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Zhisheng An *Editor*

Late Cenozoic Climate Change in Asia

Loess, Monsoon and Monsoon-arid Environment Evolution

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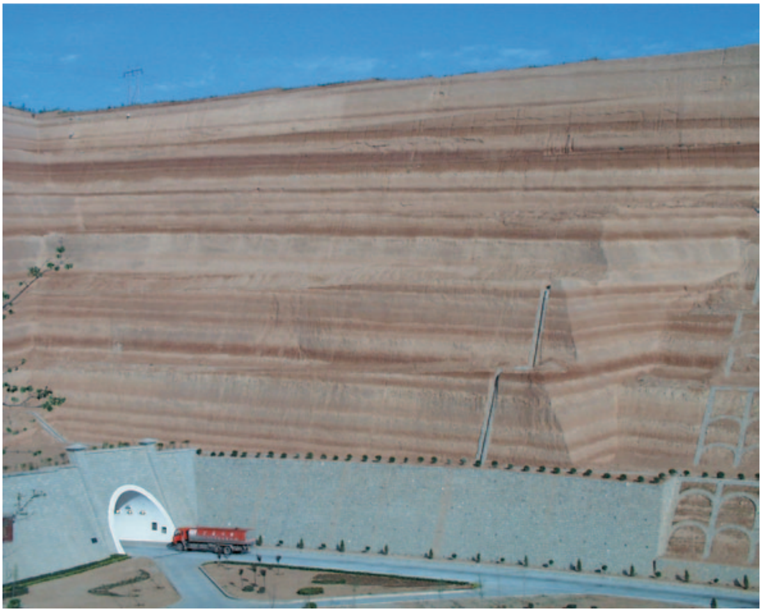

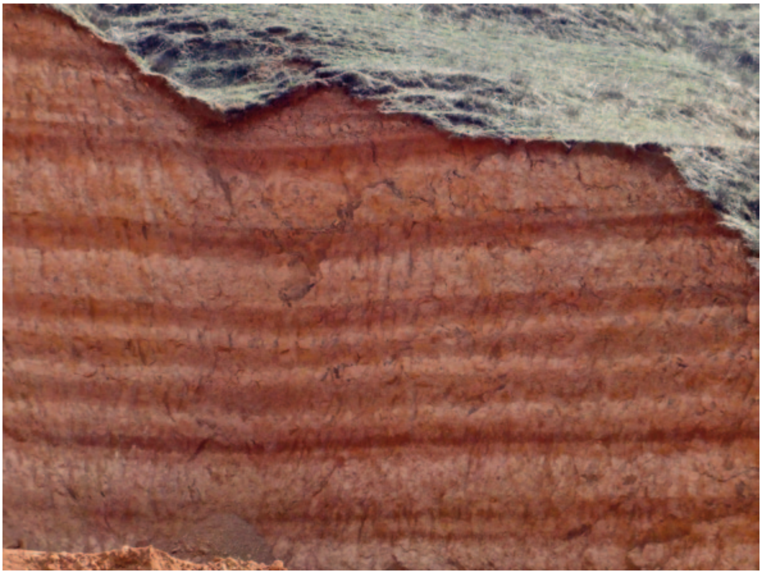

The loess-paleosol sections near Xian (photo1, by Li Li) and red clay section in Huating (photo 2, by Song Yougui), China. Loess-paleosol-red clay sequences have recorded the information about the south eastern humid summer monsoon and western inland aridification evolution. Unique archives reflecting the differentiation and coupling of Asian monsoon-arid environment, associated with the Tibetan Plateau growth.

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Editor
Zhisheng An
Institute of Earth Environment
Chinese Academy of Sciences
Xi'an
China

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Preface

Climate change in Asia has long enjoyed tremendous interest and progress in the scientific community. The overall aims and scope of this volume are to capture this excitement and document these developments. Asia climate change study has now become a priority for the international paleoclimate community for two reasons. Firstly, the Asian continent, Tibetan Plateau and marginal seas have become a focus of paleomonsoon research. A series of large scale international field projects and drilling campaigns have been conducted to enhance our understanding of the Asian monsoon-arid environment history. Secondly, a sense of urgency has arisen in Asia as it continues to develop rapidly, and is already the most populated continent in the world. The goal of sustainable growth relies on a thorough understanding of climate change and the mechanisms involved. Our intention is to address this need by synthesizing our past findings to steer our future efforts in the most fruitful direction.

Acknowledgements

The present volume is a product of group efforts mainly by the State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences. This work was supported by the National Basic Research Program of China, the National Natural Science Foundation of China, the Chinese Academy of Sciences, State Key Laboratory of Loess and Quaternary Geology and Institute of Earth Environment.

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List of Abbreviations

AMS	Accelerator Mass Spectroscopy
ARM	Anhysteretic Remanent Magnetization
CGCM	Coupled General Circulation Models
CLIMAP	Climate: Long range Investigation, Mapping, and Prediction
CLP	Chinese Loess Plateau
COHMAP	Cooperative Holocene Mapping Project
DSDP	Deep Sea Drilling Project
EAM	East Asian Monsoon
EASM	East Asian Summer Monsoon
EBM	Energy-Balance Model
EC	Elemental Carbon
EMIC	Earth system models of intermediate complexity
FOAM	Fast Ocean Atmosphere Model
GIC	Global Iron Connections
GPTS	Geomagnetic Polarity Time Scale
IPWP	Indo-Pacific Warm Pool
IRSL	InFrared Stimulated Luminescence
ITCZ	Intertropcial Convergence Zone
LGM	Last Glacial Maximum
LIA	Little Ice Age
LGM	Last Glacial Maximum
MWP	Medieval Warm Period
NADW	North Atlantic Deep Water
NRM	Natural Remanent Magnetization
OC	Organic Carbon
OSL	Optically Stimulated Luminescence
PAHs	Polycyclic Aromatic Hydrocarbons
PCBs	Polychlorinated Biphenyls
PMIP	Paleoclimate Modeling Intercomparison Project
POPs	Persistent Organic Pollutants
QGS	Quartz Grain Size

SAR	Single-Aliquot Regenerative-dose
SCS	South China Sea
SIRM	Saturation Isothermal Remanent Magnetization
SMAR	Sensitivity-corrected Multiple Aliquot Regenerative dose
SST	Sea Surface Temperatures
TOC	Total Organic Carbon
TP	Tibetan Plateau
YD	Younger Dryas

List of Contributors

Zhisheng An State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Hong Ao State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

George S. Burr University of , NSF- AMS Laboratory, Tucson, USA

Yanjun Cai State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Junji Cao State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Hong Chang State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Peng Cheng State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Yongming Han State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Zhangdong Jin State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Zhao Jin State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Baosheng Li School of Geographical Science, South China Normal University, Guangzhou, China

Li Li State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Xiaoqiang Li State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Yongxiang Li Department of Geology, Northwest University, Xi'an, China

Weiguo Liu State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Xiaodong Liu State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Yu Liu State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Zhonghui Liu Department of Earth Sciences, The University of Hong Kong, Hong Kong, China

Fengyan Lu State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Wei Pan Centre for Historical Environment and Socio-Economic Development in Northwest China; Shaanxi Normal University; Xi'an, China

Zicheng Peng University of Science and Technology of China, Hefei, China

Xiaoke Qiang State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Zhengguo Shi State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Shaohua Song State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Yougui Song State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Youbin Sun State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, China

Liangcheng Tan State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi’an, China

Lide Tian Laboratory of Environment and Processes in the Tibetan Plateau, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China

Xulong Wang State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi’an, China

Xinzhi Wu Institute of Vertebrate Paleontology and Paleoanthropology Chinese Academy of Sciences, Beijing, China

Feng Xian State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi’an, China

Hai Xu State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi’an, China

Libin Yan State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi’an, China

Xuefeng Yu State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi’an, China

Peizhen Zhang Institute of Geology, China Seismological Bureau, Beijing, China

Xiaoye Zhang Chinese Academy of Meteorological Sciences, Beijing, China

Xinbao Zhang Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, China

Yunxiang Zhang Department of Geology, Northwest University, Xi’an China

Hongli Zhao State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi’an, China

Weijian Zhou State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi’an, China

Chapter 1
Introduction

Zhisheng An, Li Li, George S. Burr, Yougui Song, Libin Yan, Hong Chang, Youbin Sun, Yanjun Cai, Zhengguo Shi, Hai Xu, Hongli Zhao, and Weijian Zhou

Abstract This chapter gives a description of the research history and development of our current understanding of paleoclimate and paleoenvironments in China. It outlines major questions that have arisen after years of study of the Asian monsoon-arid climate system. Modern natural geography is introduced and this sets the stage for detailed reviews in the following chapters.

Keywords Asian monsoon · Tibetan plateau · Geomorphology · Loess · Glacial · Monsoon-arid zone · Monsoon variability · Global change

1.1 Introduction

This book is about climate change at the interface of the monsoon and arid regions of the Asian continent. The climate of the southern and eastern humid zones within this region are controlled by the Asian monsoon, while climate in the relatively arid zone to the northwest is controlled by the westerlies and the East Asian winter monsoon. The climate of the semi-arid zone in-between is influenced by both monsoons and the westerlies. The semi-arid zone marks the inland extent of the monsoon. This region changes with time, reflecting changing climate and monsoon frontal shifts. In recent years we have extended our view of climate change in China to include the western arid regions as an essential component of Asian climate. The current framework involves an eastern humid end-member and a western arid end-member, with the dynamic semi-arid transition zone in-between. Any comprehensive evaluation of Asian environmental change must recognize the coupled evolution of the Asian monsoon and monsoon-arid climate system as part of a whole, within a global framework.

Z. An (✉) · L. Li · Y. Song · L. Yan · H. Chang · Y. Sun· Y. Cai · Z. Shi · H. Xu· H. Zhao · W. Zhou
State Key Laboratory of Loess and Quaternary Geology,
Institute of Earth Environment, Chinese Academy of Sciences,
No. 10 Fenghui S. Rd, High-Tech Zone,
Xi'an PO Box 17, Xi'an, China
e-mail: anzs@loess.llqg.ac.cn

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G. S. Burr
University of Arizona, NSF-Arizona AMS Laboratory,
85721 Tucson, Arizona, USA
e-mail: burr@email.arizona.edu

L. Li
e-mail: lili@ieecas.cn

Y. Song
e-mail: ygsong@loess.llqg.ac.cn

L. Yan
e-mail: yanlibin@ieecas.cn

H. Chang
e-mail: changh@loess.llqg.ac.cn

Y. Sun
e-mail: sunyb@ieecas.cn

Y. Cai
e-mail: caiyj@loess.llqg.ac.cn

Z. Shi
e-mail: shizg@ieecas.cn

H. Xu
e-mail: xuhai@ieecas.cn

H. Zhao
e-mail: zhaohl@ieecas.cn

W. Zhou
e-mail: weijian@loess.llqg.ac.cn

The entire region, from the monsoon-dominated zone to the arid zone, preserves unique records of past climate change. This is especially true of the semi-arid zone. Here the reader will find a comprehensive review of these records which provide evidence for spatial and temporal climatic and environmental change across the Asian continent since the Late Cenozoic. The dynamics underlying these changes are explored on the basis of these records, and an *Asian monsoon-arid environment system* is described that quantifies the controlling mechanisms of climate change and how they operate on different time scales.

The goal of the book is to present an integral framework for understanding natural environmental change and partly human-induced forcings in China that may be used to assist in the ongoing effort to manage the development of this region responsibly and sustainably. This goal extends far beyond the highly populated urban centers of East Asia because the Asian monsoon is an integral part of the global climate system, and monsoon-driven precipitation in particular, is vital to the maintenance and sustainable development of billions of people.

Monsoon circulation plays a very important role in the transportation of global water vapour and heat. The dynamics of the Asian summer monsoon is connected to the Equatorial Ocean and Southern Hemisphere, and the East Asian winter monsoon is closely associated with climatic conditions of northern high latitudes, including the North Atlantic Ocean and Arctic regions. Past Asian winter/summer monsoon variability has been shown to be influenced by changes in solar insolation, lower boundary conditions and greenhouse gases.

The Asian monsoon is the most powerful monsoon circulation system on Earth. It is driven by seasonal changes in solar radiation and the differential absorption of radiation by the oceans and continents. The Qinghai-Tibet Plateau, extending into the mid-troposphere, plays a major role in the regional energy balance and thus has a critical role in the dynamics of the Asian monsoon system. Asian monsoon dynamics interact with global climate through moisture and energy exchanges between high and low latitudes of the Northern Hemisphere, and between the Northern and Southern Hemispheres. During the summer, the Asian monsoon brings heavy rains to Asia and Africa, while monsoon winters are relatively dry. The lives of many people under the influence of the monsoon have adapted to these seasonal changes. While the wet monsoon brings much needed rain, it can also cause flooding and torrential storms that can bring crop and infrastructure damage with them. Vegetation, land use, hydrology, economy, culture, and society across the Asian monsoon region all depend on the evolution and variability of the Asian monsoon, to which this book is devoted.

Paleomonsoon research on the Asian monsoon zone began with the study of loess profiles. From the 1950's to the 1970's, scientists focused their attention on the distribution of loess on the Chinese Loess Plateau (CLP), its composition, structure and origin. In the 1970's to 1980's, Chinese loess studies explored correlations with other records of environmental change. This was the focus of the text, *Loess and Environment*, written by a Chinese group led and organized by Liu Tungsheng and An Zhisheng, that was published in 1985. This text became the Rosetta stone for Chinese loess studies. In the book, Liu and An successfully correlated Chinese loess-paleosol sequences with climatic records of deep sea marine cores. At that point, the scientific community began to realize that Chinese loess records represented a unique and valuable archive of continental environmental change that should be studied carefully alongside marine sediment and ice core records. In the late 1980's, the research group led by An Zhisheng continued to explore the dynamics of Chinese environmental change, demonstrating that loess-paleosol sequences provide sufficient resolution to study monsoon variability. The scope of the work was expanded to include research on a variety of continental archives. That research revealed that the 600,000 km^2 of loess-paleosol sequences distributed along the middle reaches of the Yellow River are formed under the influence of monsoonal climate changes, with alternating dominance between the East Asian winter and summer monsoons. Furthermore, the eolian depositional flux recorded on the Loess Plateau reflects aridity changes in the dust source region. Therefore, the eolian loess-paleosol sequences can be used as high resolution records of past monsoons and associated climate changes of arid inland Asia. This discovery solved the puzzle of how such massive and widely-distributed sediments came to be deposited. The hypothesis that the monsoon is the controlling force for paleoenvironmental change in East Asia was proposed in the late 1990s, as correlations between loess, Quaternary sediment records, and historical records made this connection increasingly clear. The monsoon control hypothesis has since been acknowledged by the international community, as it explains a series of natural phenomena, like the shifts of desert margins, lake levels, snow/forest lines, vegetative zones, mammalian migration and sea surface temperature changes in Asia.

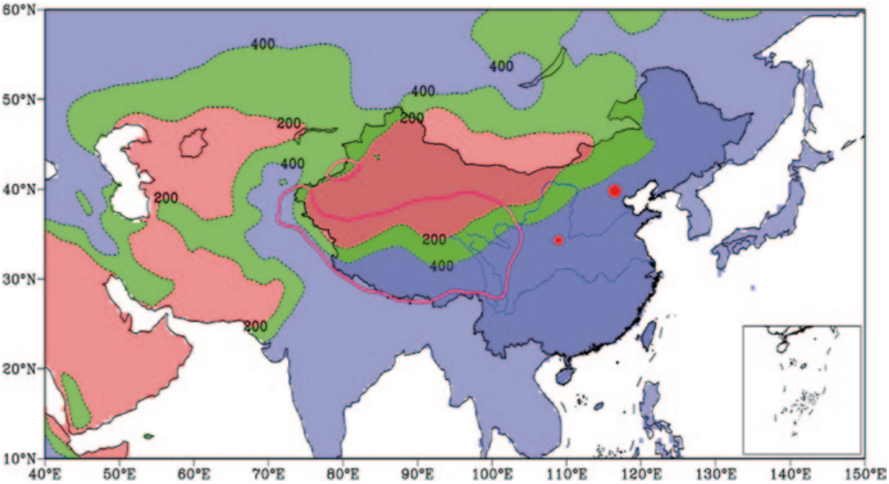

Fig. 1.1 The spatial distribution of annual mean precipitation (Unit: mm) based on the CRU dataset (New et al. 2002) from 1971 to 2000. The elevation of the pink contour is 3000 m. The red, green, and blue shaded areas indicate the regions where precipitation is less than 200 mm, between 200 and 400 mm, and more than 400 mm, respectively. The deeper red, green and blue shaded areas are located in China. The big and small red solid circles indicate the position of Beijing and Xi'an, respectively

1.2 Geography of the Asian Monsoon-arid zone

1.2.1 Climatic Setting

The continent of Asia is traversed from southwest to northeast by the Asian monsoon belt, the largest monsoon system on Earth. The Asian monsoon extends from the Arabian Sea in the west, to northeastern China and Korea in the east. What sets the Asian monsoon apart from other monsoon systems is the presence of the Tibetan Plateau (TP), which forms a massive wall along its southern margin (Wang 2006). The total annual precipitation across the monsoon belt ranges from more than 1200 mm in coastal regions, to approximately 200 mm in the Asian interior. Annual precipitation provides a convenient metric of monsoon influence and we can subdivide the Asian continent into three distinct environmental regions accordingly: 1) a relatively wet and humid southeastern region with greater than 400 mm annual precipitation; 2) an interior arid northwest region with less than 200 mm annual precipitation; and 3) an intermediate semi-arid belt with 200–400 mm annual precipitation (Fig. 1.1). These three regions are the basic components of the *Asian monsoon-arid environment system* which will be discussed throughout this text.

The Asian monsoon is mainly composed of two meteorologically distinct, but overlapping, subsystems: the Indian (South Asian) monsoon and the East Asian monsoon (Fig. 1.2). The overall Asian monsoon region is characterized by its large area, strong intensity and distinct seasonality. During summer, the Asian monsoon brings heavy rainfall to Asia, while in winter it provides for relatively colder, drier climate.

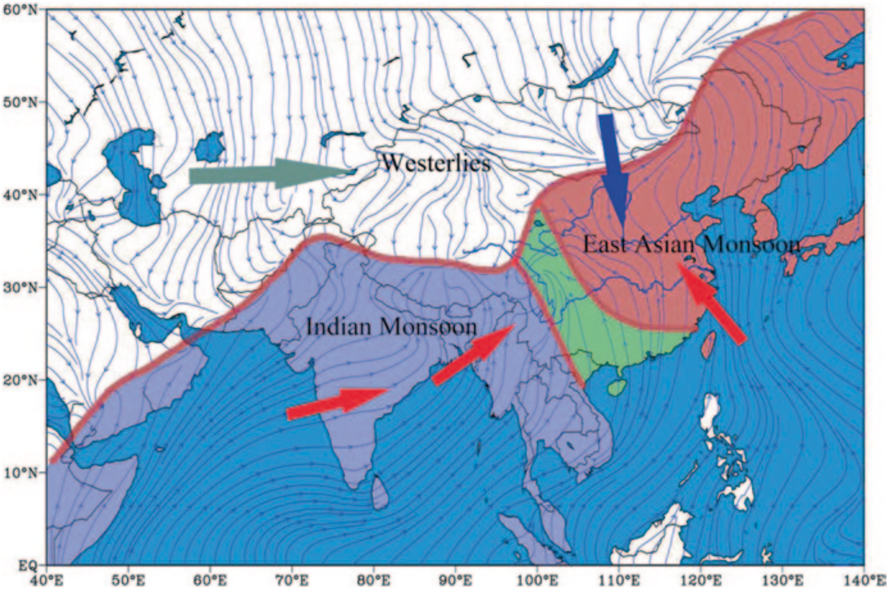

Fig. 1.2 A diagram illustrating the Asian summer monsoon, winter monsoon and westerlies. The *red line*, which is the same as the northern boundary of quasi-southern wind, 10 m above the surface (blue streamline) in July based on the ERA-40 dataset (Uppala et al. 2005), indicates the northern boundary of the monsoonal area. The *red*, *blue* and *grey* arrows indicate the frontal motions of the summer monsoon, winter monsoon and prevailing winds of the westerlies, respectively. The *light blue* and *red* regions are impacted by the Indian Monsoon and East Asian Monsoon, respectively, while the *light green* region is influenced variably by both the Indian Monsoon and East Asian Monsoon. The *left* and *right* limits of this transition region are suggested by Wang (2006) and Liao Ke et al. (1999), respectively

The Indian monsoon is a typical tropical monsoon system that is driven by the seasonal inter-hemispheric thermal contrast between the Asian continent and the Indian Ocean. The system is anchored by the Indian Low (Fig. 1.3a) and southwesterly winds dominate during the summer. The TP is the source of a latent heat anomaly within the mid-troposphere that drives the onset and development of the Indian monsoon (Yanai et al. 1992). The moisture carried by the Indian monsoon originates in the Indian Ocean. It produces copious rainfall every year which is distributed over southern Asia, southeastern Asia and southwestern China.

The East Asian monsoon is distinct from the Indian monsoon due to the very different orography bounding the two systems along their northern margins and because of zonal land-ocean configuration differences. The East Asian monsoon is a shallow system, primarily dominating the lower troposphere. It is regarded as one of the most important global climatic bridges between low and high latitudes and is the only subtropical/temperate monsoon on Earth. It delivers moisture from the tropical Pacific, which is the primary source of water vapor for northern China. Cross-equatorial air streams from Australia also contribute to the strength of the East Asian monsoon. Especially in winter, a Siberian-Mongolian high pressure cell

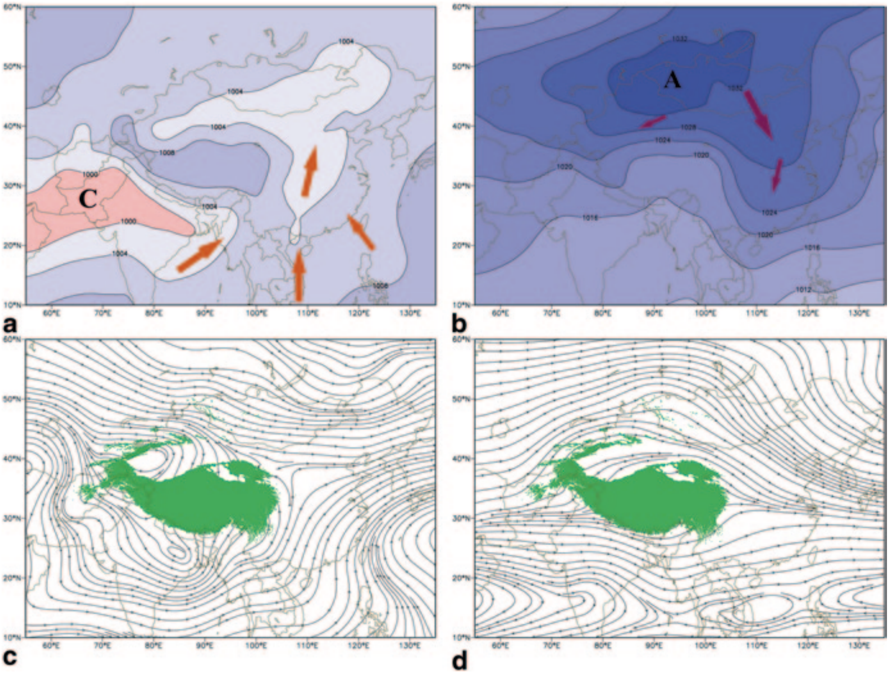

Fig. 1.3 Modern mean sea level pressure and 700 hPa flow fields in July (a, c) and January (b, d) from 1971 to 2000 based on NCEP/NCAR reanalysis (Kalnay et al. 1996). "C" in a and "A" in b indicate the center of the Indian Low and the center of the Siberian–Mongolian High. The *green* shaded areas in (c, d) indicate the TP where the elevation exceeds 3000 m

develops over the continent (Fig. 1.3b), facilitating the injection of cold air masses into Mongolia and China. The net result is the world's most intense winter monsoon.

The Asian interior is a vast arid region primarily due to the geographic barrier imposed by the TP. It is very difficult for moisture to reach this region and annual precipitation is generally less than 200 mm. The westerlies prevail for the whole year across the plateau, especially in the middle and high troposphere (Fig. 1.3c, d), providing a climatic teleconnection between the North Atlantic and Asia (Porter and An 1995). A northeasterly branch of the winter monsoon system can also impact arid areas through the lower atmosphere. Asian deserts are the main source regions for airborne dust in East Asia, and are among the three largest dust sources in the world. This dust is transported by the westerlies across the Asian continent and out to sea. Much of the dust ends up in the North Pacific Ocean, but it can travel as far as Greenland, as discussed in Chap. 4.

The phased growth of the elevated terrain of the TP has significantly intensified the Asian monsoon (An et al. 2001) as well as aridity inland (Manabe et al. 1990) since the Late Cenozoic. It also serves to divide the westerlies into two branches when they encounter the plateau, with each branch following the northern or southern margins (Fig. 1.3c, d). This contributes to enhanced divergence-driven subsidence downstream, and hence to the arid climate in the Asian interior (Manabe et al. 1990).

Under glacial conditions (e.g., the last glacial maximum, LGM), the monsoon-arid climate pattern over Asia changed. The impact of ice sheets in the Northern Hemisphere likely weakened the Asian monsoon during summer, while strengthening it during winter. As sea level decreased and the continental margin grew, the East Asian summer monsoon retreated southeastward, leaving less rainfall and more severe aridity in the interior. In winter, the intensified Siberian High increased the advection of cold air into lower-latitudes, resulting in colder temperatures in northern China (Jiang et al. 2010). The westerlies were also strengthened and shifted southward during the LGM.

1.2.2 Vegetation

Vegetation differences can be used to divide China into two regions along the line—Daxinganling-Lüliangshan-Liupanshan-eastern Tibetan Plateau, and roughly corresponding to the zonation defined by annual precipitation. The southeast region is dominated by monsoonal climate and features a variety of forest types. The northwest region is weakly affected by the summer monsoon and is comprised of dry grasslands and deserts.

In the southeastern region the vegetation zonal distribution changes significantly along a north-south temperature gradient, as reflected by forest types. From north to south, cold temperate coniferous forests give way to temperate broad-leaved forests, warm temperate deciduous broad-leaved forests, subtropical evergreen broad-leaved forests, tropical monsoon/rain forests and finally an equatorial rainforest belt. In northwest China, zonal vegetational divisions are less distinct, with only a north and south differentiation observed in the Xinjiang temperate desert region, bounded by the Tianshan. Here a temperate desert zone is found to the north and a warm temperate desert zone is found to the south.

In addition to zonal vegetation changes affected by the Asian monsoon in summer, longitudinal vegetation changes occur north of the Kunlunshan-Qinling-Huaihe line that separates temperate and warm temperate regions. From southeast to northwest, deciduous broad-leaved forests and mixed forests give way to grasslands (steppe meadow—steppe—desert steppe) and deserts (steppe desert – typical desert). In the southern subtropical and tropical forested areas, longitudinal vegetation differences are negligible. These are summarized in Fig. 1.4.

1.2.3 Hydrology

The Asian continent contains a large number of rivers and lakes, with some of the world's longest rivers, including the Yangtze, Yellow River, Lena River, and Mekong River; and large lakes like the Caspian Sea, Aral Sea, Lake Baikal, Lake

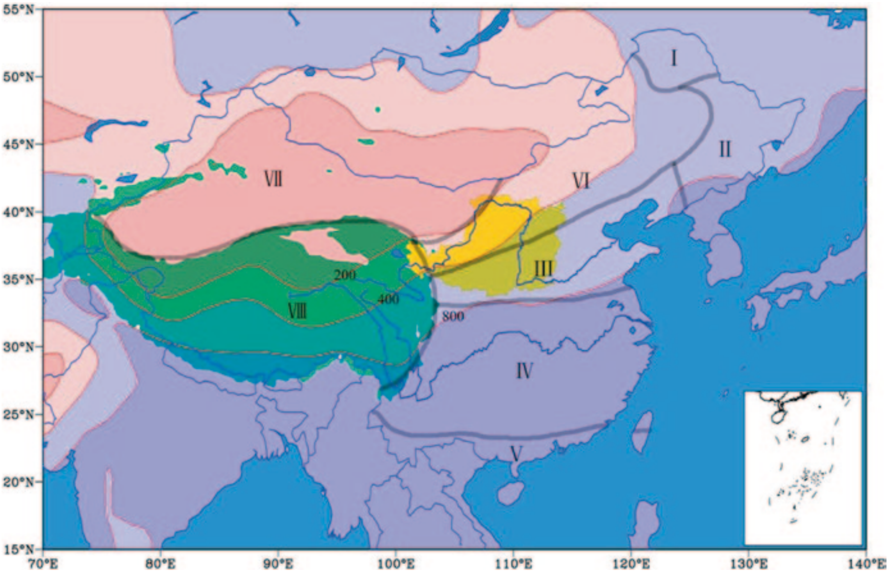

Fig. 1.4 Vegetation map of Asia. *Red thin lines* show 200, 400 and 800 mm isohyet precipitation contours. Arid areas fall within the 200 mm isohyet contours. Semi-arid areas are bounded by the 200–400 mm isohyet contours. The semi-humid zone lies within the 400–800 mm isohyet contours and the humid zone is bounded by the 800 mm isohyet contour. The *green* and *yellow* shaded areas are the Tibetan Plateau and Loess Plateau, respectively. Coarse gray lines indicate vegetation type zones. They are: I cold temperate coniferous forest; II temperate conifer/broad-leaved mixed forest zone; III warm temperate deciduous broad-leaved forest; IV subtropical evergreen broad-leaved forest; V tropical rain forest; VI temperate grassland; VII temperate desert zone; VIII Tibetan Plateau Alpine vegetation

Balkhash, and Lake Qinghai (Fig. 1.5). Most of the Asian rivers originate from high inland plateaus, and ultimately flow into the Pacific Ocean, Indian Ocean or Arctic Ocean. The distribution of these rivers is uneven, and closely related to tectonic features and climate. East Asia, Southeast Asia and South Asia have the largest river network because of abundant monsoon precipitation and large annual runoff, while central to western Asia has sparse rivers due to low precipitation and high evaporation. The Amur River, Yellow River, Yangtze River, Zhujiang River, Red River and Mekong River are mainly supplied by monsoon precipitation and flow into the Pacific Ocean. The Salween River, Irrawaddy River, Ganges River, Brahmaputra River and Indus River are tropical monsoonal rivers. They originate from the southern Tibetan Plateau and flow into the Indian Ocean. The Ob River, Yenisei River, and Lena River are supplied mainly by meltwater, and originate on the Mongolian Plateau and the north slope of the mountains in southern Siberia. These flow into the Arctic Ocean. Dry western Asia has few large rivers, with much of the runoff terminating in inland basins as playa lakes (endorheic systems). Runoff supplied by meltwater and rain is small, with the highest water levels in spring and lowest in summer.

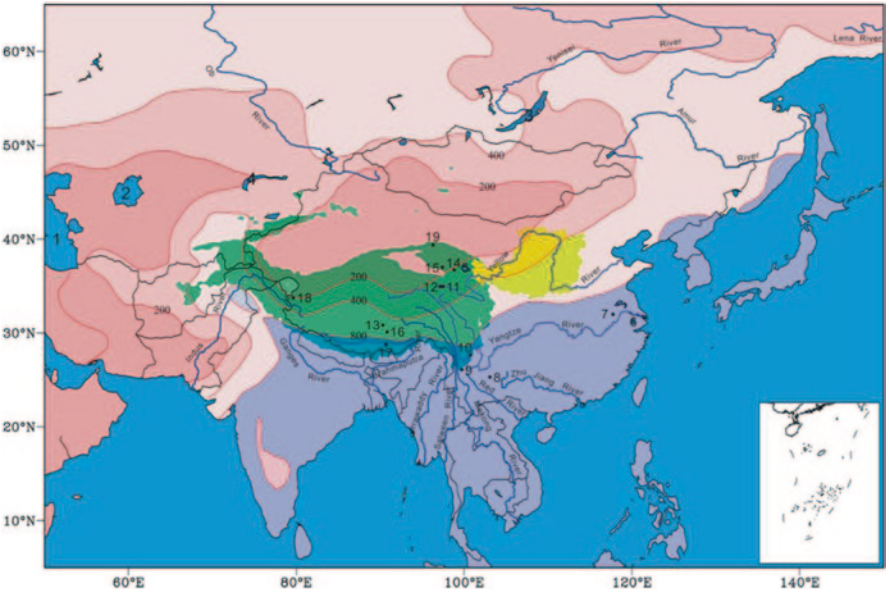

Fig. 1.5 Location of Asian rivers and lakes. Rivers are labeled on the map and lakes mentioned in the text are numbered. These include: 1) Caspian Sea, 2) Aral Sea, 3) Lake Baikal, 4) Lake Balkhash, 5) Lake Qinghai, 6) Lake Taihu, 7) Lake Chaohu, 8) Lake Dianchi, 9) Lake Erhai, 10) Lake Lugu, 11) Lake Eling, 12) Lake Gyaring, 13) Lake Selincuo, 14) Chaka salt Lake, 15) Qarhan salt Lake, 16) Lake Namtso, 17) Lake Yamdrok-tso, 18) Lake Pangong tso, 19) Lake Sugan

There are a large number of lakes widely distributed across China. The eastern plains feature freshwater lakes because of ample monsoon precipitation and relatively low evaporation. These lakes (e.g. Lake Taihu and Lake Chaohu) generally have low total dissolved solids (TDS) and high HCO_3 concentrations, and belong to the bicarbonate water type. Lakes in northeastern China have variable TDS, with freshwater, saltwater, and saline examples. The water types of these lakes are variably influenced by different bedrocks. On the Yunnan-Guizhou Plateau, monsoon precipitation is plentiful while evaporation is relatively weak. The TDS of lakes here are generally higher than those of eastern China because of stronger weathering in a karst environment. These lakes (e.g. Lake Dianchi, Lake Erhai and Lake Lugu) have relatively high HCO_3 concentrations and belong to the bicarbonate water type. On the Tibetan plateau, water sources of lakes are mainly supplied by the Indian summer monsoon on long time scales. Variable monsoon precipitation, evaporation, and melt water supply produce a wide range of TDS values within these lakes. For example, Lake Eling and Lake Gyaring are freshwater lakes, while Lake Selincuo and Lake Qinghai are saltwater lakes. In addition, there are a large number of saline lakes located in Qinghai Province (e.g. Chaka salt lake and Qarhan salt lake). These lakes belong to different water types, e.g. bicarbonate water (Lake Namtso, Lake Eling), sulfate type (Lake Selincuo, Lake Yamdrok-tso), and chloride type (Lake Qinghai, Lake Pangong Tso, Lake Sugan). Over the Xinjiang-Inner Mongolia

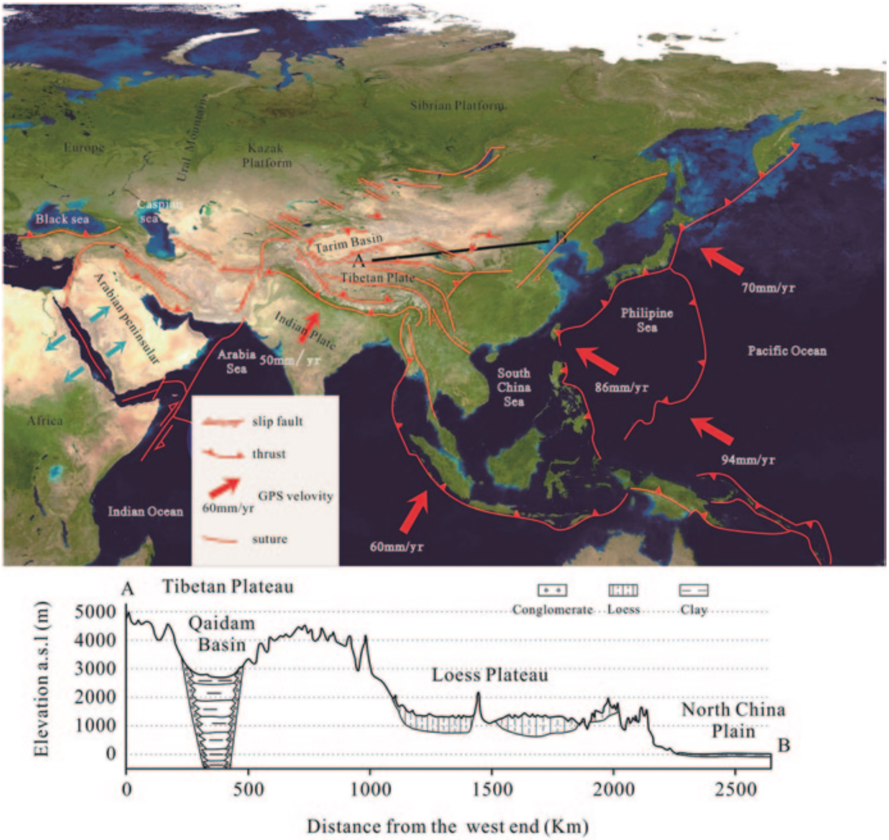

Fig. 1.6 *Upper panel* shows DEM map with simplified active tectonic map of Asia and surrounding regions. Main faults compiled from the literature. (Armijo et al. 1986, 1989; Avouac and Tapponnier 1993; Burchfield et al. 1995; Fu et al. 2004; Peltzer and Tapponnier 1988; Tapponnier and Molnar 1977; Tapponnier et al. 2001; Taylor and Yin 2009; Yin 2010). GPS data showing relative plate motions with respect to the Eurasian Plate. (Wang Q et al. 2001; Sella et al. 2002; Zhang et al. 2004; Allmendinger et al. 2007; Vergnolle et al. 2007). *Lower panel* is a profile from the Kunlun Mountains to the Bohai Gulf

region, because of strong evaporation and small precipitation, lakes generally have high TDS values, and saltwater and saline lakes are common. Water types of these lakes are also variable, and include bicarbonate, sulfate, and chloride types.

1.3 Geomorphology and tectonic background

Asia is the earth's largest continent occupying an area of 44,180,000 km^2. By virtue of its enormous size it contains many geomorphological extremes. A characteristic and dominant geomorphological feature in China is the stepped terrain that rises from east to west across the country, with three conspicuous geographic zones

(Fig. 1.6). The lowest zone is represented by coastal plains. The second zone is represented by Inner Mongolia and the Loess Plateau and the highest zone is the Tibetan Plateau.

There are many active faults in Asia, characterized by a full spectrum of styles and structural orientations over a vast region (Fig. 1.6) (Tapponnier and Molnar 1977; Armijo et al. 1986, 1989; Peltzer and Tapponnier 1988; Avouac and Tapponnier 1993; Burchfield et al. 1995; Tapponnier et al. 2001; Wang Q et al. 2001; Sella et al. 2002; Fu et al. 2004; Zhang et al. 2004; Allmendinger et al. 2007; Vergnolle et al. 2007; Taylor and Yin 2009; Yin 2010). Although Asia has had a long and complex geological history, its present morphology is largely the product of the youngest episode in its history. The collision between India and the Eurasian plate since the Eocene brought about drastic changes in the continent's evolution (Molnar and Tapponnier 1975; Besse et al. 1984; Patriat et al. 1984; Tapponnier et al. 2001; Rowley et al. 2006; Wang E et al. 2008). This magnificent event marks the beginning of the neotectonic period in Asia since the Cenozoic.

The large scale Cenozoic sutures around Asia mark the initiation of a new episode of the continent's neotectonic evolution. These can be divided into three major groups: 1) peri-Arabian, 2) Tibetan Plateau, and 3) peri-Australian. The Tibetan Plateau was the first major piece of the former Gondwanaland to collide with Asia. The collision apparently occurred diachronously from west to east during the Eocene, as a consequence of which the subcontinent rotated in a counterclockwise direction. The most dramatic effect of this collision was the formation of the Tibetan Plateau, which is the largest concentration of continental material on Earth. This event was characterized by significant lithospheric thickening accompanied by the expulsion, east- and southeastwards, of vast regions of Asia along enormous intracontinental strike-slip faults. The high seismicity associated with these mammoth structures attests to their current activity. Various lines of indirect evidence suggest an offset on the order of hundreds of kilometers for both the Altyn Tagh and Red River faults since the beginning of Cenozoic (Leloup et al. 2001; Yin et al. 2002; Yin 2010).

The gross outlines of Asia's landform are the product of neotectonic evolution, where active tectonics dominate. Second-order features in the young collisional mountain ranges and highlands of central Asia are shaped by climate. The high ranges that flank the periphery of the continent are the products of Cenozoic continental collisions, as is the highland region of central Asia. The lowland in north Asia (Siberia) lies in a region that has been essentially stable throughout the Cenozoic (Van der Voo et al. 1999).

A conspicuous aspect of Asia's Quaternary geology is the relatively restricted area affected by Pleistocene glaciation, as compared with Europe and North America. This is likely a function of Asia's enormous continental area and the aridity of the northern interior regions. During the Pleistocene, most of the Asian ice cover formed in western Siberia, where the ice sheet was confluent with northern European ice across the Urals. Elsewhere in Asia glaciers were confined to high mountains. The southernmost Quaternary glaciers in Asia were found in the Himalaya, and in the Sanjiang area of China.

1.4 Historical Perspective of Environmental Change Research

Extensive studies have been carried out over the last half-century on the monsoon-arid regions in Asia, starting with studies of the Quaternary. In the 1980s, Liu Tung-sheng (Liu et al. 1985), An Zhisheng and Lu Yanchou (An and Lu 1984) were among the first to rigorously correlate Chinese loess-paleosol sequences to marine sediment records. Later, An et al. (1990, 1991a) established a paleoclimatic link between loess-paleosol records and marine records using a multi-proxy approach that led to a paleomonsoon theory which regards East Asian environmental changes as the result of monsoon variations during the past 2.6 Ma. Since the beginning of the 21st century, Chinese scholars have further extended their research to include paleoenvironments from throughout the monsoon-arid regions. These studies form the basis for an understanding of regional environmental change and the focus has now shifted to the dynamics of Asian environmental change within a larger temporal and spatial context. Rapid development and wide application of new high-resolution dating technologies during the last 20 years have contributed to more reliable time series records. Improvements to semi-quantitative and quantitative climate proxy analyses have significantly enhanced the resolution and precision of paleoenvironmental reconstructions. These improvements have brought us to the current state of understanding of the mechanisms that control changes across the Asian monsoon-arid environmental gradient.

1.4.1 Climatic Implications of Loess-paleosol Sequences and Glacial-interglacial Cycles

Large continental ice sheets in the Northern Hemisphere have grown and retreated many times in the past. Glacial periods are colder, dustier and generally drier than interglacial periods and these differences are preserved in a variety of geologic archives. Glacial-interglacial cycles are apparent in many marine and terrestrial sediments from middle to high latitude regions, characteristic of Quaternary climate. As early as the 10th century (North Song Dynasty in China), Shen Kuo formulated the notion of cold-warm climate change that experienced geographic shifts with time, based upon paleontological evidence, such as fossil shells and petrified bamboo.

In 1840, Agassiz was the first to propose that there were glacial periods in Earth's climatic history. In 1909, A. Penck and E. Brückner published *Die Alpen im Eiszeitalter*, which divided glacial periods into four stages: *Donau*, *Gunz*, *Mindel Riss* and *Würm*. Relatively warm periods in-between were recognized as interglacials. Afterwards, corresponding glacials were located in North Europe, North America and Asia. Besides the Donau glacial period, the sequential Nebraska, Kansas, Illinios, and Wisconsin Glacial stages were recognized in North America. In the

1930–1940s, Lee recognized that the Poyang, Dagu, Lushan and Dali glacial events corresponded to the glacial sequence in the Alps (Lee et al. 1947), a conclusion which is still questioned by many scholars (Shi et al. 1989).

In the 1950s, Emiliani seized an opportunity to use oxygen isotope analyses of carbonates from the Caribbean Ocean as a means to study paleoclimate in Quaternary deposits. His work laid the groundwork for the study of sediment core Vema 28–238, from the Pacific Ocean. That record yielded excellent oxygen isotope and magnetic time series records for the past 870,000 years and provided a global chronological framework for future studies of climate change (Shackleton and Opdyke 1973). The boundaries of 22 marine isotope stages (MIS) representing alternating periods of high and low Northern Hemisphere ice volume were recognized and dated. The next step was to correlate these with continental loess records (Kukla 1977).

Loess-paleosol and red clay sequences widely distributed on the LP, are now well-known for their rich store of high resolution paleoenvironmental information. Chinese scholars have undertaken their exploration since the 1970s, initially by comparison with corresponding deep sea sediment records. This constituted a big step from the classic 4-stage glacial-interglacial framework, to a detailed multi-cyclic climate framework. It was learned that loess formed during cold dry glacial periods, while plaeosols formed during warm, wet interglacial periods. A correlation between marine sediments and alternating loess-paleosol layers was pioneered by Lu and An (Lu and An 1979). Rigorous comparisons between marine sediments and loess-paleosol sequences from the LP were made by An and Lu (1984), and Sasajima and Wang (1984), and compiled in the book *Loess and Environment* (Liu et al. 1985). A magnetostratigraphic record from the last 2.5 Ma was established through paleomagnetism studies from loess cored at Luochuan (Heller and Liu 1982). Afterwards, a good correlation was found between Chinese loess-paleosol sequences and global glacial cycles, recorded by $\delta^{18}O$ records from deep sea sediments. More detailed correlations were made by Kukla (Kukla and Cilek 1996), Rutter (Rutter et al. 1991) and Ding (Ding et al. 1998). Ding contributed a detailed correlation of loess and marine records in the early Pleistocene, especially from 1.1 ~ 2.6 Ma. The proposed theory of glacial-interglacial cycles preserved in loess marked a new stage of Chinese loess study, integrated with global environmental research (Liu et al. 1985). Continental loess-paleosol sequences have since become one of the three pillars that comprise the foundation of global climate change research, along with marine sediments and ice cores.

1.4.2 History and Variability of Paleomonsoon Activity and its Connection to Global Change

Chinese geologists have found that paleomonsoon variations are closely related to environmental evolution on geologic time scales. In the 1980s, many scholars noted the importance of paleomonsoons and their distinct influence on loess accumulation (Yang et al. 1985; Li et al. 1988). In the early 1990s, An et al. (1990, 1991b) proposed that loess accumulated as dust, transported by the northerly winter monsoon, and interbedded paleosols derived their moisture from the southerly summer monsoon. This conclusion was based on a systematic analysis of bio-geological evidence, including: loess-paleosol sequences, desert advances and retreats, lake level changes, mammal faunal migrations, SST changes in the South China Sea, and tree line and snow line changes. This finding laid the groundwork for the study of loess-paleosol sequences as archives of East Asian monsoon variations over the past 2.5 Ma, through the analysis of the alternating dominance of winter and summer paleomonsoons.

The next step in our understanding of Asian monsoon history came with loess studies that covered the past 20 and 130 ka. The improved resolution of these time series allowed for increased scrutiny with regard to the variability and behaviour of monsoon climate on different time scales. This led to the formulation of the Asian monsoon control hypothesis (An et al. 1990, 1991 a, b), that interprets environmental changes in East Asia as a consequence of adjustments of lower boundary conditions, including land-sea distribution, SST changes in the South China Sea, ice volume changes, and insolation effects. This theory provided a framework for further research on the Asian paleomonsoon and its connections to past global change (Porter and An 1995; Ding et al. 1995; An and Porter 1997).

Asian climate experienced continuous change in both time and frequency domains since the onset of the Asian monsoon (An 2000; An et al. 2006; Sun and Wang 2005; Ding et al. 1995; Guo et al. 2002; Qiang et al. 2011). These changes have been studied by placing emphasis on high resolution paleomonsoon records from the last glacial-deglacial cycle, the Holocene and especially the last 2 ka. This includes records from loess (An et al. 1990), lacustrine sediments (Zhou et al. 1996), marine sediments (Wang and Wang 1989) tree rings (Liu et al. 2006), ice cores (Yao et al. 1996; Thompson et al. 2000), speleothems (Wang Y et al. 2001; Yuan et al. 2004; Cheng et al. 2009; Cai et al. 2010; Tan et al. 2009) and historical documents (Wang and Gong 2000; Zhang and Lu 2007). East Asian monsoon climate variability, instability, periodicity, asynchroneity and the possible mechanisms underlying these variations have been explored (An et al. 2000). Fast flickering and abrupt events at millennial time scales are superimposed on the orbital winter and summer monsoon changes during the last glacial cycle. These varied in amplitude and spatial distribution, indicating relatively large variability and instability in the East Asian monsoon, and they correspond to modern day frequent cold air mass movements and distinct precipitation variability. Monsoon events are also affected by the interaction of climatic events between high and low latitudes that may have feedbacks on the monsoon at millennial time scales (Zhou et al. 2001). The influence of the Northern Atlantic meridional overturning circulation on the East Asian monsoon on millennial time scales has also been suggested (Sun et al. 2012). Cross equatorial currents from the Southern Hemisphere also impact the Asian monsoon at glacial/interglacial and millennial time scales (An et al. 2011; An 2000; Cai et al. 2006). This occurs through a pressure push and thermal pull induced by the cross equatorial pressure gradient (Tomas and Webster, 1997; An 2000; Webster and Fassulo 2003; An et al. 2011).

The relationship between East Asian monsoonal changes and the Tibetan Plateau uplift/growth have been studied extensively. A simultaneous increase in winter and summer monsoons, intensified aridification of the Asian interior, and the enhanced global ice volume may be indicative of plateau growth from 3.6–2.6 Ma (An et al. 2001). It has also been shown that monsoon variations are linked to dust accumulation and Northern Hemisphere glaciation, a conclusion that is supported by geological evidence and climate model simulations.

1.4.3 The Concept of the Asian Monsoon-arid zone as an Integrated Environmental System and its global Significance

The Asian continent is a key component of the global climate system. Climate on the continent is influenced by both the Asian monsoon and the westerlies. The interaction of cold continental high latitude air masses with warm, moist marine air masses occurs on a large scale, and as such, significant feedbacks exist in land-sea-atmosphere interactions in Asia and global climate. These have operated in tandem to produce environmental changes on the Asian continent since the Late Cenozoic.

An et al. (1991a) established the loess flux curve which is a function of aridity in the Asian interior over the past 130 ka. Later Sun and An (2002) reconstructed the aridity history of inland Asia for the last 7 Ma years. A recent study from Qinghai Lake shows that the content of >25 μm eolian dust component may reflect variations in the westerlies through time. An anti-phase relationship between the westerlies and the summer monsoon has also been identified on glacial-interglacial and glacial millennial time scales (An et al. 2012).

The existence of the Tibetan Plateau enhances Asian monsoon circulation and also obstructs the inland transport of warm moist air from the Indian Ocean (Ruddiman et al. 1989, Kutzbach et al. 1993). Descending air flow along the northern flank of the TP affects aridification in the Asian interior (Ye and Qian 1974; RGES 1978; Manabe et al. 1974; Liu et al. 2001) and so induces environmental changes. The coupling between the phased growth of the Tibetan Plateau and paleoclimate in the monsoon-arid system since the Miocene has been demonstrated within a global context, and it is responsible for changes in the paleomonsoon (An et al. 2006). This is especially evident in the northeastern expansion of the Tibetan Plateau, which has led to a simultaneous intensification of the East Asian monsoon and increased aridity in the Asian interior. Asian dust has also been shown to impact global climate (An et al. 2001; Shi et al. 2011). Iron-bearing dust that is deposited in the North Pacific Ocean increases ocean productivity which consumes atmospheric CO_2 (Jickells et al. 2005).

1.5 Scientific Significance and Major Questions of Asian Monsoon-arid Zones

1.5.1 Major Scientific Questions and Significance on a Tectonic Time Scale

The process, governing law and dynamics of climate change on a tectonic time scale refers to a period of more than 10^5 years. Marine studies show that during the Cenozoic the Earth has experienced both relatively cold and warm extremes (Zachos et al. 2001). Tectonic movements, Northern and Southern Hemisphere ice volumes and atmospheric CO_2 concentration changes are considered to be major factors that drive climate change on a tectonic time scale. Mountain and plateau growth, and the opening and closure of oceanic straits in particular, alter the land-sea configuration, and coupling of the atmosphere and ocean, leading to regional and global climate change (Broccoli and Manabe 1990; Ramstein et al. 1997). As an important component of lower boundary conditions, global ice volume changes exert a significant effect on polar-equatorial energy transfer, and so alter the global climate system (Zachos et al. 2001). As it is clear from the work described above, geologic records from the Asian monsoon-arid zone are ideal candidates for understanding long term climatic and environmental change, at least since the Oligocene. In order to explore the dynamic mechanisms of climate change on tectonic time scales in the Asian monsoon-arid zone, the following scientific questions should be addressed:

1. When and why did the Asian monsoon climate and inland aridification start?
2. What stages has the Asian monsoon-arid zone gone through and what were the dynamic drivers controlling climate?
3. How have the uplift and growth of the Tibetan Plateau, change in global ice volume, and CO_2 concentration changes affected the paleomonsoon and westerlies?
4. How did the retreat of the Tethys and subsequent land-sea redistribution affect the Asian monsoon-arid environment?

1.5.2 Major Scientific Questions and Significance on Orbital and Millennial Time scales

Orbital-scale monsoon-arid environmental changes are driven primarily by orbitally-induced changes in solar irradiation (An et al. 1991b; Wang Y et al. 2008), and are strongly modulated by changing lower boundary conditions (i.e. ice volume) (An et al. 1991b; Ding et al. 1995; Liu et al. 1999). Loess-based proxies (e.g. magnetic susceptibility and grain size) display distinct glacial-interglacial variations that are similar to marine benthic $\delta^{18}O$ records (a proxy for global ice volume) (An et al. 1991a,b; Ding et al. 1995; Bloemendal et al. 1995; Liu et al. 1999; Ding et al. 2002), suggesting a strong coupling between Northern Hemisphere ice volume and East Asian monsoon variability (Liu and Ding 1993; Ding et al. 1995). By contrast, high-resolution, absolutely-dated speleothem $\delta^{18}O$ records with a dominant precessional period are nearly in-phase, in response to Northern Hemisphere summer insolation (Wang Y et al. 2008). To fully understand the dynamics driving orbital-scale East Asian monsoon variability, the following scientific questions should be further investigated:

1. Why do the dominant periods differ between Chinese loess and speleothems?
2. What are the climatic implications of different phases for monsoon proxies at the obliquity and precession bands?
3. How can we evaluate the relative roles of external (solar radiation) and internal (i.e. ice volume and greenhouse gas) factors that may influence the orbital-scale monsoon variability?

In recent years we have seen the expansion of spatial coverage and temporal resolution of paleoclimate records from China's interior. Since environmental changes in the Asian interior are influenced by the westerlies, winter monsoon, and high-latitude climate (An et al. 2011), these should be distinctly different from those of the monsoon-affected areas. By studying the whole of the Asian arid-monsoon system we can now explore the following:

1. How did the westerlies, Asian summer monsoon and winter monsoon interact at millennial timescales?
2. How do the monsoon-arid environmental systems respond to high-latitude climate change?

   Since orbital-scale changes in the Indian monsoon differ from the East Asian monsoon in terms of frequency and phase (Clemens and Prell 2003; we may also ask:
3. How do the Asian monsoon systems interact with the Southern Hemisphere climate system, especially with regard to latent heat transport, and along cross-equatorial pressure gradients?
4. What is the different influence of changing lower boundary conditions (i.e. Northern Hemisphere ice sheets, SSTs and Antarctic temperatures) on the East Asian and Indian monsoon circulations?

An integral set of orbital-scale paleo-proxy records from both regions could greatly enhance our understanding of the dynamical mechanisms involved in these two monsoon systems.

1.5.3 Forcing of Abrupt Events: Ocean Circulation, Solar Activities, Sea Ice, Ocean-atmosphere Interactions (super ENSO), and the Interaction Between High and Low Latitude Climates

Abrupt events on millennial or centennial time scales are more immediate concerns for the well-being of the human race as compared to relatively long-term changes on tectonic and orbital time scales. Greenland ice cores preserve a detailed record