP), reaching its Holocene maximum between 9 ka and 10 ka years BP. Evidence for enhanced summer monsoon circulation during the early Holocene is also provided by pollen records from lake cores in Rajasthan, which indicate that effective summer precipitation was considerably higher than modern values (Bryson & Swain 1981; Swain *et al.* 1983).

Long records (350 ka) of upwelling from Arabian Sea cores indicate several peaks in the intensity of the summer monsoon, the most prominent of which are at approximately 9, 50, 100–120, 200–215, 260, and 350 ka BP (Clemens *et al.* 1991; Emeis *et al.* 1995). Cyclicity in the upwelling records has been shown to be in phase with Milankovitch insolation cycles. Prell & Kutzbach (1987) and Clemens *et al.* (1991) found significant coherence between monsoon intensity and the 23 000 year precession cycle and the 41 000 year obliquity cycle, with periods of strengthened summer monsoon occurring at Northern Hemisphere radiation maxima. GCM simulations have shown that insolation maxima enhance the heating over the Indian subcontinent and High Asia, increasing the land–ocean thermal and pressure gradient that drives the summer monsoon circulation (Kutzbach 1981, 1987; Kutzbach & Otto-Bliesner 1982; Prell & Kutzbach 1987).

Radiative forcing alone, however, cannot account for monsoon variability over the last 350 000 years. Anderson & Prell (1993) and Emeis *et al.* (1995) found that upwelling intensity is strongly correlated with the $\delta^{18}O$ record, which reflects global ice volume and the 100 000 year eccentricity cycle. They concluded that the most likely explanation for this correlation is the influence of snow and ice cover on the albedo of High Asia, making the assumption that the extent of snow and ice on the Tibetan plateau is in phase with global ice volume. It was argued that, at global glaciation maxima, the higher

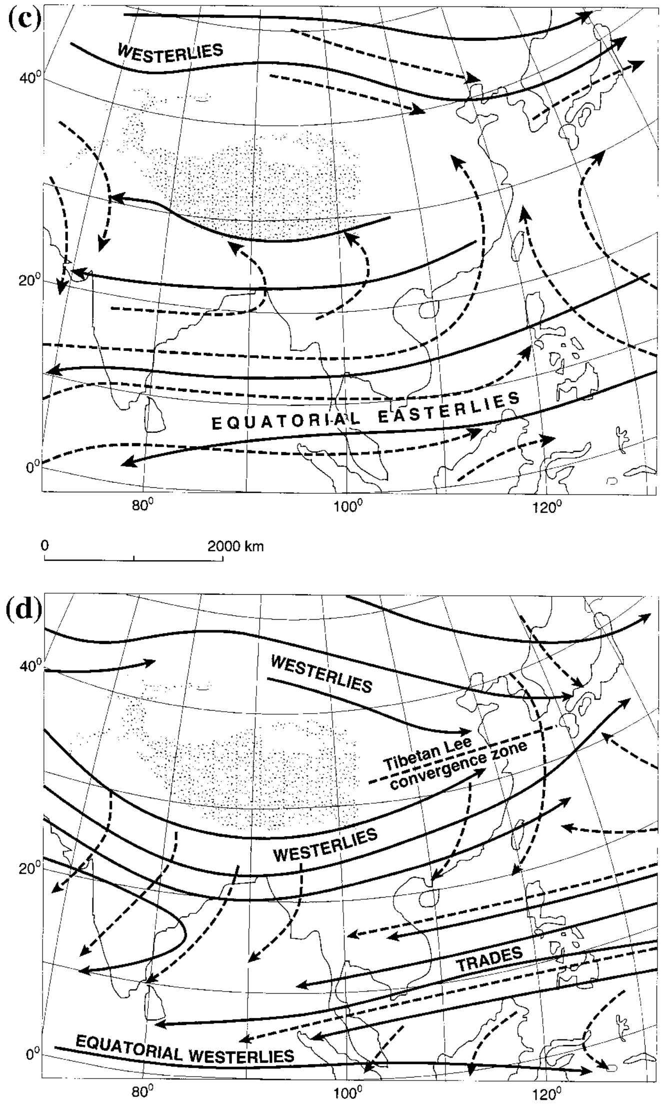

Fig. 5. The characteristic air circulation over the western hemisphere for (**a**) Summer (July) and (**b**) winter (January). (**c**) and (**d**) show the detailed circulation over southern and eastern Asia with respect to the Tibetan Plateau and bordering mountains. The solid lines indicate airflow at about 3000 m and the dashed lines that at about 600 m. The names refer to the air systems. The area of Tibet and the Himalayas that lies above 6000 m is shaded. (**c**) shows summer conditions while (**d**) shows winter conditions (Adapted from Barry & Chorley 1992 and Strahler & Strahler 1996).

albedo of the Asian land mass will tend to reduce the summer heating effect and decrease the atmospheric pressure gradient that drives the summer monsoon circulation. Furthermore, Emeis *et al.* (1995) proposed that more extensive and late-lying snow cover over high Asia would strengthen and increase the duration of the northerly winter monsoon, delaying the onset of warm, southwesterly winds in the summer and lowering Arabian sea surface temperatures. In support of this idea, they cited Kuhle's (1986) reconstruction of a Late Pleistocene icecap on the Tibetan Plateau, covering an area of 2–2.4 × 10^6 km^2 and indicating snowline lowering of 1100–1500 m relative to the present (see also Kuhle 1987, 1988). However, the existence of a large Pleistocene Tibetan icecap is disputed, and the field evidence strongly suggests that the maximum extent of glacier ice in the Late Pleistocene was much more restricted and limited to the mountain chains surrounding the plateau (e.g. Burbank & Kang 1991; Derbyshire *et al.* 1991; Zheng 1989*b*).

The lack of evidence for a Tibetan icecap, however, does not refute the idea that the winter monsoon formed an important component of the atmospheric circulation during global glacial maxima. Ding *et al.* (1995) found that grain–size variations in loess sections in north-central China, east of the Tibetan Plateau, record variations in the strength of northerly and northwesterly winds in phase with Milankovitch orbital cycles, particularly the 100 ka eccentricity cycle, with wind intensity being greatest during global glaciation maxima. Aeolian loess transport in northern China is strongly associated with the East Asian winter monsoon, when cold, dry air spreads out from the Siberian High and entrains dust in the inland deserts of northern and northwestern China (Fig. 4b). The strong coherency between grain-size variation and the eccentricity cycle, therefore, indicates that variations in winter monsoon intensity are closely related to global ice volume changes and/or times when there was a strengthened Siberian High. Two main mechanisms were suggested to explain this relationship (Ding *et al.* 1995). First, lower average temperatures during glacial periods produced a reduction in vegetation cover and an increase in albedo, tending to maintain low temperatures in the continental interior and enhancing the seasonal Siberian High and winter westerlies. Second, the presence of large ice sheets and sea-ice in Europe, northern Asia and the adjacent oceans may have intensified the Siberian High, possibly allowing it to become a perennial feature during glacial maxima. Ding *et al.* (1995) speculated that the Siberian High and the winter monsoon were dominant elements of the

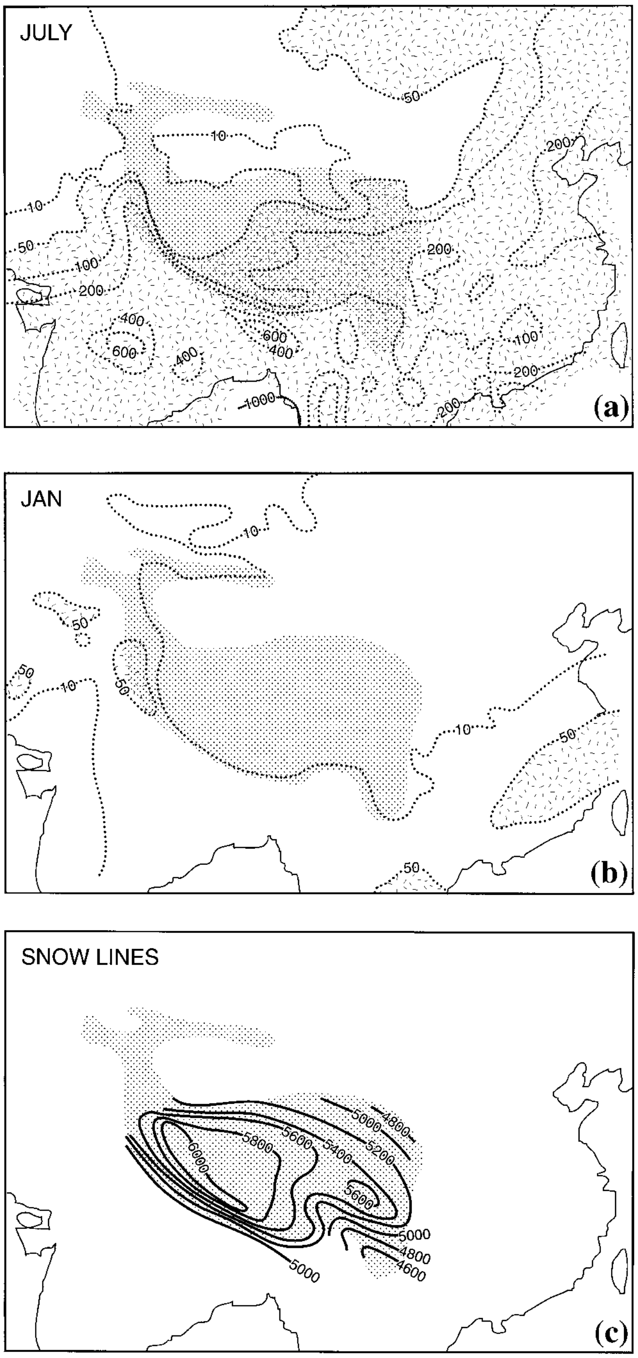

Fig. 6. (**a**) Mean precipitation for the months of July (upper panel) and (**b**) January (lower panel), and (**c**) snowline altitudes for the Himalaya, Tibetan Plateau and adjacent regions. (**a**) and (**b**) redrawn from Murakawi (1987), and (**c**) from data after Lanzhou Institute of Glaciology and Geocryology, Academia Sinica (1985).

atmospheric circulation in East Asia during glacial stages, but were not effective in the Indian subcontinent due to blocking of airflow by the Tibetan Plateau and Himalaya. An enhanced Siberian High and lower average continental temperatures during glacial periods could, however, have influenced South Asian monsoon circulation by delaying development of the seasonal heat controlled low pressure system over Tibet, through vegetation–albedo effects and, possibly, by influencing the seasonal position and duration of the southern branch of the westerly jet. Continental cooling during glacial periods could have been further enhanced through prolonged winter snow-lie, as suggested by Emeis *et al.* (1995). Furthermore, Porter & An (1995) showed that grain-size data from the Chinese loess and intercalated accretionary palaeosols of last-glacial age provided evidence of similar climatic signals to those in the North Atlantic region. They saw grain-size maxima with ages that matched those of the last six Heinrich events, which they interpreted indication of the changing strength of the East Asian winter monsoon, which largely controls the transporation and deposition of aeolian dust in central Asia. They suggested that such a correlation implies that the climates of the North Atlantic and China were linked by the effect of the westerly winds.

One of the longest continuous palaeoclimatic record in the Himalayan–Tibetan Plateau region is from ice cores from the Dunde Ice Cap (Figs 1 and 2), which extend back about 40 ka BP (Thompson *et al.* 1989, 1990). Oxygen isotope values suggest relatively warm conditions at *c.* 38–30 ka BP, followed by a cold interval, then a gradual return to warm conditions at between 12 ka and 10 ka BP. Dust concentrations are very high for the interval 30 000 to 11 000 years ago, suggesting vigorous wind circulation and aeolian transport during the cold conditions of the Late Glacial Stage (LGS). Wind strength apparently dropped abruptly at the beginning of the Holocene. The Dunde ice core records also show low concentrations of soluble species during the LGS, rising to higher values at the LGS–Holocene boundary, apparently recording variable transport of salt and calcareous dust from the Qaidam basin. The increase in solute transport can be explained by increasing desiccation of the Qaidam basin towards the end of the LGS. Chen & Bowler (1986) showed that lake levels in the basin were high from *c.* 40 000 to *c.* 25 000 radiocarbon years BP, thereafter they declined due to a reduction of precipitation and/or an increase in evaporation. A reduction of effective precipitation after about 25 000 radiocarbon years BP is also recorded in the pollen and macrofossil record in river terraces deposits in the Northern Qingling Mountains, Tibet (Pachur *et al.* 1994). Data from the Dunde Ice Cap and the northern Tibetan Plateau, therefore, indicate windy, cold and humid conditions at the Last Glacial Maximum, shifting to calmer, warmer and drier conditions towards the end of the LGS. It should be noted, however, that the dating of all these records is poorly constrained and may be revised in the future (Thompson *et al.* 1990).

A pollen record from *c.* 30 ka to 9 ka BP has been obtained from Tsokar Lake in Ladakh (Bhattacharyya 1989). During this period, the vegetation was predominantly cold, alpine steppe type, but with four periods of expansion of *Juniperus* communities at *c.* 28–30 ka BP, *c.* 22–18 ka BP, 16 ka BP, and 10 ka BP. Note that these dates, however, are based on an assumed constant sedimentation rate determined from four radiocarbon dates within the succession and they, therefore, may be subject to a quite large degree of error. These episodes of *Juniperus* expansion were interpreted as episodes of warmer and moister climate, when the tree-line extended to higher altitudes (Fig. 2). The most pronounced of these episodes was at *c.* 22–18 ka BP, which was a period of persistently dry climate in peninsular India. However, Bhattacharyya (1989) noted that evidence for warmer or wetter intervals at *c.* 18 ka BP and before 15 ka BP has been reported from Kashmir, and that episodes of warmer or wetter climate occurred at these times in parts of the Mediterranean. The apparent synchrony of climatic oscillations in Ladakh and regions to the west, but not the south, suggests that the vegetational changes recorded by Bhattacharyya (1989) reflect fluctuations in westerly atmospheric circulation or moisture advection, rather than variations in the summer monsoon.

Gupta *et al.* (1992) argued that the Tibetan Plateau and Indian subcontinent experienced a major warm episode between *c.* 20 ka and 16 ka BP, based on their interpretation of an ocean core from the eastern Arabian Sea, the evidence from Ladakh and Kashmir, and oscillations in the δ^{18}O record from the Dunde Ice Cap (Fig. 2). The Arabian Sea evidence consists of a major oscillation of δ^{18}O in the tests of planktonic formainifera (Sarkar *et al.* 1990; Fig. 2), which they interpreted as the result of a 'freshwater spike' introduced by increased runoff from Himalayan glaciers into the Bay of Bengal. By modelling the isotopic composition of the ocean, they concluded that the 'freshwater spike' could be accounted for by an increase in runoff of 176.4 $\mathrm{km}^3\ \mathrm{a}^{-1}$ sustained for 4000–5000 years, which they reasoned could have been supplied by melting of an ice cap covering the Tibetan Plateau. However, most researchers who have worked in the region agree that a late Pleistocene Tibetan Ice Cap did not exist (see above), so that Himalayan glaciers were not extensive enough to supply the necessary volume of water. Further, this isotopic model neglects rainfall over the ocean, which is a major determinant of salinity (e.g. Fairbanks 1989; Webster 1994). Therefore, there is not a strong case for large-scale ablation of Himalayan glaciers during the period 20–16 ka BP.

Holocene environmental changes in northern Tibet and on the loess Plateau are shown in Fig. 3. Lake levels in northern Tibet exhibit a broadly synchronous expansion in mid-Holocene times, indicating increased humidity approximately contemporaneously with the Holocene climatic optimum (Fig. 3a). In early and late Holocene time, however, there was a general contraction of lakes as the region experienced increased aridity. The loess record in Gansu Province in China, supports this view with palaeosol development dominating during mid-Holocene times (Fig. 3c). These episodes of high lake levels and palaeosol development are broadly contemporaneous with glacier advances in northwestern China, but appear to be out of phase with glacier expansions in southwestern China and Langtang. These data, therefore, helps support the view that glaciers throughout the Himalayas and Tibet are influenced by the monsoon and westerlies to differing extent, such that the monsoon is strengthened during times of increased warmth in the northern hemisphere supply and hence produced greater amounts of precipitation, allowing glaciers to grow. In contrast, in regions that were not influenced by the summer monsoon, the glaciers and ice sheets retreated.

In summary, long-term variability in the intensity and/or duration of the South Asian summer monsoon is correlated with the 23 000, 41 000, and 100 000 year orbital cycles. The precession and obliquity cycles determine the timing of insolation maxima and the magnitude of the thermal and pressure gradients between the Indian Ocean and the South Asian landmass which drive the summer monsoon. A strong influence is also exerted by the 100 000 year eccentricity cycle, probably due to the effects of global cooling on continental albedo and the effects of the large mid-latitude ice sheets on atmospheric circulation. At the time of the last glacial stage (*c.* 30–11 ka BP), the South Asian monsoon was less intense and/or had a shorter seasonal duration than today. In Kashmir, Ladakh, and the Tibetan Plateau, conditions appear to have been windy and humid, probably as the result of enhanced westerly circulation. Climate in the region was variable at this time, with millennial-scale fluctuations in temperature and humidity. On the loess plateau, windy, continental conditions predominated. Around the beginning of the Holocene, the South Asian monsoon increased in intensity, and there was a decrease in wind intensity on the northern Tibetan Plateau. At the same time, the Plateau became more arid. During the Holocene, climatic fluctuations in the northern Tibetan Plateau and regions to the south appear to have been out of phase.

Discussion

The timing of glacier expansions in the Himalayan and Tibetan Plateau region suggests that glaciers responded to a variety of climatic signals. In the northern regions of Tibet and northern Karakoram, the local late Pleistocene glacial maximum was apparently synchronous with northern hemisphere ice sheet maximum of *c.* 20–18 ka BP (oxygen isotopic stage 2: Fig. 2a & b). This suggests that in this area, glaciers expanded in response to mid-latitude cooling and/or an increase in precipitation advected by westerly winds. The early Holocene was apparently arid in northern Tibet, but lakes expanded during mid Holocene times, broadly correlating with the Holocene climatic optimum (Fig. 3). Glaciers in northwest China advanced during early and mid Holocene times, possibly fed by precipitation carried by westerly air systems (Fig. 3b).

The available dating evidence indicates that Late Pleistocene glacier expansions in Lahul, Garhwal and the Karakoram Mountains were not synchronous with the global ice-volume maximum. Instead, glacier advances culminated between 60 ka and 30 ka BP (Fig. 2), and during the early and late Holocene times. The two earlier of these periods of glacier expansion coincide with the two most recent Northern Hemisphere insolation maxima and episodes of enhanced summer monsoon circulation as reconstructed from the Arabian Sea upwelling record (Berger 1978, 1988; Prell & Kutzbach 1987; Clemens *et al.* 1991; Emeis *et al.* 1995). A more intense and/or longer-lasting summer monsoon during the early Holocene is also indicated by patterns of dust transport over the Arabian Sea and precipitation records from Rajasthan (Bryson & Swain 1981; Swain *et al.* 1983; Sirocko *et al.* 1991). On the basis of alkenone-unsaturation index of sedimentary lipids extracted from sediment samples off the coast of Oman, Emeis *et al.* (1995) showed that sea-surface temperatures were high during interglacials (up to 27°C, although upwelling is enhanced) and low during glaciations (22–24°C, although upwelling is suppressed). This indicated a glacial–interglacial change of >3°C in spite of a dampening effect of enhanced or weakened upwelling. The expansion of Karakoram and western Himalayan glaciers between 60 ka and 30 ka BP and during the early Holocene, therefore, probably reflects increased summer monsoon precipitation and positive glacier mass balances. Conversely, glaciers in this region were less extensive during global glacial maxima due to increased continentality of the climate of High Asia. Albedo effects and the influence of the great Northern Hemisphere ice sheets on energy balance and atmospheric circulation may have led to less northerly penetration and/or shorter duration of the summer monsoon, resulting in precipitation starvation and negative glacier mass balance.

It may appear paradoxical that glacier expansions should have occurred during maxima in monsoon intensity, because the sensible and latent heat released by monsoon storms should be expected to cause increased glacier ablation. However, the very high altitude of most glacier catchment areas in the Himalaya, particularly avalanche source areas, means that a large proportion of summer precipitation will fall as snow even if summer temperatures are higher than present values. Avalanching is particularly common in the Karakoram and neighbouring ranges in summer during 'break-monsoon' situations, when an equatorward-penetrating trough in the upper westerlies (at a time of highly meridional upper flow) overlies the low-level monsoon flow and draws it unusually far north, thus causing drought in the Gangetic Plain. During precipitation maxima, the additional input of snow from avalanches could have been sufficient to counteract higher ablation. Additionally, the debris cover on the snouts of many Himalayan glaciers would tend to dampen the effects of increased temperatures on glacier mass balance.

Glaciers were in an expanded state at the time of the last global glaciation maximum in the Khumbu Himal, Garhwal, and possibly Lahul, areas which presently receive substantial precipitation during the summer monsoon (Figs 2 & 6). This period of glacier expansion probably cannot be explained by increased summer precipitation, because monsoon intensity was reduced at that time. Similarly, it is unlikely to reflect increased winter, westerly precipitation, because glaciers situated to the west (Swat, Hunza: Fig. 2) apparently did not expand at that time. Instead, the expansion of southern and eastern Himalayan glaciers may have resulted from regional cooling, which reduced ablation during the summer accumulation season. Thus, effective precipitation may have been increased, resulting in positive glacier mass balances.

Clearly, many more absolute dates for glacier chronologies and a much better spatial coverage are needed to test the hypotheses outlined above. If the climatic controls on glacier fluctuations can be demonstrated, then spatio-temporal patterns of glaciation in High Asia have the potential to elucidate the extent of summer monsoon circulation in the past, and its interaction with mid-latitude systems under glacial and interglacial conditions. Additionally, the relationships between monsoon circulation and glacier response have important implications for the human population of South Asia, because glacier response to more vigorous summer monsoon circulation may influence catchment hydrology and the frequency of glacier-related hazards such as lake outburst floods and slope failures.

Thanks to J. Jackyno for drafting the diagrams, and A. Dawson and N. Rutter for useful comments on the manuscript.

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Received 22 October 1997; revised typescript accepted 31 July 1997.
Scientific editing by Ian Fairchild.