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SCIENCE DIRECT®
Quaternary International 154–155 (2006) 128–135

Climatic signals in the Chinese loess record for the Last Glacial: The influence of northern high latitudes and the tropical Pacific

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Abstract

The high-resolution Shagou loess section near the northwest limit of the East Asian Summer monsoon, northwest China, was analyzed. The timescale of this section was set up based on a grain size age model and age controls. The record of the Shagou section shows that the millennial-scale oscillations are superimposed on an orbital-scale trend which can be correlated with the variations found in Greenland and the Sulu Sea. Differences in the corresponding Dansgaard–Oeschger cycles between the records in Greenland and the Chinese loess sections, including the orbital-scale trend, the timing and the amplitude, suggest that the climatic signals in Chinese loess might not be singularly regulated by the North Atlantic. The differences in trend and amplitude can be reasonably explained when compared with the Sulu Sea record. This suggests that the western tropical Pacific also exerted an important influence on climatic signals found in the Chinese loess record, possibly countering the impact of high latitude factors during the Last Glacial.

1. Introduction

During the Last Glacial, the Heinrich events (Heinrich, 1988; Bond et al., 1993) left signals in the Chinese loess, implying that the climate of the North Atlantic and China were linked by the westerlies (Porter and An, 1995). High-resolution records from the northwestern part of the loess plateau have demonstrated that most of the Dansgaard–Oeschger (D–O) cycles in Greenland (Dansgaard et al., 1993; GRIP members, 1993; Grootes et al., 1993) are matched by equivalents in the Chinese loess record (Ding et al., 1996; Chen et al., 1997). The enhancement of the Asian Summer monsoon, reflected in magnetic susceptibility and pedogenic layers, can also been correlated with the Bond cycles and major warm periods in D–O events in the North Atlantic region (Fang et al., 1999). The teleconnection between changes in the North Atlantic and the Chinese loess record has become a widely accepted means of interpreting the millennial-scale climate variability, especially Winter monsoon strength, in the loess record of the Last Glacial.

Factors other than the North Atlantic may also have influenced the loess record. There are two major global climate forcing regions, the North Atlantic and the tropical Pacific (Cane, 1998). The role of the tropical Pacific is receiving increasing attention. The East Asian monsoon system, consisting of the Summer and Winter monsoons, is the most important component of eastern China's climate. The Chinese loess plateau is affected both by the high latitudes and the tropics. Thus, it is reasonable to accept that loess deposits may contain records of changes in both the North Atlantic and the western tropical Pacific. However, more attention might be accorded to the tropics in attempts to explain of climate record in the loess. The East Asian Summer monsoon originates in the western tropical Pacific, generating a northerly or northwesterly

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doi:10.1016/j.quaint.2006.02.007

airflow into the continental interior, including the Chinese loess plateau and the eastern Hexi Corridor.

In the arid and semi-arid regions along the advancing front of the Summer monsoon, the effect of the tropical Pacific may be prominent because the precipitation is sensitive to the Summer monsoon's strength, and the vapor carried by the Summer monsoon is the most important environmental factor. If the western tropical Pacific experienced substantial variations during the Last Glacial, the impact on the Summer monsoon and its influence on the loess record should be recognizable. Indeed, variations in Winter monsoon strength as shown by the grain size record bear a generally inverse relation to those in Summer monsoon record as indicated by susceptibility proxies (Porter and An, 1995).

The eastern part of the Hexi (Gansu) Corridor, West of the loess plateau and adjacent to the Tengger Desert, is located close to the northwest limit of the present influence of the Summer monsoon (Fig. 1). The paleoclimatic records here show a high sensitivity to climatic change (Chen et al., 1997; Fang et al., 1999). In this paper, we present evidence from a loess section in the eastern Hexi Corridor, and discuss the effect of the North Atlantic and the tropical Pacific on the climatic signals preserved in the loess of the last glacial.

2. Chronostratigraphy and methods

2.1. Stratigraphy, field sampling and dating

The Shagou loess section (37°33′N, 102°49′E) is situated in the Hexi Corridor on the northern side of the Qilian Mountains, part of the arid and semi-arid region of northwest China (Fig. 1). The present-day climate at Shagou is semi-arid with a mean annual rainfall of 300 mm and an annual mean temperature of 5 °C. Bioturbation and leaching are limited because both annual temperature and precipitation values are significantly lower than in the central part of the loess plateau. In the absence of strong post-depositional pedogenesis, the climatic record is well preserved. The Shagou section is close to the Tengger Desert and has a high dust depositional rate. Loess layer L9 forms the base of the Shagou section, but here we discuss only loess layer L1, which corresponds to the Last Glacial. With a thickness of about 28 m, L1 is a yellow (7.5YR), loose silty loess, becoming a coarse silt and sand in the uppermost part. Three intercalated weak pedogenic layers are found in the middle of L1, corresponding to the paleosol Sm in the central loess plateau (Porter and An, 1995). Another pedogenic layer was also found above paleosol S1. The Holocene loess deposit and paleosol (S0) is very thin because of denudation (Fig. 2).

Samples were taken at 2.5 cm intervals in S1, the Holocene deposit and the sand layer corresponding to the Last Glacial Maximum (LGM), and at 5 cm intervals in the remainder of L1, yielding a theoretical resolution of 100 yr between samples.

The age of a given level in the Shagou loess section between the neighboring two age controls is calculated using the grain size age model (also named dust accumulation model) for loess deposition with orbitally tuned age controls. This model is based on the assumption that the dust flux is proportional to the grain size (Porter and An., 1995). Before the calculation, we need to establish the age controls. Some samples have been dated for the Shagou section. Thermoluminescence (TL) dating was undertaken at Xi'an State Key Laboratory of Loess and Quaternary Geology, Chinese Academy of Sciences, and ^{14}C dating

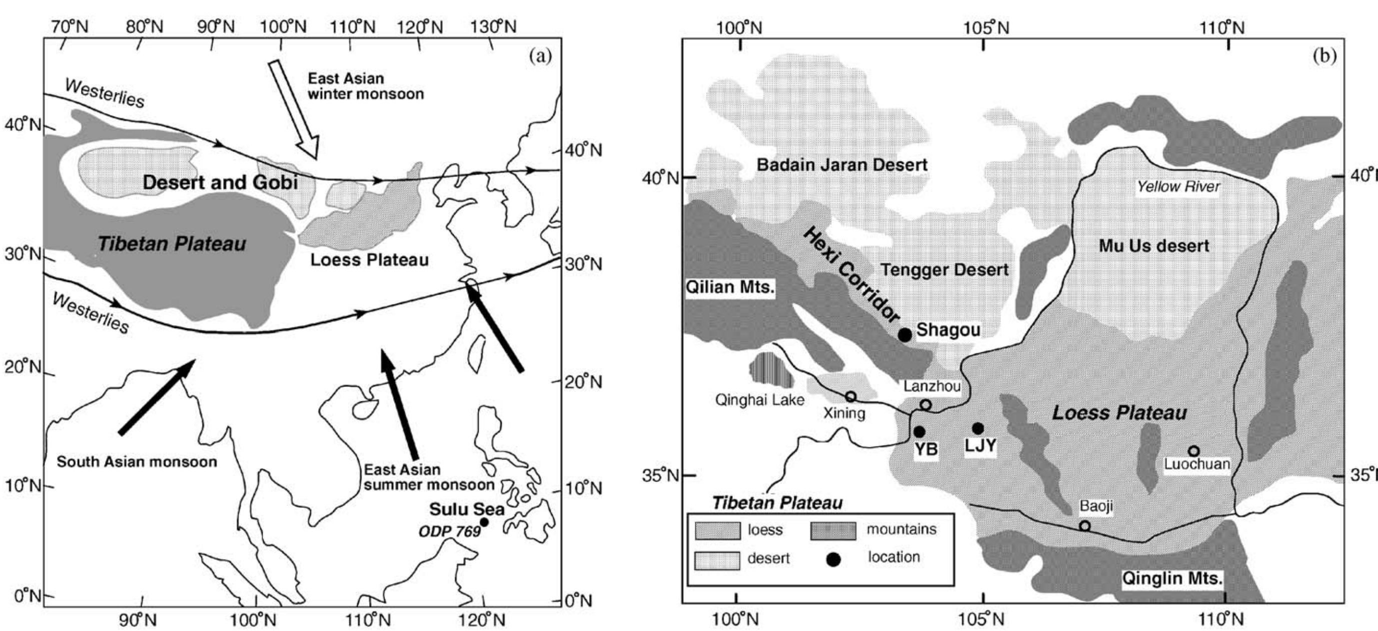

Fig. 1. (a) Sketch map of the East Asian monsoon. (b) Location of the Shagou loess section. YB and LJY indicate the Yuanbao and Lijiayuan loess sections, respectively.

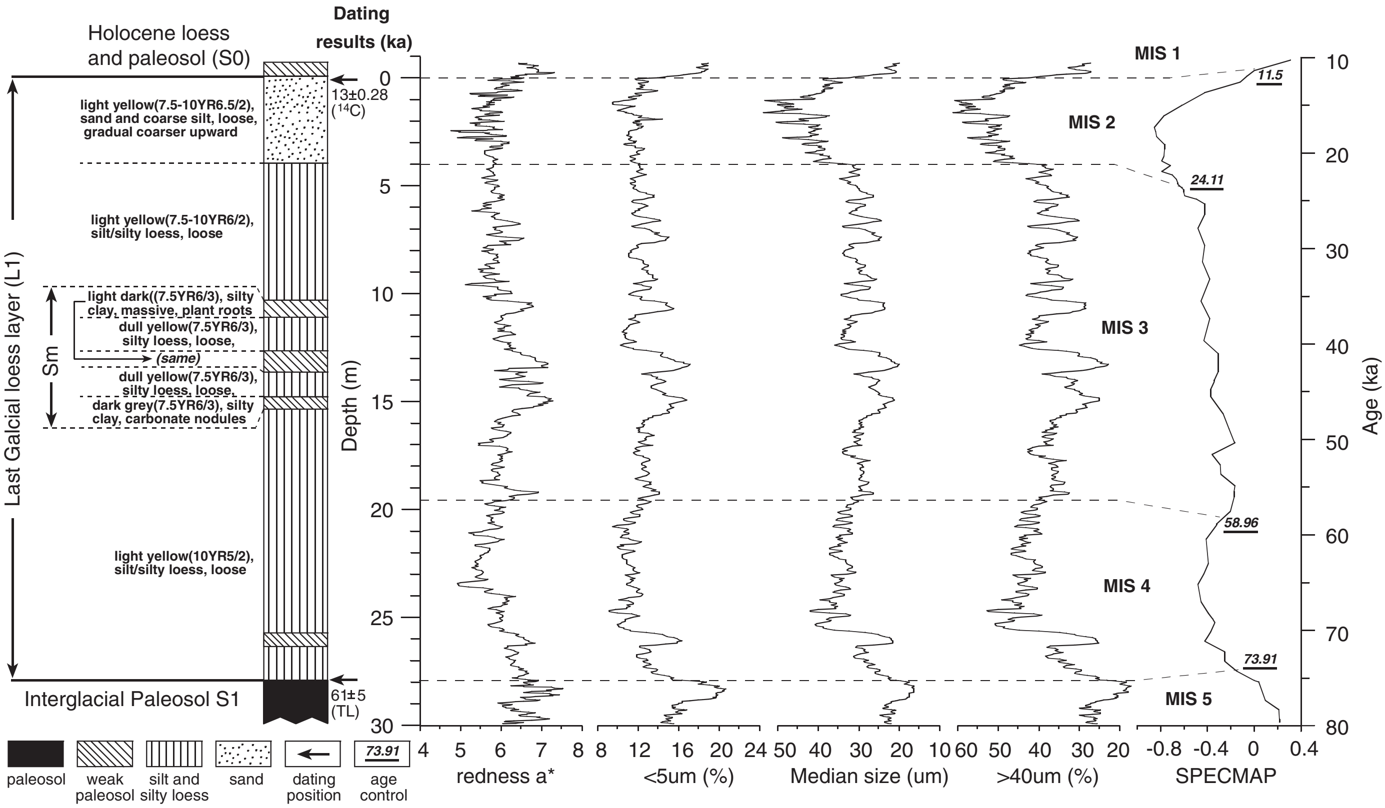

Fig. 2. Stratigraphy, dating results and records of the Shagou section for the Last Glacial. All the records have been smoothed using a three-point running mean.

was completed at Lanzhou University (Fig. 2). The dating results can help to define the framework the chronology and to mark out the S1, L1 and Sm units in the Shagou section. The distinct transition of stratigraphy and change of proxies at depth of 0 and 27.85 m, with our dating results, suggest that there should be the boundary of L1/S0 (MIS 2/1) and S1/L1 (MIS 5a/4). However, in loess researches, the dating results, no matter it is ^{14}C or TL, is with several hundred or even thousands year error and is not accurate enough to be directly used as age control. For example, our TL dating result of S1/L1 boundary is 61 ± 5 ka, but we cannot take the 61 ka as the exact age of this boundary and to calculate timescale. Other age controls must be sought. The SPECMAP timescale has been a benchmark for paleoclimate studies over the past 2 decades, while it provides a ''standard'' criterion for marine deposits by orbital tuning (Martinson et al., 1987). To use the SPECMAP timescale by ''curving matching'' to calculate a timescale for a loess section is very popular (e.g. Fang et al., 1999). In this paper, we also use ''curve matching'' to take the SPECMAP curve and use its age controls to calculate the timescale of Shagou section.

Three stages can be recognized within the Last Glacial at the Shagou section. Although there are no precise dating results between S1/L1 and L1/S0 boundaries in L1 loess layer, this pattern is consistent with the three-fold subdivision of the Last Glacial, presumably corresponding to MIS 4, MIS 3 and MIS 2 (Fig. 2). The age at the boundary of MIS 5a/4, MIS 4/3 and MIS 3/2 is set at 73.91, 58.96 and 24.11 ka, respectively (Martinson et al., 1987). The age of the boundary of MIS 2/1 is set at 11.5 ka (Golsar et al., 2000). Their corresponding positions in the Shagou section are set at depths below the base of S0 of 27.85, 19.45, 4.05 and 0 m, respectively. The content of the $>40\,\mu m$ fraction was chosen for calculation of the time-scale.

2.2. Climatic proxies

Both East Asian Summer and Winter monsoon records should be considered in order to access the relative influence of the North Atlantic and tropical Pacific. The most commonly used proxy for the Winter monsoon and Summer monsoon in the loess is particle size and magnetic susceptibility, respectively. Particle size parameters, such as the median size and the $>40\,\mu m$ fraction, are sensitive proxies of the Winter monsoon winds (Porter and An., 1995; Derbyshire et al., 1997; Ding et al., 1999a). The sand content has also been used as a proxy indicator of desert margin variations (Ding et al., 1999b).

The magnetic susceptibility record of the Shagou section does not match that of other sections, showing no systematic change with grain size and stratigraphy. Accessing the climatic significance of magnetic susceptibility in the loess sections is still something of an open question (Feng and Chen, 1999); it is not used here as a

Summer monsoon proxy. Thus, an alternative proxy is used, viz. color. The color of eolian dust depends largely on parent material and post-depositional weathering, the former being broadly the same for both paleosol and loess. In arid and semi-arid regions, high temperatures favor weathering and oxidation of iron. Consequent variation in the degree of redness in loess and paleosol has been used as a proxy of Summer monsoon strength (Fang et al., 1999). During the warm periods enhanced by the Summer monsoon, increased temperature favored dust weathering over North China, including the dust source area(s) that supplied the Shagou section. As dust flux was low in the warm periods, its effect upon color range was also probably minimal. The $L^*a^*b^*$ color system (Commission Internationale de l'Eclairage) is used here. L^* indicates lightness. Proxy a^* is the ratio between redness and greenness, while b^* is the ratio between yellowness and blueness. The higher a^* means more red the stratigraphy is. Proxy a^* is an efficient proxy for the weathering intensity of loess deposits (Yang and Ding, 2003) and chosen to indicate Summer monsoon strength during the Last Glacial (Yamada et al., 1999), and compares quite well with the grain size record during MIS 5 in the Shagou section (Wu et al., 2002), showing reliable results for the last glacial.

Particle size was measured using a Malvern Mastersizer 2000 laser particle analyzer, with a size range of 0.02–2000 μm. Grain size measurements were completed using a Malvern Mastersizer 2000, ranging from 0.02 to 2000 μm. Organic matter and carbonates were removed prior to measurement. The precision ($n = 15$) of the median grain size and the sand content for a sample from the lower part of the S1 paleosol is 1.1% and 2.7%, respectively. The color of dried and powdered samples was measured using a Minolta SPAD-503 Soil Color Reader.

3. Shagou record during the Last Glacial

The main characteristic of the Shagou record is that millennial oscillations, both in Summer and Winter monsoon proxies. The Shagou record shows a correlation with the Greenland and the global ice volumes (Fig. 3). During MIS 4, grain size coarsened rapidly, the coarsest component being deposited around the time of Cold event 19 (C19). Thereafter, mean grain size decreased gradually with very short and minor oscillations. The Summer monsoon strength, reflected by the redness a^* proxy, declined rather slowly as the climate turned into glacial. The two-step abrupt retreat of the Summer monsoon is very clear, being similar to that in the Zhaitang section near Beijing (Xiong et al., 2001, 2002).

During MIS 3, all proxy records indicate a warm and less windy period during the Last Glacial. Decrease in the >40 μm fraction and in the sand content suggest that the Winter monsoon weakened and the desert margin retreated. The Summer monsoon strengthened, indicated by the increase of the redness a^* proxy. Both the redness a^* and grain size records show a high amplitude and

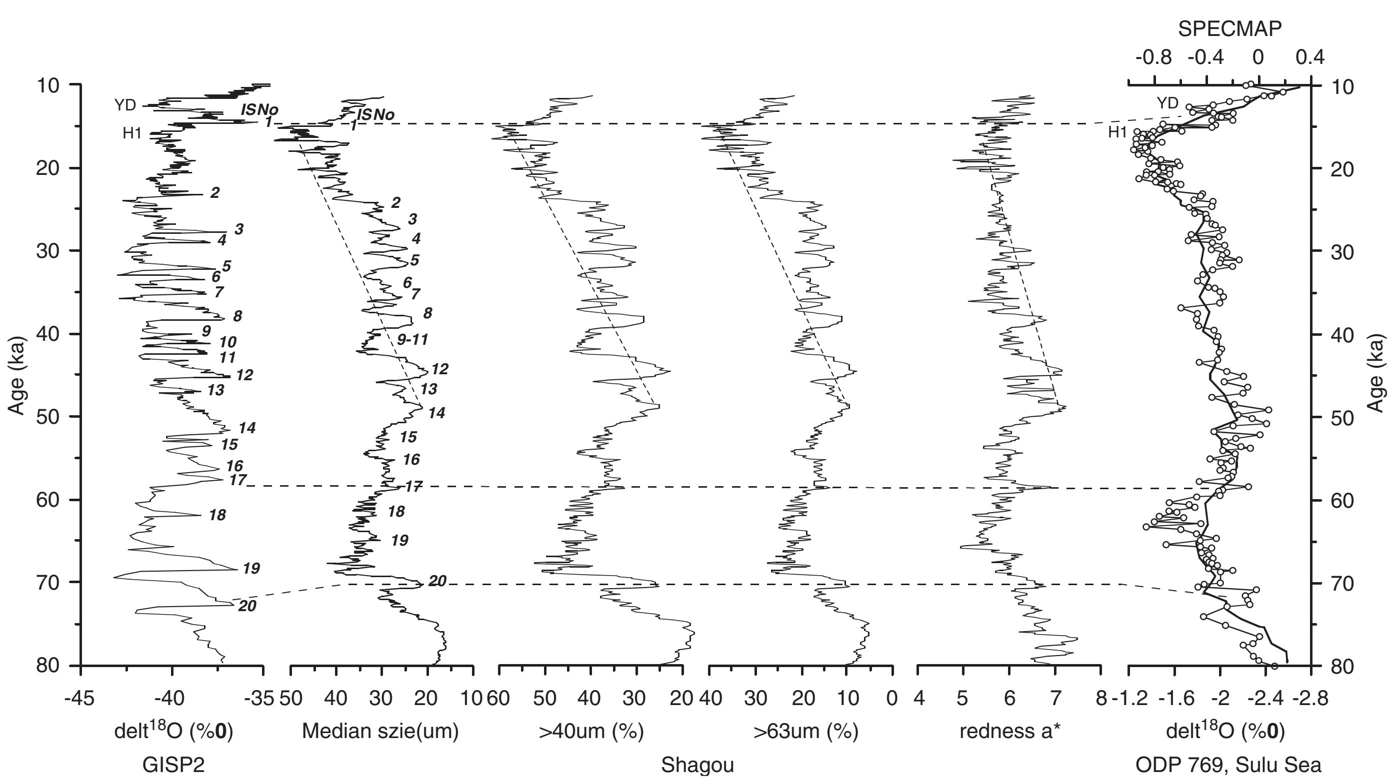

Fig. 3. SHAGOU record compared to the $\delta^{18}O$ of GISP2 in Greenland, the ODP Site 769 in the Sulu Sea (Linsley, 1996), and the stacked isotope of SPECMAP (Martinson et al., 1987). The numbers in italics indicate the IS events.

millennial-scale variations, and changes in Summer and Winter monsoon appear to be coupled. The warm events in MIS 3 correlate with the interstadials (IS) events in high latitudes of the northern hemisphere, like other sections (Ding et al., 1996; Chen et al., 1997). The records show clearly that the Summer monsoon was the strongest and the Winter monsoon was the weakest during the period 50–45 ka.

The coarsest part of L1 corresponds to the LGM. A distinct increase in coarse particles appeared at the MIS 3/2 transition, showing that the Winter monsoon strengthened rapidly. However, the redness a^*, which is the Summer monsoon proxy, showed no substantial change at the initiation of the LGM. During the LGM, median size and the $>40\,\mu m$ fraction increased gradually with short period variations. The desert margin also advanced considerably and reached its maximum southward extent, as indicated by the highest sand content in the section. This is consistent with considerable strengthening of the Winter monsoon and the westerlies during the LGM. The Younger Dryas event is not very obvious in Shagou section, largely because of the already extreme dry and cold environment during the LGM. However, the transition from LGM to the Holocene is very distinct in stratigraphy and record profiles.

In other loess sections, these characteristics are similar, especially for the millennial oscillation that is superimposed on the orbital trend (Porter and An., 1995; Ding et al., 1996; Chen et al., 1997).

4. Comparison with Greenland

4.1. General trend

The Shagou records clearly show a trend consisting of an increase in grain size and a decrease in redness a^* between ca. 50 ka and the end of the Last Glacial. The same particle size trend is also evident in the loess sections at Yuanbao (YB) and Lijiayuan (LJY) (Fig. 1), indicating an increase in Winter monsoon strength after about 57 or 50 ka in the loess plateau (Ding et al., 1996; Chen et al., 1997). The magnetic susceptibility record, used widely as a Summer monsoon proxy, also shows a decline after ca. 50 ka at Yuanbao (Chen et al., 1997) and Zhaitang (Liu et al., 1998) sections. This trend is not clear in the Greenland ice core record, although it is consistent with the global ice volume record.

4.2. Difference in relative timing

Correlation of some IS events between Greenland and Shagou is unconvincing when viewed against the timescale. This is not surprising, given that the GRIP and GISP2 also show some temporal differences. The absolute timing of IS events during the Last Glacial might not strictly match records from Greenland and the Chinese loess because of the difference in timescales. Even using relative timing, including the duration of IS events and the interval between the neighboring events, does not eliminate the inconsistency. So, the differences attributable to relative timing cannot be neglected. For example, the IS 19 event is relatively long in Greenland, but appears to have been rather short in the Shagou and Lijiayuan loess sections (Ding et al., 1996). Some short IS events in Greenland, such as the IS 5 event, are quite prolonged in the Shagou loess record (Fig. 3). It is not clear how such timing differences can be explained.

4.3. Change amplitude of IS events

When compared to the Greenland record, the timing is the main criterion for D–O oscillation (IS events) correspondence in the Chinese loess record, while the amplitude change has not been considered careful. Some differences between the amplitudes of those events are very obvious. The absolute amplitude is surely not worthy of discussion. However, the relative amplitudes of D–O cycles are not proportional between Chinese loess records and that in Greenland. In the grain size record of the Shagou, Lijiayuan and Yuanbao loess sections, such differences also clearly existed, especially for the IS 1 and IS 19 events (Ding et al., 1996; Chen et al., 1997). The IS 1 event, also called the Allerod/Bolling warm period, was the warmest episode during the Last Glacial in Greenland; yet it appears to have been far weaker, both in the Summer and Winter monsoon proxies, than most IS events in the Shagou and other loess records. In Greenland, the oxygen isotope data indicates that the Younger Dryas event was colder than the H1 event. However, the grain size in the loess records considered here shows no such a phenomenon (Fig. 3). In the Shagou loess section, there is a weak pedogenic layer that corresponds to the IS 20 event, with fine grain size and increased redness a^*. A similar layer was found in the Lijiayuan loess section (Ding et al., 1999a). The IS 19 event was very similar to the IS 20 in Greenland, with very similar amplitude and time span. However, the IS 19 event in the loess records is rather weaker than IS 20, and has no corresponding pedogenic layer.

5. Discussion

Differences between the Greenland and Chinese loess records can be seen in most loess sections. Thus, other factor(s), not been emphasized in former studies, must have influenced the climatic signals in the loess records. Among the more likely factors explaining those differences is the tropical Pacific.

The El-Nino and southern oscillation (ENSO) signal is propagated to high latitudes as the North Atlantic oscillation (NAO) and the North Pacific oscillation (NPO) by way of changes in air pressure gradients (Haigh, 2001). NAO and NPO pressure oscillations affect the strength of the Siberia–Mongolian High (Hoerling et al., 2001), which in turn modulates the strength of the East Asian Winter monsoon. The strength of the East Asian

Summer monsoon influencing the southern Mongolian Plateau is directly related to the interactions between ENSO and ITCZ in the tropical Pacific (Tudhope et al., 2001). The NAO also modulates westerlies in the middle latitudes. Thus, the tropical Pacific not only directly affects the strength of the East Asian Summer monsoon, but may also affect the Winter monsoon via the North Atlantic at a different timescale. Because of the complexity of the mechanism by which the tropical Pacific affects the North Atlantic, only its direct influence on the Summer monsoon and its record in the loess deposit will be discussed here.

Another question concerns whether it is valid to compare different single climate proxies, such as the grain size for the Winter monsoon strength and susceptibility or soil color for the Summer monsoon. Grain size proxies in loess appear to provide valid comparisons with the Greenland ice core record. If it can be shown that the Summer monsoon proxies also correlate well with the Greenland record, then, it would be reasonable to expect that the Summer monsoon was also directly affected by high latitude conditions. The records from ODP Site 769 and MD97-2141 in the Sulu Sea can be correlated with the high-amplitude and high-frequency variations in Greenland, showing a sea surface temperature (SST) variation of less than 2 °C at present during the Last Glacial (Linsley, 1996; Dannenmann et al., 2003). Although the West tropical Pacific was influenced by the Winter monsoon during the Last Glacial (Chen and Huang., 1998; Dannenmann et al., 2003), there was also an effect on the East Asian Summer monsoon, which raises the possibility that it affected Summer monsoon proxies found in the loess. Here we take the record of core ODP Site 769 in the Sulu Sea to represent variations in the western tropical Pacific and the Summer monsoon during the Last Glacial. If indeed the tropics experienced stronger cooling with a 5 °C maximum (Broecker, 1996), the Summer monsoon's effect on the climatic signals in the loess would expected to be more distinct.

The Siberian High is a major caused factor in the strength of the Asian Winter monsoon. Rapid climatic oscillations in polar regions might result in instability of the East Asian monsoon system over northern China in Glacials via the Siberian High (An and Porter, 1997; Ding et al., 1999a). This mechanism has been widely used in comparison between the loess record and the Greenland ice core record. However, the differences cited above require consideration of the effect of tropical Pacific. Because of the relatively low resolution of the ODP 769 Site record, the IS events and their correlation with the Shagou record are poor for in the middle of the Last Glacial. Some particular characteristics in the loess records that differ from Greenland have a reasonable explanation when compared to the tropical Pacific record.

Around 55–45 ka, grain size records from the Shagou, Yuanbao and Lijiayuan loess sections show obvious decreases in median size and in sand content, corresponding to a weak Winter monsoon. Magnetic susceptibility and redness a^* reached their peaks during this period, showing the strongest Summer monsoon reflected in the lowest oxygen isotope value in the Sulu Sea records during the Last Glacial. Between about 50 ka and the end of the LGM, those three loess sections illustrate a clear trend of increasing grain size and a decline in Summer monsoon proxies, suggesting that the Winter monsoon strengthened and Summer monsoon weakened after ca. 50 ka. This trend correlates with both the SPECMAP and the Sulu Sea records, but it is not clear in Greenland ice core record. The coupled evolution of the Winter and Summer monsoon in the long-term trends might reflect characteristics of the global background.

The weak IS 1 event in the Sulu Sea records, both in ODP 769 and MD 97-2141, indicates that the Summer monsoon strengthened very slightly. This correlates with the weak IS 1 event in the Shagou loess record, as shown by the redness a^* proxy (See Fig. 3). The ODP 769 record also shows that the IS 20 event was strong, while the IS 19 was weak. The Summer monsoon proxies in the Shagou, Lijiayuan and Yuanbao loess sections show that the IS 20 event was far stronger than the IS 19.

Two possible explanations may be offered for the smaller amplitude of D–O cycles in the loess records compared to those found in the Greenland ice cores. First, climatic variations in the middle and low latitudes are smaller than that in high latitudes in the northern hemisphere. Second, the effect of the Summer monsoon might counteract the Winter monsoon and the westerlies. The Summer monsoon's influence becomes stronger with proximity to the tropics. Amplitudes of the Winter monsoon proxy decline from northwest to southeast. Based on the grain size records, the Shagou section appears to show more obvious variations than that found in the Lijiayuan section for the Last Glacial. However, the extent to which and the mechanism by which the Summer monsoon counteracted the Winter monsoon and the westerlies remains unresolved.

A distinct change can also be seen in the ODP 769 site record at the MIS 3/2 transition, suggesting that the Summer monsoon weakened at this time (Figs. 2 and 3). The Summer monsoon proxy in the Shagou loess record, however, shows no substantial change. However, the grain size, which is the Winter monsoon proxy, increased sharply (See Figs. 2 and 3). The large dust input rate associated with MIS 3/2 also exists in the Lanzhou loess section (Fang et al., 1999). Why this Winter monsoonal shift matches the change seen in the tropical Pacific record remains an open question.

Evidence from other sources tends to confirm the loess proxy indicators. The oxygen isotope record in stalagmites from Hulu Cave, situated in the lower reaches of the Yangtze River, shows that this environment was affected both by the Summer and Winter monsoons for the Last Glacial. This record shows that the IS 1 and IS 19 events were relatively weak, the H1 event was far colder than the Younger Dryas event, and that cooling occurred after about ca. 58 ka (Wang et al., 2001). The Hulu Cave record confirms the effect of the western tropical Pacific and the Summer monsoon on the climatic record during the Last Glacial in eastern China.

It is interesting that the Shagou records also indicate that high latitude climate variation affected the East Asian monsoon even during the Last Interglacial (Wu et al., 2002). This suggests that both the North Atlantic and the tropical Pacific has an important effect on climatic changes recorded in Chinese loess for both Glacials and Interglacials.

We would emphasize that the tropical Pacific played an important role in addition to that of the high latitudes, the evidence cited here providing an explanation of some of the differences between those two records. However, the precise mechanism and the extent of the influence of the tropical Pacific on climatic record preserved in loess, and their detailed discussion is beyond the scope of this paper.

6. Conclusions

We conclude that:

(1) The Shagou loess section record shows that, during the Last Glacial, the eastern Hexi Corridor experienced millennial climatic changes that were superimposed on the orbital-scale global ice volume trends.
(2) Both the North Atlantic and the tropical Pacific ocean affected the climate signals of the D–O cycles (IS events) found in the Chinese loess record for the Last Glacial.
(3) The Summer monsoon may have acted to counter the climatic effects of the Winter monsoon.

Acknowledgments

We are grateful to Prof. Edward Derbyshire, Ian Smalley and Lewis Owen for valuable reviews and improving the English. This work is supported by National Natural Science Foundation of China (Grant nos. 40301009, 40471016, 40401007).

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