2 State of the art

2.1 Introduction

Landscape evolution is governed by a variety of factors. The importance of these factors varies with the temporal and spatial scale of the investigated time frame and geographic extent of the study site (Brunsden, 1996). Since this study focuses on the Holocene evolution in central Mongolia on a local to regional scale, the major underlying assumption is, that evolution in the Ugii Nuur basin is largely controlled by two major factors. First, climate variability is thought to have a significant influence on the ecosystem and feedback mechanisms involving vertical and lateral material fluxes (Earth surface processes). Second, human activities cause additional, considerable changes to the natural system. Thereby, direct impacts such as the agricultural use of natural ecosystems are important to understand landscape evolution. Indirect effects generated by changing the natural systems capacity to resist to the variability of external forces have to be taken into account in order to understand the interactions of climate variability and human impact.

This chapter aims at reviewing the current state of knowledge of climate and landscape evolution in the region of interest. Due to the large scale interactions of wind systems governing climate evolution, a concise definition of the region of interest is difficult to obtain. Moreover, since only a few studies have focused on climate and landscape evolution in or nearby the study site, paleoclimatic and archaeological information are gathered from a variety of sites, that may be more or less eligible for a comparison in particular due to their affiliation with different natural-spatial units and variable geographical nearness. However, such a comparison allows for the identification and separation of global, regional or local trends.

2.2 Definitions

This study is concerned with the climate and landscape evolution of the Ugii Nuur basin. *Climate evolution* is understood as a subject of paleoclimatology, the study of climate prior to the period of instrumental measurements (Bradley, 1999). Paleoclimatology allows for a longer perspective on climatic variability. It requires natural phenomena which are related to climate and which contain a measure of this dependency (*proxies*) in their structure (Bradley, 1999). Natural phenomena that incorporate a memory of past environments are referred to as *archives*.

Yet, archives usually incorporate more than proxies on past climate variability. Much of the recorded variance in archives is due to landscape evolution. The term *landscape evolution* accounts for the multiple causality recorded in archives invoked by the variability of many factors and their interactions. Climate, tectonics, living organisms and humans play important roles among these factors. Nonlinear feedback mechanisms – in geomorphology and ecology expressed as process–form interactions (Ahnert, 1996; Stallins, 2006) –, thresholds and other characteristics of complex systems (Phillips, 2003; Dikau, 2006) produce additional variability that cannot be attributed alone to the aforementioned factors, but are inherent in the system's behavior.

In this study the term *Central Asia* is used to describe the greater area of interest. The spatial definition of this term, however, is ambiguous mainly due to geopolitical aspects (Stadelbauer, 2003). Here, we largely adopt the physical geographical definition of Central Asia as determined by Richthofen (1877). Accordingly Central Asia comprises the endorheic basins between the Tibetan Plateau and the Altai Mountains, the Pamir and the Tien Shan and Chingan Mountains. In addition, the Mongolian Plateau is included as well as its northern declivity and the bordering areas belonging to southern Siberia. This definition is adopted in order to account for the broader region where the East Asian (EA) Monsoon, the Indian Monsoon and the Westerlies form a triangle (Fig. 2.1) and interact.

2.3 Rationales of climate and landscape evolution research in Central Asia

Central Asia has been a central focus in climate and landscape evolution research on several temporal and spatial scales. This special attention is due to several reasons:

- Large parts of Central Asia are influenced by an extreme continental climate (Domrös and Peng, 1988; Weischet and Endlicher, 2000). Since Quaternary climate variability has been vastly investigated by the analysis of marine records, paleoclimate research in this area contributes to a better understanding of the response of continental ecosystems to changes in atmospheric and oceanic circulation patterns and feedback mechansims.

- Climatic fluctuations in the past cannot be only explained by variations in solar activity (*Milankovic-Cycles*) but also result from changes in land surface patterns. Landscape evolution research contributes to an enhanced knowledge of the complex feedback mechanisms in climate evolution in the past and in the future (Yang and K.-M., 1998). The uplift of the Tibetan Plateau, for example, has significantly altered the northern Hemisphere climate on geological timescales (Molnar *et al.*, 1993; An *et al.*, 2001), while differences in surface albedo and soil moisture have been shown to effect circulation patterns on regional and local scales during decades (Xue *et al.*, 2004).

- Central Asia offers a huge variety of lake and terrestrial archives. Lake Baikal sediments and the Loess Plateau, for instance, provide complete records for the past 5 respectively 22 Ma (Guo *et al.*, 2002). Moreover, a large number of endorheic basins (Herzschuh, 2006), speleothems (Dykoski *et al.*, 2005; Wang *et al.*, 2005b, 2008b), ice cores (Schotterer *et al.*, 1997; Yao *et al.*, 1997; Thompson *et al.*, 2000; Davis *et al.*, 2005) and treerings (Jacoby *et al.*, 1996; Pederson *et al.*, 2001; D'Arrigo *et al.*, 2005) offer more or less continuous records of Pleistocene and Holocene environmental change.

- In addition to research on the natural forcings of environmental evolution of Central Asia, there is ongoing debate on how humans have altered ecosystems in this area since prehistoric and historic times (Rost *et al.*, 2003; Tarasov *et al.*, 2007a; Bemmann *et al.*, 2008) and how, in turn, rise and collapse of civilizations were catalyzed by climatic triggers (Yancheva *et al.*, 2007).

2.4 Atmospheric circulation and moisture supply to central Mongolia

Central Asia is located in the triangle of the Indian Monsoon, the EA Monsoon and the Westerlies, that are important wind systems governing moisture advection to the continental interior (Fig. 2.1) (Böhner, 2006). In particular, the Indian and the EA Monsoon (summer monsoon), that invade China during the summer months, are of moist, warm and unstable nature (Domrös and Peng, 1988). Since Central Asia's environments are strongly influenced by moisture supply, the temporal and spatial variability of the wind systems are crucial for landscape evolution in this area (Herzschuh, 2006).

The advance of the summer monsoon is governed by the northward migration of the subtropical anticyclone in the western Pacific and the cross-equatorial flow from the southern hemisphere. The monsoon dynamics are connected to the circulation patterns both on the northern and the southern hemisphere. The instability of the summer monsoon air masses generated by the uptake of water vapor on the Pacific, mass convergence and orographically induced convection result in a wet summer climate in the area of influence (Fig. 2.1). Moreover, exposition and relief are important controls on the frequency and magnitude of rainfall events in this area (Liu and Ding, 1998; Weischet and Endlicher, 2000).

Beyond to the monsoon limit, however, the atmospheric mechanisms governing moisture supply become less apparent. Some authors attempt to explain moisture supply to central and northern Mongolia by variations in the summer monsoon. Such interpretations are partly valid when indirect effects on circulation patterns by the monsoon circulation are considered. Yet, various evidences show that moisture supply in this area is attributed to the Westerlies, at least to the largest extent (Weischet and Endlicher, 2000).

The prevalence of westerly winds in all pressure levels in central Mongolia, leeward

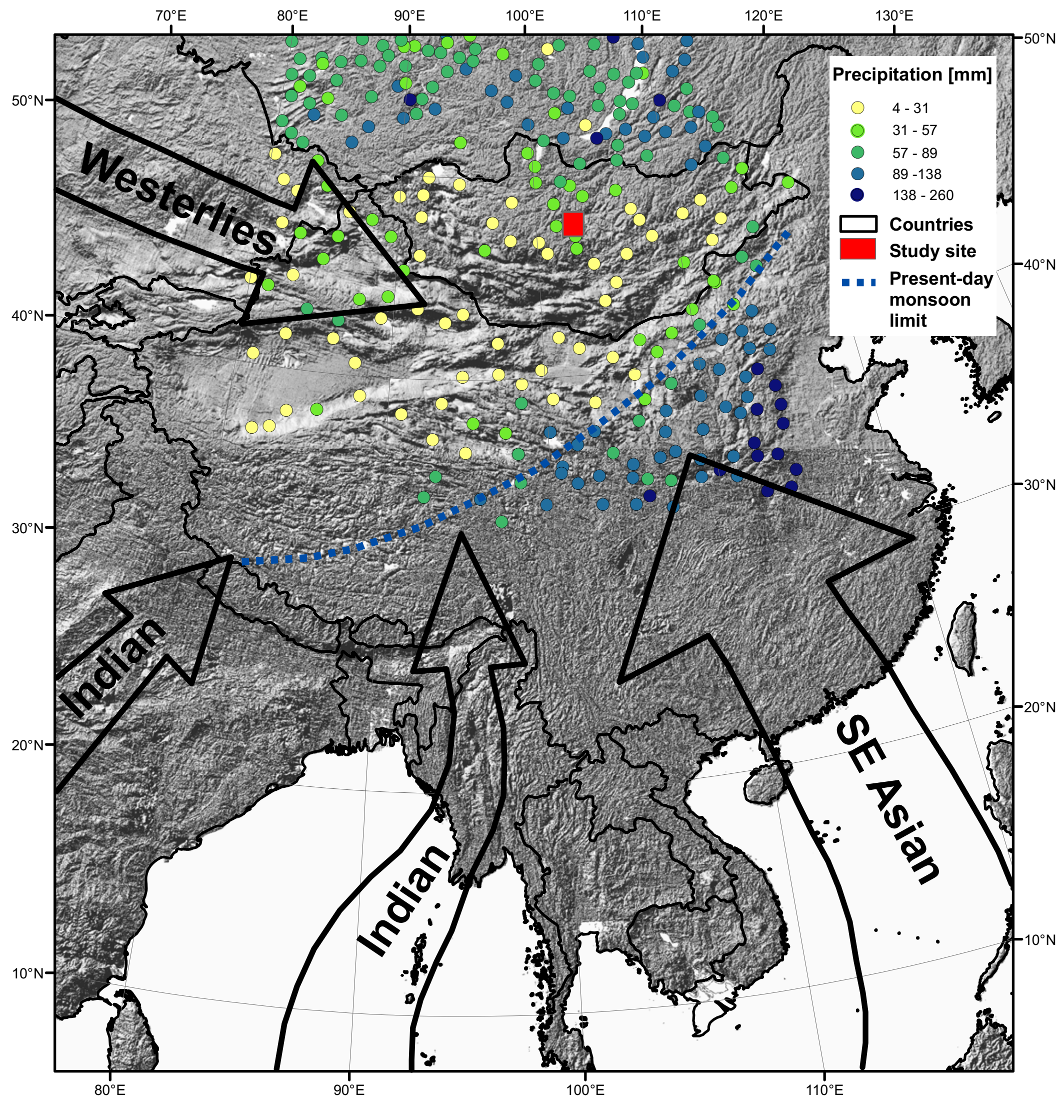

Figure 2.1: Summer wind systems, mean july precipitation amounts and the present-day monsoon limit after Herzschuh (2006). Precipitation data is obtained from the GLOBALSOD database (1994–2004, ftp://ftp.ncdc.noaa.gov/pub/data/globalsod), Relief shading is based on GTOPO30 digital elevation data.

decrease in annual precipitation amounts in the South and East of mountain barriers and high precipitation values in the northern declivity of the Mongolian Plateau suggest a predominant moisture supply by the Westerlies (Weischet and Endlicher, 2000)

Seasonal variations in the Westerlies' influence in Mongolia are mainly governed by the establishment and decay of the winter Siberian High (SH). After the gradual decline of the SH until April Westerlies dominate from May to September. During that time atmospheric fronts develop along the polar front between the polar air masses and the southerly air currents that reach the Inner Mongolian Plateau (Domrös and Peng, 1988). Highest track frequencies of these frontal systems are recorded along a WSW-ENE running transect through Mongolia, pointing at a potential interaction of the Westerlies with the monsoonal air masses. However, the relatively large annual number of rainy days (128 in Tsetserleg) and the associated low rainfall amounts indicate that moisture supply is attributed to a highly continental character of the polar front with low moisture contents of the air masses involved (Weischet and Endlicher, 2000).

This present day circulation pattern governing moisture supply in Mongolia raises the question, in how far the paleoclimatic evolution in this area differs to or resembles developments recorded in the summer monsoon dominated regions to the south or the Westerlies dominated, boreal regions to the North.

During winter, climate in the region of interest is highly influenced by the SH and the winter monsoon. Extremely dry air causes a strong radiative cooling of the surface and mean January and February air temperatures drop below -20°C in central Mongolia and Siberia (Bao, 1987; Weischet and Endlicher, 2000). Spells of cold air from the eastern part of the SH advance in south-east direction affecting large parts of China and may be intensified by the northern branch of the Westerlies bringing cold and dry air from the Tibetan Plateau.

2.5 Present-day atmospheric dust dynamics in Central Asia

One of the most important paleoclimatological archives in Central Asia are the loess deposits on the Loess Plateau in North China. The history of accumulation of the silt sized sediment in this region can be traced back for the past 22 Ma (Guo *et al.*, 2002). While dust deposition was strongest during the cold phases of the Pleistocene epoch in this region, deposition of loess and loess-like material in other regions was more prominent during the Holocene pointing to the variability of dust sources and sinks and their atmospheric controls (Grunert and Lehmkuhl, 2004; Küster *et al.*, 2006). In order to understand past dust dynamics, recent spatial distributions of dust sources and sinks, the dust generating and transporting wind systems and their variability in space and time have to be taken into account.

Central Asian dust sources are among the most important worldwide (Prospero *et al.*, 2002). They are among the most productive and they generate dust transported as far as Japan, North America and Greenland. Moreover, they exert severe effects on air quality in heavily populated areas of China (Gao *et al.*, 2003).

The most important sources are the large endorheic basins that are supplied with material generated by frost and salt weathering, and comminuted by fluvial processes (Jäkel and Grunert, 2003). The largest among these sources are the Tarim Basin, Qaidam Basin, Junggar Basin, the Balqash-Alaköl Basin northwest of the Tian Shan and the Alashan Plateau (Zhang *et al.*, 1998; Prospero *et al.*, 2002; Wang *et al.*, 2008a). Other sources are the Hexi Corridor and areas with rapid population growth, land reclamation and rapid population growth (Goudie and Middleton, 1992; Derbyshire *et al.*, 1998; Dong *et al.*, 2000; Prospero *et al.*, 2002; Li *et al.*, 2004). The geomorphological setting is important for the characterization of dust sources. The alluvial fans and anastomosing rivers adjacent to the deserts are regarded as the dominant sources. These fans have persistent supply of dust-sized particles by intermittent floods that originate in the adjacent mountains and carry glacially ground material (Derbyshire *et al.*, 1998; Jäkel, 2004; Wang *et al.*, 2008a). Aeolian abrasion by sand sized particles plays an important role in mineral dust production (Bullard, 2004). Salt and ion contents in the surface material are also responsible for variation in the intensity of dust sources since different rates of salt weathering can lead to significant differences in the abundance of dust-sized particles (Wright, 2001; Wang *et al.*, 2008a).

Dust mobilization decreases northward of the Alashan Plateau (Xuan *et al.*, 2004). In the south Gobi area the annual dust storm frequency is higher than 30 days per year, while in the northwest of Mongolia frequency is less than 10 days/year (Middleton, 1991; Natsagdorj *et al.*, 2003). Present day dust storms in Mongolia can be largely attributed to human impact (vehicle tracks, overgrazing) leading to vegetation removal and soil surface destabilization (Goudie and Middleton, 1992), and annual precipitation variability (Natsagdorj *et al.*, 2003). Dust sources in Mongolia are regarded as the most upwind origin of Asian dust (Xuan *et al.*, 2004). This has been inferred from a general trend from coarse-

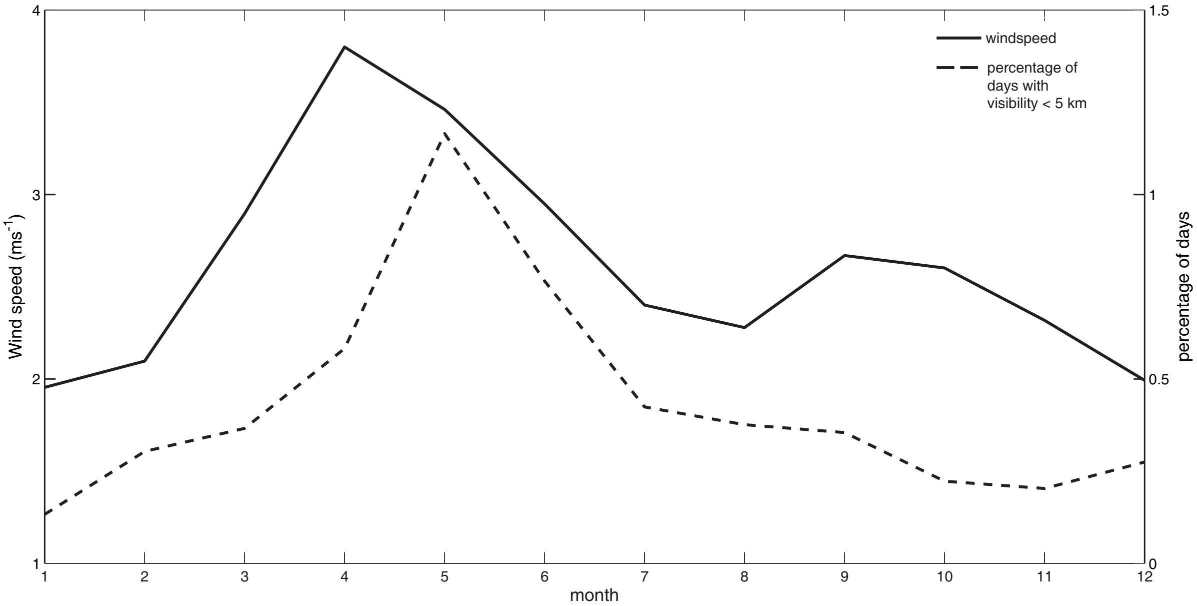

Figure 2.2: Mean surface wind velocities and horizontal visibility reduction for Mongolian climate stations. Data is obtained from the GLOBALSOD database (1994–2004, ftp://ftp.ncdc.noaa.gov/pub/data/globalsod).

to-fine trend in particle sizes along the prevailing wind direction in spring from northwest to southeast (Xuan *et al.*, 2004).

Wind systems of different spatial scales are involved in dust mobilization (Jäkel, 2004). Local to regional wind systems are particular important during summer and autumn owing to high insolation and strong free atmospheric convection. During late winter and spring, large-scale meteorological factors predominantly govern dust mobilization and transport. Dust storms during this time are associated with strong WNW winds linked to the SH and the passage of cold fronts (Xuan *et al.*, 2004). Dust mobilization from Mongolian sources is particularly strong during spring (see Fig. 2.2) (Natsagdorj *et al.*, 2003). During this time the SH becomes unstable and successions of frontal systems traverse the plateau. Strong surface winds are associated with these frontal systems (see Fig. 2.2) (Xuan *et al.*, 2004; Dulam, 2005). Due to the absence of a stabile temperature inversion as found in the Saharan and Sahelian trade wind zone, dust mobilized in Central Asian sources can be easily lifted into altitudes up to 10 km and transported westward (Jäkel, 2004).

The largest part of dust mobilized in China (50%) is subject to long-distance transport to the Pacific Ocean and beyond. 30% is redeposited in arid- and semiarid areas of China and 20% is transported to humid China (Zhang *et al.*, 1997). Today dust deposition is regionally concentrated in the Loess Plateau, which shows a close relation between today's dust dynamics and the distribution of Quaternary loess deposits (Derbyshire *et al.*, 1998). Grainsize distributions of dust deposits in the Loess Plateau have a higher fraction of small sized particles than in the windward deserts indicating a eastward fining from the sources (Li *et al.*, 2008). Dust deposition in farmland of Inner Mongolia is an important nutrient supply to soils that is, however, countervailed by wind erosion (Li *et al.*, 2004).

Extensive data on magnitude and nature of dust deposition in China and Mongolia are still lacking and spatially detailed predictions are difficult to obtain (Li *et al.*, 2008). Modeling studies, however, point at the importance of the dust deposition mechanisms. While dry deposition is the major mechanism of dust accumulation in deserts, wet deposition becomes increasingly important downwind of the sources (Zhao *et al.*, 2003). Mechanisms of wet deposition are difficult to quantify but are thought to especially effect smaller sized dust particles (Zender *et al.*, 2003). Yet, it can be expected that this climate–dust deposition interaction are important for the generation of loess profiles and their spatial distribution.

2.6 Climate and landscape evolution in Central Asia

Holocene climate and landscape evolution in Central Asia has been investigated using a variety archives and proxies in various locations. The reader is referred to reviews and compilations of many of these records by Fang *et al.* (1999), An (2000), Lehmkuhl and Haselein (2000), Yang *et al.* (2004), Lehmkuhl and Owen (2005), Wang *et al.* (2005a), An *et al.* (2006), Herzschuh (2006), Prokopenko *et al.* (2007) and Chen *et al.* (2008). Considerable differences exist among records and a straight forward deduction and interpretation of the governing forces are often not possible. Hence, in addition to reviewing previous records of climate and landscape evolution, the following text aims at discussing the forcing mechanisms of climate change in Central Asia and considering the difficulties to assess and interpret these records, in particular from a geomorphological perspective.

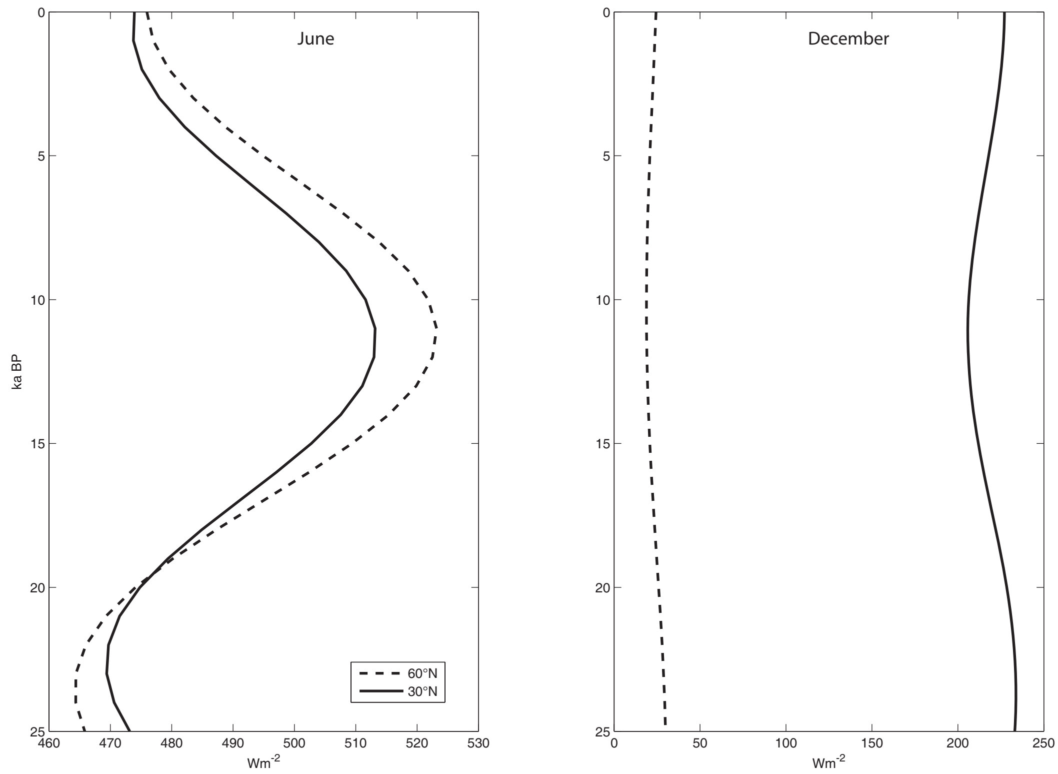

Figure 2.3: Insolation variability during the late Pleistocene and Holocene in June and December at 60°N and 30°N (Berger and Loutre, 1991). Data obtained from ftp://ftp.ncdc.noaa.gov/pub/data/paleo/insolation/.

2.6.1 The Last Glacial Maximum

The Last Glacial Maximum (LGM, $\sim$ 23 ka BP (hereafter noted simply as ka; only calibrated ^{14}C ages are reported) was characterized by a minimum in summer insolation in the Northern Hemisphere (Fig. 2.3) (Berger and Loutre, 1991). Low insolation and low atmospheric carbon dioxide concentrations are associated with a generally more arid and colder climate throughout Central Asia (Pachur *et al.*, 1995; An *et al.*, 2000; Bush *et al.*, 2004; Tarasov *et al.*, 2007c). The orbitally driven weakening of the EA monsoon, which extended only to the southern margin of the Loess Plateau, and a strengthening of the winter monsoon resulted in decreased moisture advection to monsoonal Asia (An, 2000; Wang *et al.*, 2005a; An *et al.*, 2006). Moreover, aridification was driven by alternations in the ocean-land configuration and lower sea surface temperatures in the South China Sea and low-latitude ocean (Wang, 1999).

The Westerlies dominated part of Central Asia was characterized by more arid conditions due to the windward presence of the Fennoscandian Ice Sheet, which combined the effects of orographic induced convection and cooling and caused moisture depletion of the Westerlies' airmasses and persistently blocked anticyclones in summer (Harrison *et al.*, 1996; Bush, 2004; Bush *et al.*, 2004). Fang *et al.* (1999) suggest a shift of the Westerlies south of the Tibetan Plateau even during summer and a provenance of the winter monsoon. The LGM climate resulted in a generally decrease in woody cover Eurasia (Tarasov *et al.*, 2007c) and a lowering of the glacier equilibrium line altitude (ELA). Considerable differences exist among opinions concerning the extent of glaciers. While Kuhle (2004) advocate the notion of extensive ice sheets in the Tian Shan and Lake Baikal region, various evidences point to glaciated areas in the high mountain ranges only (Zech *et al.*, 1996; Lehmkuhl and Owen, 2005). In the Khangay Mountains, the ELA was lowered by around 1000 m during the LGM (Lehmkuhl and Lang, 2001; Lehmkuhl *et al.*, 2004).

Owing to the dry climate most lakes in monsoonal Asia and the continental interior were dried out during the LGM (Pachur *et al.*, 1995; Wünnemann *et al.*, 1998; Naumann, 1999; Walther, 1999; Grunert *et al.*, 2000; Wünnemann and Hartmann, 2002; Fedotov *et al.*, 2004; Prokopenko *et al.*, 2005; Herzschuh, 2006). Lake Baikal and Hovsgol experienced a collapse of the ecosystems owing to a lack in nutrients, changes in water chemistry, ice cover and lowered water temperature (Karabanov *et al.*, 2004). Increased aridity was accompanied by high aeolian activity as documented by dune formations in western Mongolia (Grunert *et al.*, 1999; Naumann, 1999), increased aeolian flux in lake sediments (Wünnemann *et al.*, 2005) and increase of coarse quartz grains and high accumulation in loess sections (Porter and An, 1995; Porter, 2001). Owing to the general lack of vegetation, erosion and sediment transport were more efficient and large alluvial fans and pediments (*bajadas*) were active producing large amounts of fanglomerates in the basins and foothills (Richter *et al.*, 1963; Owen *et al.*, 1997, 1998; Grunert *et al.*, 2000; Lehmkuhl and Lang, 2001).

2.6.2 The late Pleistocene/Holocene transition (19-10 ka)

The late Pleistocene/Holocene transition faced a gradual increase in summer insolation in the Northern Hemisphere (Fig. 2.3). At the same time a general trend towards higher effective moisture availability can be detected in Central Asia. A sharp local minimum in moisture availability can be recognized during the Younger Dryas between 13.0 to 11.6 ka. Moisture supply increased again after 11.5 ka both in the southern and northern part of Central Asia (Porter, 2001; Wang *et al.*, 2001; Walther *et al.*, 2003; Boës *et al.*, 2005; Demske *et al.*, 2005; Dykoski *et al.*, 2005; Herzschuh, 2006; Westover *et al.*, 2006; Ilyashuk and Ilyashuk, 2007; Yancheva *et al.*, 2007).

The general increase of moisture supply during the late Pleistocene/Holocene transition is attributed to the onset of summer monsoon circulation and the decreasing influence of the Scandinavian Ice Sheet on moisture supply by the Westerlies (Sirocko *et al.*, 1993; Harrison *et al.*, 1996; Wang *et al.*, 1999; Blyakharchuk *et al.*, 2004; Herzschuh, 2006). The increase in available water and air temperature caused a widespread establishment of vegetation (Blyakharchuk *et al.*, 2004; Tarasov *et al.*, 2007a).

Still, there are vast differences in the moisture signals gained from lake sediment analysis during this time. The asynchronous reaction of lake systems can be attributed to several factors. Meltwater supply from declining glaciers, for example, may reflect temperature changes but not precipitation changes. The nearness to glaciated regions may thus be an important factor for the reactivation of prior dried out lake systems (Walther, 1999; Ilyashuk and Ilyashuk, 2007). Basin characteristics such as aquifer type, aquifer thickness and their different depletion during the LGM may result in significantly different rates of groundwater recharge and lake refill (Hartmann and Wünnemann, 2007). Geochemical properties of sediments of large lakes such as Lake Baikal may be affected by the the long mean residence time of water and thus have a strong response lag to climate change (Morley *et al.*, 2005). Finally, tectonics play a major role in the formation of many lakes (Yang *et al.*, 2004).

The difficulties in assessing the time lag between climate change and lake system reaction are overcome by investigating terrestrial archives that show a more immediate response to variable climatic boundary conditions. One of the most important terrestrial records of environmental change is loess. This clastic sediment, composed predominantly of silt-size particles and formed by the accumulation of wind-blown dust (Pye, 1995) is an almost ubiquitous deposit in Central Asia.

Loess and loess-like sediments (Lehmkuhl, 1997; Grunert and Lehmkuhl, 2004) provide indications of a changing climate during the late Pleistocene/Holocene transition. According to Lehmkuhl and Haselein (2000) and Lehmkuhl and Lang (2001) a phase of sand accumulation and dune activity is followed by a loess phase at the end of the Pleistocene (ca. 15 ka) in the southern Khangay Mountains. Chlachula (2003) finds highest loess accumulation rates in the northern Altai Plain and in the Yenisei Basin during 18-16 ka and Küster *et al.* (2006) detect an onset of loess accumulation at 13 ka in the Qilian Shan. Large dunefields in the Uvs-Nuur basin were active during 20-13 ka (Grunert *et al.*, 1999, 2000).

Significant differences in the interpretation of loess occurrence and mass accumulation rates exist. From a source perspective, there is a strong influence by the availability of loess and regional wind and precipitation patterns (Frechen *et al.*, 2003). Given the availability, loess is predominantly mobilized during cold and dry events (Wünnemann *et al.*, 2005). In the depositional areas, grainsize distributions of the loess deposits tend towards coarser grainsize composition during dry periods which are connected to an intensification of the Westerlies and the SH (Liu and Ding, 1998).

Other depositional areas provide evidence for a predominance of loess accumulation during more favorable climates (Yair and Bryan, 2000; Küster *et al.*, 2006). Thereby the change from a bare surface which promotes resuspension (Pye, 1995) to a vegetation cover is particularly important. Vegetation acting as dust trap and reduced wind speeds are regarded as the major forces controlling loess accumulation during these periods (Grunert and Lehmkuhl, 2004; Küster *et al.*, 2006). Another important process is wet deposition (cloud or subcloud scavenging of particles by precipitation) that is particularly important for the deposition of small grainsize fractions (Zender *et al.*, 2003) and may be a dominant process during wet climates.

Thus, from the mere presence of loess or loess-like deposits it is thus difficult to infer the climatic conditions in the study site during their accumulation. Lehmkuhl (1997) and Grunert and Lehmkuhl (2004) provide a regional model for the spatial and temporal dynamics of loess mobilization and deposition for Western Mongolia (Fig. 2.4).

The model describes a dust cycle governed by climatic controls. During cold and humid

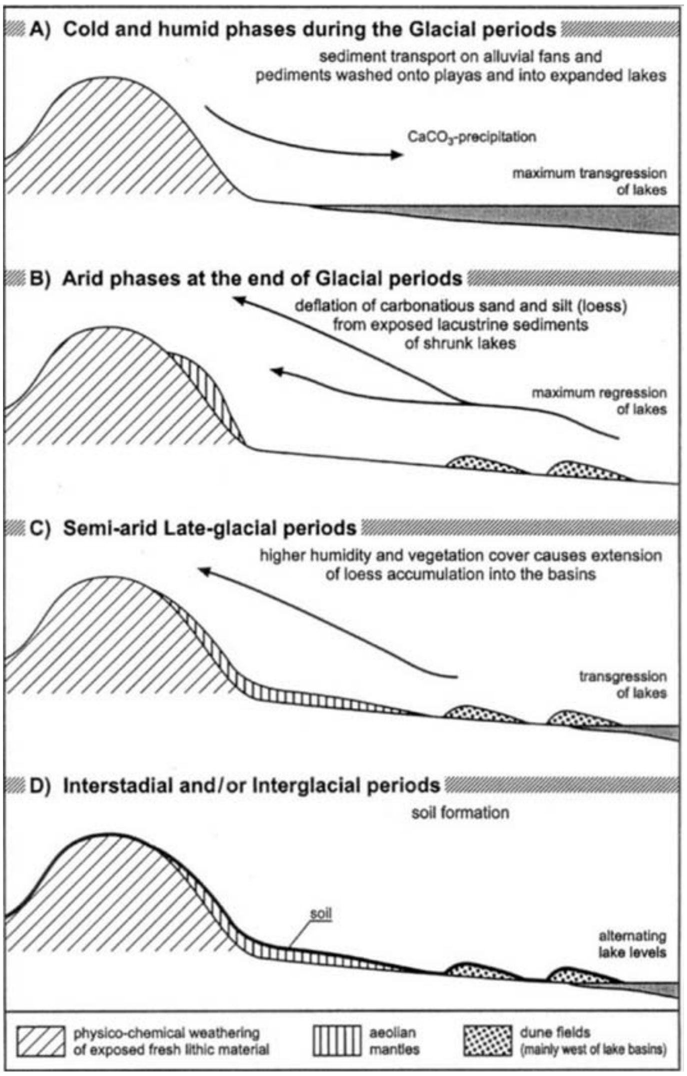

Figure 2.4: Model of horizontal and vertical sediment transport in the basin and range area of Western Mongolia during the Pleistocene and Holocene depending on temperature (glacial and periglacial activity), aridity (aeolian transport and accumulation), and humidity (lake transgression and soil formation) (Source: Grunert and Lehmkuhl, 2004).

phases, intensified weathering produces silt-sized material transported to lakes, where it is deposited together with lake carbonates. Regression of lakes at the end of glacial periods leads to erosion of the prior deposited material. While sands are accumulated in the adjacent area of the lake, smaller particles are transported over long distances. The establishment of vegetation during semi-arid late glacial periods acts as dust trap, leading to a vegetation density dependent accumulation in the vicinity of the dust sources. Following the altitude controlled moisture gradient distinct spatial patterns of loess deposits can occur. Finally, during interstadials and/or interglacial periods soil formation may prohibit aeolian dynamics (Grunert and Lehmkuhl, 2004). This model can be regarded as an explanation for the observed patterns of loess and loess-like accumulation and reconciles them with observations from other records.

2.6.3 Early Holocene (10-8 ka)

During the Early Holocene summer insolation on the northern Hemisphere was stronger than during the Mid and Late Holocene (Fig. 2.3). The heating of the Tibetan Plateau and warmer sea surface temperatures during summer caused the northernmost frontal zone of monsoon rainfall to advance northward into the present arid and semi-arid regions and invoked an effective precipitation maximum in this area (Fig. 2.5) (An *et al.*, 2000; Chen *et al.*, 2008). This pattern is supported by findings from Dongge Cave stalagmites (Dykoski *et al.*, 2005; Wang *et al.*, 2005b) and various lake records (Chen *et al.*, 2006; Herzschuh, 2006; Jiang *et al.*, 2006).

The Baikal region experienced a warm and wet climate during the Early Holocene, too (Demske *et al.*, 2005; Prokopenko *et al.*, 2007; Tarasov *et al.*, 2007a). Warmer and more humid climate can also be inferred for steppe regions where afforestation (Naumann, 1999; Westover *et al.*, 2006) and permafrost degradation occurred (Tarasov *et al.*, 2007a). A wetter Early Holocene in the boreal region of Central Asia is explained by the weakening of the SH that gave way to Atlantic cyclone activity (Blyakharchuk *et al.*, 2004).

Yet, the image of a wet Early Holocene cannot be drawn for parts of semiarid and arid Central Asia. Various records from the Westerlies dominated areas encountered a dryer climate (Peck *et al.*, 2002; Wünnemann *et al.*, 2003; Xiao *et al.*, 2004; Herzschuh, 2006; Chen *et al.*, 2008; Hartmann and Wünnemann, 2007). This contrast is explained by large scale effects of the convective heating on the Tibetan Plateau. Divergence of ascending air masses in the upper troposphere are associated with intensified subsidence north to the Tibetan Plateau and dryer climate in these regions (Broccoli and Manabe, 1992; Duan and Wu, 2005; Chen *et al.*, 2008). The northward extent of this atmospheric mechanism is largely unknown. But various records in the Mongolian Plateau suggest a dryer climate

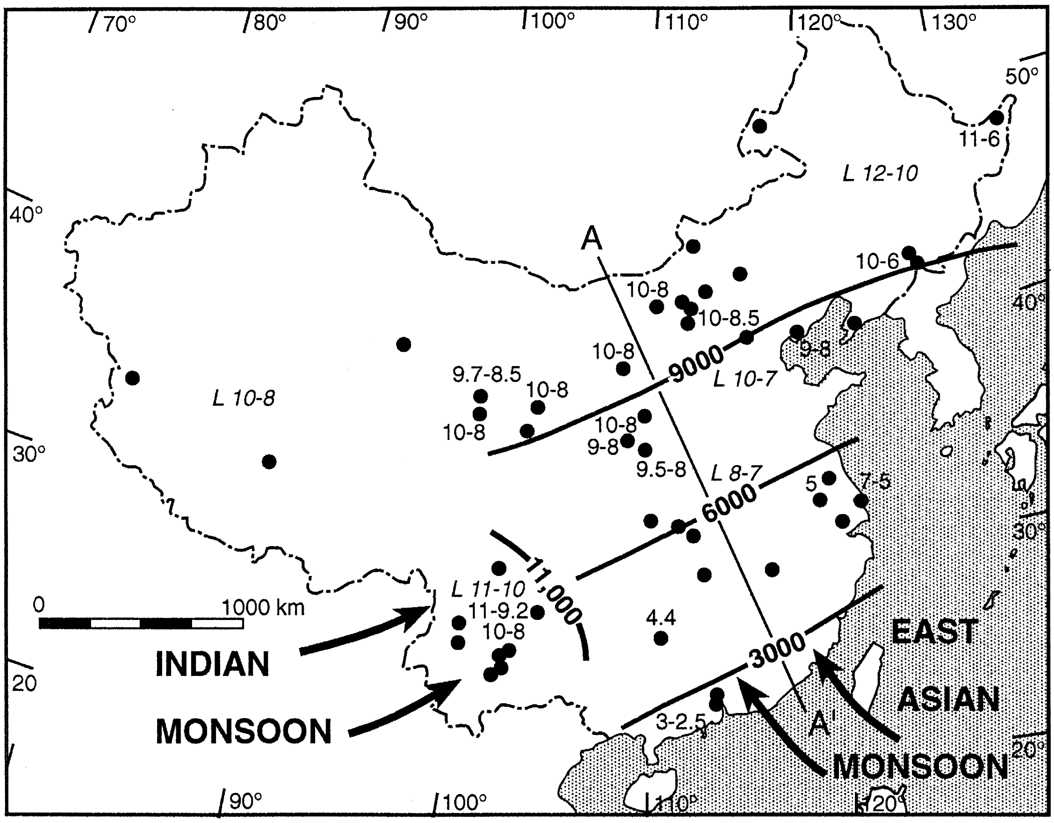

Figure 2.5: Temporal and spatial variability of maximum effective precipitation in summer monsoon controlled China based on paleoclimatic proxy data (Source: An *et al.*, 2000).

during the Early Holocene, too. Grunert *et al.* (2000), for example, report active dunes from the Uvs Nuur basin and Kowalkowski (2001) identifies a dry-warm phase with an increase of meadow steppe and steppe vegetation from 11 to 8.5 ka in the Altai Mountains. According to Gunin *et al.* (1999) steppe vegetation dominated at most sites in Mongolia and deserts occupied large depressions in western Mongolia from 11.5 to 8.9 ka.

A prominent feature in various records is the 8 k event related to the outflow of Lake Agassiz during deglaciation of North America. This event caused a retreat of the summer monsoon and a ca. 300 year cool and dry period in East Asia (Alley and Agustsdottir, 2005; Wang *et al.*, 2005b; Hartmann and Wünnemann, 2007).

2.6.4 Mid Holocene (ca. 8–4 ka)

Weakening summer insolation (Fig. 2.3) has been shown to cause a retreat of the maximum EA Monsoon limit (Fig. 2.5) (An *et al.*, 2000; Dykoski *et al.*, 2005). Particularly in west

China, but also in north China there is evidence for a decline in moisture supply (Chen *et al.*, 2006; Herzschuh, 2006; Hartmann and Wünnemann, 2007).

A trend towards dryer conditions is also found in the Hovsgol and Baikal region especially around 7 ka followed by a period of a prolonged minimum of the precipitation/evaporation ratio between 6 and 4 ka (Prokopenko *et al.*, 2007). Arid conditions are also found for Lake Telmen (Peck *et al.*, 2002; Fowell *et al.*, 2003) during the Mid Holocene. Yet, relative to the Early Holocene effective moisture in the Lake Telmen basin was higher (Peck *et al.*, 2002; Fowell *et al.*, 2003).

Weakening summer insolation has mostly been interpreted to decrease regional temperatures. Yet, according to Prokopenko *et al.* (2007), the lower effective moisture availability in the Hovsgol and Baikal region during the Mid Holocene can be largely attributed to rising temperatures, a notion that challenges the thinking of insolation as ultimate driving force of climate (Tarasov *et al.*, 1999a; Prokopenko *et al.*, 2007). Instead, CO_2 concentrations and water vapor may significantly influence climate during this time (Bush, 2005; Prokopenko *et al.*, 2007).

The trend towards lower moisture availability is far from unambiguous during the Mid Holocene. Various areas influenced by the Westerlies or the monsoon indicate a moisture maximum (Shi *et al.*, 1993; Dorofeyuk and Tarasov, 1998; Tarasov *et al.*, 2000; Mischke *et al.*, 2003; Grunert and Dasch, 2004; Herzschuh *et al.*, 2004; Yang *et al.*, 2004; An *et al.*, 2006; Herzschuh, 2006; Westover *et al.*, 2006; Xiao *et al.*, 2006; Chen *et al.*, 2008). Hartmann and Wünnemann (2007) find indications for a phase of maximum humidity from 5.4-4 ka. An *et al.* (2006) argue that higher sea surface temperatures increased water vapor content in the monsoon and the Westerlies, and that better vegetation coverage selfpromoted the summer monsoon. According to An *et al.* (2006) the major aridity occurred at around 4 ka. Chen *et al.* (2008) argues that higher North Atlantic sea surface temperatures and high-altitude air temperatures intensified cyclonic activity and synoptic disturbances along the Westerlies that result in higher convective precipitation rates in Westerlies dominated Central Asia during the Mid Holocene.

2.6.5 Late Holocene (ca. 4–0 ka)

The Late Holocene is regarded as the transition from Mid Holocene to modern climate triggered by changes in insolation (Claussen *et al.*, 1999). According to An *et al.* (2000) Central Asia faces further gradual monsoon weakening (Fig. 2.5) and a shift of the regional precipitation peak to southern China (An *et al.*, 2000). EA monsoon dominated areas show lower effective moisture (An *et al.*, 2000; Herzschuh, 2006). Areas dominated by the Westerlies, however, lack an uniform decrease in moisture availability (Herzschuh, 2006; Chen *et al.*, 2008) and records from boreal Central Asia show moisture conditions similar to present since $\sim$ 4 ka (Gunin *et al.*, 1999; Tarasov *et al.*, 2000; Walther *et al.*, 2003; Yang *et al.*, 2004).

Other records, however, show significant variability throughout the Late Holocene (Wu and Liu, 2004). The Lake Telmen record, for example, shows favorable moisture conditions during 4.5 ka to present interrupted by a phase of aridification from 1.6-1.2 ka. Hartmann and Wünnemann (2007) report various short-term dry spells in the Lake Juyanze basin during the last four millenia and increasing ariditiy during the past 1–2 millenia. Records in boreal Central Asia also point to significant climatic oscillations from 4 to 2.5 ka that are not well dated and understood (Karabanov *et al.*, 2000; Demske *et al.*, 2005; Prokopenko *et al.*, 2007). Vipper *et al.* (1989) report distinct gravely lamina in various Mongolian lakes with an average calendar age of $\sim$ 3.6 ka. According to these records, a smooth climate transition governed by declining insolation cannot be assumed for most regions in Central Asia.

Similar abrupt changes can be seen in North Africa during the Mid and Late Holocene and have been explained in terms of internal, mainly regional vegetation-atmosphere feedbacks in the climate system (Claussen *et al.*, 1999). Yet, Wu and Liu (2004) and Wang *et al.* (2005b) argue that the Late Holocene was characterized by at least one climatic anomaly that was independent of and superimposed upon Holocene monsoon variations. Wu and Liu (2004) relate this variability to 'Bond events', global climate system reactions to weak perturbations in the sun's energy output (Bond *et al.*, 2001). They argue that cooling in the continental interior caused a retreat of the summer monsoon, producing droughts in northern China and floods in southern China (Wu and Liu, 2004).

While speleothem and loess records provide high-resolution records of the late Holocene precipitation variability in the monsoon dominated region (Wang *et al.*, 2005b; Maher and Hu, 2006), such information on the climate and landscape evolution in the Mongolian Plateau is largely lacking. Tree-ring data span the last 2000 a (D'Arrigo *et al.*, 2001). The data reveals both warm and cold epochs during 800-1400 a AD supporting evidence that the Medieval Warm Epoch was not a period of sustained warmth in Mongolia (D'Arrigo *et al.*, 2001). Most prominently the 20th century is a time of unusual warmth relative to the past 450 a (Jacoby *et al.*, 1996). Northern Mongolia has been warming twice as fast as the global average during the last 40 years and faces a decline in permafrost (Nandintsetseg *et al.*, 2007; Bohannon, 2008). Projections indicate a more arid climate in the future (Sato *et al.*, 2007).

2.7 Anthropogenic influence

A strong interrelation between human activities and environmental evolution has characterized at least the Late Holocene in Central Asia (Grunert *et al.*, 2000; Roberts *et al.*, 2001; Fu, 2003; Rost *et al.*, 2003; Ruddiman, 2003; Wu and Liu, 2004; Rösch *et al.*, 2005; Wang *et al.*, 2005b; Schlütz and Lehmkuhl, 2007; Tarasov *et al.*, 2007b; Yancheva *et al.*, 2007). Increase in human populations, deforestation, shifts from nomadic lifestyle to sedentary, farming activity, but also warfare largely affected steppe ecosystems (Rost *et al.*, 2003) and natural forests as early as 6.5 ka (Ren, 2000). Likewise, the Orkhon Valley was prone to various types of human activity. Unlike other regions it had a particular role as a spatial, political nucleus in Central Asia (Drompp, 1999) and as such was a preferred area for colonization during the last three millennia (Fig. 2.6) (Bemmann *et al.*, 2008). Yet, the environmental effects of human activities in this area are largely unknown.

The discussion on the human induced environmental effects in the steppe region of Mongolia was mainly provoked by botanists debating the origin of steppe ecotones in Mongolia and Russia (Gunin *et al.*, 1999; Hilbig, 2000; Dulamsuren *et al.*, 2005a; Rösch *et al.*, 2005; Miehe *et al.*, 2007; Schlütz *et al.*, 2008). Gunin *et al.* (1999) argues that Holocene vegetation changes are controlled by natural forcings. This view is mainly adopted by Dulamsuren *et al.* (2005a) and Schlütz *et al.* (2008) who report a lack of evidence for a anthropogenic removal of forest vegetation. They conclude that human population densities were to low to leave a significant mark in the vegetation distribution (Schlütz *et al.*, 2008)

According to Hilbig (2000), vegetation in grassland areas is similar to ground vegetation in the forest-steppe ecotone, which provides evidence for a human origin of grasslands where naturally forest-steppe would occur. Forests in these areas disappeared due to logging for fire-use and pasture land extension (Rösch *et al.*, 2005; Miehe *et al.*, 2007). Overgrazing in grasslands resulted in a remobilization of sand sheets and deflation of silt sized particles (Lehmkuhl *et al.*, 2007).

It is generally agreed on that most of the results supporting or rejecting human influence are limited to the respective study area (Dulamsuren *et al.*, 2005a; Schlütz *et al.*, 2008). Hence, the regional and local degree of human influence needs to be considered when assessing their environmental effects. As a prime step towards assessing human-environment interactions, archaeological records on the Orkhon Valley should be evaluated to gain insight in the human history of this area.

The Orkhon Valley was a preferred place for settlement during three millenia (Fig. 2.6). An anthropogenic influence since the Palaeolithic can be traced back by a vast range of legacies like tombs (Kurgans and Khirigsuurs) (Wright, 2007), petroglyphs and wall remnants (Bemmann *et al.*, 2008). A cemetery nearby the Tamir and Orkhon confluence with more than 250 burials is likely of Xiongnu origin (3-2th c. BC) (Batsaikhan *et al.*, 2006), the memorial Khoshöö Tsaidam documents the influence of Turks ($6-8$th century (c.) AD) (Batmunkh *et al.*, 2004). The Uighurs ($8-9$th c. AD) devised their capital Kharabalghasun and a rampart in the west to Lake Ugii Nuur (Minorsky, 1948; Drompp, 1999, 2005; Bemmann *et al.*, 2008).

In 840 AD the Uighurs were defeated by the Turkic Kirghiz, a people living in the Yenisei River region (present-day Minusinsk and Abakan) in south Siberia northwest of the Mongolian plateau. It is assumed that this semi-sedentary society never established a long or significant presence in the Orkhon Valley (Drompp, 1999).

Since the Turkic Kirghiz did not leave any legacies in the Orkhon Valley, it is assumed that that remainders of the Uighur population stayed in and shared the Orkhon Valley

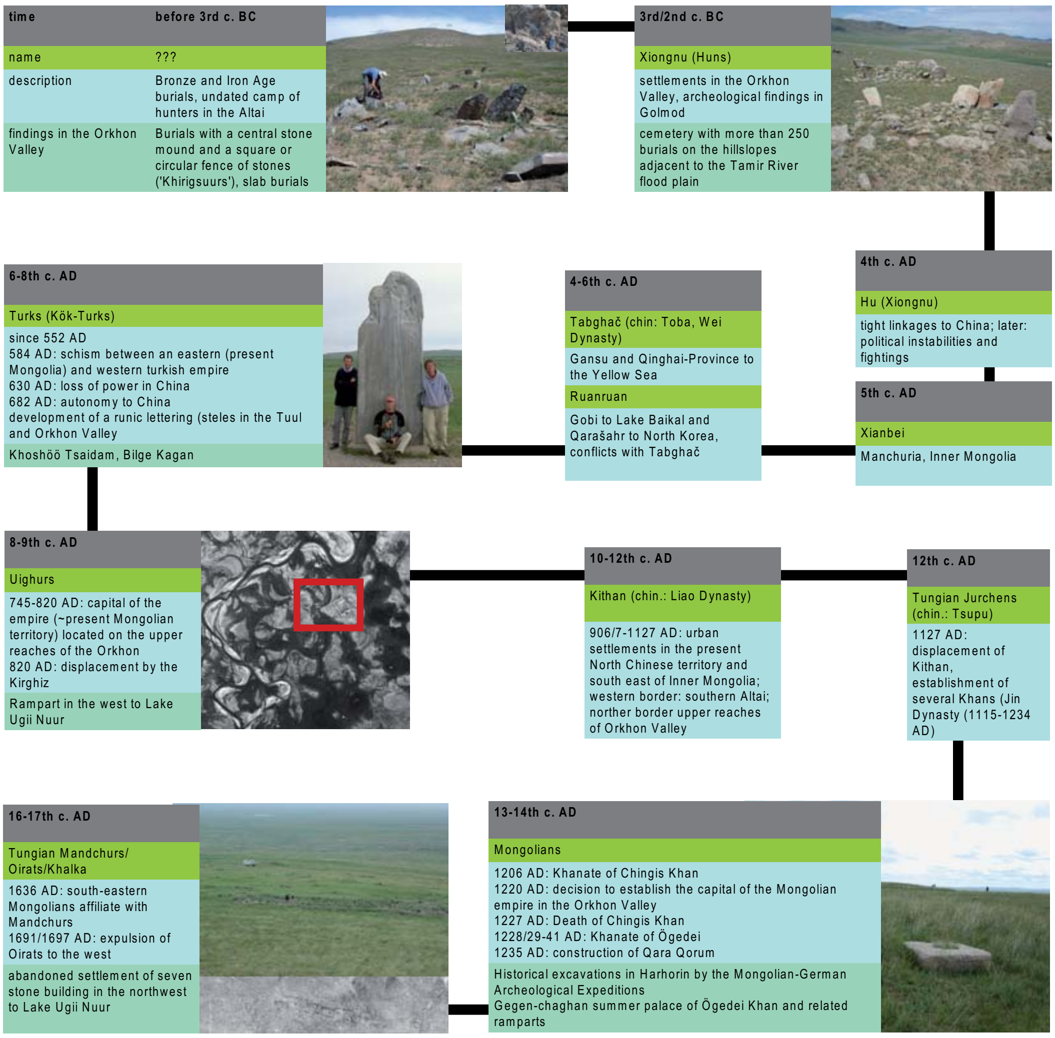

Figure 2.6: Simplified timeline of anthropogenic influence in Central Asia and the Ugii Nuur basin according to Weiers (2005) and Bemmann *et al.* (2008).

with other tribes. One of them were the Tatars who were encountered by the Khitans who campaigned into Mongolia in 924 AD and defeated them (Drompp, 1999). During the Khitans era there was probably an important transition in cast iron technology in Mongolia (Gelegdorj *et al.*, 2007).

Mongolia's history is most famous for its emperor Chengis Khan (1155, 1162 or 1167 - 1227), who was the Mongol founder by unifying several tribes and confederations in the Mongolian Plateau and who lead the wars of conquest against vast regions in Eurasia and conquered the Mongol Empire in the early 13th c. AD, the largest contiguous empire in history. There are various theories on the reasons for the conquests. One, for example, refuses the quest for land *per se*, but emphasizes the appropriation of culture, technology and, in particular, human resources (Allsen, 1997). Another theory is especially interesting from a geoarchaeological point of view. Fagan (2008) suggests that the rapid expansion of the empire can be explained by deterioration of environmental conditions during the Medieval Warm period (D'Arrigo *et al.*, 2001).

The Orkhon Valley experienced a major anthropogenic influence in the early 13th c. AD. In 1220, Chengis Khan decided to establish Karakorum (47°11.53'N, 102°47.3'E) as the capital of the the Mongolian empire in the Orkhon Valley. Ugii Nuur was part of the peri-urban area of Karakorum, a domain where nomadic traditions mixed with various forms of agricultural activities to supply the political, economic and cultural center (Shiraishi, 2004; Erdenebat and Pohl, 2005). Travelogues report grain and vegetable cultivations on the bank of the Orkhon River (Shiraishi, 2004). Archaeobotanical investigations reveal that local agrarian production included the cultivation of millet, barley, wheat and foxtail millet (*Panicum miliaceum, Hordeum vulgare, Triticum aestivum, Setaria italica*) as summer crops (Rösch *et al.*, 2005). It is most likely that cereal production was accomplished with irrigation and fertilization (Rösch *et al.*, 2005). A more humid climate than present during this time, however, is indicated by findings from the spring palace of the Mongolian emperor. It is located on an elevation in the Orkhon floodplain and was surrounded by numerous lakes (Shiraishi, 2004). Today the lakes are only episodically filled with water during wet spells (Bemmann *et al.*, 2008).

Rearing and keeping animals within the surroundings of Karakorum was common in particular with regard for sheep (von den Driesch *et al.*, 2008). The degree of pressure on the Orkhon Valley ecosystem is difficult to assess but it is assumed to be high when a sufficient supply of the capital was to be met. The demand for meat is assumed to have been high because of a relative high level of living (Rösch *et al.*, 2005). The operation of furnaces with wood was an additional stress to the ecosystem (Franken, 2005) and may have strongly altered vegetation during this time.

Karakorum experienced a strong decline from the early 16th c. AD and lost it important role as political, economical and religious center. By 1585/86 the first temples of Erdeni

Joo were built that are still existent today. An abandoned settlement of seven stone buildings in the northwest to Lake Ugii Nuur is of Tungian Mandchurs origin (16 – 17th c. AD) (Weiers, 2005; Bemmann *et al.*, 2008). This repeated occupation of the Orkhon Valley by humans was accompanied by extensive livestock farming that effects vegetation cover and likely intensified soil erosion processes (Batkhishig and Lehmkuhl, 2003).

2.8 Discussion

The scientific community discusses the significance of mechanisms of climate changes in Central Asia at different temporal scales. On a millennial time scale insolation and glacial boundary conditions (ice volume, sea surface temperature, albedo) influence monsoon and westerly wind systems. The importance of each respective factor is still matter of debate. Insolation is regarded as one of the most important factors during the late Pleistocene and Holocene. Insolation was highest during the Early Holocene and declines until present (Fig. 2.3) (Berger and Loutre, 1991). Various studies suggest a significant relation between the orbital forcing mechanism and environmental change in the EA monsoon dominated region (An *et al.*, 2000). In particular, oxygen isotope ratio (δ^{18}O) records obtained from high resolution and densely dated speleothem records show a strong accordance with the constant decline of orbital forcing during the Holocene (Dykoski *et al.*, 2005; Wang *et al.*, 2005b). δ^{18}O values are interpreted to reflect changes in the amount of precipitation and thus characterize the summer monsoon strength (Wang *et al.*, 2005b).

Yet, there is clear mismatch between the speleothem derived rainfall proxies and loess/paleosol sequences, that indicate widespread, submillennial intervals of paleosol formation throughout the entire Holocene. Increased precipitation in the Late Holocene recorded in loess profiles provides evidence for a lack of decline of the summer monsoon (Maher, 2008). Maher (2008) argues that the cave records do not reflect changes in rainfall amount but in rainfall source and air mass trajectory, since present-day oxygen isotope composition in rainfall in China varies with the relative influence of the more continental Indian Monsoon. While the Indian Monsoon experienced a decline during the Holocene, internal feedback via changes in land-ocean temperature gradients strengthened the EA monsoon in an antiphase behavior (Maher and Hu, 2006; Maher, 2008).

Such feedback mechanism may largely control the evolution of the wind systems and thus temperature and moisture evolution during the Holocene. Others have stressed the role of glacial boundary conditions in modifying the response of the monsoon to orbital forcing (Sirocko *et al.*, 1993; Yuan *et al.*, 2004; Wünnemann *et al.*, 2005; Herzschuh, 2006). Evidence for a positive feedback mechanism between rising temperatures induced by regional warming and northward expansion of boreal forests and precipitation increase has been provided by Foley *et al.* (1994). Annual to decadal variations in monsoon intensity have been suggested to result from the El Niño-Southern Oscillation (ENSO) (Dykoski *et al.*, 2005; Wang *et al.*, 2005a) and snow cover changes (Shukla and Mintz, 1982).

The complex interactions between different spatial scales involve dominant processes governing climate and landscape evolution and require the incorporation of spatial nonlinearities, threshold behavior and cascading effects in landscape evolution models (Peters *et al.*, 2004). Various difficulties arise when assessing the complex characteristics of the interactions in paleoenvironmental reconstructions. Basin characteristics govern the sensitivity of lake and terrestrial systems to climate change (Hartmann and Wünnemann, 2007). For example, changes in surface properties owing to loess accumulation may significantly alter the hydrological cycle (Yair and Bryan, 2000). Since lake deposits are the last link in the sediment cascade from source to sink, they may show a delayed signal to changes in erosion and sediment fluxes in the basin. The same difficulties apply to loess sediments, where the interactions between climate, sediment supply in the source areas, dust-transporting wind systems and capabilities of source regions to trap dust have to be taken into account. It may, however, prove difficult to distinguish, if time lags between predictor and target variables are due to dating uncertainties or a delayed system response (Herzschuh, 2006).

The signal-to-noise-ratio during the Holocene is much lower compared to the glacial-interglacial cycles. This makes it far more difficult to detect climate change in the Holocene relative to over longer time scales (Cronin, 1999). Moreover, feedback mechanisms on the local or regional scale between vegetation and climate or topography and Earth surface processes (Stallins, 2006) may gain weight as driving factors of environmental change in the Holocene. This may be regarded as an incentive to concentrate more on smaller spatial units. Yet, a decrease in scale of observation makes generalizations even more difficult due to increasing variability between different units (Fuhlendorf and Smeins, 1996).

In addition to natural forcings, environmental variability is partly due to human activities during the Holocene. Yet, natural and anthropogenic forcings are difficult to discriminate since their signals may be similar (Mainguet and Da Silva, 1998). Moreover, anthropogenic impacts happen on the global (Ruddiman, 2003) to the local scale. Hence, assessing archaeological records is indispensable for interpreting records of environmental change during the Holocene.

2.9 Conclusions

Central Asia was subject to significant environmental variability during the Holocene. The drivers of climatic change are highly disputed, but there seems to be an overall notion of the underlying complexity involving global to local feedback mechanisms governing climate change and lastly landscape evolution. This complexity is certainly one reason that environmental changes of the Holocene do not always manifest themselves similarly in different regions (Wu and Liu, 2004). Other reasons comprise different sensitivities of ecosystems or basins to climatic change, tentativeness in the interpretation of proxies, uncertainties in datings and the variable influence of mankind latest by the Mid Holocene.

Despite the difficulties in interpreting archives of climate and landscape evolution, this review highlights various differences between Monsoon dominated and Westerlies dominated regions. Most important, the Westerlies must be regarded as an additional wind system governing moisture supply to Central Asia despite the extreme distance from the Atlantic Ocean. So far the interactions of the Indian Monsoon and the EA monsoon have been intensively investigated to assess environmental evolution in Central Asia. In order to better understand the climate and landscape evolution it is also necessary to account for the variability of the Westerlies in this region.