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Chinese deserts and sand fields in Last Glacial Maximum and Holocene Optimum

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The Last Glacial Maximum (LGM, c. 26–16 ka) and the Holocene Optimum (HO, c. 9–5 ka) were characterized by cold-dry and warm-wet climates respectively in the recently geological Earth. How Chinese deserts and sand fields responded to these distinctive climatic changes is still not clear, however. To reconstruct environments of the deserts and sand fields during the LGM and HO is helpful to understand the forcing mechanisms of environment change in this arid region, and to test paleoclimatic modeling results. Through our long-term field and laboratory investigations, 400 optically stimulated luminescence (OSL) ages and more than 100 depositional records in the Chinese deserts and sand fields were obtained; on the basis of these data, we reconstruct spatial distributions of the deserts and sand fields during the LGM and HO. Our results show that the sand fields of Mu Us, Hunshandake, Horqin and Hulun Buir in northern and northeastern China had expanded 25%, 37%, 38% and 270%, respectively, during the LGM; the sand fields of Gonghe in the northeastern Qinghai-Tibetan Plateau had expanded 20%, and the deserts of Badain Jaran, Tengger in central northern China had expanded 39% and 29% separately during the LGM; the deserts of Taklimakan, Gurbantünggüt and Kumtag in northwestern China had expanded 10%–20% respectively, compared to their modern areas. On the other hand, all of the sand fields were nearly completely covered by vegetation during the HO; the deserts in northwestern and central northern China were reduced by around 5%–20% in area during this time. Lakes in this arid region were probably expanded during the HO but this conclusion needs more investigation. Compared with the geological distributions of deserts and sand fields, human activity has clearly changed (expanded) the area of active sand dunes at the present time. Our observations show that environmental conditions of Chinese deserts and sand fields are controlled by regional climate together with human activity.

deserts and sand fields in China, Last Glacial Maximum, Holocene Optimum, OSL dating, active sand dunes

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There is an area of around 2.0×10^6 km^2 made up by deserts, sand fields and potentially desertified land in China [1]; their environment and ecosystem are vulnerable to climatic change and human activity. In addition, changes in the deserts and sand fields have also influenced climate and human life at local to hemispheric scales, thus, to understand

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*Corresponding author (email: huayulu@nju.edu.cn) environment changes in these deserts and sand fields is not only a scientific question, it is also important to combating desertification. The deserts and sand fields have changed greatly in time and space during late Quaternary, and to reconstruct spatial changes in extent of active dunes is particular important [2–6]. There were a few reconstructions of desert changes during the Last Glacial Maximum (LGM) and Holocene Optimum (HO) [7–26], however, because of limited dating work and field investigation, the results need tested. Moreover, some previous reconstructions were speculation based on comparison with paleoclimatic records, without direct and specific stratigraphic evidence; therefore, the conclusions [7–26] should be clarified. In China, some early investigations have advanced our knowledge of environment changes in the desert and sand fields, but there were quite a few issues that were not well resolved in this previous research, including: (1) Because of the limitation of dating techniques, accurate, independent high-quality ages for the deserts and sand fields were limited in number; previous research always compared the sand deposition with established time series such as that of Chinese loess-paleosol sequence and marine oxygen isotope stages to obtain age control [9,10,15–17,21–26] which was quite speculative. (2) The ages were not well-distributed spatially across the deserts and sand fields. (3) By reconstructing changes in the boundaries of deserts and sand fields only indirectly from paleoclimatic zone migration, without direct evidence, has probably led to misleading conclusions. (4) There was not a clear distinction made between the deserts and sand fields dominated by Asian monsoon circulation, the North Hemisphere westerlies and even local landform effects on climate, therefore, it was difficult to identify forcing mechanisms of change in specific deserts and sand fields. These previous limitations hindered proper understanding of the spatial changes of Chinese deserts and sand fields during the late Quaternary.

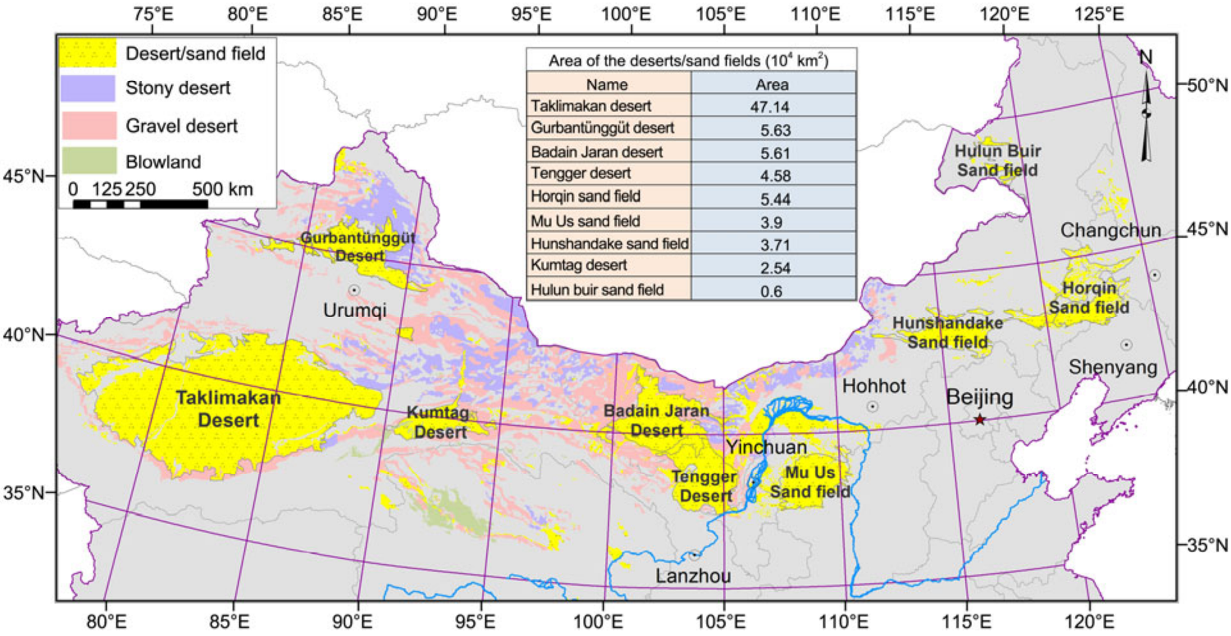
Chinese deserts and sand fields are mainly located in northern China, with dry climate (we do not discuss the scattered and fragmentary sand fields in southeast China and on the Qinghai-Tibetan Plateau), controlled separately by Asian monsoon circulation and/or the Northern Hemisphere westerlies. The sand fields of Mu Us, Hunshandake, Horqin and Hulun Buir in central northern China are dominated by the monsoon climate, whereas the deserts of Taklimakan, Gurbantünggüt and Kumtag are not influenced by the monsoon climate (some suggest that these deserts are dominated by the westerlies [27–31]). The deserts between northwestern and northeastern China such as Badain Jaran, Tengger, Ulan Buh and Hobq are located in the marginal region of the Asian monsoon climate, and are also very dry. Therefore, the different atmosphere circulations that control the deserts and sand fields' environments should be separately investigated.

Since the spring of 1997, we have investigated these deserts and sand fields in order to reconstruct their environment changes during the late Quaternary; in particular in the past six years, we investigated the sediments and depositional records by gridding-route reconnaissance in the field and collected numerous samples which were dated by the optically stimulated luminescence (OSL) technique and measured to obtaining proxy indexes of the environment changes. On the basis of this long-term study, we try to reconstruct Chinese deserts and sand fields in the LGM and HO, and, compare the reconstruction results with the modern deserts and sand fields, to investigate possible forcing mechanisms of environmental change in the deserts and sand fields.

1 Methods and data

Figure 1 shows distribution of the modern deserts, Gobi and sand fields in northern China [32]. We produced this map based on combination of remote sensing (RS) including Enhanced Thematic Mapper (ETM) images and the spectral angle method, observations located with global positioning systems (GPS), and geographic information system (GIS) analysis. We first applied geometric precision correction, image mosaicking, wave band combination and image enhancement to ETM images from 2010; then bands 7, 5 and 2 of these enhanced ETM images were used to establish markers of desertification. Third, the spectral angle method was used to identify margins of active dunes, soil and vegetation covers. Observations in the field, located by GPS were used to correct the boundary data. An existing data set was combined with our results to create a new GIS database for the deserts and sand fields, containing numerical data of landforms, soils and vegetation.

Figure 2 shows the detailed field reconnaissance in Chinese deserts and sand fields as an example; we have chosen good outcrops for sampling through extensive field reconnaissance. At each site, the location, stratigraphic and sedimentary characteristics were carefully logged. Samples were dated by OSL technique and measured for grain size, magnetic susceptibility and organic matter content in order to identify depositional environment. Previous studies [8–10,18,21] have shown that the aeolian deposits in marginal regions of these deserts and sand fields can be used as indicators of desert and sand field expansion and contraction during the late Quaternary. That is, when the East Asian winter monsoon circulation was strengthened, the climate in these regions was dry and the wind velocity was increased, the sand dune would be active and the deserts and sand fields expanded along direction of the strengthened monsoon wind; on the other hand, the strengthened East Asian summer monsoon circulation brought more precipitation to this dry region, vegetation cover expanded and stabilized the active sand dunes, so the desert and sand field were probably covered by loess and sandy soil. The sand, loess and soil in the depositional sequences can be used as proxy indicators of the deserts and sand fields change in the



Area of the deserts/sand fields (10^4 km^2)

Name	Area
Taklimakan desert	47.14
Gurbantünggüt desert	5.63
Badain Jaran desert	5.61
Tengger desert	4.58
Horqin sand field	5.44
Mu Us sand field	3.9
Hunshandake sand field	3.71
Kumtag desert	2.54
Hulun buir sand field	0.6

Figure 1 Chinese deserts and sand fields obtained by newly remote sense images interpretation and the existed geographic information data.

past. After dating many sedimentary sites near the margins of the deserts and sand fields, we used both of the ages and depositional records to reconstruct the distribution of active sand dunes and soils [8–10,18,21]; many dated sites are used in combination to delineate borders of the deserts and sand fields in the LGM and HO.

Figure 3 shows specific depositional records with the OSL ages and proxy indicators of the paleoenvironment, for an example. The single aliquot technique using coarse quartz particles is used [33] to date the samples; the chemically extracted pure 90-150 μm particles were measured by Risøe TL/OSL-DA-20C/D OSL reader to obtain equivalent dose rate; for estimating dose rate to grains, concentrations of ^{238}U, ^{232}Th and ^{40}K were measured by Neutron Activation Analysis (NAA). Thus, more than 400 OSL ages have been obtained [18,34–44]; at the same time, the grain size distribution, magnetic susceptibility and organic matter content were measured. As a total, more than 100 depositional sections were analyzed, plus the previous published ages [8,10,11,21,45–57] that can be used to identify sediments deposited in the LGM and HO, to provide estimation of the borders of the deserts and sand fields during that time (Figure 4 and Table 1) [32].

2 Results

Compared with the modern distribution, the deserts of Taklimakan, Gurbantünggüt and Kumtag were expanded 10%–20% during the LGM; the deserts of Badain Jaran and Tengger were expanded 39% and 29% respectively, and the sand fields of Mu Us, Hunshandake, Horqin and Hunlun Buir were expanded 25%, 37%, 38% and 270% respectively during the LGM; The Gonghe Basin dune field was expanded 20% (Figure 4, Table 1, all compared with the modern areas). There was a great change in the sand fields and deserts during the HO: the sand field of Hulun Buir, Horqin, Hunshandake and Mu Us were nearly completely covered by vegetation and black sandy loam soil or black sandy chestnut soil, as was the Gonghe Basin sand field; the margins of the Tengger, Badan Jarain, Kumtag and Takilamakan deserts were shifted near the piedmonts of the Qilian Mountains, Kunlun Mountains, Altyn Tagh Mountains and Tianshan mountains, where conditions were relatively humid during the HO and loess or loess-like sediment was deposited with thicknesses of several meters to tens of meters, indicating retreat of the active sand dunes over an estimated distance of 20–60 km. In contrast to the great retreat (several hundred kilometers) of the sand fields in northeastern China, the margins of the deserts in northwestern and central northern China had a smaller change; they were mainly characterized by active sand dunes even during the HO, which was also the case in the Qaidam Basin [57]. This finding supports the view that climatically driven evolution of sand dune activity differed between northwestern and northeastern China.

3 Discussions

3.1 Reliability and accuracy of the reconstruction of deserts and sand fields

Our results are based on long-term field reconnaissance and numerous independent OSL ages. In particular, we used a gridding-routes strategy to investigate depositional records in these deserts and sand fields, paying particular attention

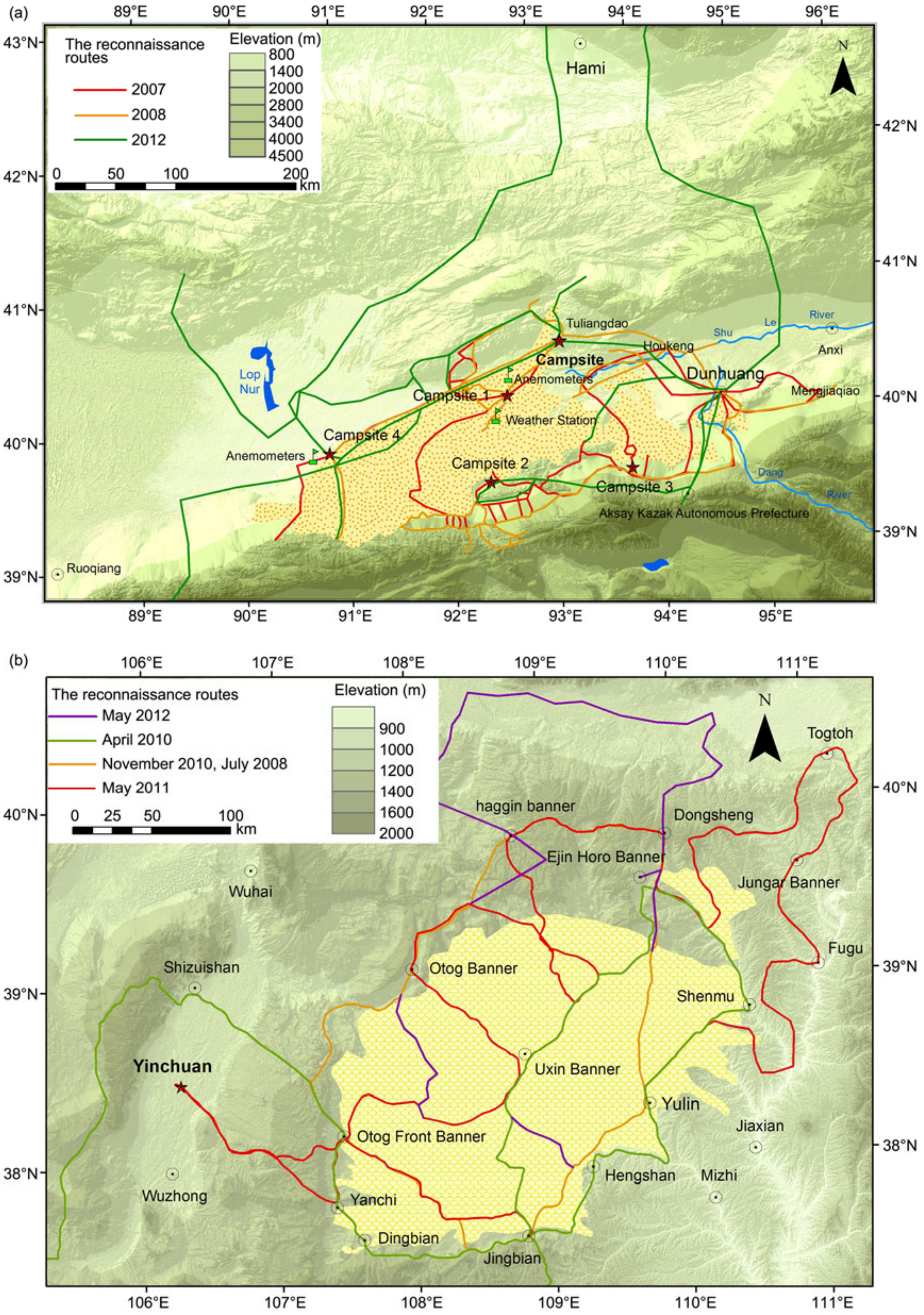


Figure 2 The reconnaissance routes in the deserts and sand fields, as an example. (a) Kumtag desert; (b) Mu Us sand field.

to depositional exposures along transects across boundaries between the sand fields and adjacent loess. Thus, the uncertainty of reconstructed border locations is less then 10 km in some places, providing the most accurate results to date in delineating the distribution of Chinese deserts and sand fields during the LGM and HO. In addition, significant improvement of the OSL dating technique has provided rapid [58], accurate and replicable dating for these aeolian sand sediments

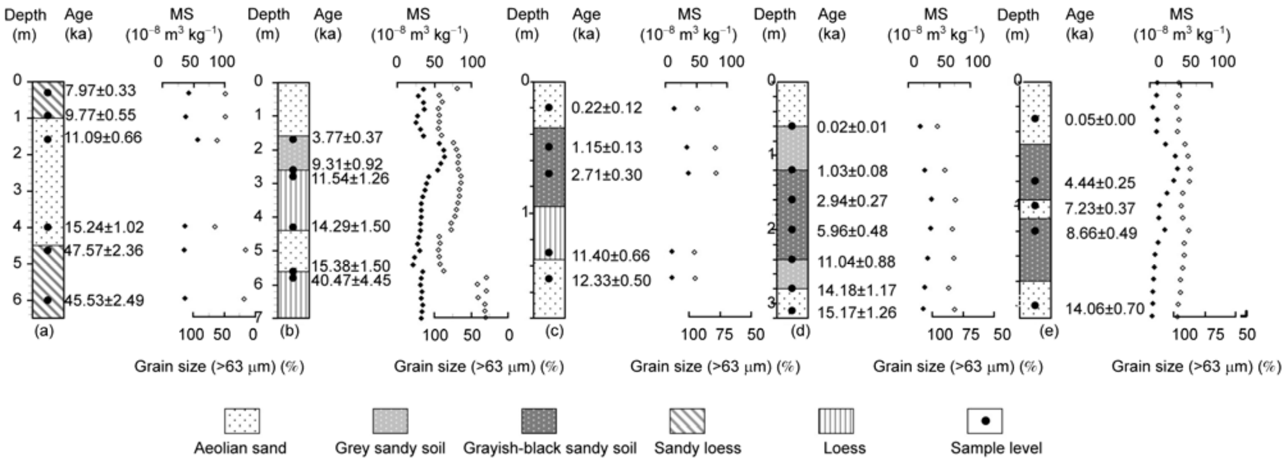


Figure 3 Representative sections investigated by this study. (a) South margin of Tengger Desert; (b) Mu Us sand field; (c) Hunshandake sand field; (d) south margin of Horqin sand field; (e) Hulun Buir sand field.

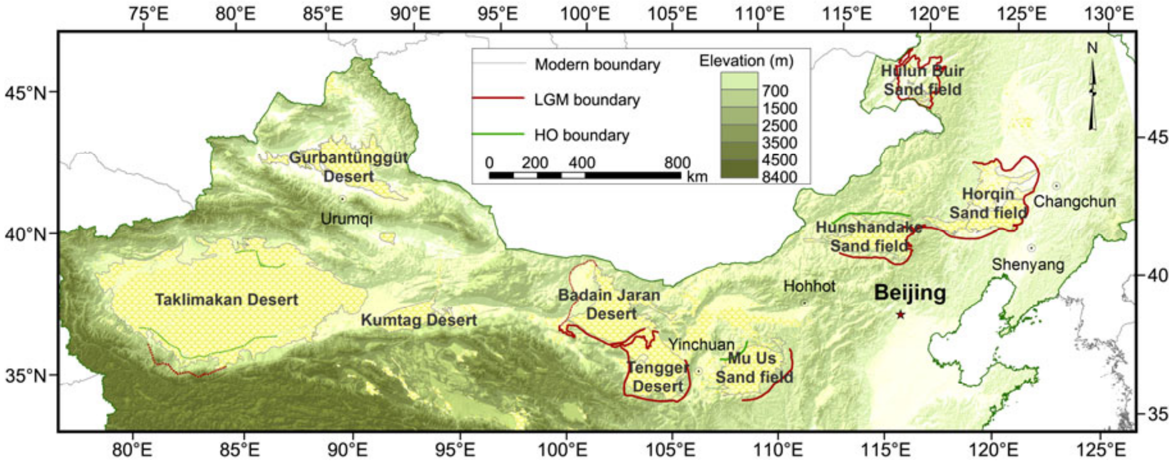


Figure 4 Chinese deserts and sand fields during the LGM and HO.

Table 1 Quantitative estimation of distribution of the active dunes in Chinese deserts and sand fields during the LGM and HO

Deserts/sand fields	Modern area (10^4 km^2)	LGM expanded (%)	HO contracted (%)
Hulun Buir	0.60	270	−100
Horqin	5.44	38	−100
Hunshandake	3.71	37	−100
Mu Us	3.90	25	−100
Gonghe Basin	0.25	20	dunes were probably stabilized
Tengger	4.58	29	border moved 20 km to north
Badain Jaran	5.61	39	–
Kumtag	2.54	minor changes	border retreated to north 60 km
Taklimakan	47.14	migrated 60–100 km to the south and east	minor changes
Gurbantünggüt	5.63	–	border moved to north c.100 km

age with errors less than 10%, therefore, we believe that this study presents the most accurate and reliable results for reconstructing the spatial distribution of Chinese deserts and sand fields during the late Quaternary. Moreover, this study provides the first evidence that the deserts in northwestern China and the sand fields in northeastern China have evolved differently during the LGM and HO, showing that the area of active dunes in the northeastern China has had a greater amplitude of fluctuation than that in central northern and northwestern China. This finding demonstrates that climate was an important factor that dominated the dune field evolution.

The deserts and sand fields in China are mainly scattered in the Cenozoic basins (Figure 1). Our reconnaissance along transects across desert and sand field boundaries allowed us to identify buried soils or sands that are direct evidence of border migration. This kind of work has never been undertaken before, unfortunately. Previous research suggested that subtropical deserts could have expanded to 30°N and 30°S during the LGM, so that half of the land area of the continents was covered by deserts [7] (the modern proportion is 22.6%, UNEP, 2006, Global Deserts Outlook. http://www.unep.org/geo/gdoutlook/). However, these previous results are quite speculative because the authors deduced the desert borders indirectly based on paleoclimatic reconstructions, unsupported by direct stratigraphic evidence. In China, previous investigators used precipitation of 200–400 mm as the boundary between the loess and sand field, thus, they concluded that border of sand fields and deserts would move south to 30°N during the LGM, in accordance with the climatic zone migration. If so, the desert border would be located at the line along Hangzhou-Nanchang-Changesha-Chengtu to the Gongga Mountains [59], within the present monsoon core region with an annual precipitation more than 1000 mm. Indeed, the reference [59] used the word "desert" as a climatic zone indicator but not a real desert, and an actual desert landscape never existed in this monsoonal evergreen region at the LGM or since that time. Unfortunately, this concept was misunderstood, so that someone believed the region from Hangzhou, to Nanchang, Changsha, Chengdu and Gongga Mountains was covered by desert in the LGM. In fact, it is difficult to find aeolian sand deposits more than 50–60 km beyond the modern active dune area. For instance, the aeolian sand and silt form continuous deposits southward from the modern Mu Us sand field. We scrutinized extensive outcrops to identify any buried sand along transects from the Mu Us dune field to the Loess Plateau, and we found the sand deposits of the LGM were replaced by loess 50–60 km away from the modern sand dunes; we did not find sand deposits of the LGM even in the Yan'an region, less than 100 km away from the Mu Us dune field. This observation clearly reveals that the Mu Us sand dunes did not migrate to more than 100 km away during the LGM, compared with the modern border. Thus, LGM expansion of the dune field was quite limited.

For a long-time, the monsoon precipitation has been regarded as the most important factor that controls the border location of Chinese deserts and sand fields [8,13,17–19,21, 23,33,59,60]. This is accurate for the sand fields in the east of Helan Mountains, however, the deserts west of the Helan Mountains, especially the Kumtag desert and Taklimakan desert are barely influenced by the monsoon circulation, and their evolution and environment change were different from the dune fields in the northeastern China. An early paper [61] concluded that the Chinese deserts and sand fields probably changed in different style between the west and the east sides of Helan Mountains, our findings support this conclusion; the border migration amplitude of the non-monsoon region was much smaller than that of the monsoon dominated region.

3.2 Factors that force Chinese deserts and sand fields' changes in LGM and HO

The distribution of deserts and sand fields in China is dominated by climate (aridity and wind velocity), sand source production, topography and human activity. We believe that the major changes of the sand fields in the northeastern China during the LGM and HO are mainly controlled by paleoclimatic changes. That is, the LGM was characterized by a cold and dry climate, with weaker water vapor transport and atmospheric circulation than today, lower sea-level and increased continentality, and precipitation decreased in inland China at that time. There is evidence for both strengthened wind and increased aridity during the LGM [19,62,63], and these two factors directly forced the expansion of the active dunes. On the other hand, the rise of sea-level, increased water vapor transport and atmospheric circulation and reduced wind velocity in the HO drove decrease of the sand dune mobility, with expansion of vegetation and soil covers. However, climate is not the unique factor that controls the deserts and sand fields' variations. In the deserts of Taklimakan, Kumtag and Qaidam, active sand dunes are located in basins bounded by high mountains, therefore, even though there was a significant climate changes between the LGM and HO, the active sand dunes never expanded across the high mountains such as the Altyn Tagh, the high topography clearly blocked expansion of the active sand dunes to the south.

The modern climate in the sand fields in northeastern China is more close to the climate of the HO (interglaciation) than that of the LGM (glaciation), therefore, the modern border location of the sand fields and deserts should be closer to that of the HO rather than the LGM, if the climate was the most important and unique factor that controlled the active dune distribution. However, our reconstructions show that area of the modern sand fields is 20%–40% less than that of the LGM, but is at least several times more than that of the HO (Figure 4 and Table 1). This observation shows that the distribution of the modern active dunes is more likely close to that of the LGM than that of the HO, even though the modern climate is closer to that of the HO rather than the LGM. This mismatching between the active sand dune distribution and the climate probably indicates that the climate was not the unique driver of the sand dune distribution, but other factors such as the human activity and clearing of the vegetation have significantly modified distribution of the active sand dunes in the northern China [47,64]. Our recently collected data of the Neolithic archaeological site distribution in the sand fields shows that human activity/

living sites have significantly increased since middle Holocene [65] (Table 2), demonstrating that the human activity has significantly been involved in land surface processes and vegetation clearing. This human impact is probably a major factor that remobilized the stable dunes in northern China during the late Holocene. More investigation is needed to clarify this question (When we revised this paper, we read a paper in Guangming Daily (March 25, 2013) that an ancient city of around 4000–5000 years ago was unearthed at Shimao site, Shenmu County, Shaanxi Province, at the transitional zone between the modern sand field and the loess deposition at southeastern margin of the Mu Us sand field. The archaeological report shows that the ancient city had an area of 4.0×10^6 m^2 with the time of Huangdi (Yellow Emperor) era. The grand town proves that people had significantly influenced the surface process in this region since the middle Holocene).

There is an enigma that we did not find much well- preserved sand deposit of the LGM in these sand fields even we have analyzed numerous deposition records inside and out of the deserts and sand fields. Direct depositional evidences show that the sand fields of Mu Us and Horqin were existed since at least 1.0 Ma ago [23,66], demonstrating that the sand dunes were developed since at least that time. However, where are the dune sediments from the LGM? Here, we have three possible explanations: one is that the LGM sand sediments were still in the deserts and sand fields, but our OSL-based research methods did not detect it. Because the OSL dating technique indicates the time since the sediment was buried, we speculate that the wind was very strong and climate was very dry during the LGM, the sand dunes were mobile all the time, thus the sediments were continually re-exposed to light so no OSL signals/ages were acquired. Only when the wind velocity decreased and climate became relatively humid at the end of the LGM, was the sand sediment buried, so that the OSL "clock" started running. The second possibility is that the wind was strong and climate was very dry during the LGM, but there was relatively little new sediment brought into the sand fields because of drying of the rivers; at the same time, the strengthened winds transported existing sand sediments away, so there was little sediment preserved in the sand fields. The third possibility is that the extreme cold climate during the LGM in the sand fields, together with reduced evaporation, caused frequent sand surface stabilization by frost and snow; thus, there were not sand dunes formed. These explanations all need to be tested by more work, but we prefer the first one at this stage.

Table 2 Neolithic archaeological sites in the sand fields of northern China

Age	Hulun Buir	Horqin	Hunshandake	Mu Us
9–4 ka	42	579	30	467
4–2 ka	6	672	43	217
Since 2 ka	67	2932	171	934

4 Conclusions

Chinese deserts and sand fields have expanded 10% to 270% during the LGM, compared with their modern areas. The active sand dunes in the sand fields of northeast China were nearly completely stabilized, and the deserts in the northwest China have reduced 5% to 20% in area during the HO. The variations of Chinese deserts and sand fields were responded to paleoclimatic changes in the LGM and HO, but human activities have significantly modified the desert and sand field distribution in the late Holocene.

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