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The history and variability of the East Asian paleomonsoon climate

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Abstract

Changes in the East Asian paleomonsoon reflect interactions between the global atmosphere, ocean, land and ice systems, and are also an expression of their combined effect within the boundary conditions imposed by the East Asian continent and solar radiation. The history of the East Asian monsoon is an alternation between dominance by the dry-cold winter and warm-humid summer monsoons. High-resolution eolian sequences preserved in the Chinese Loess Plateau reveal that the East Asian monsoon may have commenced at least 7.2 Ma ago. They also provide evidence indicating that the pulsed uplift of the Tibetan Plateau at about 3.4 and 7.2 Ma may have played an important role in inducing climate change. The palaeoclimatic records of the last glacial cycle show high-frequency variability on time scales of 1000-year or even shorter, and instability of the East Asian paleomonsoon system. The high-frequency variability could be due to a non-linear response to orbital forcing, or a result of the coupling processes between different components of the global system. Cold air activity in northern high latitudes, the trans-equatorial air streams from the Southern Hemisphere and, possibly, ENSO may have played an important role in East Asian monsoon variability. The synchroneity of all the palaeoclimatic events along the polar-equator-polar (PEP) transect is still an open question. Correlation of limited palaeoclimatic records for the last 30 kyr obtained from East Asia and Australia suggests that the trans-equatorial air streams driven by the monsoon and trade winds may have had an influence on opposite hemispheres.

1. Introduction

The East Asian monsoon is an integral part of the global climatic system. Monsoon climates, and especially monsoon-associated precipitation, are important to the maintenance of living environments and socially sustainable development in populous regions of East Asia. As a result, they have attracted the attention of many climatologists and geographers (e.g. Gao and Xu, 1962; Ye and Gao, 1979; Zhang and Liu, 1992). The importance of monsoon research has been acknowledged by Chinese Quaternary scientists (Yang and Xu, 1985; Li et al., 1988), but until the late 1980s, they did not realise that East Asian monsoon evolution is a principal and direct factor that controls palaeoenvironmental changes in East Asia. This contention has been derived from geological and biological studies of the well-known loess-paleosol sequences in central China. Loess is dust transported and deposited from its source areas by the northerly winter monsoon, while the development of interbedded paleosols is closely associated with the southerly moisture-bearing summer monsoon (An et al., 1990a, 1991a,b). Much research has been carried out on paleomonsoon records of various types, and has provided a framework of dynamic control for East Asian monsoon evolution over the last 130 kyr and 20 kyr, and lead to the hypothesis that the monsoon is the controlling force for palaeoenvironment changes in East Asia. As a result, the study of East Asian paleomonsoon changes has been an area of increasing interest in the last few years (Porter et al., 1992; Shi et al., 1992; Zhou et al., 1992; Ding et al., 1992; An et al., 1993; Liu and Ding, 1993; Rutter and Ding, 1993; Ding et al., 1994; Zhou et al., 1994; Porter and An, 1995; Wang et al., 1995; Xiao et al., 1995; An and Porter, 1997; Vandenberghe et al., 1997; Huang et al., 1997; Thompson et al., 1997; An and Thompson, 1998; Zhou et al., 1998; Xiao et al., 1998; Zhang et al., 1998).

Palaeomonsoon and palaeoenvironment research in China currently targets two research areas: (1) the examination of high-resolution records such as loess, lake, palaeo-ocean, ice core and cave deposits for the last glacial cycle, the last deglaciation and the Holocene; as well as tree rings and historical documents for the last 2000 years, to evaluate climatic instability and its possible relation to the East Asian monsoon climate; (2) the extraction of information dealing with the inception

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and/or evolution process of the East Asian monsoon from the eolian sequences deposited over the last 7 Ma in the Chinese Loess Plateau, exploration of the relationship between East Asian monsoon evolution, global ice volume and uplift of the Tibetan Plateau (An et al., 1999), and understanding of the contribution of the East Asian monsoon and this plateau uplift to the global climatic system. Spatially, palaeomonsoon research has extended from the Loess Plateau to the Chinese marginal seas and the West Pacific Warm Pool (WPWP). Specific attention has been given to the frontal migration of the monsoon regime for the last 130 ka, and the diachroneity of the Holocene optimum (An et al., in press; Sun et al., 1996). It is clear that the study of the East Asian monsoon system should be placed within the context of global change. A better investigation of the response and contribution of the East Asian monsoon to the integrated behaviour of the entire global climatic system will result in a better understanding of processes involved in the evolution of the East Asian monsoon itself.

East Asian monsoon circulation is closely associated with climatic features of northern high latitudes, and is also linked with the equatorial ocean and the Southern Hemisphere (Zhao and Wang, 1979; Wang and Li, 1982; Tao and Chen, 1988; Chen et al., 1991). The transportation of water vapour and heat from the equatorial ocean to the middle and high latitudes is of vital importance in understanding global water patterns and global changes (Broecker, 1994a,b; Thompson et al., 1997). This paper will first examine its modern characteristics, and then will review the history and variability of the East Asian monsoon regime, its relationship with the palaeoclimates of the northern high latitudes, low latitude oceans and the Southern Hemisphere. This may provide important information for the prediction of future climatic changes in East Asia and the world.

2. East Asian monsoon

The East Asian monsoon regime is a sub-system of the Asian monsoon circulation. It affects an area to the east of the Bay of Bengal and the Tibetan Plateau. Climatic observations indicate that it is independent of, but interacts with, the Indian monsoon (Gao and Xu, 1962; Chen et al., 1991; Zhang and Liu, 1992). The East Asian monsoon is formed as a result of thermal differences between the Asian landmass and the Pacific Ocean, and is further enhanced by the thermal and dynamic effect of the Tibetan Plateau. The East Asian monsoon and the monsoon rains are also linked with cold air in high latitudes, low latitude SST and water vapour, the ocean–atmosphere interaction associated with the WPWP and the tropical circulation system containing the Intertropical Convergence Zone (ITCZ), which is under the influence of trans-equatorial streams. In the northern winter season, cold air from high latitudes is controlled by the continental high-pressure system, and propagates southward along the eastern margin of the Tibetan Plateau to form the strongest northerly dry and cold winter monsoon in the world. The northern winter monsoon can extend to tropical South China, even crossing the Equator to trigger southern summer monsoons; while in the northern summer season, warm and humid air originating from the low latitude oceans migrates north along with the seasonal changes of planetary scale circulations, and is further driven by the east–west pressure gradient in East Asia. Warm and humid air can extend northwesterly into China's interior as far as the China-Mongolia border, thus forming the northernmost summer monsoon in the world. The East Asian monsoon climate is characterised by prominent seasonal changes in wind direction, precipitation and air temperature between winter (cold and dry) and summer (hot and humid).

The Australian monsoon system is relatively weak compared with the Indian and East Asian monsoon systems, but it possesses all the main features of a typical monsoon regime (Suppiah, 1992). The Australian summer monsoon and monsoon rain affects an area which includes Indonesia, Papua New Guinea and northern Australia, but does not extend very far into the interior of Australia. Australian monsoonal precipitation is closely linked to the trans-equatorial cold surge of the northern winter monsoon, and the boundary conditions of the Australian continent. It is also closely associated with the seasonal shifts of the ITCZ and tropical cyclone variations. The trade wind outflow from travelling mid-latitude anticyclones can be referred to as the Australian winter monsoon (Wasson, 1995).

The 1000 hPa streamlines of Australia and East Asia in Fig. 1 show the relationship between the East Asian and Australian monsoons (Kalnay et al., 1996). In January, cold air controlled by the Siberian high migrates south along the eastern margin of the Tibetan Plateau in the form of anticyclones. It passes over the South China Sea, crossing the Equator near Singapore to enhance the Australian summer monsoon. In July, the southeasterly outflow from the trade winds of northern Australia migrates north, crossing the Equator and then changes direction to become a south-westerly wind which can extend to the northern interior of China as far as 40°N. This warm and humid air can enhance the East Asian summer monsoon. It is therefore believed that there exists a large-scale air exchange with seasonally opposite directions between East Asia and Australia (Zhao and Wang, 1979; Wang and Li, 1982). This direct interconnection along PEP II longitudes implies that both East Asian and Australian monsoons are linked with a "pressure push" from the opposite hemisphere, and are also linked with a "thermal pull" resulting from the low pressure and high SST, as generalised in Fig. 2.

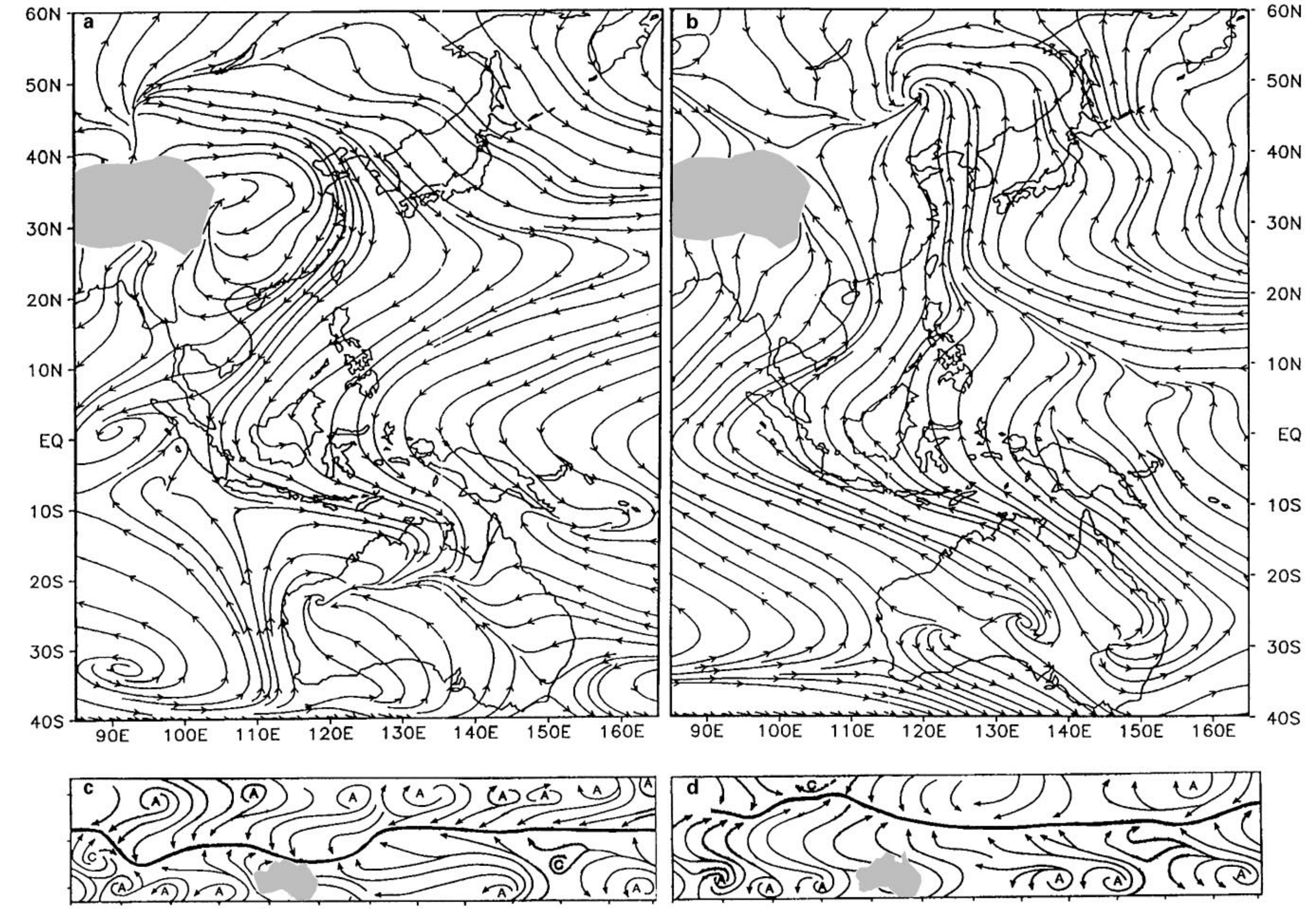

Fig. 1. 1982–1994 mean 1000hPa streamlines for January (a) and July (b) over the East Asia-Australia regions (cf. Kalnay et al., 1996). The two diagrams illustrate the atmospheric exchange between the Northern and Southern Hemispheres and indicate the dynamical basis for teleconnections in the pattern of climate change between Australia and East Asia. c and d show mean positions of the Intertropical Convergence Zone in January (c) and July (d), and streamlines of near surface flow in the tropics. The shaded areas indicate the Tibetan Plateau and Australia, respectively. A denotes an anticyclonic center. C denotes a cyclonic center (modified after Hastenrath, 1988).

Palaeoclimatic records of the late Quaternary period to be discussed later will provide evidence for the East Asia–Australia connection and this "pressure-push" hypothesis.

3. The history of the East Asian monsoon climate

Loess deposits are widespread in central China, covering an area of about 500,000 km^2 with a thickness of 150–300 m. Geological, biological and chemical evidence derived from loess-paleosol sequences for the last 2.5 Ma in the Loess Plateau (Fig. 3) (Liu, 1985; Kukla, 1987; Kukla et al., 1988; Kukla and An, 1989) indicates that loess is the deposition of dust transported by the northerly winter monsoon. Particle-size, aeolian flux and detrital quartz composition can be used as proxy indices of the winter monsoon (An et al., 1991a; Ding et al., 1994; Xiao et al., 1995). In contrast, the interbedded paleosols were formed by pedogenesis under summer monsoon conditions. Magnetic susceptibility, organic carbon content, stable carbon isotope ratio, ^{10}Be content, chemical weathering index and carbonate content of paleosols can be used as proxy indices of the summer monsoon (An et al., 1991b; Shen et al., 1992; Lin and Liu, 1992; Jia et al., 1995). The loess-paleosol sequences in central China basically record a history of alternation between winter and summer monsoon dominance, which can be seen as a reflection of global climatic cycles in East Asia (An et al., 1990a; Porter et al., 1992).

The time series of monsoonal fluctuations for the last 2.5 Ma recorded in the loess-paleosol sequences can be correlated with deep-sea oxygen isotope records (Liu, 1985; Kukla, 1987; Kukla et al., 1988; Kukla and An, 1989; Ding et al., 1994). Changes in the intensity of the winter monsoon reflected by particle-size distribution within loess deposits at Baoji (34°24′N, 107°18′E), central China, agree well with global ice volume variations (Ding et al., 1994), while changes in the intensity of the summer monsoon reflected by magnetic susceptibility variations

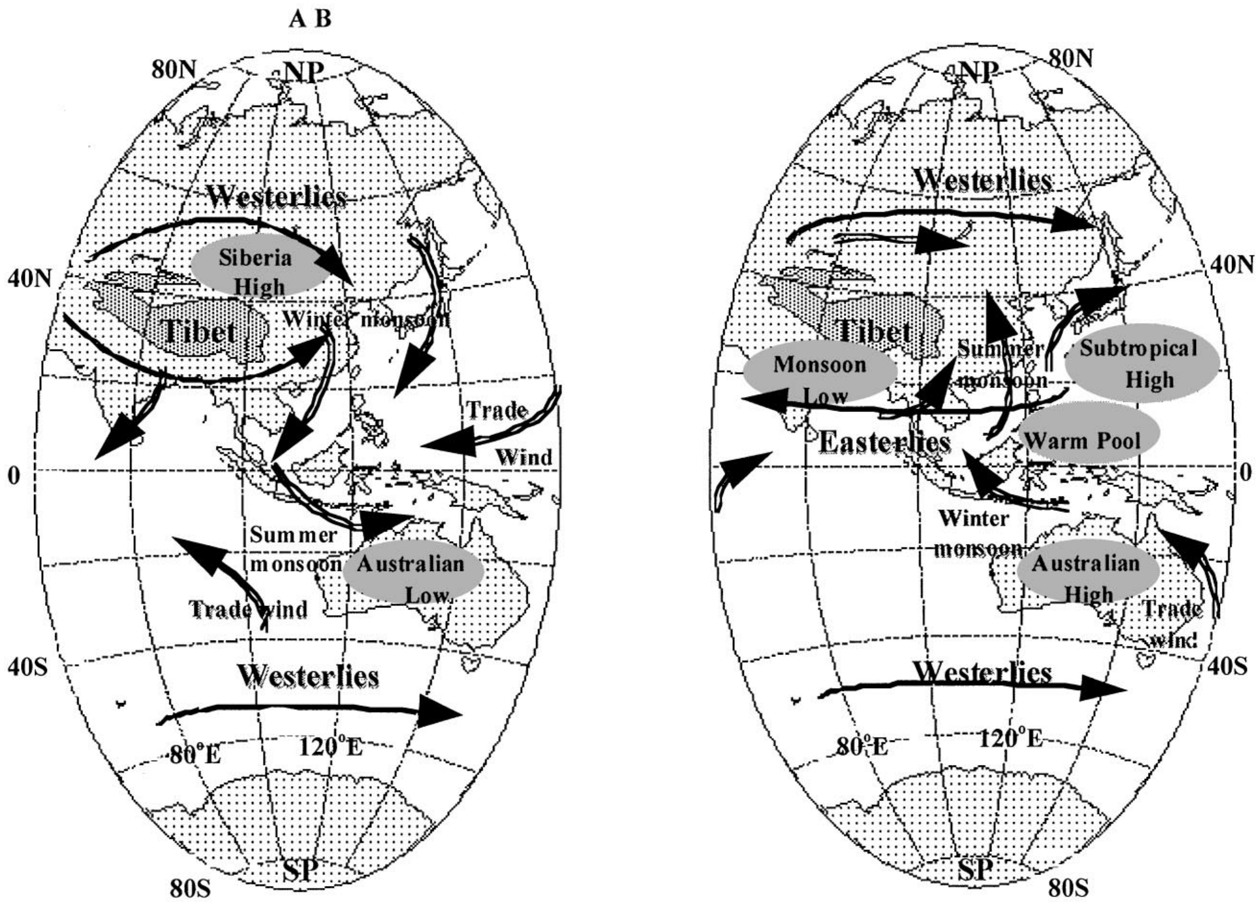

Fig. 2. Schematic view of the main atmosphere characteristics along the PEP-II longitudes during the northern Hemisphere winter (A) and summer (B). The dominant flows in the middle and low tropospheres are indicated by closed and open arrows respectively. The most important pressure systems are the Siberian high and the Australian low for the Northern Hemisphere winter; the Indian Monsoon low, the western Pacific subtropical high, and the Australian high for the Northern Hemisphere summers. The thermal effect of lower boundary conditions changes seasonally, which causes seasonal reversal of the pressure system. This illustrates that a pressure-driven exchange of monsoon circulation or trade winds exists between Australia and East Asia.

show both similarities in climatic cycles and differences in amplitudes of climatic fluctuations with global ice volume. Spectral analysis of the monsoon proxy time series from the central Loess Plateau shows strong Milankovitch periodicities, including 100 kyr, 41 kyr (obliquity) and 23 and 19 kyr (precession) (Hua et al., 1990; Kukla et al., 1990; Ding et al., 1994, 1995). It is worth noting that the 100 kyr cycles are quite prominent for the last 800 kyr. These have been correlated with climatic records obtained from Lake Baikal (53°40′N, 108°22′E) in northern East Asia, where spectral analysis has also suggested strong nonlinear 100 kyr. and relatively weak 41 and 23 kyr periodicities (Colman et al., 1995; Williams et al., 1997). This evidence indicates that, like the Lake Baikal record, East Asian monsoon evolution is driven by the nonlinear rhythm of the ocean and ice sheets, together with orbitally induced changes in insolation and global ice volume.

The "red clay" underlying the loess-paleosol sequences in the Loess Plateau is composed mainly of reddish/yellowish loess and reddish paleosols. It has long been referred to as "Pliocene Red Clay" due to the fact that it contains *Hipparion sp.* (Zdansdy, 1923; Qiu et al., 1987). Recent work has shown that the red clay is of aeolian origin (Liu et al., 1988; Zhao, 1989; An et al., 1991c). The red clay is distributed over an area similar to the Early Pleistocene Wucheng Loess. A great deal of grassland mammal fossils and dry land snails have been found in this material (Zhang and Xue, 1995). The chemical composition (Zhao, 1989), magnetic susceptibility (Liu et al., 1988; Zhu et al., 1996) and particle-size distribution of the clay are comparable to those of the overlying loess and paleosols. Red clay is composed mainly of a silt fraction (5–50 μm) (Table 1), slightly finer than loess. The grain-size composition of the red clay also has a normal, or near-normal distribution, typical of aeolian deposits. An et al. (1991c) pointed out that the red clay was also formed under monsoon climatic conditions since there are many pedo-carbonate nodule layers indicating seasonal formation through the profiles.

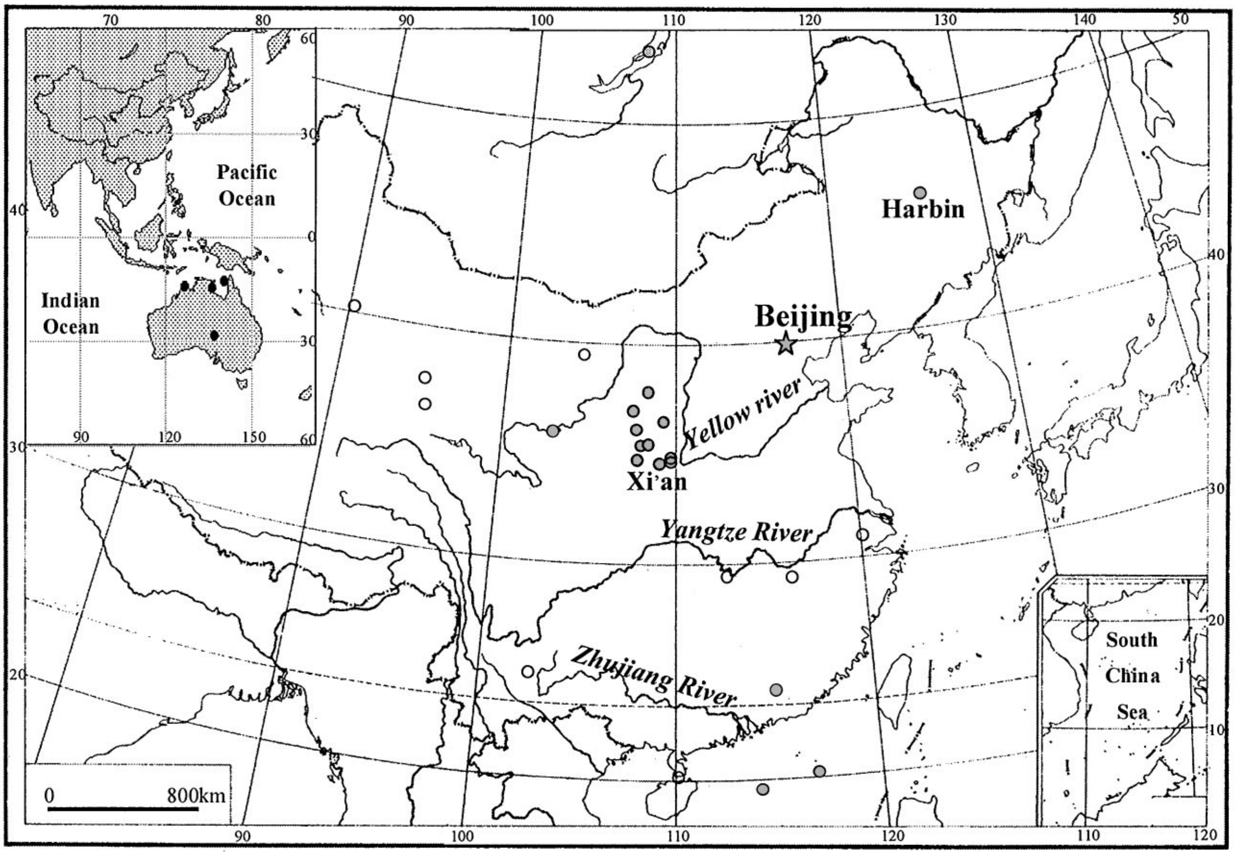

Fig. 3. Map indicating the locations of sites (closed circles) containing key climatic records. These are listed below from north to south: Baikal (53°40′N, 108°22′E); Harbin (45°48′N, 126°54′E); Beijing (39°54′N, 116°24′E); Midiwan (37°39′N, 108°37′E); Huanxian (36°30′N, 107°18′E); Xifeng (35°38′N, 107°25′E); Luochuan (35°45′N, 109°25′E); Beiyuan (35°37′N, 103°12′E); Xunyi (35°20′N, 108°18′E); Lingtai (35°04′N, 107°39′E); Baoji (34°24′N, 107°18′E); Weinan (34°20′N, 109°29′E); Xi′an (34°17′N, 108°51′E); Daping (24°15′N, 115°02′E); Core 17940 (20°07′N, 117°23′E); Core SO49-8KL (19°11′N, 114°12′E); Core GC-2 (12°31′S, 140°21′E); Kapalga (14°12′S, 126°36′E); Groote Eylandt (14°25′S, 136°25′E); Lake Eyre (28°30′S, 137°15′E). High lake levels during late MIS3 in China are marked by open circles. The major lake level data are taken from Fang (1991), the data associated with Baijian and Beizhuancun are taken from Pachur *et al.* (1995) and An *et al.* (1990b) respectively. These sites are listed below from north to south: Lop (40°12′N, 90°09′E); Baijian (39°01′N, 104°01′E); Dachaidan (37°30′N, 95°14′E); Qarhan (36°18′N, 95°18′E); Beizhuangcun (34°20′N, 109°29′E); Taihu (31°07′N, 120°06′E); Dongting (29°12′N, 112°30′E); Poyang (29°03′N, 116°12′E); Dianchi (24°51′N, 102°42′E); Tiangyang (20°30′N, 110°18′E).

Many recent studies of the magnetostratigraphy of the Xifeng (35°38′N, 107°25′E) and Lingtai (35°04′N, 107°39′E) loess-paleosol-red clay profiles indicate that aeolian deposition in China started as early as 7.2–7.3 Ma (Sun et al., 1997, 1998), much earlier than 5.0 Ma which was proposed by Zheng et al. (1992). This indicates a possible earlier inception of the East Asian monsoon, implying that at about 7 Ma the Tibetan Plateau might have reached a sufficient height to induce aridification in the interior of China, and also northward migration and intensification of the Siberian high.

The loess-paleosol-red clay sequence in Lingtai (35°04′ N, 107°39′ E) is an ideal continuous record for the late Cenozoic period (Fig. 3). The total thickness of the section is 300 m, with the red clay component being up to 120 m thick. Magnetostratigraphy (Sun et al., 1998), particle-size distribution and magnetic susceptibility variations of the section are shown in Fig. 4. Magnetite, haematite and maghemite are the major magnetic minerals found in the red clay. The magnetic properties of red clay are similar to those of loess. Those clays with a higher degree of pedogenesis have higher susceptibility values. As discussed earlier, the magnetic susceptibility of the red clay can be used as a proxy index of the intensity of the summer monsoon (An et al., 1991b, 1998a; Liu, pers. comm.). It can be seen in Fig. 4 that both the particle-size and susceptibility curves show prominent amplitude changes around 2.6 Ma, indicating that the East Asian monsoon passed some threshold at that time. Both the winter and summer monsoons show greater variability after 2.6 Ma, and it is proposed that this was caused by an increase in global ice volume and an increase in the height of the Tibetan Plateau to a threshold level.

Between 3.4 and 2.6 Ma, the red clay at Lingtai is characterised by a strongly developed paleosol complex

Table 1
Comparison of grain-size distributions of loess, paleosol and red clay from Luochuang (35°45′N, 109°25′E), Lingtai (35°04′N, 107°39′E) and Xifeng (35°38′N, 107°25′E).

Profile	Lithology	Mean (Φ)	> 0.0 5μm (%)	0.05–0.00 5μm (%)	< 0.005 μm (%)	MSD
Luochuan	loess	6.06	8.63	69.71	21.66	1.78
	paleosol	6.80	2.57	66.20	31.23	1.77
Lingtai	loess	6.09	12.91	62.46	24.63	1.92
	paleosol	6.52	5.73	64.63	29.64	1.72
	red clay	7.31	1.49	56.73	41.78	1.63
Xifeng	loess	6.46	13.86	63.74	22.67	1.79
	paleosol	6.93	6.05	61.38	32.75	1.76
	red clay	6.98	1.76	64.47	33.77	1.67

Note: The grain-size data for loess and paleosols are the average values of 15 randomly selected samples; those for red clay are the average of 30 randomly selected samples; MSD is mean standard deviation, reflecting grain-size distribution.

with a deep-reddish colour, Fe and Mn skins, prismatic structure, and high susceptibility values, indicating a period of progressively intensified summer monsoon activity. The aeolian accumulation rate during this period also increased from 2.8 to 6.6 cm/kyr (Sun et al., 1998), indicating an intensification of the winter monsoon. This correlates with eolian evidence from the north Pacific indicating that dust accumulation increased abruptly after 3.6 Ma (Rea et al., 1998), which was consistent with the increase in global ice volume (Shackleton et al., 1995). However, the coincidence of an intensification of the East Asian summer monsoon, global ice volume increase during 3.4–2.6 Ma and the accelerated uplift of the Tibetan Plateau during this period indicates a connection between the plateau uplift and global cooling, development of major glaciations in the Northern Hemisphere and aridification in the interior of Asia (Ruddiman and Kutzbach, 1989; Rind et al., 1997).

4. Variability of the East Asian Paleomonsoon Climate

Multi-monsoon climate cycles characterised by the alternating dominance of warm-humid and dry-cold conditions recorded in the loess-paleosol sequences in central China correlate well with multi-glaciation cycles recorded in deep sea sediments. High-resolution loess records as well as lacustrine evidence also indicate that monsoonal variations exhibit both orbital periodicities of 10 kyr scale and sub-orbital oscillations of 1 kyr scale, which agree well with high-frequency Late Quaternary climatic oscillations shown in Greenland ice cores and the North Atlantic deep-sea records (Porter and An, 1995; An and Porter, 1997).

The modern East Asian winter monsoon system is characterised by frequent invasions of cold air, (i.e., the "cold wave") from the Siberian high into the East Asian interior. A 500-year documentary record of dust-fall shows that dust-fall events occurred 3.7 times per 10 years during cold periods, 2.1 times per 10 years during warm periods (Zhang, 1982), and that there have been 5 high-frequency dust-fall periods during the past 1000 years, each from decades to around a century in length, reflecting frequent oscillations of the East Asian winter monsoon (Zhang, 1984). The Siberian high and the polar front shifted southward during the Little Ice Age and significantly strengthened East Asian winter monsoon circulation (Yoshino, 1978). All of these lines of evidence point to the high-frequency (10–100 year periodicity) oscillating nature of the East Asian winter monsoon system.

Based on a study of the distribution of > 20 μm grains and the Al flux in the Late Pleistocene Malan Loess, a probable instability of the East Asian winter monsoon during the Last Glaciation was proposed by An et al. (1995). Porter and An's study (1995) of grain size data in the Luochuan (35°45′N, 109°25′E) loess sequence revealed that the last glacial loess at Luochuan contains a signature of 6 cold events, comparable to those preserved in the Greenland ice cores and to the Heinrich events in the North Atlantic records (Fig. 5), indicating that cold air activity in the high latitudes of the North Atlantic region has fundamentally influenced the East Asian winter monsoon through westerly winds and associated pressure systems. Successive studies of loess grain size composition have revealed finger prints of North Atlantic cold events, in the last glaciation loess (Chen et al., 1997; Ding et al., 1997). Variance in the chemical composition of dust from the source area (represented by Al) has preserved Heinrich event signals (Zhang et al., 1997) that can be correlated with Ca analyses in the GRIP ice core (GRIP members, 1993) (Fig. 5). These results show that dust from the Asian interior has made some contribution to that found in the Greenland ice core (Biscaye et al., 1997).

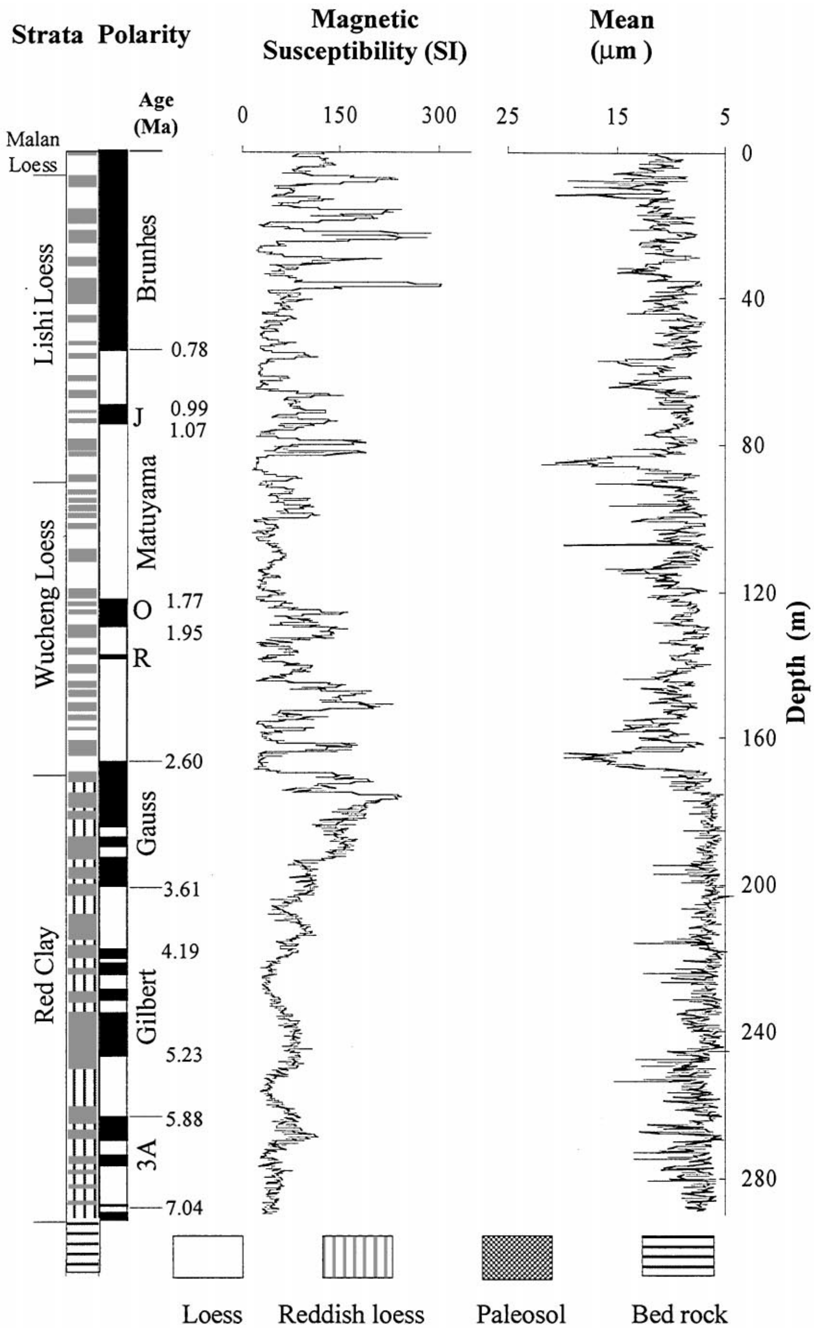

Fig. 4. Magnetostratigraphy (Sun et al., 1998), lithology, magnetic susceptibility and grain size variations of the Lingtai section (35°04′N, 107°39′E). The boundary between the Pleistocene Wucheng loess and Late Miocene and Pliocene red clay is close to the M/G boundary.

Plots of the content of the >40 μm quartz fraction in the last interglacial soil (S1) at Luochuan and Xian (34°17′N, 108°51′E) show 9 dust events and high-frequency changes in dust flux (Fig. 5) (An and Porter, 1997). The 6 dust events between 110–70 kyr BP can be correlated with 6 cold events (C19–C24) in the North Atlantic (McManus et al., 1994), together with the other two dust events during S1SS3 (corresponding to marine isotope stage, MIS, 5e) exhibit a high-frequency variability of winter monsoon climate in East Asia during the last interglacial. Spectral analysis of grain-size data from the last interglacial soil S1 at Luochuan and Xian has revealed a marked periodicity of 1.5 kyr. (An and Porter, 1997), comparable with the periodicity of ca. 1470 yr which has been found in the Holocene record in the North Atlantic region (Bond et al., 1997). (Fig. 6).

Guo et al. (1996) studied the chemical weathering index of 4 last glacial loess profiles and found that there are

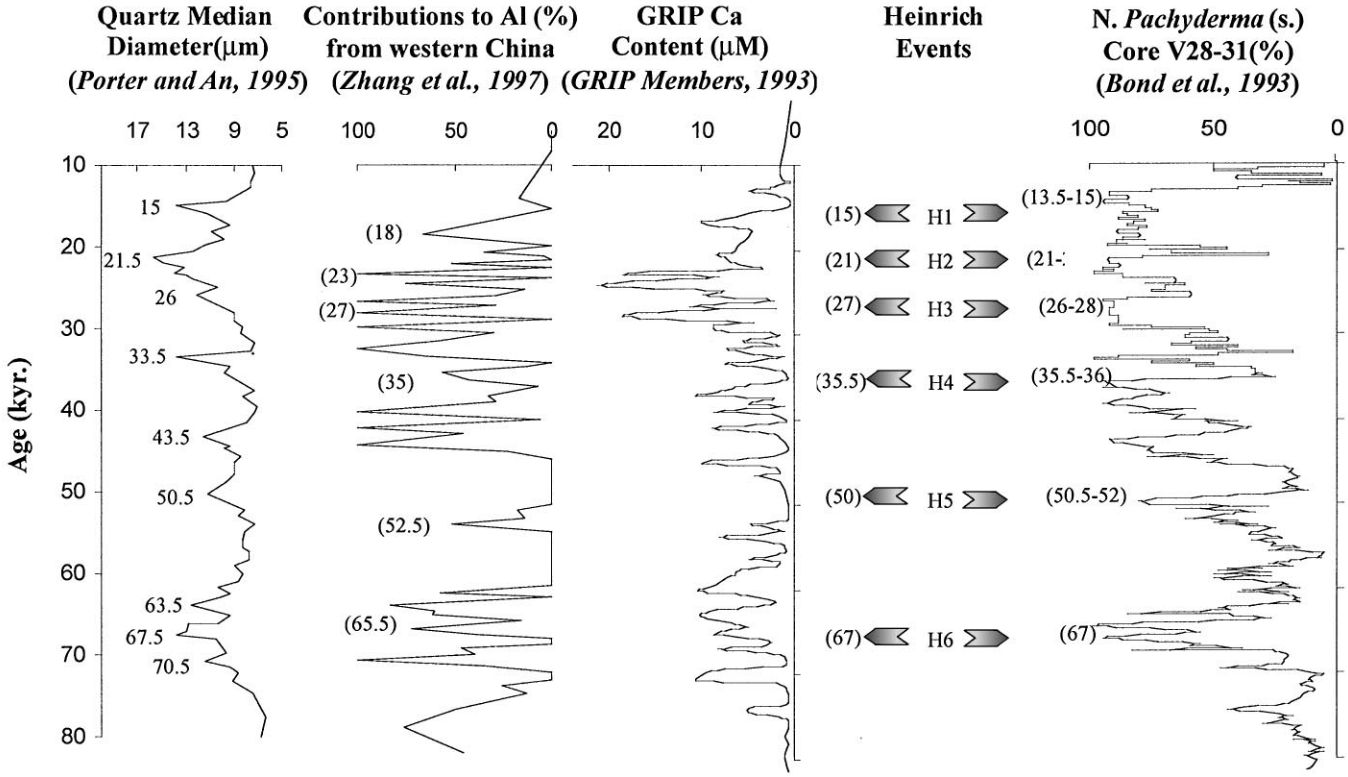

Fig. 5. Climatic records from north China show paleoclimatic instability during the last glaciation and their correlation with those from North Atlantic region. The quartz fraction data of Luochuan (35°45′N, 109°25′E) are from Porter and An (1995), *N. Pachyderma (s.)* data from Bond et al. (1993). The variation of atmospheric dust is represented by Al deposited on the Loess Plateau from western China during the last glaciation (Zhang et al., 1997), and matches well with the Ca content variations of the GRIP ice core (GRIP members, 1993). This figure shows that the signals of Heinrich events are preserved in the Chinese loess records during the last glaciation.

6 events with a low weathering index. They claimed that these events were comparable with the Heinrich events. However, the indices that are used to express the weathering degree of Al and Fe minerals are related to the degree of pedogenesis and thus to variations of summer monsoon rain. The micromorphology and carbonate content of the S1 soil at Beiyuan (35°37′N, 103°12′E) also show a significant variability of summer monsoonal rainfall during the last interglacial (Fang et al., 1996).

The East Asian monsoon climate also shows significant spatial variability. Sun et al. (1996) examined the migration of the summer monsoon front (represented by the 250 mm rainfall boundary) for the last 130 kyr by reconstructing the precipitation variations reflected by magnetic susceptibility of loess and paleosols. During the last interglacial, the summer monsoon front reached the desert area, north-western to the Loess Plateau, while during the Last Glacial Maximum (LGM), the front extended only to a line from Xi'an to Qinling at the southern margin of the plateau. An et al. (in press) pointed out that the occurrence of maximum monsoon precipitation in central and east China did not occur at the same time during the Holocene. The maximum occurred at, or earlier than, 9 kyr BP in north China, at about 6 kyr BP in the middle and lower reaches of the Yangtze River, and at about 3 kyr. BP in the Zhujiang region in the south. This trend of frontal migration parallels the trend of decreasing summer insolation in the Northern Hemisphere for the last 10 kyr.

Zhou et al. (1996, 1997, 1998) reconstructed proxy time series of East Asian monsoon variation for the last deglaciation from Midiwan (37°39′N, 108°37′E) peat deposits at the northern margin of the Loess Plateau (Fig. 7). Like the North Atlantic, the East Asian monsoon system oscillated frequently during the last deglaciation, including the Younger Dryas interval. Rapid climatic changes (with a time scale as short as hundreds of years) during the Younger Dryas, from dry-cold (11,200–10,600 yr BP) to humid-cold (10,600–10,200 yr BP), and to dry-cold (10,200-10,000 yr BP) again, are believed to have resulted from the shifts of the summer monsoon front partly due to cold air variations in the North Atlantic and Norwegian Sea (Zhou et al., 1996, 1997). Changes in the content of evergreen broad-leaf forest and deciduous broad-leaf forest tree pollen from a peat deposit in Daping of Nanling (24°15′ N, 115°02′ E) (Xiao et al., 1998) also

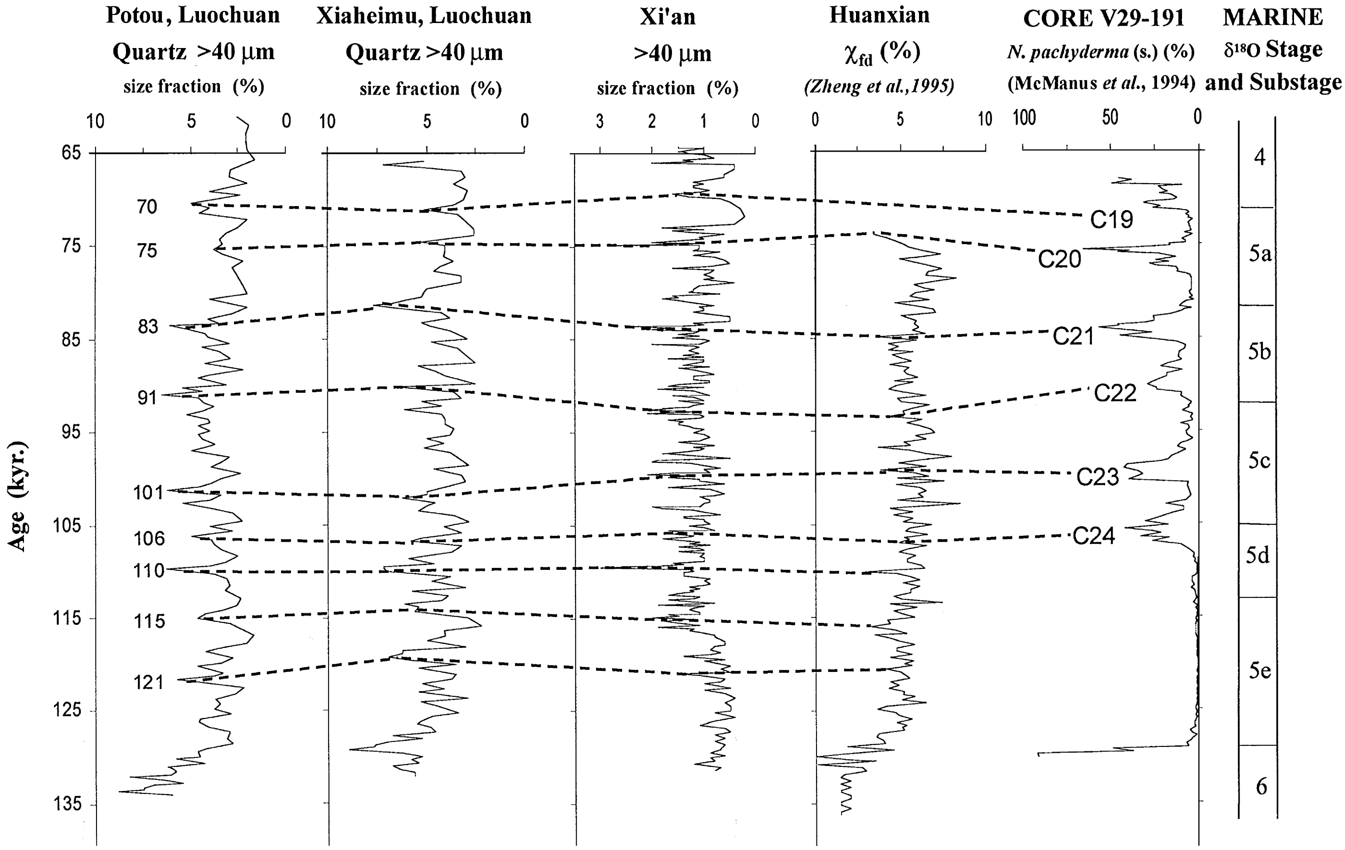

Fig. 6. Comparison of climatic records between the Chinese Loess Plateau and the North Atlantic region during the last interglacial period. The climatic records used above are: quartz particle size variations of two profiles near Luochuan (35°45′N, 109°25′E), and Xi'an (34°17′N, 108°51′E) (An and Porter, 1997). Quartz particles resist pedogenic alteration and thus are ideal proxy index for winter monsoon conditions. Also shown is the frequency dependence of the magnetic susceptibility plot from the Huanxian profile (36°30′N, 107°18′E), which reflects variations in the relative importance of fine, pedogenic magnetic minerals. The chronology of the Huanxian profile is transferred from Zheng et al. (1995). Six events between 110 and 70 kyr can be correlated with cold peaks (C19-C24) identified from North Atlantic records (McManus et al., 1994).

show evidence of a climate event with decreased temperature and increased rainfall at around 10,400 yr BP.

In summary, during the last interglacial–glacial cycle, both the East Asian winter and summer monsoons show high-frequency oscillations and associated abrupt climatic events with periodicities of 100 years up to 1000 years. The magnitude of climatic oscillations during the last interglacial may be smaller than that during the last glacial. The variable and unstable nature of the monsoon regime persists in East Asia through to the contemporary period, during which there have been frequent incursions of cold air and great variability of precipitation (Fu and Zheng, 1998).

5. Comparison and teleconnection of palaeoclimates between the Southern and Northern Hemispheres

It is still an open question as to how the palaeoclimates of the Southern and Northern Hemispheres are correlated and connected together. An understanding of the palaeoclimatic signals from the Southern Ocean and the Southern Hemisphere that had effects on the East Asian monsoon is attempted here. Further understanding of some oceanic–atmospheric processes will be attempted by examining palaeoclimatic data obtained from the marginal seas of China, the WPWP, and northern Australia.

During the last glacial cycle, the marginal seas and continental shelves which are well developed in East Asia and West Pacific Ocean apparently changed in their extent due to changes in sea level (Fig. 8). The lowered sea level during the last glacial would have reduced the marginal seas and led to the exposure of the continental shelves. For instance, the marginal sea from East Asia to Australia exposed about 4,000,000 km^2 during the LGM (Wang et al., 1997). Decreased moisture and heat transported to the atmosphere resulting from the shrinkage of the low latitude oceans and the decreased SST contributed to the palaeoclimatic variability of the South China

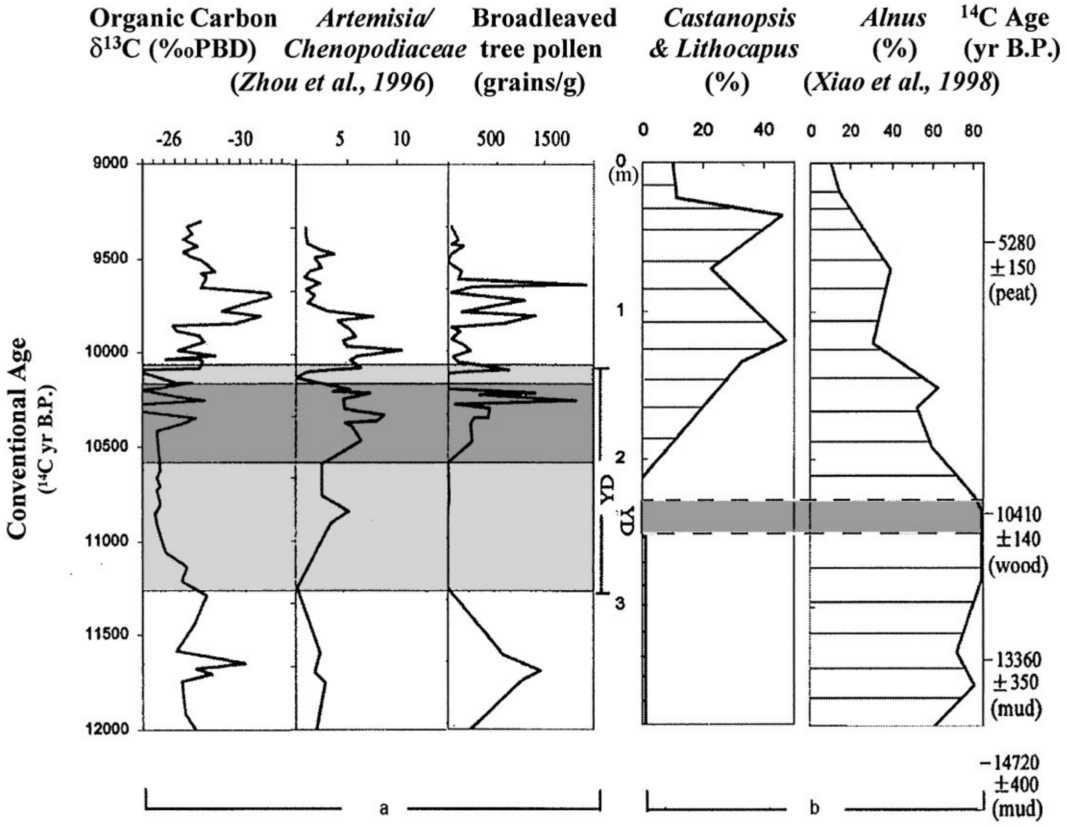

Fig. 7. The cold-humid climatic events recorded in the loess-desert transitional zone (a) and Nanling mountain (b) during the last deglaciation. The figure shows: (a) Climatic proxies of the Midiwan peat profile (37°39′N, 108°37′E) (Zhou et al., 1996), the chronology of the Midiwan profile is derived from a series of more than 20 AMS ^{14}C datas; (b) Pollen indices from the Daping peat-mud profile (24°15′N, 115°02′E), Jiangxi province (Xiao et al., 1998a). The climatic proxy curves in the middle-eastern China appear to indicate significant precipitation variability during the cold events within the last deglaciation.

Sea and WPWP during the last glaciation. The powerful winter monsoon lowered the sea surface temperature (SST) of the West Pacific and the marginal seas including the South China Sea (An et al., 1991c; Wang and Wang, 1990; Huang et al., 1997). The winter SST decrease in the Chinese marginal sea was greater than that in the West Pacific, and thus strengthened the climate seasonality in the South China Sea. However, a strengthened East Asian winter monsoon also lowered the SST of the WPWP and carried moisture to tropical islands, thus lowering the snow line and tree line in these islands during the glacials (Wang, 1998). The marked lowering of temperature in the low latitudes of the West Pacific region during the LGM may be inferred from geological and biological evidence (Webster and Streten, 1978; van der Karrs and Dam, 1995) which differs significantly from previous findings. The lowering of SST in the tropical West Pacific could be as great as 6°C according to the atmosphere–ocean coupling simulation by Bush and Philander (1998). It is worth noting here that changes in the ocean–land configuration and a decrease in the SST of the South China Sea and low latitude ocean resulted in a decrease of monsoon rain which caused the aridification of the East Asian continent during the last glaciation (Wang, 1999).

The synchroneity of palaeoclimatic events of the Southern and Northern Hemispheres has not yet been resolved. During the late part (35–25 kyr BP) of MIS 3, East Asian and Australian records show different rainfall responses. At this time, many lakes in China reached their highest levels (Fang, 1991). High lake levels were distributed from southeast to northwest China including the Qaidam Basin (Fig. 3), which indicates that a strengthened summer monsoon could have reached into the interior of northwest China.

The cold-humid character of the late MIS 3 is also indicated by the following evidence: a black loam paleosol, L1SS1, was observed on the Loess Plateau; there appears to have been some spread of coniferous forest (represented by *Picea* and *Abies*) in the river valleys of the Loess Plateau and plains in east China (An et al., 1990b); and the presence of a *Mammuthus–Coelodonta* antiguilis fauna in mud deposits near Harbin (45°48′N, 126°54′E) in northeast China (Zhou, 1984). Another piece

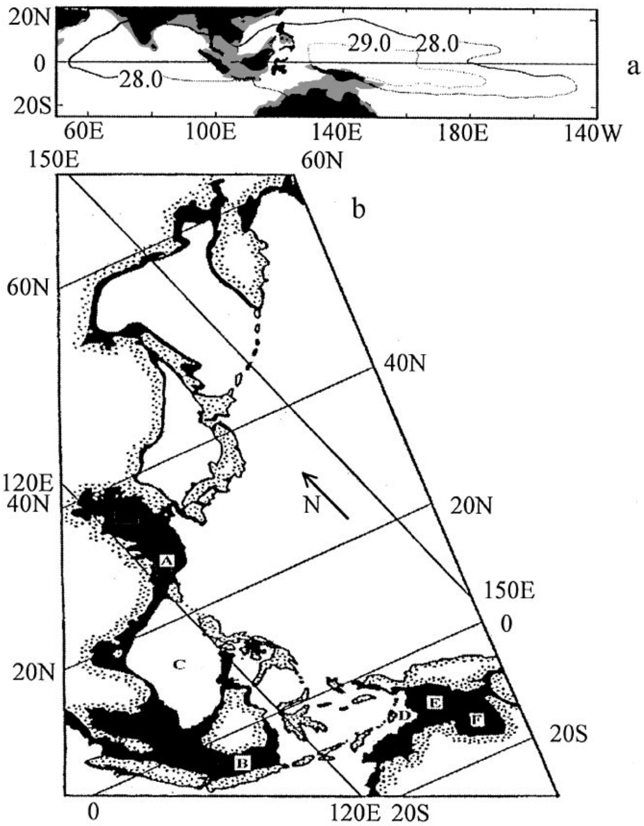

Fig. 8. Map showing the Western Pacific Warm Pool (WPWP) and the marginal seas. During the LGM, the marginal seas and WPWP shrank and this enhanced the development of aridification in East Asia and Australia. The figure shows: a. The WPWP outlined approximately by the 28° isotherm (Wang, 1998). Shaded areas indicate the shelf seas that emerged during the LGM; b. Marginal seas at the LGM. Black area denotes emerged shelves. The three most extensive emerged shelves are: A The East China Sea Shelf (850,000 km^2); B and C Sunda Shelf (1,800,000 km^2); D,E and F Sahul Shelf of Great Australia bank (1,230,000 km^2). The total area is 3,900,000 km^2 (Wang et al., 1997).

of evidence is that both the ^{10}Be curve of the Weinan (34°20′N, 109°29′E) Loess (Gu et al., 1997) and the pedogenic magnetic susceptibility flux curve of Luochuan loess (An and Sun, 1995) show an unusual increase in the precipitation in the Loess Plateau during late Stage 3. This observation can be correlated with SST changes in a South China Sea core (Wang et al., 1995), but it differs from the SPECMAP curve (Martinson et al., 1987) which shows that the global ice volume during late Stage 3 was significantly greater than during early Stage 3 (Fig. 9). Wasson (1986) reconstructed the history of dune building in the interior of Australia and found that late Stage 3 and the LGM were periods of desert development. De Deckker et al. (1991) also pointed out that aeolian events in northern Australia resulted from strengthened south-easterly trade winds during the period 36–10 kyr BP. The intensification and northward shift of the Australian high indicated by dune building and aeolian events during late Stage 3 would have contributed to the increase in East Asian monsoon rain due to the effects of the trans-equatorial air streams.

Increasing rainfall and rising lake levels in Australia, including the northern monsoonal region (Kershaw, 1983; Chappell, 1991; Harrison, 1993; Bowler et al., 1995; Wasson, 1995), are consistent with increasing East Asian monsoon rain during the early Holocene (An et al., 1991c; Shi et al., 1992). It is well known that summer solar insolation in the Northern Hemisphere peaked at about 9000 yr BP, while in the Southern Hemisphere, solar insolation at this time was at a minimum. The nearly simultaneous increase of precipitation during the early Holocene in East Asia and Australia cannot be explained by orbital forcing. It is worth noting that during 9000–5000 yr BP, we have observed a black loam paleosol with the structure of a typical chernozem on the Loess Plateau with thicknesses up to 1–2 m, indicating relatively cold and humid conditions. The aeolian accretion rate of the Holocene soil in the Loess Plateau is greater than the last interglacial (Fig. 10). Higher dust flux reflects both greater aridity in the source area and higher velocity of the transporting winds (An et al., 1991a), which indicates a strengthened winter monsoon regime during the early Holocene. This simultaneous strengthening of the East Asian winter and summer monsoon during the early Holocene agrees well with the strong seasonality of the Northern Hemisphere solar insolation (Kutzbach and Street-Perrott, 1985). The overall increase of monsoonal rain and rising lake levels in monsoonal northern Australia (Fig. 10) shows a relationship to the enhanced trans-equatorial air streams driven by the East Asian winter monsoon.

Sun and Li (1999) studied a high-resolution core 17 940 (20°07′N, 117°23′E) obtained from the South China Sea. They found that during 36–10 kyr BP the mountain coniferous forest (*Picea*, *Abies* and *Tsuga*) alternated with grass-land dominated by *Artemisia*, indicating frequent oscillations from cold-humid to temperate-dry conditions in the coastal areas of south China (Fig. 11). Some of these cold-humid events occurred contemporaneously with the Younger Dryas, and Heinrich events H1, H2 and H4. These results indicate that the Younger Dryas and Heinrich signatures have been preserved in tropical and sub-tropical regions of south China as cold-humid events. The character of these events is consistent with a significant variability of precipitation revealed in peat deposits from the northern regions of the Loess Plateau and the Nanling area. De Deckker et al.'s (1991) study of the distribution of the > 60 μm particulate eolian fraction in the Carpentaria Core GC-2 (12°31′S, 140°21′E) (Fig. 11) revealed over 10 eolian events during 36–10 kyr BP, indicating strengthening of the southeast trade winds and a northward shift of the ITCZ. Furthermore, most of the eolian events observed in northern

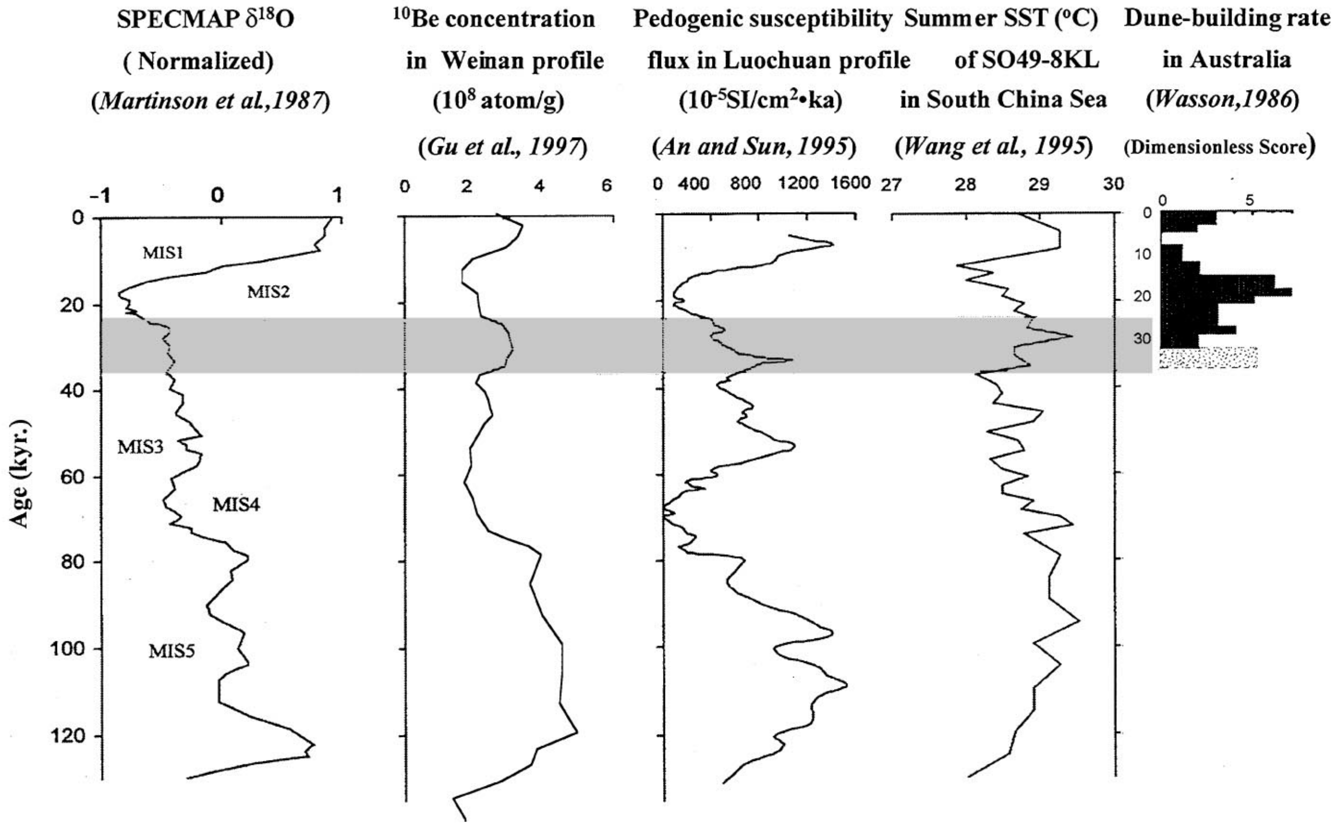

Fig. 9. Strengthened summer monsoon variation indicated by ^{10}Be from the Weinan profile (34°20′N, 109°29′E) (Gu et al., 1997), pedogenic susceptibility flux from the Luochuan profile (35°45′N, 109°25′E) (An and Sun, 1995) and summer SST from SO49-8KL Core (19°11′N, 114°12′E) (Wang et al., 1995) around 30 kyr, and their correspondence to the global ice volume variation. The comparable results show that an unusual increasing precipitation (strengthening summer monsoon) in the late MIS3 is not compatible with the SPECMAP reconstruction. This may be associated with a strengthened high in Australia indicated by renewed activity of Australian sand dunes from the late MIS3. The dune building rate figure shown is modified from the data of De Deckker et al. (1991).

Australia can be correlated with cold-humid events preserved in marine Core 17 940 from the South China Sea. This shows that strengthening of the southern trade winds and the associated Southern Oscillation (De Deckker et al., 1991) has infulenced increased precipitation in East Asia by cross-equatorial flow. Grimm et al. (1993) found that the humid intervals represented by the peak content of pine in a pollen record from Florida coincide with a Heinrich interval. Broecker (1994b) proposed that the humid events recorded by the Florida pollen record indicated a re-arrangement of rain belts, similar to the situation during El Nino. Bush and Philander's (1998) atmosphere–ocean coupled simulation revealed that the influence of the El Nino cycles may have played a part in climate variations during the LGM. Therefore it is speculated that the strengthening of the East Asian winter monsoon (Barnett et al., 1988) or the southern trade winds during cold periods is favourable to the intensification of El Nino cycles, and thus also to the significant temporal and spatial variability of monsoonal rain.

6. Concluding remarks

Long-term variations of the East Asian monsoon regime are a reflection of the interaction between atmosphere, land, ocean and ice, and are an expression of their combined effects within the boundary conditions imposed by the East Asian continent and changing solar insolation. High-resolution measurements of proxy indices of monsoon climate from loess-paleosol-red clay sequences suggest that the East Asian monsoon may have commenced at least 7.2 Ma ago. The history of the East Asian monsoon can be regarded as an alternation between the dominance of the dry-cold winter monsoon and the warm-humid summer monsoon. Both the winter monsoon circulation and summer monsoon rain show relatively strong temporal and spatial variability. Frequent monsoonal events suggest that the East Asian monsoon exhibits climatic oscillations with periods of 1000 years or less, which is closely connected with other climate change mechanisms as indicated in previous studies.

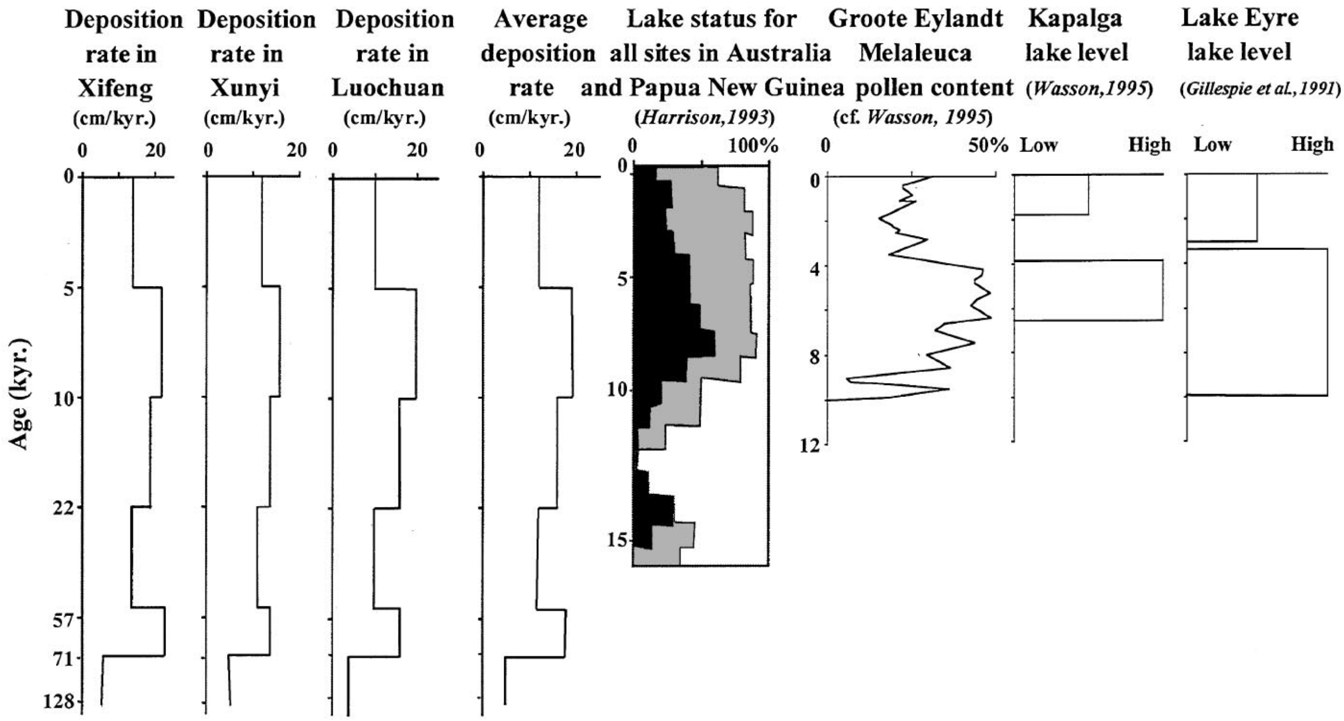

Fig. 10. Dust deposition rates in the central Loess Plateau of China and lake level changes in Australia. The relatively high dust deposition rates in Xifeng (35°38′N, 107°25′E), Xunyi (35°20′N, 108°18′E) and Luochuan (35°45′N, 109°25′E) in China may reflect a strengthening winter monsoon in East Asia during the early Holocene (An et al., 1991a). The stronger winter monsoon circulation crossed the equator to strengthen the Australian summer monsoon. This may have resulted in increased precipitation and associated high lake levels in Australia.

The evolution of the East Asian monsoon is a response to the orbitally induced solar radiation received by the earth's surface and changing boundary conditions (Prell and Kutzbach, 1987), and is closely affected by the integrated behaviour of the global climatic system. In addition to the effects already mentioned, the uplift of the Tibetan Plateau affects summer monsoon behaviour, while the long-term evolution of the winter monsoon is mostly related to global ice volume. Proxy index variations of the East Asian monsoon in loess-red clay sequences indicate that an accelerating uplift of the Tibetan Plateau during 3.4–2.6 Ma enhanced the monsoon regime, had an impact on global cooling and eventually on the development of major Northern Hemisphere glaciation. Monsoon climate variability on a time scale of 1000 yr or less results from a nonlinear response to orbital forcing and/or from internal system dynamics. For example, trans-equatorial air streams exert an influence on both hemispheres. The interaction between monsoon and ENSO activities may also influence the precipitation distribution in East Asia (An and Thompson, 1998).

On the basis of modern meteorological data and paleoclimatic evidence from the Southern and Northern hemispheres mentioned above, a simplified model is proposed to illustrate the synchroneity of palaeoclimatic events in both Hemispheres. Intensification of either the Siberian or Australian high associated with the Arctic or Antarctic ice sheets enhances the winter monsoon or south-east trade winds, respectively, which can bring vapour and heat around the equator to strengthen the Australian or the East Asian summer monsoon circulation. In other words, the trans-equatorial air streams driven by both the monsoon and trade winds have an important influence on the precipitation in the opposite hemisphere. In fact, the formation of these streams is closely related to the "pressure push" exerted from the hemisphere which is experiencing winter at the time.

A comparative study of palaeoclimates between the Southern and Northern Hemispheres has just begun. Monsoon and trade winds are a means for atmospheric exchange between the high and low latitudes and between both hemispheres. One should also note a possible interaction between the Asian monsoon and ENSO phenomena, which is related to a contribution of tropical ocean to mid and high latitude climate. All of these are therefore significant to the understanding of environmental change in East Asia, and also to the prediction of future climatic change.

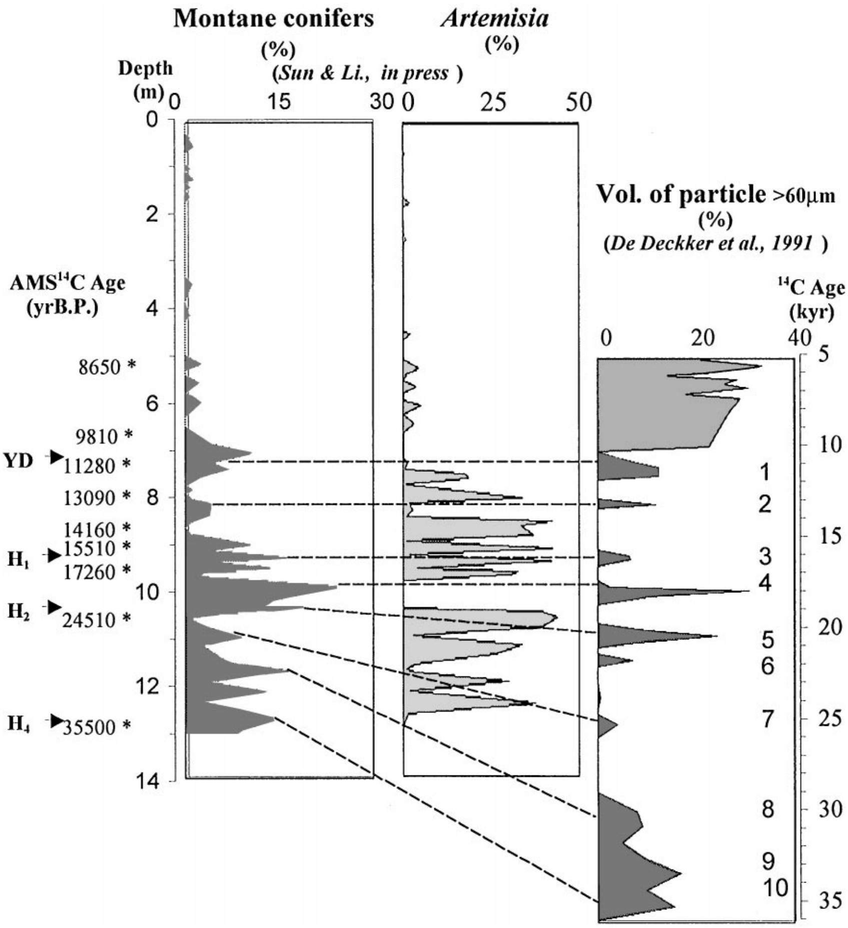

Fig. 11. Pollen data from Core 17940 (20°07′N, 117°23′E) in the South China Sea (Sun and Li, in press) and comparison with the eolian events preserved in the Carpentaria Core GC-2 (12°31′S, 140°21′E) (De Deckker et al., 1991). The montane conifer pollen from core 17940 is dominated by *Picea, Abies* and *Tsuga*. The chronological framework of GC-2 has been been obtained from a series of 8 ^{14}C ages from carbonate material of biogenic origin. The upper part of core GC-2 contains sand reworked during the marine transgressive phase. The Carpentaria dust events can be compared with the cold-humid events corresponding to the YD, H1, H2 and H4 events recorded in the South China Sea during the late interval of the last glaciation. This agreement may show a paleoclimatic teleconnection between the South China Sea and North Australia through the interaction of East Asian monsoon and ENSO activity.

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