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ARTICLES

Vegetation and climate changes during the last 8660 cal. a BP in central Mongolia, based on a high-resolution pollen record from Lake Ugii Nuur

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Based on modern pollen studies and reliable chronology of nine AMS ^{14}C dates, a detailed history of vegetation and climate changes during the past 8660 cal. a BP was reconstructed by a high-resolution pollen record from Ugii Nuur in central Mongolia. Poaceae-steppe dominated the study area and the climate was mild and semi-humid before 7800 cal. a BP with a noticeable cool and humid interval at 8350—8250 cal. a BP. Xerophytic plant increased and the climate became warm and dry gradually since 7800 cal. a BP. From 6860 to 3170 cal. a BP, semi-desert steppe expanded, suggesting a prolonged warm and dry climate. Between 3170 and 2340 cal. a BP, regional forest steppe expanded whereas semi-desert steppe retreated, indicating the climate became cool and wet gradually and the humidity reached the maximum at the end of this stage. From 2340 to 1600 cal. a BP, a general cool and wet climate prevailed. And the climatic instability increased after 1600 cal. a BP. Review of regional published palaeoclimatic records implies that the mid-Holocene dry climate might have prevailed in vast areas from central Mongolia to arid areas of northwest China. Pollen-based climate reconstruction for UG04 core was well correlated with the result of climate model on Central Asia by Bush. In addition, several abrupt climatic events (cool and wet) were found and some could be broadly compared with the cool events in Atlantic.

central Mongolia, lake sediment, pollen record, vegetation and climate change, Holocene

Holocene climate and environmental changes are of particular interest for its potential not only to understand the past but also to predict the future and assess the anthropogenic impacts. Many Holocene climate sequences were reconstructed worldwide since the discovery of the climatic instability in Greenland ice core and Atlantic deep sea sediments[1,2]. However, those uneven distributed climate data, especially scarce in key and climatic sensitive areas, greatly constrain us from understanding the temporal and spatial climate patterns and associated dynamics[3]. Therefore, high quality Holocene climate sequences in key areas are greatly needed. The arid and semiarid Mongolian Plateau, situated in the Asian continental interior and controlled or modulated by the Asia Monsoon (mainly winter monsoon) and the North Atlantic Oscillation (NAO)-associated westerlies nowadays[4,5], is such a highly focused and climatic sensitive area. A thorough comprehending of the temporal and spatial Holocene climate pattern in the Mongolian Plateau is vital for us to understand the interacting history of the aforementioned climate systems. But, the Holo-

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cene studies of Mongolia are in relatively poor level for its specific physiographic settings and history. That is, existing Holocene palaeo-lake climatic records[6–14] and eolian sequences[14,15] are mostly distributed in northern and northwestern Mongolia. Most of them are not only in low resolution but also short of detailed chorological control and sensitivity of climatic proxies[12,14]. In central Mongolia, few climate data with good quality can be found. It should be mentioned here that Walther[16] had investigated the Holocene sediment of Ugii Nuur, the lake this paper focused, but the poor chronology and discontinuity of sediment hampered the high-resolution climatic reconstructions. In addition, contradictions and disputes remain regarding the regional Holocene climate changes, especially in the mid-Holocene[6–11,13–15].

Here, based on modern pollen studies and reliable chronology of nine AMS ^{14}C dates, a detailed history of vegetation and climate changes during the past 8660 cal. a BP was reconstructed by a high-resolution pollen record from Ugii Nuur in central Mongolia. We hope that some basic details will be provided for understanding the Holocene climate changes and mechanism(s) in central Mongolia.

1 Study area

The Ugii Nuur (47°46′N, 102°46′E, 1332 m a.s.l., Figure 1), a freshwater lake with a surface area of 12 km^2 and a maximum depth of 17 m, is situated at ~350 km west of the Mongolian capital (Ulan Bator) and to the north of the Hangay Mountain. A branch of Orhon River, originated from the eastern Hangay Mountain, flows into the Ugii Nuur in the southwest, and the lake water overflows into the Orhon River in the northwest (Figure 1). The modern climate of the study area is temperate continental with cold and dry winters dominated by the Siberia High, and warm and humid summers influenced by the Asian Low. The mean annual temperature is about –2℃, and the mean annual precipitation ranges from 250 to 300 mm and occurs mostly in June, July and August[17].

The modern zonal vegetation in the study area is *Stipa capillata-Cleistogenes squarrosa-Artemisia frigida* steppe, which is dominated by *Stipa capillata*, *Cleistogenes squarrosa*, *Artemisia frigida* and accompanied by *Agropyron cristatum*, *Carex duriuscula*, *Koeleria gracilis*, *Poa botryoides*, *Potentilla tanacetifolia*, *Pulsatilla turczaninovii*, *Heteropappus hispidus*, *Convolvulus ammannii*, *Kochia prostrate*, *Salsola ruthenica*, *Chenopodium aristatum,* etc. *Stipa*-forbs montane steppe, which is dominated by *Stipa* and mixed with *Agropyron cristatum*, *Carex duriuscula*, *Potentillla tanacetifolia*, etc., presents on the nearby mountains. *Carex*-dominated meadow mixed with *Aster alpinus*, *Taraxacum* and other mesophytic forbs is widely distributed at the riverbank, lakeshore and depression[18,19].

Festuca-forbs montane steppe and *Pinus sylvestris-Festuca* montane forest steppe develop in the areas north of the study site (Figure 1). And forest steppe mainly consists of *Pinus sibirica*, *P. sylvestris*, *Larix sibirica* and *Festuca ovina* present in the Hangay Mountains, where vegetation vertical zonation is distinct[18,19]. *Festuca-Poa-Carex* montane steppe and *Stipa-Cleistogenes-Artemisia* steppe are the main vegetation types in the catchments of the Ugii Nuur, where montane steppe mixed with *Agropyron*, *Carex, Stipa*, *Artemisia*, *Thymus*, etc. is distributed between 2300 and 1900 m a.s.l., and *Stipa-Cleistogenes-Artemisia* steppe mainly develops below 1900 m a.s.l.[18,19].

2 Lithology, chronology and methods

2.1 Lithology and chronology

An 854-cm-long core (UG04 core) was drilled with gravitational piston corer in 2004 at the east-central part of the Ugii Nuur where the water depth was 14.5 m. Three major lithofacies are distinguished based on field visual inspection and laboratory analysis (Figure 2): Unit 1 (854—480 cm) and Unit 3 (242—0 cm) are clayey silt layers, Unit 2 (480—242 cm) is a silt layer with two carbonate-rich interlayers at 450—492 cm and 368—348 cm.

AMS radiocarbon measurements were performed in NSF-AMS-Arizona and eleven AMS ^{14}C ages were obtained from bulk sediment samples (Figure 2). Two dates at the depth of 260 cm and 330 cm were excluded for their remarkable reverses with adjacent dates, which might be attributable to the bio-disturbance and the re-deposit of littery organic matter. It should be noted that the radiocarbon reservoir effect of Ugii Nuur might be negligible for its freshwater and carbonate-poor sediment. This could be supported indirectly by the chronological study in Lake Daihai (in north China), which suggests a positive-correlation between lake salinity and radiocarbon reservoir effect[20], and also by the

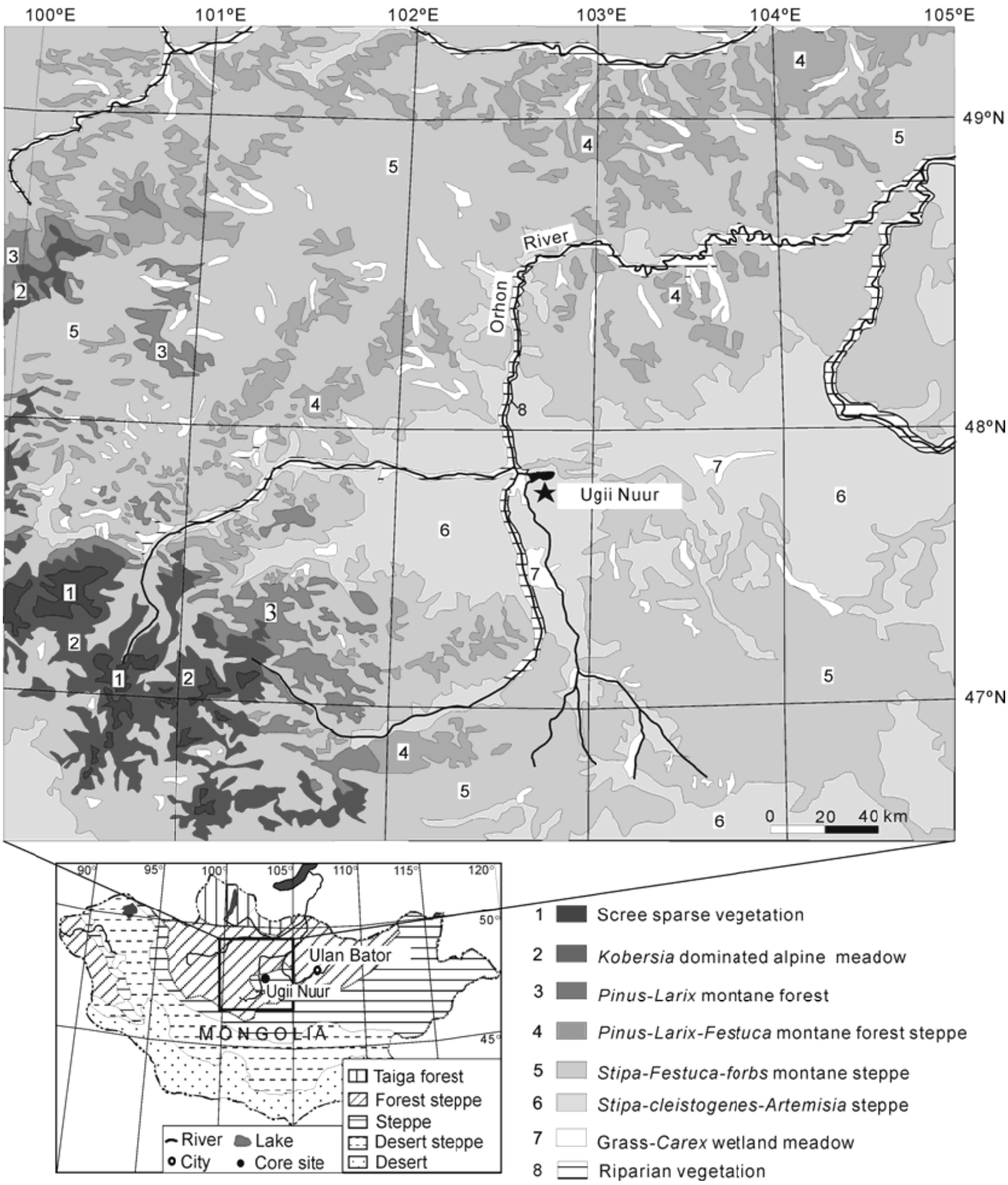

Figure 1 The location of the studied site and regional vegetation map.

excellent agreement between the AMS ^{14}C dates of the humic acids and pollen extracts from the topmost Telmen lake core (in central-north Mongolia), which suggests that the reworked carbon is not currently a problem[9]. For convenience of comparison, the selected nine AMS ages were calibrated using the Calib 4.5 program[21]. Based on these nine calibrated ages, an age-depth model was constructed by linear regression for three different lithofacies and deposit rates were calculated respectively (Figure 2). The bottom age of 8660 cal. a BP and the top age of 87 cal. a BP for this core were extrapolated.

2.2 Methods

386 fossil pollen samples from UG04 core were obtained at ~2 cm intervals. The mean theoretic resolution could reach ~20 years per sample. To provide references for fossil pollen interpretations, modern pollen samples were collected from the river and lake surface sediments, and surface soils of piedmont steppe and montane steppe.

One *Lycopodium* spore tablet (manufactured by Lund University, Batch No. 938934) was added to each sample prior to processing. The procedure for fossil pollen

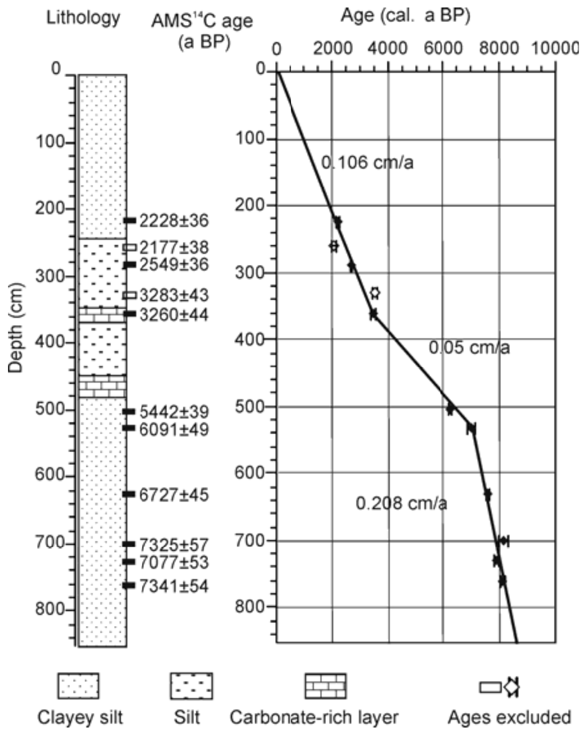

Figure 2 Lithology, AMS ^{14}C dates and chronology model.

analysis involves treating 1—2 g of sediment sample with 10% HCL, 10% KOH, 36% hydrofluoric acid (HF) to eliminate the organic matter, carbonate and silicate. The surface samples were processed using acetolysis solution consisting of a 9:1 mixture of acetic anhydride and sulphuric acid (boiling for 10 minutes). Furthermore, the pollen in the residue was concentrated with a 7-μm mesh sieve in conjunction with ultrasonic vibration. Finally, water-free glycerol was used for storage and preparation for microscopic slides. The pollen residues were mounted on slides and examined at 400× (oil immersion of 1000× was used if necessary). A minimum of 350 pollen grains (not including spores) were counted from each sample. Pollen types were identified using pollen reference-slides, published pollen books and photographs[22–24]. Pollen percentages were calculated on the sum of pollen counts excluding spores. Pollen concentrations were calculated on the basis of exotic *Lycopodium* spore counts and were expressed as the number of grains per gram (grains/g). Graph and CorelDraw software were used to plot the pollen diagrams. CONISS cluster analysis was used to provide reference for zoning. Temperature (*T*) and moisture (*M*) sequences were reconstructed with the reference of the modern pollen-based temperature and moisture indices, which were calculated on the ratios between the groups of pollen taxa that represent different moisture or temperature conditions in the studied south-north transect in Mongolia (42°45′55" — 51°35′08"N and 99°57′56" — 110°07′35"E)[25]. These groups of pollen taxa were largely classified based on the results of numerical analysis (HCA and NMS) and their ecological conditions[25].

3 Pollen results

3.1 Modern pollen

The pollen transport mechanism is complicated in lakes of semiarid areas. Modern pollen studies are vital as a vigorous aid to the interpretations of fossil pollen spectra. So we conducted a survey of modern pollen assemblages in the study area on river surface sediments (samples 1—4), lake surface sediments (samples 5 and 6), surface soils of piedmont steppe (samples 7 and 8) and montane steppe (samples 9 and 10) (Figure 3). The fluvial pollen assemblages are dominated by *Pinus* (38.99%—48.21%), Cyperaceae (19.35%—26.76%) and *Taraxacum*-type (5.63%—13.10%) together with Poaceae (3.63%—13.10%). The percentages of *Artemisia* and Chenopodiaceae are relatively low with average less than 10% respectively. The lacustrine pollen assemblages mainly consist of *Pinus* (51.39% and 63.67%), Chenopodiaceae (8.30% and 17.96%), *Artemisia* (5.54%% and 13.93%) and Poaceae (3.63% and 13.10%), and the Cyperaceae percentages are below 10%. The pollen assemblages from piedmont steppe and montane steppe are dominated by *Pinus*, Chenopodiaceae and *Artemisia*. The Poaceae pollen percentages are less than 5% (exception for sample 7 with percentage of 7.96%). It is noticeable that the Chenopodiaceae percentages from piedmont steppe (20.73% and 25.81%) are remarkably higher than that of montane steppe (6.82% and 8.15%).

The *Pinus* pollen always has a high value in all modern pollen assemblages (normally higher than 40%) of the study area where pine forest are absent. Previous studies also show that the pollen percentages of *Pinus* could reach 30% in areas lack of pine forest[25–28]. Therefore, the *Pinus* pollen was assumed to be extra-local and its variations should have the potential to reflect the conditions of regional montane pine forest and a larger scale climate. *Betula* and *Picea* pollen might be lack of climatic significance probably attributed to their trace values in modern and fossil pollen assemblages.

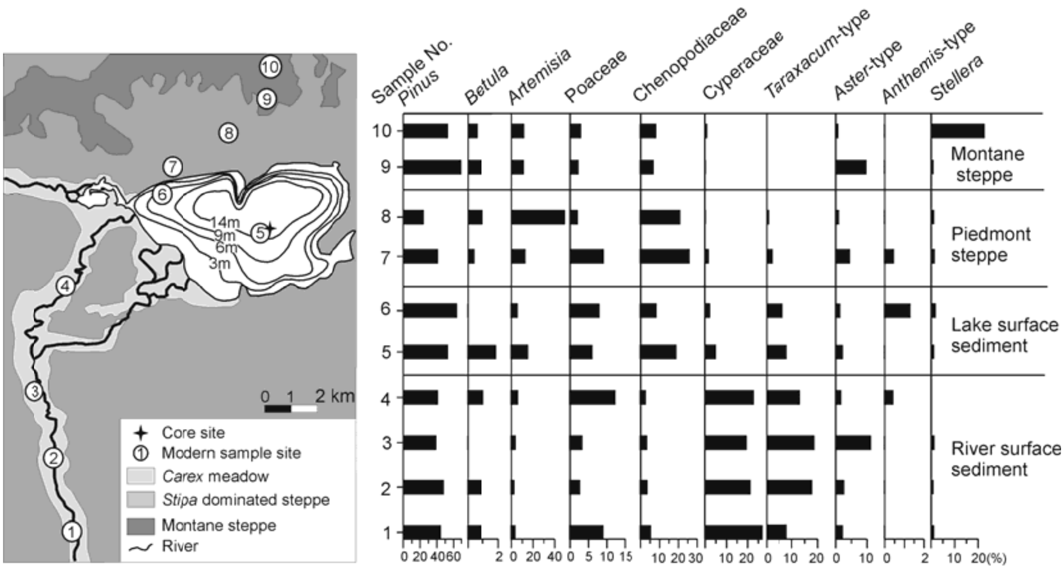

Figure 3 Modern pollen sample sites and associated pollen assemblages.

Poaceae pollen percentages are usually below 10% in most modern samples from the Poaceae-dominated vegetation, which probably indicates its under-repre- sentation as many researchers suggested[29,30]. Many previous studies have shown that Chenopodiaceae pollen percentages are commonly higher in the desert and desert steppe than in the forest steppe and steppe, and its relative abundance could be employed as a proxy to reflect the moisture conditions[25,27,29,30]. The recent modern pollen survey on the south-north transect of Mongolia even shows that the Chenopodiaceae pollen might have the potential to reflect warm and dry conditions[25]. These are also confirmed by our modern pollen survey, which shows higher Chenopodiaceae values in the drier piedmont steppe than in the montane steppe. Mesophytic forbs (such as Ranunculaceae, *Thalictrum*, *Sanguisorba*, *Aster*-type, *Saussurea*-type, Labiatae, *Taraxacum*-type, etc.) commonly grow in montane steppe and wetland meadow[18,29]. So the mesophytic forbs pollen should be paid special attention to as a climatic indicator in paleoclimatic reconstructions[31].

The ratio of *Artemisia* to Chenopodiaceae (A/C) was widely used as a moisture indicator in the Middle East and Central Asia. However, many previous studies show that a small number of *Artemisia* and Chenopodiaceae in pollen spectrum could be viewed as extra-local pollen for their over-representation[27,32], and the A/C ratio could be used as a moisture indicator if the sum of them exceeds 50%[32,33]. Therefore, we did not use this ratio as moisture indicator because the sum of *Artemisia* and Chenopodiaceae is lower than 40% in modern pollen and lower than 50% in fossil pollen record of UG04. In addition, recent studies debated on the reliability of the pollen concentration as a proxy to reflect vegetation cover and moisture conditions[33–37]. Many factors such as wind strength, rainfall intensity, runoff variations, pollen productivity, preservation and sedimentary rate could weaken the reliability of the pollen concentration to reflect vegetation and climatic conditions[33,36,37]. It should be noted that the high pollen concentration in middle part of UG04 core corresponds to the lowest deposition rate. The lowest deposition rate and drought-related lake retreat might have effectively concentrated pollen grains. So our reconstructions of vegetation and climate primarily rely on the variations of pollen percentages.

3.2 Fossil pollen record

Fifty-four pollen taxa were identified in the UG04, including *Pinus*, Chenopodiaceae, *Artemisia*, Poaceae, Cyperaceae, *Picea*, *Larix*, *Betula*, *Alnus*, *Ulmus*, *Salix*, *Aster*-type, *Taraxacum*-type, *Saussurea*-type, *Thalictrum*, *Sanguisorba*, Labiatae, *Plantago*, Rosaceae, Cruciferae, Liliaceae, *Polygonum*, Primulaceae, *Convolvulus*, *Ephedra*, etc. The pollen spectrum was divided into six pollen assemblage zones based on the variations of main pollen percentages, pollen-based climate indices and the result of CONISS analysis (Figure 4).

Zone 1 (854—688 cm, 8660—7800 cal. a BP). This pollen assemblage zone mainly consists of *Pinus* (23.08%—49.17%), Chenopodiaceae (14.32%—

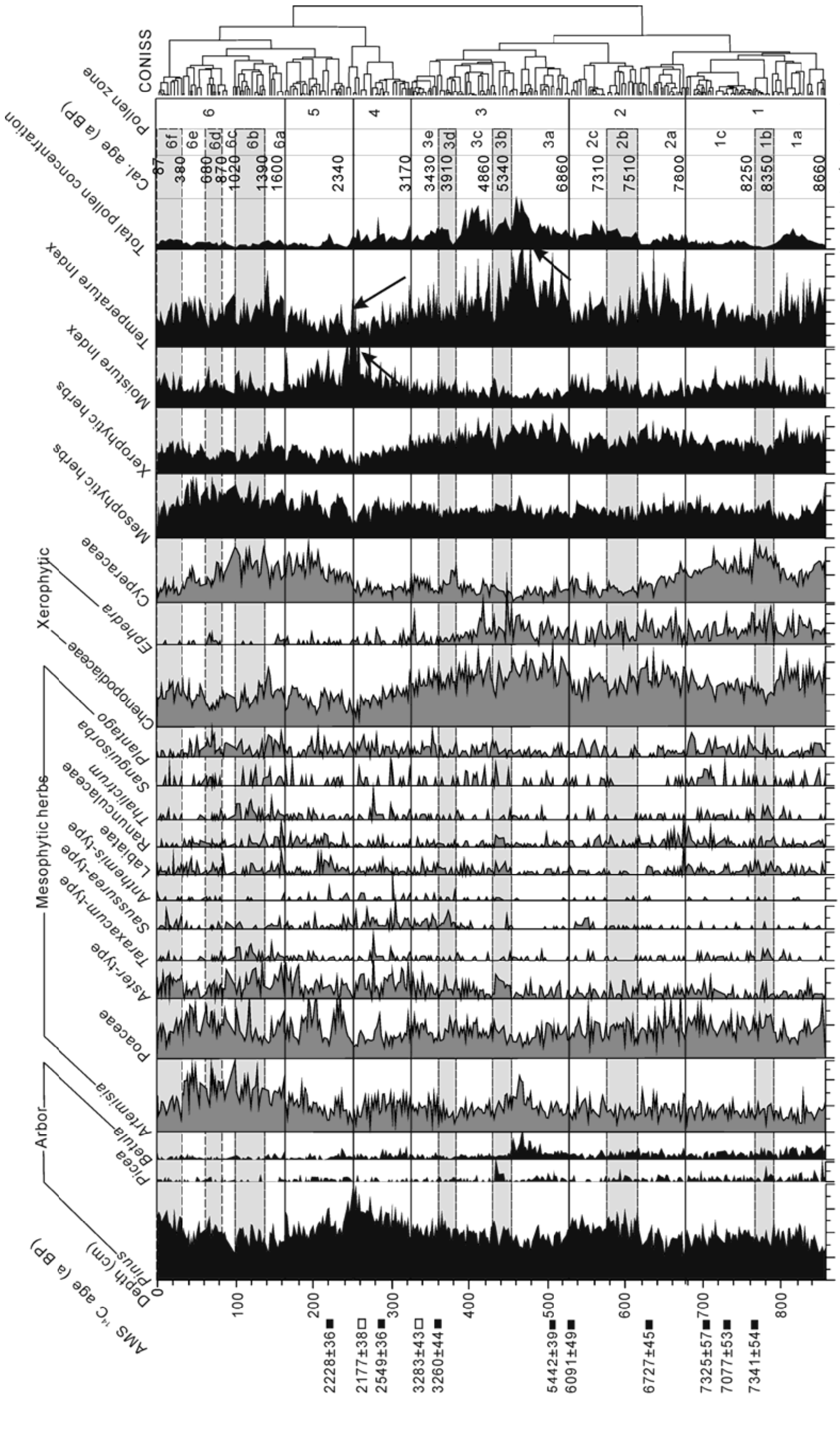

Figure 4 Pollen percentage plot of UG04 core.

39.51%), Cyperaceae (6.53% — 23.05%), Poaceae (4.56% — 20.27%) and *Artemisia* (3.75% — 14.38%). *Ephedra* and mesophytic forbs (e.g. *Aster*-type, *Thalictrum*, *Sanguisorba*, *Taraxacum*-type, Labiatae, Ranunculaceae, etc.) are relatively common. The total pollen concentration is relatively low (<40000 grains/g). This pollen assemblage probably reflects that Poaceae- dominated steppe prevailed in the study area, whereas *Carex*-dominated meadow developed in the riverbank, lakeshore and valley lowland, and pine forest and pine forest steppe grew in regional mountains. The pollen-based temperature index (*T*) ranges between 0.5 and 1.0, and the moisture index (*M*) varied from 1.2 to 2.6. All indicate that a mild and semi-humid climate might have prevailed in the study area.

Three subzones could be distinguished. In contrast with subzone 1a and 1c, the pollen assemblage of subzone 1b (790—766 cm, 8350—8250 cal. a BP) is characterized by high Poaceae and Cyperaceae pollen percentages and moisture index, low Chenopodiaceae pollen percentages and temperature index, suggesting a relatively cold and wet interval.

Zone 2 (688—530 cm, 7800—6860 cal. a BP). This zone is characterized by the increases of Chenopodiaceae (19.08%—41.56%) and *Pinus* (28.25%—55.91%) at the expense of Cyperaceae (1.83%—14.55%) and Poaceae (3.85% — 17.42%). *Artemisia*, *Ephedra* and total pollen concentration change little. Xerophytes increased in abundance as implied by the increase of Chenopodiaceae in pollen assemblages, the temperature index increases and the moisture index decreases, suggesting that the regional climate might have become warm and dry gradually. But, a notable cool and wet interval can be found between 7510 and 7310 cal. a BP as indicated by the increase of *Pinus* (28.25%—58.31%) and moisture index, and the decrease of Chenopodiaceae (20.47%—36.29%) and temperature index in subzone 2b (618—578 cm, 7510—7310 cal. a BP).

Zone 3 (530—324 cm, 6860—3170 cal. a BP). The most striking features of this zone are that the Chenopodiaceae (18.91%—50.00%) increases greatly and maintains peak values whereas *Pinus* (26.90%—57.75%) decreases noticeably. Poaceae (3.78%—12.22%) and Cyperaceae (0.58%—11.73%) decline gradually, *Artemisia* is consistently present, mesophytic forbs appear sporadically, and total pollen concentration reaches its maximum (60000—80000 grains/g). The variations in pollen assemblages suggest that semi-desert steppe expanded whereas montane forest steppe and wetland meadow shrank under a persistent warm and dry climate, and this was also indicated by the highest values of temperature index (~1.8) and the lowest value of moisture index (~1.0).

Zone 3 consists of five subzones. Subzone 3a (6860—5340 cal. a BP) might be the warmest and driest spell of the entire core, which was reflected by the highest percentages of Chenopodiaceae (25.30%—50.00%), the lowest Poaceae, Cyperaceae, mesophytic forbs, and the maximum temperature index and the minimum moisture index. Subzone 3b (5340—4860 cal. a BP) and 3d (3910—3430 cal. a BP) are both marked by the decreases of Chenopodiaceae and temperature index, and the slight increases of *Pinus*, Poaceae, Cyperaceae, *Aster*-type and moisture index, suggesting two cool and humid intervals.

Zone 4 (324—240 cm, 3170—2340 cal. a BP). Chenopodiaceae pollen percentage decreases continuously to the lowest of the entire core. *Pinus* (41.33% — 75.50%), Cyperaceae (3.03% — 11.04%), Poaceae (3.77% — 13.54%), *Artemisia* (3.50% — 14.71%) and mesophytic forbs (*Aster*-type, *Saussurea*-type, *Thalictrum*, etc.) increase whereas *Ephedra* and total pollen concentration (20000—40000 grains/g) decrease. The temperature index decreases gradually to the lowest and the moisture index increases to the highest. These probably indicate the expansion of regional montane pine forest steppe, the shrinkage of semi-desert steppe and a cool and wet climate, and the maximum humidity at the end of this zone.

Zone 5 (240—164 cm, 2340—1600 cal. a BP). The pollen percentages of Chenopodiaceae (7.85% — 25.33%), Poaceae (4.18%—19.46%) and Cyperaceae (7.56% — 21.36%) increase at the expense of *Pinus* (33.33%—59.72%), whereas mesophytic forbs pollen show any significant changes, and the pollen concentration abruptly decreases (<20000 grains/g). The pollen-based temperature index increases and the moisture index decreases. These probably indicate that the Poaceae-dominated steppe prevailed in the study area, and the wetland meadow expanded in riverbank, lakeshore and valley lowland, and the regional montane forest steppe retreated. The climate might have become a little warmer and dryer than Zone 4.

Zone 6 (164—0 cm, 1600—0 cal. a BP). This zone is marked by the increase of *Artemisia* (4.97%—25.00%), Poaceae (4.56%—18.33%), *Aster*-type (0.31%—2.26%) and the temperature index, and the decrease of the moisture index, suggesting that grass-wormwood steppe prevailed and the climate became warmer and drier in the study area. Concurrently, there are remarkable fluctuations in the percentages of main pollen types and six subzones could be distinguished. *Pinus* pollen percentages and moisture index increase, Chenopodiaceae and temperature index decrease in subzone 6b (1390—1020 cal. a BP), subzone 6d (870—680 cal. a BP) and subzone 6f (380—0 cal. a BP), implying three cool and wet intervals. In addition, since subzone 6d (84—64 cm, 870—680 cal. a BP) pollen percentage of Cyperaceae abruptly declines, probably suggesting that the meadow degraded and retreated.

4 Discussion and conclusion

High-resolution pollen record from UG04, controlled by nine AMS ^{14}C dates, reconstruct a detailed history of vegetation and climate changes during the past 8660 years in central Mongolia. Four stages of climate changes could be inferred, i.e., a mild and semi-humid climate before 6860 cal. a BP with a remarkable cool and humid interval (8350—8250 cal. a BP), a prolonged warm and dry climate from 6860 to 3170 cal. a BP, a cooler and wetter climate between 3170 and 1600 cal. a BP, and an increased climatic instability after 1600 cal. a BP. In addition, several abrupt climatic events were distinguished by the variations of pollen assemblages and pollen-based climatic indices.

4.1 Warm and dry climate during the middle to late Holocene (6860—3170 cal. a BP)

High-resolution pollen record from Ugii Nuur convincingly reveals that a prolonged warm and dry climate prevailed between 6860 and 3170 cal. a BP. This dry climate is further confirmed by the variations of lithology. That is, the coarsening grain-size and decreasing deposition rate in the middle of UG04 core might be related to the warm and dry phase as pollen records suggested. Specifically, the grain size might become coarse when lake retreated, and the decrease of runoff might lead to the decline of deposition rate in the case of warm and dry climate.

Many recent climatic records documented a dry mid-Holocene climate in areas of central-east Asia. Reviews and comparison of them might provide us a chance to understand the temporal and spatial pattern of this dry climate. In central-north Mongolia, the Telmen Lake area experienced a dry climate between 7110 and 4390 cal. a BP inferred by low lake level and high pollen-based aridity index[8,9]. Pollen and diatom records from Lake Hovsgol indicate that steppe expanded between 5500 and 4000 cal. a BP, and a warm and dry climate between 6000 and 3500 cal. a BP could be suggested by the decline of diatom abundance and the disappearance of cold water genus (*Cydlotella bodanica*)[13]. The Khyaraany and Sharmmar eolian sections in northern Mongolia show sand layers interbedded in paleosols with ^{14}C ages of 8300±100 and 4070±70 a BP in the Khyaraany section, and 8672±90 and 4780±80 a BP in the Sharmmar section, and the percentages of *Pinus* pollen from sand layers in the Sharmmar section are relatively low, suggesting a dry mid-Holocene cli- mate[14,15]. Furthermore, the BIOME climatic recon- struction over Eurasia indicated that the summer tem- perature was at least 1—2℃ higher and the effective moisture was 10% lower than at present in central Mongolia around 6000 ^{14}C a BP[38]. In the west China and margin of East Asian monsoon, the mid- Holocene dry climate is also extensively documented. A dry cli- mate suggested by the decline of A/C ratio occurred between 6000 and 4500 ^{14}C a BP in Lake Manas (Northern Xinjiang)[39]. The Tengger Desert might have experienced a dry mid-Holocene climate as reconstructed by the pollen records from Lake Zhuyeze (7100—3800 cal. a BP)[40] and Hongshui River (7500—5070 cal. a BP)[41,42], and by multi-factor analysis records from the Lake Juyanze[43] (7500—5400 cal. a BP). The dry mid-Holocene climate was also reported from the sedimentary records of the Lake Yanhaizi[44] in the Ordos Plateau and the pollen records of the Midiwan section[35] in the northern Loess Plateau. In addition, the dust flux records from the west Pacific suggest that the arid area in the Asian interior might have expanded and the aridity might have enhanced during the mid-Holo- cene[45].

Chen et al.[40,46] proposed that a dry mid-Holo- cene climate might have prevailed in the margin of Asian summer monsoon including the Inner Mongolia Plateau, Ordos Plateau and even Loess Plateau. Feng et al.[47] and

An et al.[48] reviewed published literature in west China and argued that a warm and wet mid-Holocene climate is well-documented in semi-arid and semi-humid areas while dry mid-Holocene climate existed in the arid and hyper-arid desert and semi-desert. UG04 pollen record and many existing data suggest that a dry mid-Holocene climate might have prevailed in vast areas of central-east Asia, which centered at southern Mongolia and extended northward to central-north Mongolia and southward to arid areas of west China. However, northernmost Mongolia and adjacent south Siberia might have experienced a warm and wet middle Holocene as revealed by the data from Honton Nuur[10], Uvs and Bayan Nuur[7], Gun Nuur[12,14] and Lake Baikal[49]. Thus, the north boundary of the dry mid-Holocene climate might be delimited at the transitional areas between forest steppe and Taiga forest in northern Mongolia. And the difference between the two might be attributed to the fact that the areas to the north of the boundary might be more influenced by the vapor input from Siberia lowland.

Comparison of the warm and dry mid-Holocene climate reconstructed by UG04 pollen records to the climatic conditions (maybe warm and dry as indicated by the increase of winter and summer temperature and the decrease of annual relative humidity) as the results of GCM model on Central Asia by Bush[50] implies that good correlations existed between them, especially during the mid-Holocene (Figure 5). Bush[50] proposed a reasonable mechanism to this warm and dry climate, i.e., the combination of still high insolation and the increased atmospheric CO_2 concentration resulted in the increase of atmospheric temperature, and the temperature rising led to the enhancement of transpiration and the heightening of saturation vapor pressure, thus decreased the cloud cover and precipitation chances and formed dry climate in the end. Apparently, the temperature rising-dictated transpiration enhancement and the changes of vapor input might be accounted for the mechanisms of the dry mid-Holocene in central Mongolia. In addition, the temperature rising in mid-Holocene has been confirmed by many previous studies, but, warm/wet or warm/dry? Special cautions should be made because the mid-Holocene climatic conditions might be different in areas of specific geographic and hydrologic settings.

4.2 Warm/dry and cold/wet climatic combinations

In contrast with the synchronous water and heat combination in adjacent south Siberia[51] and Chinese monsoon areas[52], the climate in central Mongolia revealed by the pollen record from UG04 core was characterized by asynchronous water and heat combinations. That is, a mild and semi-humid climate prevailed in early to middle Holocene (8660—6860 cal. a BP), a warm and dry

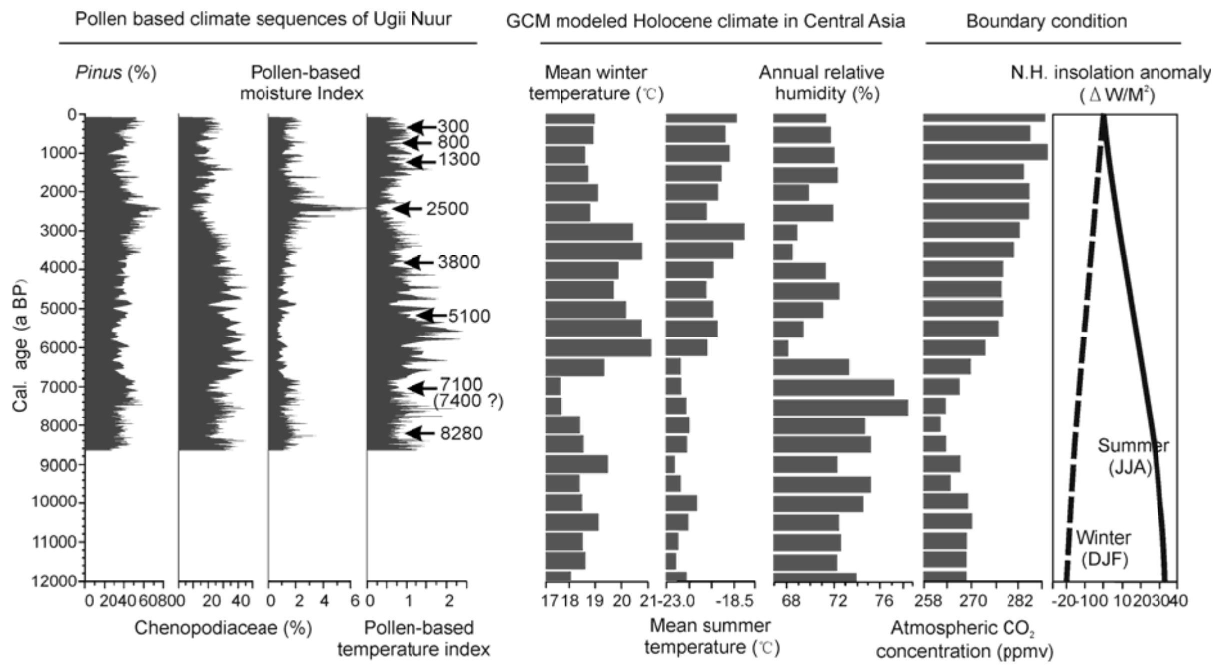

Figure 5 Comparison between the pollen-based climatic reconstructions of UG04 core and the GCM modeled climate in Central Asia, the boundary conditions are also presented.

climate dominated the middle to late Holocene (6860—3170 cal. a BP), and a cool and wet climate in late Holocene (3170—1600 cal. a BP). Yang et al.[53] reviewed numerous records and depicted that the precipitation variations indicated by the ice deposition rate of Guliya ice core are in anti-phase with the temperature variations inferred by the tree-ring records on Xingjiang and Central Asia over the past 1500 years, indicating a warm/dry and cool/wet climate pattern in decades to centuries scale, which was widely supported by the palaeoclimatic data from Central Asia and Xinjiang. This asynchronous climate pattern is similar to the warm/dry and cool/wet climate pattern in centuries to millennia scale inferred by the pollen record from Ugii Nuur in central Mongolia. The term of 'mid-Holocene optimum' defined by high primary production of vegetation may be of little use in central-northern Mongolia[14,15], but the pollen record from Ugii Nuur still reveal a mid-Holo- cene thermal optimum.

4.3 Climatic events

Under the reliable chronological control of nine AMS ^{14}C dates, several abrupt climatic shifts from warm/dry to cold (cool)/wet conditions are inferred by the pollen record of UG04 core. The climate events are characterized by abrupt decreases of Chenopodiaceae pollen percentages, the increases of *Pinus*, Poaceae and Cyperaceae pollen percentages in pollen assemblages and associated changes of pollen-based climatic indices. Those climate events are centered at around 300, 800, 1300, 2500, 3800, 5100, 7100 and 8280 cal. a BP respectively (Figure 5). It is noticeable that the cold and wet event around 8280 cal. a BP could be well correlated to the 8.2 ka cold event in Greenland ice core[1,54], suggesting that some mechanisms of teleconnection might have existed between the North Atlantic and the central Mongolia (maybe the NAO controlled or modulated westerlies account for this). Considering the age uncertainties, the events around 300, 1300 and 5100 cal. a BP could be broadly related to the climate events recorded in north Atlantic[2] and Chinese stalagmites[55]. But those events were characterized by cold and wet in central Mongolia rather than cold and dry in the north Atlantic and Chinese monsoon areas. And this difference might be attributed to the regional response differences to global climate changes. The cold and wet event around 2500 cal. a BP is also confirmed by regional climate records[7–9,56]. That is, Lake Uvs and Bayan Nuur in northwest Mongolia transgressed at about 2500 cal. a BP[7], the Lake Telmen area in central-north Mongolia experienced a cool and wet climate during 3000—1600 cal. a BP[8,9], the cool and wet climate since 2850 cal. a BP boosted the Scythina civilization in Tuva Republic of Altai adjacent to northern Mongolia[56]. The stage is also correlated well to the glacial advance widely reported globally. It is a pity that the drastic climatic fluctuations in the past two millennia could not be chronologically recognized because there are no AMS ^{14}C dates in the upper horizon (0—200 cm) of UG04 core, and this age uncertainties greatly handicapped our understanding the coupling and interaction between the climate and the development of human society.

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