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Pattern of abrupt climatic fluctuation in the East Asian Monsoon during the Last Glacial: Evidence from Chinese loess records

Enregistrement de fluctuations climatiques abruptes pendant le Dernier Glaciaire : preuve apportée par les archives de loess chinois

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ABSTRACT

Records of two loess sections located in mid-eastern and western margins of the East Asian Monsoon area captured 20 Dansgaard-Oescher events and six Heinrich events. All these suggested that the climate in the East Asian Monsoon area fluctuated rapidly on millennial to century timescales during the whole Last Glacial. We found that these loess-based events of rapid climate fluctuations were generally synchronous with those of GRIP records, but that there were differences between the Shagou loess section in the west and the Wangguan loess section in the east: the former was more sensitive to climate change than the latter. Compared with earlier studies on loess records covering the Last Glacial from neighboring areas, we discovered that the magnitude of Dansgaard-Oeschger cycles decreased gradually from west to east and we suggest that it resulted from the combined effect of the Westerlies and the East Asian Monsoon.

RÉSUMÉ

Deux sections de loess des marges moyenne-orientale et occidentale de l'aire de la mousson est-asiatique ont enregistré 20 évènements Dansgaard-Oescher et six évènements Heinrich. Ils suggèrent tous que le climat de l'aire de la mousson est-asiatique a fluctué rapidement à l'échelle du siècle au millénaire pendant tout le Dernier Glaciaire. Basés sur l'étude de loess, ces évènements de fluctuations rapides du climat se révèlent généralement synchrones des enregistrements GRIP, mais des différences sont observées entre la section loessique de Shagou à l'ouest et celle de Wangguan à l'est : la première a été plus sensible au changement climatique que la seconde. Par comparaison avec des études plus récentes à partir d'enregistrements sur des loess recouvrant le Dernier Glaciaire dans des régions proches, nous avons découvert que la magnitude des cycles Dansgaard-Oeschger décroît graduellement de l'ouest à l'est et nous suggérons que ceci résulte de l'effet combiné des Westerlies et de la mousson sud-asiatique.

1. Introduction

Marine records from the North Atlantic and ice cores of Greenland first promulgated that the last glacial period

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was characterized by a series of abrupt climatic events (e.g. Heinrich and Younger Dryas cold event; Dansgaard-Oeschger warm event) in the Northern Hemisphere high latitude area (Bond et al., 1993; Dansgaard et al., 1993; GRIP, 1993; Heinrich, 1988). Subsequent works revealed that these rapid climatic events may not be restricted to the North Atlantic area, but may have also occurred in other parts of the Northern Hemisphere. These records include ice cores (NGICPM, 2004; Yao et al., 2001), pollen (Benson et al., 1998), loess (Lü et al., 2004; Porter and An, 1995; Ren et al., 1996), stalagmites (Gently et al., 2003; Wang et al., 2001, 2008) and ocean sediments (David et al., 2003; Schulz et al., 1998). Despite the differences in the magnitude and variability from those of the North Atlantic, Heinrich and Dansgaard-Oeschger events (abbreviated as H and DO respectively) were well recorded. The Greenland events have been explained by changing rates of North Atlantic deep water formation, resulting in changing heat transport to the North Atlantic (Broecker, 1994). Wang et al. (2001) suggested that millennial-scale changes in the East Asian Monsoon during the Last Glacial may similarly result from massive and rapid changes in oceanic and atmospheric circulation patterns and may be affected by orbitally induced insolation variations. While it is clear that a rapid climatic shift occurred in the East Asian Monsoon area during the Last Glacial, the relationship it had with the climate transformations in the high or low latitude areas is still not clear. Understanding the driving mechanisms of extreme climatic events on sub-orbital scale strongly depends on comparative investigation of high-resolution paleoclimatic records in various areas of the global climate system.

The Chinese loess deposits provide unique long-term terrestrial records, and rapid climate fluctuations during the Last Glacial have been well documented in loess records (Lü et al., 2004; Porter and An, 1995; Ren et al., 1996). However, the majority of previous loess work covered a geographic area that is limited to the middle part of the Loess Plateau (Porter and An, 1995; Ren et al., 1996). In addition, the temporal resolution in these records is relatively low (Porter and An, 1995; Ren et al., 1996) and this can prevent a reliable reconstruction of abrupt climatic events. High-resolution loess records covering a wide geographic area of the Loess Plateau are greatly needed to verify the evolution of the East Asian Monsoon and assess its role in the climate system of the North Hemisphere during the Last Glacial. Therefore, we take two high-resolution loess records (the Wangguan loess section and the Shagou loess section which are located in mid-eastern and western margins, respectively, of the East Asian Monsoon area) as the research object (Fig. 1), and discuss the questions listed above.

2. Materials and methods

The Wangguan loess section (34°47′N, 111°16′E) is located on the second terrace of the south bank of the Yellow River. Detailed information of this 30-m eolian loess section is given in Guan et al. (2007). The Shagou loess section (37°33′ N, 102°49′ E) is situated on the fifth terrace of the Shagou River to the north of Qilian Mountains (see Pan et al., 2001 for more details). These two sections had thick loess during the Last Glacial: approximately 16 m with a sedimentary rate of 21.52 cm/ka of L1 stratum in the Wangguan loess section, and 28 m with a sedimentary rate of 37.65 cm/ka in the Shagou loess section. Because the L1 strata of both the Shagou and Wangguan sections are each the thickest sections within their neighboring areas, we had not discovered the obvious hiatus in the field. Therefore, we thought that the strata of the Shagou section and Wangguan section were continuous during the Glacial. We collected the samples at intervals of 5 cm for the whole profile in each case, except for the upper 3.35 m in the Shagou loess section L1, which was sampled at 2.5-cm intervals. All samples were gathered simultaneously to achieve good control of dating. Construction of the age models was detailed in Guan et al. (2007). The chronology of the Wangguan and Shagou loess sections were obtained with the Grain Size-Age Model (Porter and An, 1995). The obtained age controlling points are compared with the recent high-resolution stalagmite records of the Last Interglacial in China (Wang et al., 2001; Yuan et al., 2004), as the stalagmite records were precisely dated in a high resolution and were also obtained from the Quaternary sediments in the region of the East Asian Monsoon.

Since the grain size of loess is closely related to the loess-desert boundary shifting as a result of monsoon climate changes, or to the distance from the dust source (Ding et al., 1999; Ren et al., 1996; Yang and Ding, 2008), the expansion or shrinkage of desert during the Interglacial-Glacial cycle would result in the grain size becoming coarser or finer (Liu, 1985; An et al., 1991). Therefore, we can still employ the grain size to indicate the history of the East Asian Winter Monsoon under the present conditions. The median diameter (Md) of grain size has been found to be one of the most reliable winter monsoon proxies (An et al., 1991; Chen et al., 2000; Fang et al., 2002; Lü et al., 2004), so in this study, we use this parameter to track the evolution of the winter monsoon. The chemical components of the loess strata from China were found to respond strongly to palaeoclimatic fluctuations during the Quaternary period (Liu, 1985; Diao and Wen, 1999). Chemical indicators of distribution, migration, enrichment, etc. in the loess strata can be used to reconstruct palaeo-climatologic environments during the times when the loess was forming (Diao and Wen, 1999; Liu, 1985).

All air-dried samples were analyzed for grain size and chemical elements in the Key Laboratory of Western China's Environmental Systems, Lanzhou University. The grain size was measured with Mastersizer 2000 (Malvern Instruments Ltd., UK) with a measurement range of 0.02 to 2000 μm. The treatment procedures are as follows: 0.3 to 0.5 g of each sample is placed into a beaker and H_2O_2 is added. The solution is boiled for 30 min (to remove the organic matter), then diluted hydrochloric acid is added (to remove carbonate). The beaker is then filled with distilled water (making sure not to overflow), and after being left static for 24 h, the superstratum water is pumped away. Sodium hexametaphosphate (used as a dispersant) is added, and the resultant sample surged for 7 to 8 min, then

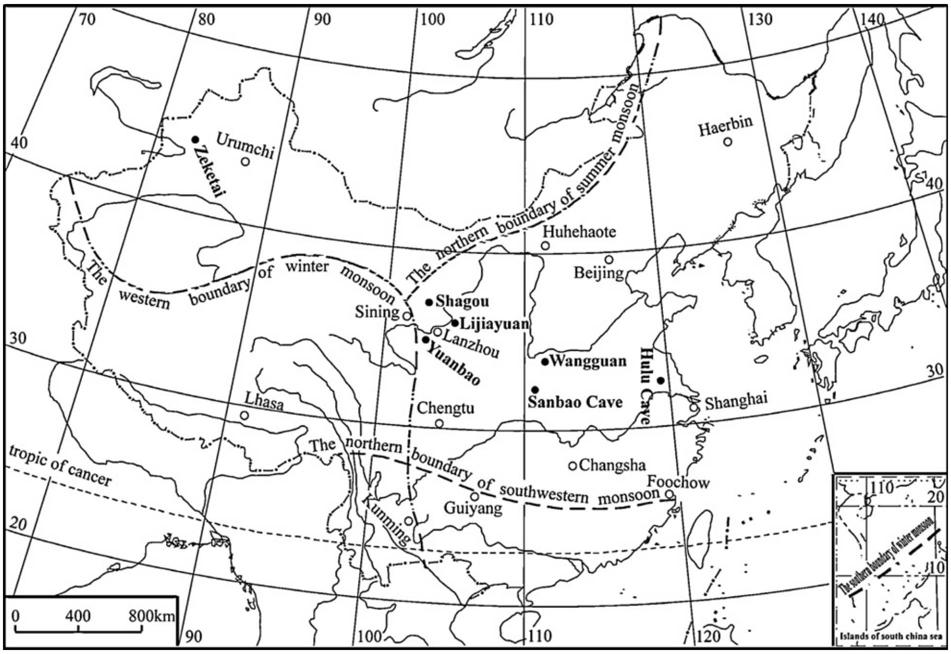

Fig. 1. Map showing the study sites and the modern monsoon boundaries in China (Ren, 2004).

Fig. 1. Carte représentant les sites étudiés et les frontières de la mousson moderne en Chine (Ren, 2004).

tested with the Mastersizer 2000 (the results are shown in Figs. 2 and 3).

Fluorescence X-ray (Philips Panalytical Magix PW2403 X-ray fluorescence [XRF] spectroscope, Holland) was used in the chemical element analysis. Sample preparation involved air-drying samples completely, grinding and sieving at 75 μm. Up to 4 g of sample was weighed and poured into the center of the column apparatus, together with boric acid, and pressurized to 30 t/m^2 for 20 sec. The processed sample of approximately 4 cm diameter and 8 mm thickness was analyzed by Philips Panalytical Magix PW2403 XRF spectroscope. Analytical results are reported in oxide compound form apart from trace elements which are given in elemental form. The standard deviation based on repeat sample analysis was approximately 2% (the results are shown in Fig. 2).

Aluminum (Al) and iron (Fe) are relatively stable during chemical weathering under warm and wet environmental conditions, while some elements (like chlorine [Cl], sulfur [S], potassium [K], sodium [Na], and magnesium [Mg]) can be easily dissolved and mobilized. As a result, elements with poor ability to migrate (e.g. Al and Fe) will remain and form new minerals like clays in the form of oxide compounds. Therefore, the increased contents of Al_2O_3 and Fe_2O_3 in the depositional strata represent warm and wet conditions. Because SiO_2 is more active than Al_2O_3~Fe_2O_3 and is lost earlier, we used the rate (SiO_2/ Al_2O_3 + Fe_2O_3) to reflect the degree of chemical weathering within the loess deposits (Diao and Wen, 1999; Wen et al., 1995). Sodium (Na) in the Earth's crust mainly exists in the form of silicate or silicon-aluminates (Wang, 1995); however, the majority of sodium and its simple compounds can easily be carried off by the water in the process of weathering (Liu, 1985). Therefore, we use the value of Al_2O_3/Na_2O to reflect the intensity of chemical weathering due to the differences between Al_2O_3 and Na_2O in the process of chemical weathering. In the process of weathering and soil formation, the plant root system significantly concentrates zinc (Zn) and copper (Cu) (Wang, 1995). In deposition strata, zinc can be concentrated in the humus by the way of clay – humus – zinc compounds. Because of a high alkalinity in the loess, copper can be concentrated through organic matter adsorption. Research involving the Luochuan section confirmed that the average levels of Zn and Cu in the palaeosoil were substantially higher than those in the loess strata (Liu, 1985). Moreover, the Rb/Sr ratio, one commonly used as a proxy in loess studies, can reliably reflect the intensity of weathering and soil formation (e.g. Chen et al., 2003).

In the Shagou loess section, we noticed that the concentrations of SiO_2/ Al_2O_3 + Fe_2O_3, Al_2O_3/Na_2O, Na_2O, Al_2O_3 and Fe_2O_3 can track variations in the intensity of weathering and soil formation much better than other geochemical indicators. Therefore, in the Shagou loess section, we use these five geochemical indexes as the proxies to infer the summer monsoon intensity. However, these five constant element indices were found to be less sensitive to environmental fluctuations than Zn, Cu and Rb/Sr in the Wangguan loess section. Therefore, we use these three trace element indexes for reconstructing the past summer monsoon in the Wangguan loess section.

3. Results and discussion

3.1. Results

Geochemical and grain-size indicators in both Wangguan and Shagou loess sections show that the Last Glacial can basically be divided into three stages: the early stage of

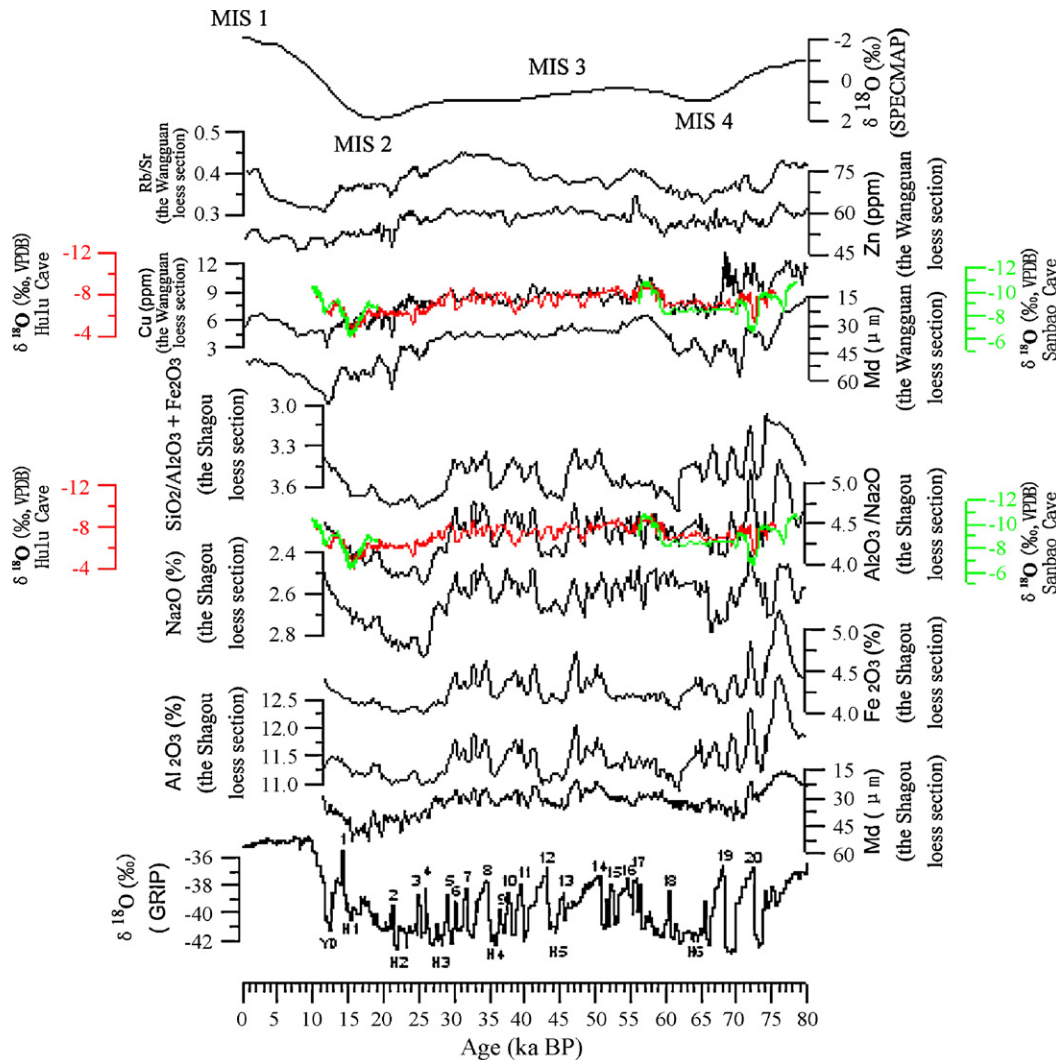

Fig. 2. Comparison of the paleoclimatic records of the Wangguan and Shagou loess sections with the SPECMAP records (Martinson et al., 1987), the GRIP records (GRIP, 1993) and the stalagmite records (Wang et al., 2001, 2008; the green curve is the Sanbao Cave record, the red curve is the Hulu Cave record), respectively, during the Last Glacial. (1–20: Dansgaard-Oescher events; H1-H6: Heinrich events).

Fig. 2. Comparaison des enregistrements paléoclimatiques dans les sections Wangguan et Shagou avec les enregistrements SPECMAP (Martinson et al., 1987), GRIP (GRIP, 1993) et les enregistrements stalagmitiques (Wang et al., 2001, 2008 ; la courbe verte correspond à la grotte Sanbao, la rouge à la grotte Hulu), respectivement pendant le Dernier Glaciaire. (1–20 : évènements Dansgaard-Oescher ; H1-H6 : évènements Heinrich).

the Last Glacial (MIS 4), the interstadial of the Last Glacial (MIS 3) and the Last Glacial Maximum (MIS 2) (Fig. 2). Winter monsoon intensity fluctuated from strong to weak to strong, with the summer monsoon varying in the opposite direction. There were also rapid fluctuations on the millennial scale. In the Wangguan loess section, both the summer monsoon proxies (Rb/Sr, Zn, and Cu) and the winter monsoon proxy (Md) show rapid synchronized fluctuations on sub-orbital scales. Among the three summer monsoon proxies, Rb/Sr showed the largest magnitude of variation, with a similar magnitude for both Zn and Cu. The magnitude of the variation in the winter monsoon proxy (Md) is not more than those of the summer monsoon proxies Zn and Cu. The magnitude of variation in both the winter and the summer monsoon proxies of the Shagou loess section on the millennial scale are larger than those from the Wangguan loess section. The magnitude of variation in the summer monsoon proxies is much larger than in the winter monsoon proxies in both sections. In both sections, the winter and the summer monsoon proxies both have a high degree of uniformity on millennial scales.

3.2. Discussion

The grain-size and geochemical proxies in the Shagou and Wangguan loess sections all display the sub-orbital scale fluctuations which were discovered by the GRIP ice core records (GRIP, 1993) (Fig. 2), suggesting that the intensities of the winter and summer monsoons in East Asia were extremely unstable on sub-orbital scales during the Last Glacial. The proxies of the two loess sections all can be divided into three stages corresponding to MIS 2,

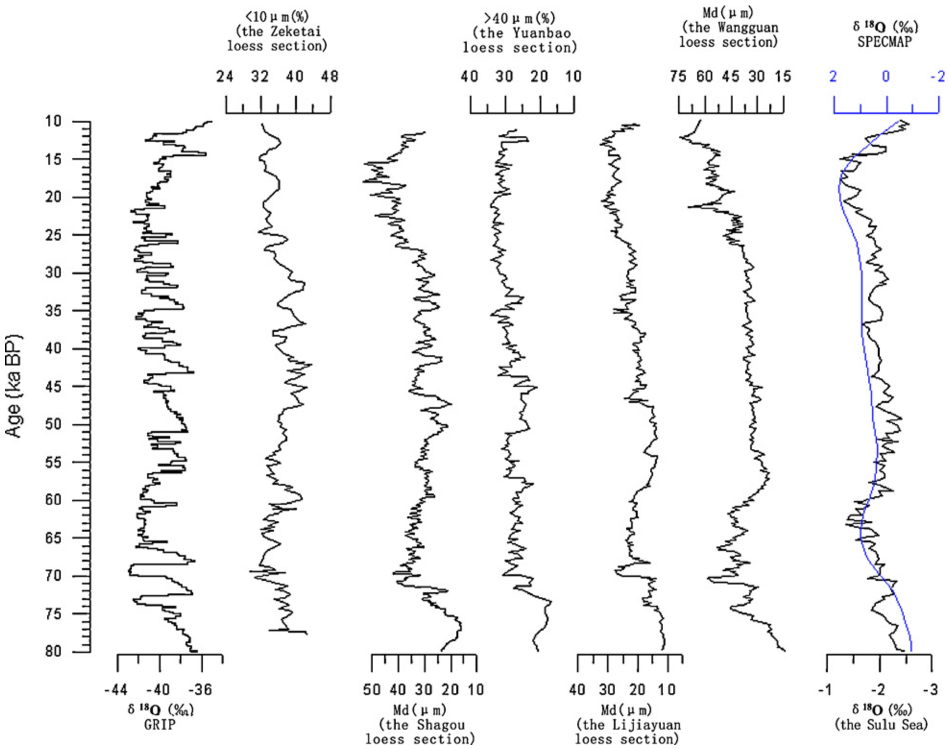

Fig. 3. The grain size of the Zeketai loess section (Ye et al., 2000), the Shagou loess section, the Yuanbao loess section (Chen et al., 1997), the Lijiayuan loess section (Ren et al., 1996) and the Wangguan loess section, compared with the GRIP record (GRIP, 1993), the SPECMAP record (Martinson et al., 1987; blue [smooth] curve) and the Sulu sea record (Linsley, 1996).

Fig. 3. Granulométrie des sections loessiques Zeketai (Ye et al., 2000), Shagou, Yuanbao (Chen et al., 1997), Lijiayuan (Ren et al., 1996) et Wangguan comparée à celle de l'enregistrement GRIP (GRIP, 1993), SPECMAP (Martinson et al., 1987 ; courbe bleue [lisse] et l'enregistrement de la mer de Sulu [Linsley, 1996]).

MIS 3 (a weak paleosol Sm in the two sections corresponded to MIS 3), and MIS 4 as shown in the SPECMAP data (Martinson et al., 1987).

At the early stage of the Last Glacial (MIS 4), when global ice volume increased, the intensity of the summer monsoon weakened but the winter monsoon was strengthening, with strong fluctuations. Both the Shagou and Wangguan loess sections captured three DO warm events (DO 18, DO 19, and DO 20) and one Heinrich cold event (H 6). All these suggested that strong climatic variability and instability across Loess Plateau corresponded with those in the North Atlantic. We noticed that the western Loess Plateau responded stronger than the eastern part, namely in terms of a larger magnitude of variation. Moreover, our loess sections also recorded a warm event (Fig. 2) between DO 19 and DO 20, which lasted approximately 69 ~ 70 ka. However, this warm event in the ice core recording (GRIP, 1993) was lacking or non-existent.

In the interstadial of the Last Glacial (MIS 3), global ice volume was lower than in the early and later times of the Last Glacial; the palaeosoil Sm of the interstadial was generally well-developed in the loess strata. In the Qinghai-Tibet Plateau and surrounding areas, the later period of MIS 3 was characterized by intensified summer monsoon and widespread high lake levels in the Tengger and the Badain Jaran Deserts (Shi et al., 1999). The northern boundary of the summer monsoon may have extended over this area with monsoonal intensity similar to that of the Holocene Megathermal (Yang and Liu, 2003). Both of our loess sections show weakly developed palaeosoils (Sm) in this period. However, the grain size and geochemical indicators demonstrated that the East Asian Monsoon was unstable in the interstadial of the Last Glacial (MIS 3), as evidenced by the presence of DO 5–DO 17 warm events and the H 4 & H 5 cold events. All these events of rapid climate fluctuations showed strong synchrony with those recorded in the ice core (GRIP, 1993) (Fig. 2). The magnitude of variation of these rapid climatic events during MIS 3 in the western Loess Plateau was remarkably larger than that in the eastern part of the Plateau, as found during the MIS 4. Moreover, the Shagou loess section also recorded a warm event between DO 13 and DO 14; however, this warm event is not manifested in the majority of the proxy curves of the Wangguan loess section. In addition, the climate of MIS 3 in the Wangguan loess section was entirely more stable and warmer than in the Shagou loess section.

During the Last Glacial Maximum, the quantity of ice on land increased, causing the temperature to decrease rapidly. The trace of frost was found in the Chagelebulu section located in the southeastern section of the Badain Jaran Desert, and the Dishaowan and Milanggouwan sections in the Mu Us Desert (Dong et al., 1996, 1998; Li et al., 1998). At that time, the temperature of the western area of the Gansu Hexi Corridor was 6 to 15 °C lower (Wang et al., 2000) than today. Under the effect of this cold climate, winter monsoon was remarkably enhanced and desert was rapidly expanding. Since that time, the boundary belt of desert-loess totally covered Lanzhou (Dong et al., 1997). The two loess sections in our study areas recorded three Heinrich events (H 1, H 2, and H 3) and the result of proxies indicated that the climate during the Last Glacial Maximum was the driest and the coldest of the Last Glacial. However, even if dominated by the East Asian Winter Monsoon, the study areas still captured some warm fluctuations (DO 1, DO 2, DO 3, and DO 4).

To summarize, the 20 DO warm events and 6 H cold events which were recorded in ice cores (GRIP, 1993) were also found in the loess sections with high resolution, especially in the Shagou loess section in the western Loess Plateau (Figs. 2 and 3). These rapid cold and warm events described by the two loess records and the GRIP ice core record (GRIP, 1993) were basically synchronous (Figs. 2 and 3). In a given section, the magnitude of variation in the summer monsoon proxies is much larger than that in the winter monsoon proxies, suggesting that the summer monsoon may have played more important roles in reinforcing the magnitude of the DO events.

In the study of loess in China, including our two loess sections, although there is scarcity of high-resolution records of the Last Glacial (Chen et al., 1997; Ren et al., 1996; Ye et al., 2000), signals of the rapid climate fluctuations that occurred during the Last Glacial are recorded to some degree (Fig. 3). It should be noted that, because there are differences in the method of dating and in age transformation among the loess sections in Fig. 3, we still could not strictly compare the DO events and H events recorded in the sections. However, this has little effect on the discussion of those events. On orbital scales, the loess record (Fig. 3) is basically consistent with the SPECMAP record (Martinson et al., 1987), which indicates that the global ice volume on timescales of tens of millennia is the main factor related to climate change. On sub-orbital scales, the loess record is more similar with the GRIP record (GRIP, 1993), but from west to east, the similarity becomes less obvious. That is, the Xinjiang-Yili-ZeKetai loess section (Ye et al., 2000), which is influenced by Westerlies all year, has the most obvious DO cycles, followed by the Shagou loess section, the Yuanbao loess section (Chen et al., 1997) and the Li Jiayuan loess section (Ren et al., 1996). The DO cycles of the Wangguan loess section are the least apparent. It is possible that the reduced amplitude in the grain-size variation curves (Fig. 3) is due to the stronger weathering in the east, which may have produced more fine-grained particles and less grain-size variability. However, this should not be the case as the weathering was extremely weak during the Last Glacial.

In records of the Last Glacial, stalagmite records characteristically are precisely dated in high resolution. Because they also pertain to the Quaternary sediments in the East Asian Monsoon area, we compared the proxies of the loess records (the Shagou section and the Wangguan section) with the $\delta^{18}O$ proxy of two stalagmite records (Sanbao Cave, Hulu Cave) (Fig. 2). The loess records and the $\delta^{18}O$ results were basically synchronous on the sub-orbital scale, which indicated that the millennium-scale climate events that happened in the East Asian Monsoon area during the Last Glacial had higher coherence (Fig. 2). However, the loess records are more intensive fluctuated than the $\delta^{18}O$ results (especially in the MIS 3 in the Shagou section) (Fig. 2).

The East Asian Summer Monsoon was affected by the tropical ocean during the Last Glacial, with the strength of the effect a function of distance from the tropical ocean (Ding and Yu, 1995). In a given section, the summer monsoon may have played more important roles in reinforcing the magnitude of the DO events (Fig. 2). If the DO events which are reflected in the geological records in the East Asian Monsoon area were completely or mainly driven by the East Asian Summer Monsoon, the fluctuation range of the DO events should gradually decrease from the east to the west. However, every loess section shown in Fig. 3 reflects that the fluctuation range of the DO events gradually decreased from the west to the east. It suggests that other factors must have played extremely vital roles with regard to the DO events.

The source areas, transit paths and depositional areas of eolian dust of northern China are significantly affected by Asian monsoon circulation (Spring heating of Asia initiates the summer monsoon, which transports northward moisture and heat from North of Australia across the Warm Pool, as far as northern China. The winter monsoon is characterized by cold, dry Siberian air flowing southward across eastern China [Wang et al., 2001]). However, these areas are also located within the latitudinal zone of northern westerly circulation (Chen, 1991). The Westerlies function as the planetary circulation system in middle latitudes of the Northern Hemisphere, and the monsoon circulation generally functions as a low-level circulation system under the Westerlies (Chen, 1991). The atmospheric circulation regime over the Asian continent is generally controlled by the monsoon overlying westerly circulations (Chen, 1991). It is this kind of double-structure circulation system that is responsible for the transportation and deposition of eolian material of northern China (Sun et al., 2002, 2003). Systematic grain-size analysis has found that Chinese loess generally shows a bimodal distribution composed of overlapping coarse and fine components (Sun et al., 2002, 2003). Recent researches indicate that the coarse component was mostly the product of low-level monsoonal circulation, and the fine component was mainly transported by high-level circulation dominated by Westerlies in northern China (Sun et al., 2002, 2003). The East Asian Winter Monsoon is obviously influenced by the Siberia high pressure and the ice cap in the high latitude area of the Northern Hemisphere (An et al., 1995; Ding et al., 1998). The intensity of the East Asian Winter Monsoon or the intensity and position of the Siberia high pressure were unstable during the Last Glacial, and the frequency of their unstable fluctuation is basically consistent with the records in the high latitude area of the Northern Hemisphere (Ding et al., 1998). The frequent fluctuation signals of the ice cap in the Northern Hemisphere high latitude might be transmitted to the Siberia area by the Westerlies through the Kara Sea ice cap and the Barents Sea ice cap, and then reflected in the intensity of the Winter Monsoon (Ding et al., 1998; Porter and An, 1995;). The activity of the cold air in the high latitude area of the Northern Hemisphere controlled the variation of the East Asian Winter Monsoon to a great degree through the Westerlies and some related pressure systems (Porter and An, 1995).

Whether in the area of the Westerlies or in the East Asian Monsoon area, the climate change is driven by the global ice volume, but the climate of the two areas change in two different ways (Li et al., 1992). In the Westerlies area, the climate is mainly controlled by the Westerlies and the tropical ocean has little or almost no influence on the climate. But in the East Asian Monsoon system, the winter monsoon dominated during the Last Glacial and its influence may even have extended to the south of the China Sea (Chen and Huang, 1998). And although the Summer Monsoon was weak, its influence cannot be neglected. The rapid climate fluctuations events in the high latitude area (the North Atlantic area) of the Northern Hemisphere caused changes in ocean surface and subsurface temperature in the North Atlantic (NADW), and then the signals of climate change were transported to other areas in atmosphere and ocean currents. Based upon the Chinese loess record, this kind of rapid fluctuation within high latitude areas in the Northern Hemisphere was brought by the westerlies (Chen et al., 1997; Ding et al., 1998; Porter and An, 1995; Ren et al., 1996). But in the upstream and downstream area of the Westerlies, the magnitude of the DO cycles was not same; that is, the magnitude in the upstream areas was greater than in the downstream area (Fig. 3). That was why the magnitude of the DO cycles in the Chinese loess record was smaller than in the record in Greenland (GRIP record); and why the magnitude of the DO cycle in the western China loess record was bigger than in the loess record in the eastern part (Fig. 3).

The effect of the Westerlies and the East Asian Winter Monsoon is more obvious in areas generally under control of the Westerlies (for example, the Zeketai loess section). As a result, the rapid climate fluctuations of the North Atlantic area were most clearly captured by the climatic record in areas dominated by the Westerlies (Fig. 3). In the area of the East Asian Summer Monsoon, the magnitude of the DO cycle gradually decreased from northwest to southeast with decreasing strength of the rapid climate fluctuations signal of the North Atlantic area (Figs. 2 and 3).

4. Conclusions

In the western margin (the Wuwei area) and mid-eastern margin (the Sanmenxia area) of the East Asian Monsoon area, high resolution loess deposits all captured 20 DO warm events and 6 H cold events, which were first reported in the North Atlantic area. It is suggested that during the Last Glacial, the East Asian Monsoon climate also underwent rapid fluctuations on millennial to century timescales. The 20 DO warm events and 6 H cold events were basically synchronous in the Wangguan loess section, the Shagou loess section and the GRIP ice core. The magnitude of a series of rapid climate fluctuations on sub-orbital timescales during the Last Glacial gradually decreased from west to east in the Chinese loess record. We suggest that this was a result of the Westerlies and the East Asian Monsoon working together.

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