From Quaternary Science to Earth System Science

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Abstract: This article details how AN Zhisheng and his colleagues, through decades of dedicated research, began with the study of loess in China and integrated it with climatic and environmental researches. AN and his team developed a novel research approach to identifying the dynamics of changes of natural environments, including loess environment in East Asia. Their work has not only highlighted the global significance of Chinese loess as a record for global climate change, but also led to the formulation of the monsoon control theory regarding environmental changes in East Asia, as well as insights into Asian and global monsoon dynamics. The paradigm shift from a singular discipline of Quaternary science into a comprehensive Earth system science has happened. Their contributions have been instrumental in promoting sustainable development of the society in the Chinese Loess Plateau and western China.

Keywords: Loess and global change, Quaternary science, Earth system science and Sustainable development

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On the occasion of the Chinese Academy of Sciences (CAS) approaching its 75th anniversary, I have been invited by the *Bulletin of the Chinese Academy of Sciences* to contribute an article on global change and sustainable development. With great pleasure, I'd like to share my perspective on how Chinese scientists have progressed from Quaternary science to Earth system science through decades of research and achievements.

My journey in Quaternary science began in 1962 under the mentorship of Prof. LIU Dongsheng (also known as Tungsheng Liu, 1917–2008, a CAS Member). It was through him that I first encountered the complexities of some of the most striking phenomena on Earth. Soon came the Cultural Revolution (1966–1976), yet even in such adversity, we found ways to extend the scope of China's Quaternary chronol-

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1. AN Zhisheng, Professor of the Institute of Earth Environment, Chinese Academy of Sciences (CAS), Member of CAS, Member of the World Academy of Sciences for the advancement of science in developing countries, International Member of the U.S. National Academy of Sciences, Fellow of the American Geophysical Union (AGU). His research interests focus on Quaternary science and Earth system science. He has won the National Natural Scientific Awards of China for six times, and received the 2023 AGU Roger Revelle Medal for his exceptional contributions to understanding the global significance of Chinese loess, fundamental monsoon dynamics, and global climate changes, and providing key international leadership.

ogy. After the Cultural Revolution, with Prof. LIU's continued guidance, I was able to combine loess studies with environmental research—A step that later helped establish China's loess deposits as a vital record of global climate change. As I continued my research, the physical significance of the loess deposition inspired me to propose the monsoon control theory of environmental change in its region.

With the rise of global change and Earth system science on the international stage, I worked to integrate Quaternary studies into Earth System Sciences, where it began to play a more important role in guiding sustainable development and managing our planet's future.

Quaternary Science

In the 1950s and 1960s, Prof. LIU initiated Quaternary science research in China, with a focus on the study of Chinese loess. He organized field expeditions for soil and water conservation in the middle reaches of the Yellow River, as well as large-scale geological and geomorphological profile surveys of the Chinese Loess Plateau. These efforts culminated in the publication of several seminal works by Science Press, including "*Quaternary Geological Survey Report of the Middle Reaches of the Yellow River*", "*Loess in the Middle Reaches of the Yellow River*", "*Loess Accumulation in China*" (Fig. 1), and "*Material Composition and Structure of Loess*". In these works, Prof. LIU presented compelling evidence supporting the aeolian origin of Chinese loess, and he classified the Chinese loess into three major groups: the Early Pleistocene Wucheng Loess, the Middle Pleistocene Lishi Loess, and the Late Pleistocene Malan Loess. His research on the loess-paleosol sequences laid a solid foundation for loess studies and the Quaternary geology in China.

The Quaternary period, spanning the last 2.6 million years, is a key bridge between the past and the present, and Quaternary science is an interdisciplinary field that integrates a wide array of disciplines, including human origins, the development of civilizations, climate and environmental changes, biological migration, and geological processes. Under Prof. LIU's guidance, I studied "Glacial Geology and The Pleistocene Epoch" (1947) by Prof. Flint of Yale University. Prof. LIU also arranged for me to intern at the geochemistry, sedimentology, and pollen laboratories at the CAS Institute of Geology, as well as the archaeology and mammalian fossil laboratories at the CAS Institute of Vertebrate Paleontology and Paleoanthropology.

My early fieldwork included expeditions to the Loess Plateau to study loess deposits, as well as research on the alkaline lake at Chagan Nur in Inner Mongolia. These experiences sharpened my practical skills and reinforced my

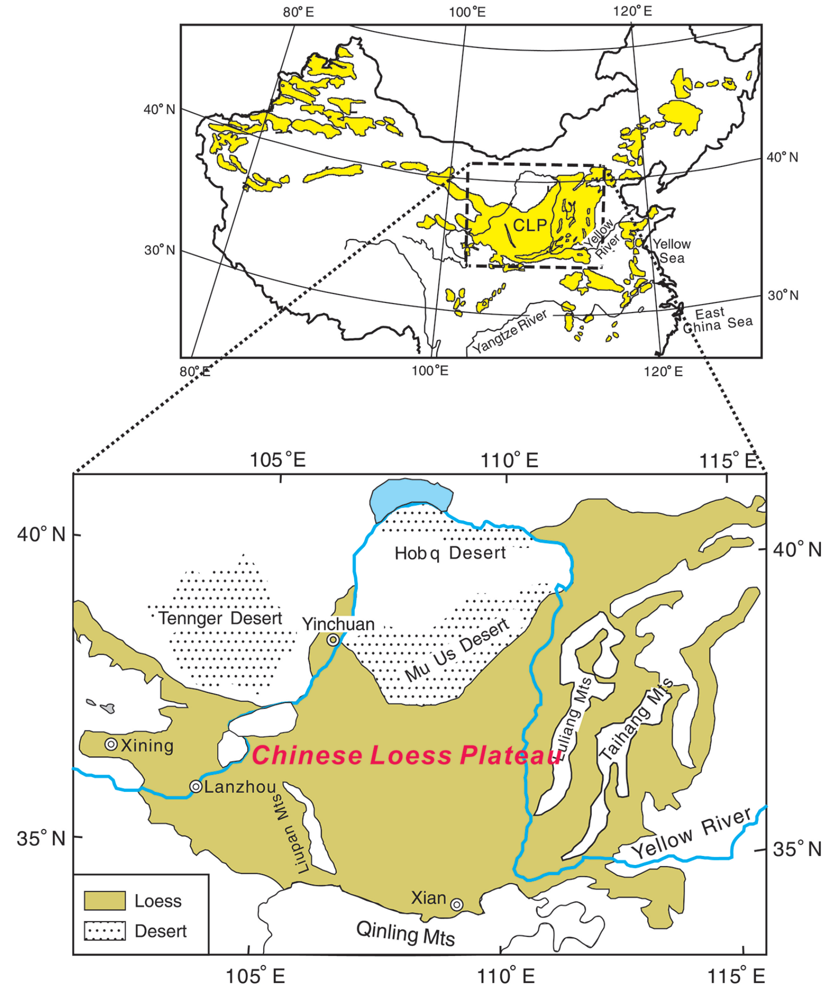


Fig. 1. Geographical distribution of Chinese loess (upper panel) and the Loess Plateau (lower panel). The distribution area of Chinese loess is about 640,000 square kilometers. The Loess Plateau in the middle reaches of the Yellow River covers an area of about 440,000 square kilometers and is deeply affected by the monsoon climate.

Graphic: Modified from Liu *et al.* (1985)

understanding of climate and environmental changes in the broader context of the Quaternary.

Extending Chinese Quaternary Chronology

After 1966, I relocated with Prof. LIU to the CAS Institute of Geochemistry in Guiyang, where we continued our research. During the difficult period of the Cultural Revolution, I took every opportunity to study foreign literature, gradually realizing the importance of accurate chronological dating to Quaternary science. In 1975, I translated Cox's *Magnetic Stratigraphic Chronology* (An, 1975), introducing magnetostratigraphy to Earth sciences in China. With the support of Prof. TU Guangchi (1920–2007, a CAS Member), I worked with LI Huamei and others at the CAS Institute of Geochemistry to establish a paleomagnetic laboratory, where we conducted preliminary magnetostratigraphy dating of the Luochuan loess (An *et al.*, 1977).

In 1979, I worked with WANG Naiwen and others to study the Beijing S-5 core, applying both magnetostratigraphy and planktonic foraminifera analysis. We were the first to propose that the base of the Matuyama Chron, dated 2.4 million years ago, could serve as the lower boundary of the Quaternary (An *et al.*, 1979). This conclusion was formally presented in English at the International Geological Congress in Moscow in 1984. We also determined the age of the Lantian *Homo erectus* fossils in Xi'an to be approximately 1.15 million years old (An and Ho, 1989).

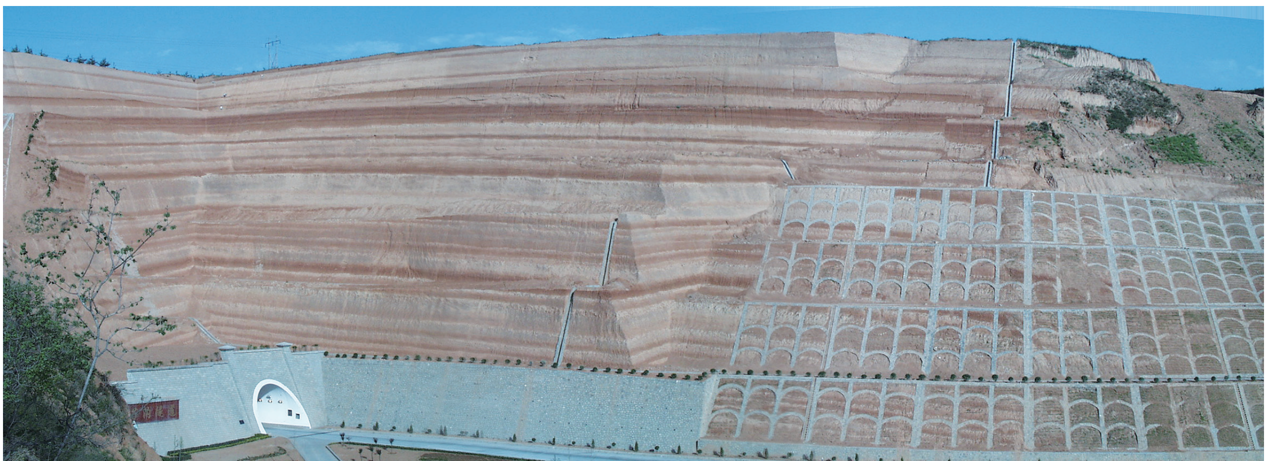
In early 1980, I conducted drilling in Heimugou of Luochuan and provided a complete stratigraphic profile of the Luochuan loess borehole, as well as prepared standard samples for paleomagnetic measurements, which Prof. LIU Dongsheng and Prof. Heller later did paleomagnetic measurement in Switzerland. These data revealed that Chinese loess began to accumulate 2.4 million years ago (Heller and Liu, 1982). Following this, my work of magnetic dating of Beihanzhai, another loess section in Luochuan confirmed this finding, contributing to the advancement of Chinese loess and Quaternary geology studies in China (Liu *et al.*, 1985).

In addition, in 1979, together with Prof. LU Yanchou, we proposed the concept and naming system of the Chinese loess-paleosol sequence in the *Science Bulletin* (Lu and An, 1979) (Fig. 2). This framework provided the precondition for the correct comparison between the loess-paleosol sequence and the climatic record of deep-sea sediments.

Loess and Environment

In the summer of 1982, after I returned from the Australian National University, Prof. LIU tasked me with assisting him in organizing the preparation of

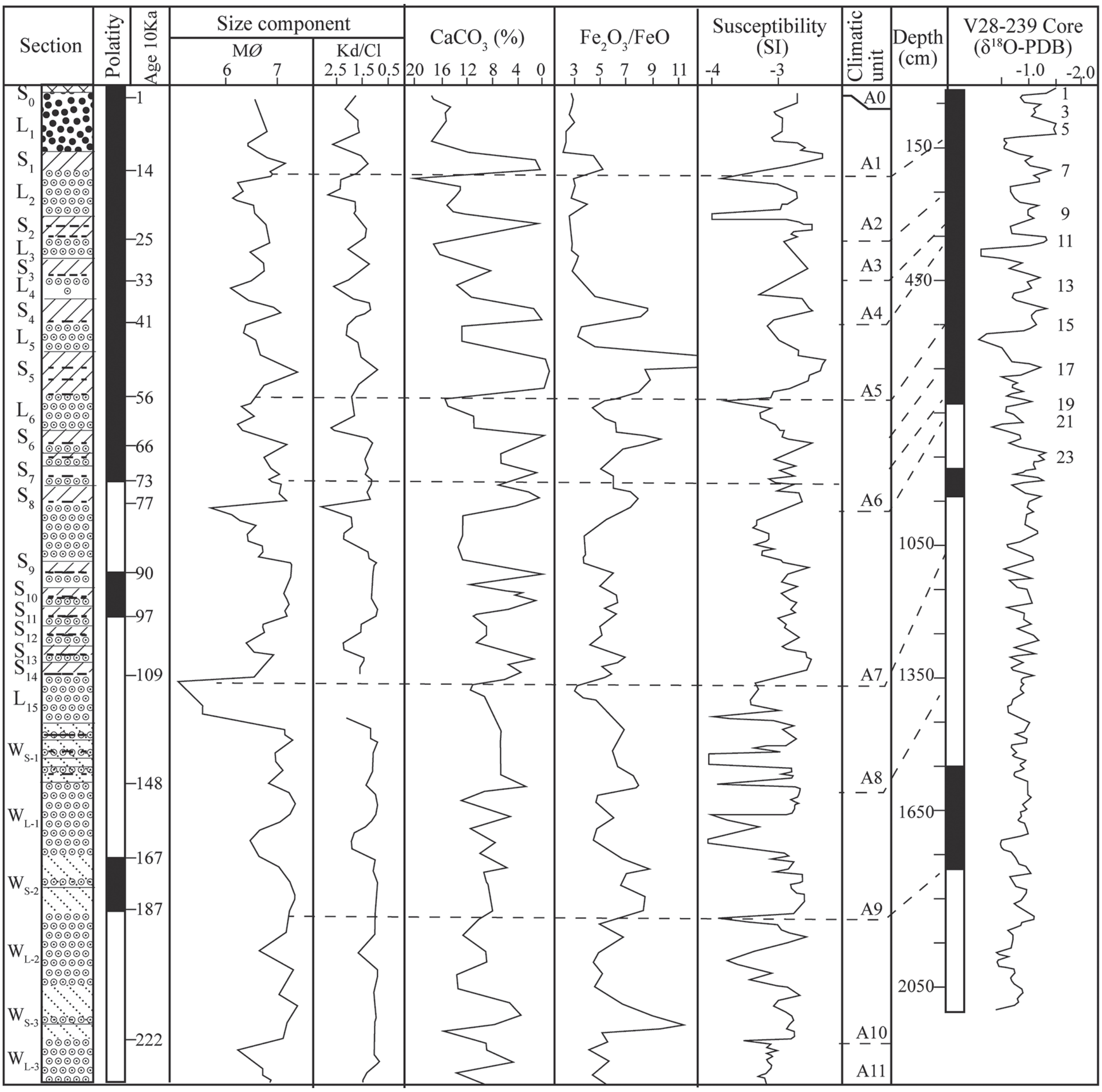
Fig. 2. The Outcrop of a well-known Chinese loess-paleosol sequence of the last 1.34 Ma with a thickness of ~85 m was exposed by Louzigou Tunnel highway construction in Tongchuan, a city near Xi'an, China. Brown-reddish and yellow-greyish layers in the photo show buried paleosols and eolian loess, respectively. The interbedded loess/paleosol layers indicate the alternating dominance of the East Asian winter and summer monsoons.



Graphic: LI Li

the book *Loess and the Environment*. The book, which was published in 1985 by Science Press (Chinese version) and by Ocean Press (English version), attracted considerable attention from colleagues both domestically and internationally. In 1989, its English edition, *Loess in China* was reissued by the German publisher Springer-Verlag in collaboration with China's Ocean Press. While in 1984, LU Yanchou and I had already successfully compared the last 160,000 years of the Chinese loess-paleosol sequence with the $\delta^{18}O$ record from deep-sea sediments (An and Lu, 1984), the more substantial achievement was presented in *Loess and the Environment,* where I assisted Prof. LIU in correctly correlating the last 2.6 million years of Chinese loess with the climatic record from deep-sea sediments (Fig. 3). Therein, we proposed that the Chinese loess-paleosol sequence documented multiple glacial and interglacial cycles, clarifying the relationship between loess and global climate change. The key step is that I found that the fifth complex paleosol (S5) corresponds with marine isotope stages 13, 14, and 15, which solves the most difficult problem in the

Fig. 3. Comparison of loess-paleosol sequence with climatic record of deep sea sediments.

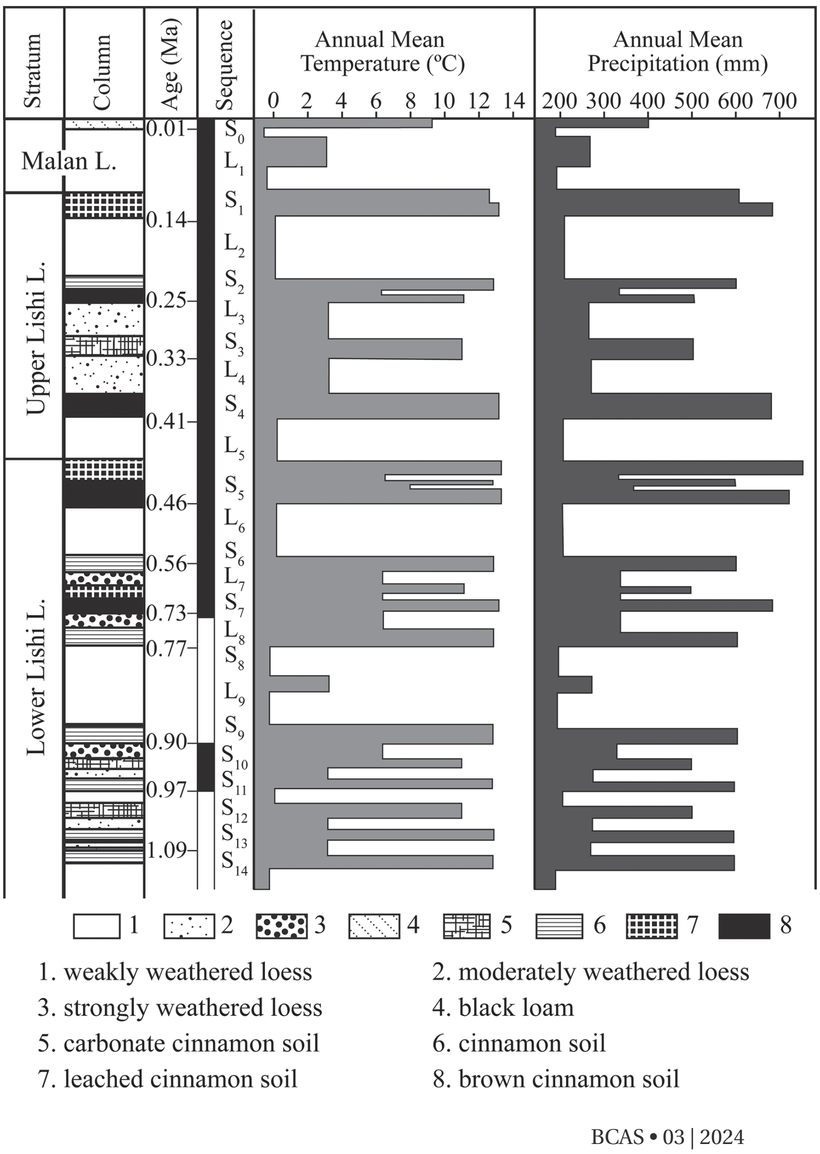


Graphic: Liu *et al.* (1985)

correlation. Chinese loess, deep-sea sediments, and polar ice cores became the three pillars for global climate change studies.

Loess and the Environment also defined the concept of loess and provided a brief history of its study, outlining the spatial and temporal distribution of Chinese loess alongside its relationship with climate and environmental changes. In Chapter 5, I presented the first quantitative curve, indicating temperature and precipitation changes over the past 1.1 million years on the Chinese Loess Plateau (Fig. 4). Furthermore, the book discussed the connections between loess and agricultural production, endemic diseases, engineering geology, as well as soil erosion and conservation, emphasizing the environmental and practical implications of loess research. This book has been widely recognized as a classic in the field of Chinese loess studies, receiving extensive acclaim from Quaternary scientists both domestically and internationally, and it has established a solid foundation for further research on Chinese loess and Quaternary environmental changes.

Fig. 4. The quantitative curve of temperature and precipitation changes in Luochuan over the past 1.1 million years.



Graphic: Liu *et al.* (1985)

Monsoon Control Theory of Environmental Change

In the late 1980s, I and my colleagues compared Chinese aeolian loess with periglacial loess from Europe and North America. We found that Chinese loess is primarily distributed within the East Asian monsoon region. By correlating the spatiotemporal distribution of loess-paleosol sequences on the Loess Plateau with modern climatic parameters, I developed a proxy index system for the East Asian winter and summer monsoons, represented by loess grain size and magnetic susceptibility respectively (An *et al.*, 1990; 1991). This work demonstrated that the Chinese loess-paleosol sequence over the past 2.6 million years recorded alternating periods dominated by warm, humid summer monsoons and cold, dry winter monsoons, highlighting the periodicity (An, 2000), instability (Porter and An, 1995), and asynchrony (An *et al.*, 2000) of Asian monsoon changes.

I proposed that changes in the East Asian paleomonsoon reflect interactions between the global atmosphere, ocean, land and ice systems, and are also an expression of their combined effect within the boundary conditions imposed by the East Asian continent under solar radiation. This led to the formulation of the Monsoon Control Theory of Environmental Change (An *et al.*, 1990; 1991) (Fig. 5). This theory broke through the classic global glacial-interglacial theory, solved long-standing mysteries, including the presence of enormous thickness of widely distributed Chinese loess, the advance and retreat of deserts, the fluctuations of lake levels, elevation changes of the forest and snow lines, the migration of bio-climatic zones, and sea surface temperature changes in the South China Sea.

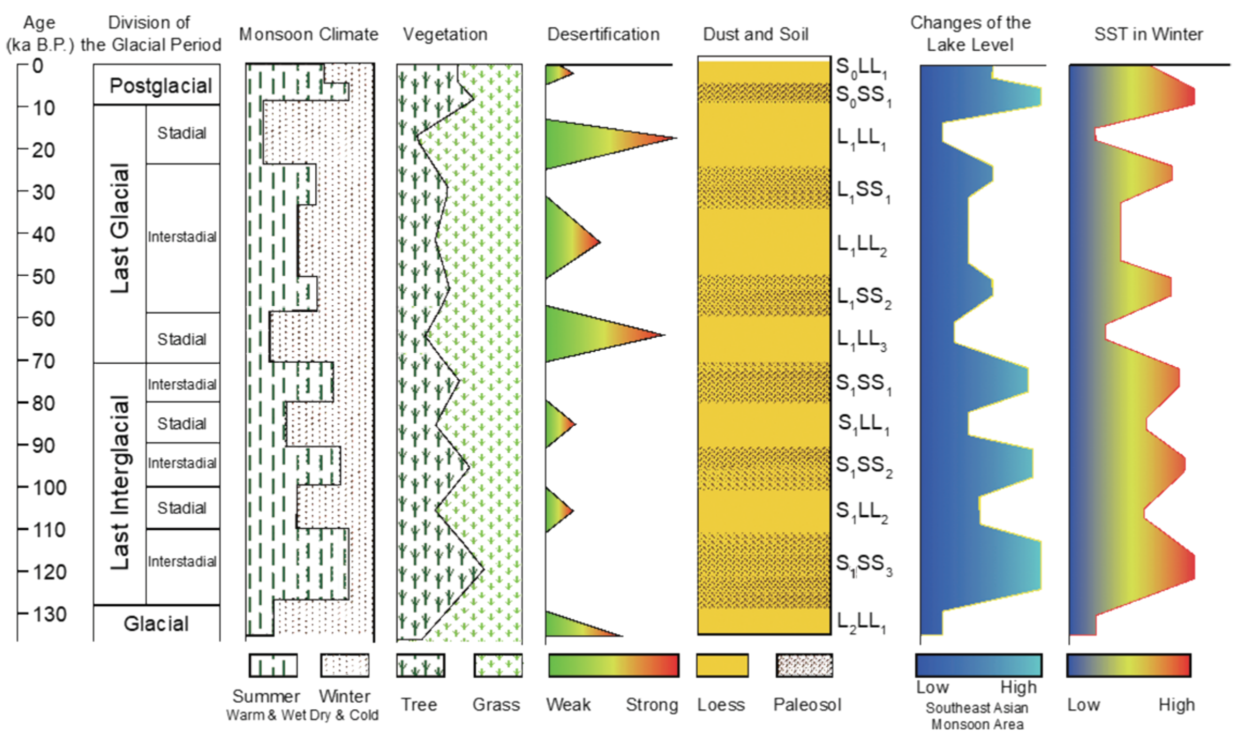
John Kutzbach, a respected Member of the U.S. National Academy of Sciences, remarked that this work has "shed light on the climatic and environmental changes of a large region of East Asia." The introduction of the Monsoon Control Theory transformed the study of loess and Quaternary geology towards a new paradigm of research focused on the dynamics of climate and environmental changes. It has greatly advanced knowledge of past and present Asian monsoon variability.

Integration of Quaternary Science and Earth System Science and Asian Monsoon Dynamics

As early as 1984, I provided Prof. YE Duzheng (1916–2013, a CAS Member) with the precipitation and temperature curves from loess records over the past 1.1 million years, who attended the inaugural meeting of the International Global Change Commission. This marked the beginning of my research in global change. Since the late 1980s, I collaborated with esteemed American scientists, including John Kutzbach, Stephen Porter, George Kukla, Raymond Bradley, Peter Molnar, Larry Edwards, and Inez Fung, on projects funded by the U.S. National Science Foundation (NSF). Our research focused on loess, the monsoon, the Qinghai-Tibet Plateau, and their connections to global change. In particular, my collaborations with George Kukla and Stephen Porter on Chinese loess have made significant contributions to the study of loess stratigraphy and its implications for monsoon climate research.

In the early 1990s, I assisted in editing and publishing a four-volume collection of papers titled *Loess, Quaternary Geology, and Global Change* (Science Press). In addition, I wrote an article titled "*Some Problems of the Study on Global Change*" (An, 1990), where I discussed the relationship between Quaternary science, global change, and Earth system science. Later in 2001, Prof. FU Congbin (later elected a CAS Member)

Fig. 5. Environmental changes in East Asia controlled by the monsoon climate changes.



Graphic: An *et al.* (1991)

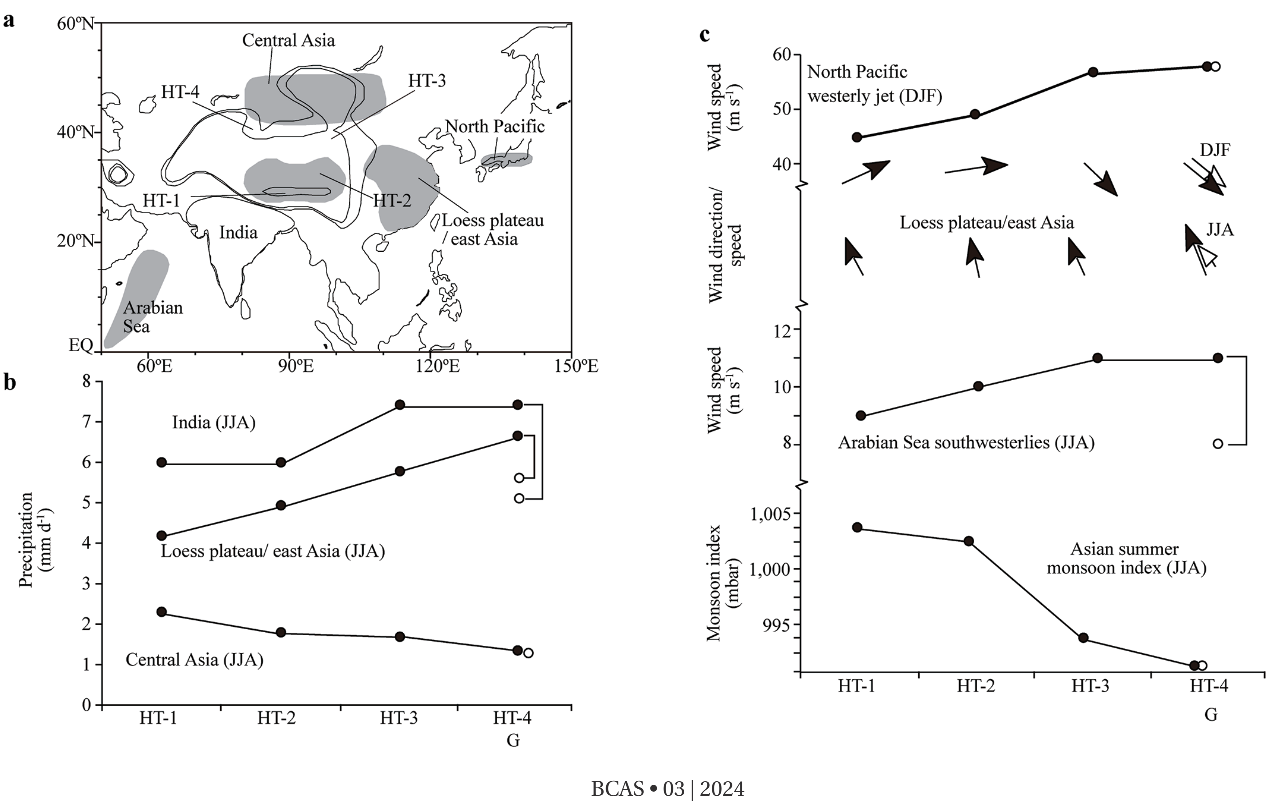
and I published *Progress in Global Change Science*, which was one of the earliest works in China to acknowledge the internationally proposed concept of the Anthropocene (An and Fu, 2001).

In the early 21st century, with support from CAS, we initiated a series of continental environmental scientific drilling projects in China. Assisted by the International Continental Scientific Drilling Program (ICDP), we launched the first international environmental drilling project at Lake Qinghai in 2005, which provided valuable records for the study of the Chinese monsoon and arid environments. The study of Qinghai Lake core revealed the impact of the interplay between the westerlies and Asian monsoon on the environment of the Qinghai-Tibet Plateau (An *et al.*, 2012).

Based on the study of the evolution history and variability of the monsoon, we positioned the Asian climate and environment within a global framework, clarifying the main controlling factors and dynamic processes of climate change across tectonic, orbital, millennial, and even shorter timescales (An, 2000; An *et al.*, 2014). By pioneering the integration of numerical simulations with geological evidence, we revealed the coupling relationship between the evolution of the Asian monsoon and the phased uplift of the Qinghai-Tibet Plateau at tectonic timescale (An *et al.*, 2014; An *et al.*, 2001) (Fig. 6). Peter Molnar, a recipient of the Crawford Award, remarked, "This reconstruction is compelling; it is the first to draw all the evidence together."

On the orbital scale, we proposed that the Asian monsoon is primarily influenced by orbital parameters, ice volume, CO_2 levels, and lower boundary conditions, with modulation from the growth of the Qinghai-Tibet Plateau. At millennial and shorter timescales, I identified that abrupt events in the Asian monsoon are governed by interactions between high and low latitude climates, the climates of the Northern and Southern Hemispheres, nonlinear feedbacks, and solar activity.

Fig. 6. Climate indices from an experiment with four idealized stages of Qinghai-Tibet Plateau elevation (HT-1 to HT-4) and one glacial maximum stage (G) made with the NCAR climate model CCM3. These changes in continent-scale monsoon circulation are caused primarily by large increases in sensible heating and latent heating (precipitation) that are focused over or along the slopes of the high plateau. In central Asia, precipitation decreases.



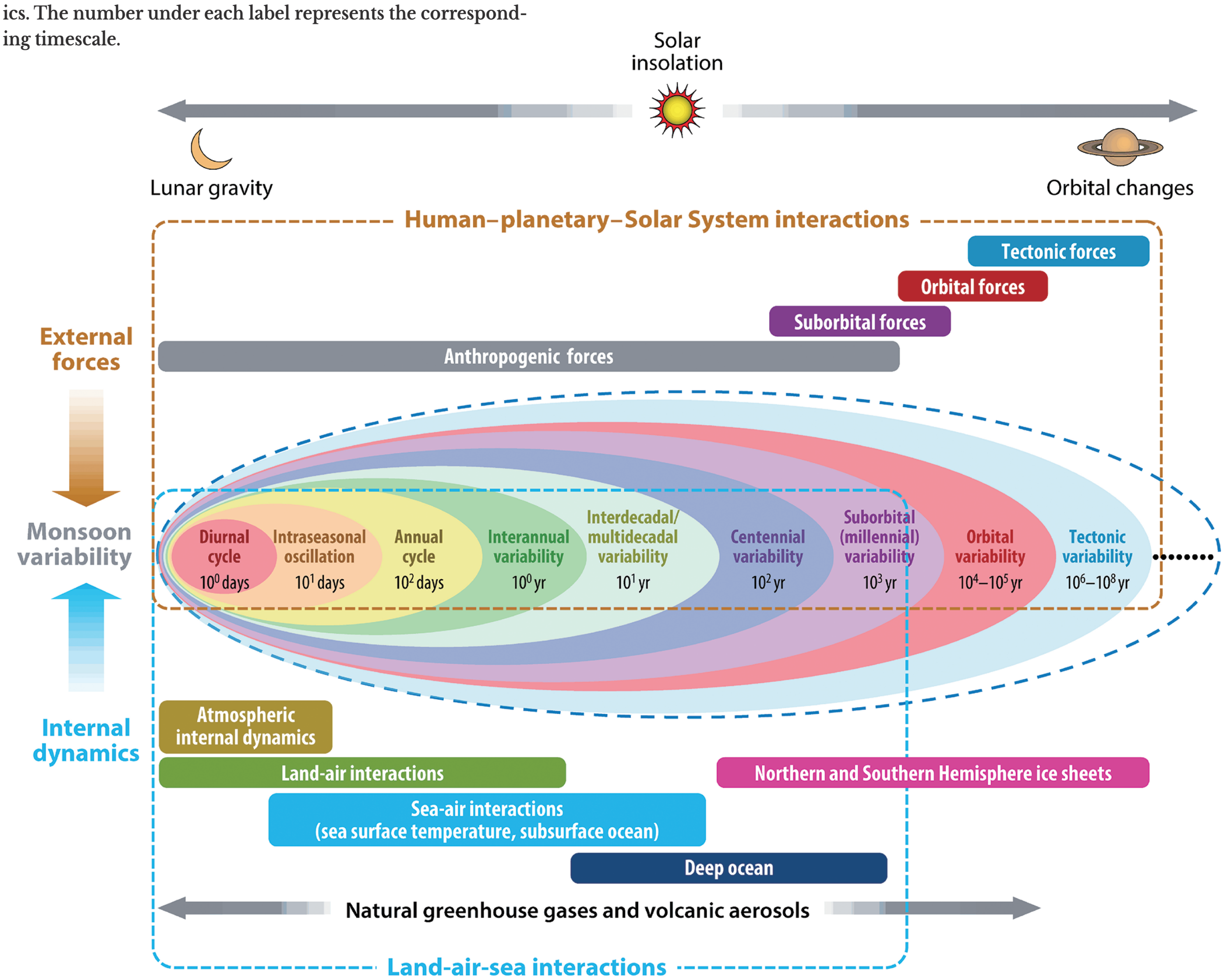
Graphic: An *et al.* (2001)

These studies laid the foundation for the basic framework of Asian monsoon dynamics, leading to the development of the concept of the Asian monsoon-arid environment system.

In the early 21st century, I served as a member and later vice-chair of the Steering Committee of the International Geosphere-Biosphere Programme (IGBP), which pioneered global change and Earth system science. This role allowed me access to the latest developments in international global change and Earth system science, inspiring me to advocate for the three shifts in the direction of Quaternary research: from focusing solely on the "past" to integrating both the "past and present," from a "regional" perspective to a combined "regional and global" perspective, and from concentrating on "natural processes" to studying the "interaction between nature and humans." This proposition was highly welcomed by CAS.

Around the same time, I also proposed a fast-track initiative for iron-rich dust research in IGBP, demonstrating that iron contained in soil dust is transported from land through the atmosphere to the oceans, where it affects ocean biogeochemistry and reduces atmosphere CO_2 concentration and thus affecting global climate and dust production (Jickells *et al.*, 2005; An *et al.*, 2014). Our group suggested that wildfire can be another main contributor of soluble iron to the ocean biogeochemistry process, possibly rivalling that from mineral dust (Han *et al.*, 2020). In short, integrating regional Quaternary geological issues with global change dynamics has greatly improved the research level of Quaternary science in China.

Fig. 7. Monsoon variability and multi-scale monsoon dynamics. The number under each label represents the corresponding timescale.



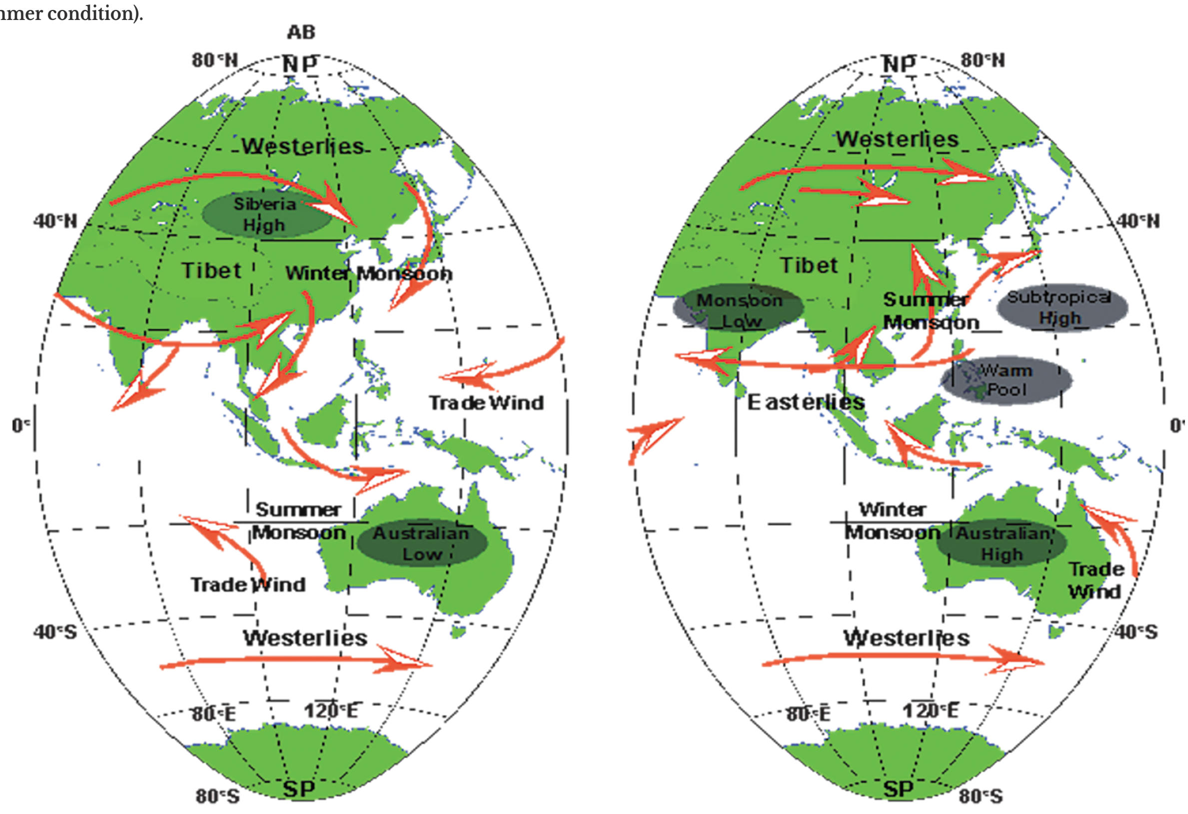
Graphic: An *et al.* (2015)

Earth System Science and Global Monsoon Dynamics as Well as Interhemisphere Climate Interactions

Since 2010, I have been promoting integrated research in Earth system science that combines observations with numerical simulations, emphasizing multi-sphere, multi-scale, and multi-factor interactions. By synthesizing monsoon records from Asia, Africa, Australia, and the Americas, my team identified the distinct influences of solar radiation, ice volume in both the Northern and Southern Hemispheres, greenhouse gas concentrations, lower boundary conditions, and ocean-land-atmosphere coupling processes, as well as human activities, upon global monsoon systems across various timescales, including tectonic, orbital, millennial, centennial, decadal, annual, seasonal, and even daily scale (An *et al.*, 2015) (Fig. 7), the team first proposed a theoretical framework for global monsoon dynamics (Duce and Zhang, AGU website, 2023). This work "summarizes the basic monsoon dynamics" (Schoeberl *et al.*, 2020), "comprehensively reviewed the studies on global monsoon dynamics and climate change, and pointed out that both natural processes and anthropogenic impacts are of great significance to the understanding of monsoon behavior" (Zhang, 2015).

We were the first to recognize the "thermal pull and pressure push" hypothesis, highlighting the importance of the interaction between the northern and southern hemisphere climates on the Asian-Australian monsoon (An, 2000) (Fig. 8), revealing the impact of changes in hemispheric ice volumes on the Indian monsoon, demonstrating the physical nature of the cross-equatorial pressure gradient driving monsoon variability, and proposing the dynamics of the Indian monsoon during the glacial-interglacial period (An *et al.*, 2011). The comment by *Science* considered that this finding "challenges traditional views of Indian monsoon dynamics". Recently, we combined geological records with numerical simulations, demonstrating the significant impact of the asym-

Fig. 8. Interaction between the Northern and Southern Hemisphere climates (the left panel shows winter condition, the right panel shows summer condition).



Graphic: An Z. (2000)

metric evolution of the polar ice sheets since the Early Pleistocene on global climate change, and proposed a hypothesis that the growth of the Antarctic ice sheet triggered the mid-Pleistocene climate transition and the increase in ice volume in the Northern Hemisphere (An *et al.*, 2024), which also provided a novel perspective for answering "the cause of the great ice ages" partly, one of the 125 world frontier scientific questions proposed by *Science* magazine.

In 2014, through integrated research, we published *Late Cenozoic Climate Change in Asia: Loess, Monsoon and Monsoon–Arid Environment Evolution*, where we suggested that the Asian monsoon activity began in the Eocene, and we proposed a dynamical model of Asian monsoon-arid environment changes at different time scales and their coupling with the phased growth of the Qinghai-Tibet Plateau and global environmental changes (An *et al.*, 2014). Bradley commented that this work "provides an up-to-date summary of research in China and adjacent regions, and demonstrates the significance of changes in that region for the broader earth system. ...Overall, this is an invaluable resource for paleoclimatologists", and Clemens believes that "Late Cenozoic Climate Change in Asia ... places the findings in the broader context of global climate change and helps to define avenues for future research."

From the perspective of Earth system science, we were the first to point out that the synergistic effects of anthropogenic emissions and atmospheric processes are the cause of severe haze events in northern China (An *et al.*, 2019), clearly summarizing that the formation of heavy haze pollution is the superposition effect between anthropogenic emissions and atmospheric processes (Wang *et al.*, 2020), settling the debate on whether human emissions or atmospheric processes are responsible for winter haze events in northern China. I have participated in international scientific efforts to apply Earth system science knowledge to the study of the Anthropocene (Waters *et al.*, 2016) and organized China's involvement in international comparisons of Anthropocene stratotype section (Han *et al.*, 2023), pioneering new areas of research in the Anthropocene within China.

I presided over the writing of the research report "*China Discipline Development Strategy for the Next 10 Years—Earth Science" (2011,* Science Press*)*, which, for the first time, comprehensively articulated the definition, content, significance, observation and simulation support system of Earth system science. This report proposed development strategies and priority directions, emphasizing that Earth system science should be viewed as the study of the entire Earth system and its subsystems across multiple scales and factors. It focuses on their interactions, dynamic relationships, change patterns, and development trends. The report aims to adapt and predict global environmental changes, facilitate orderly management of the Earth, and support the sustainable development of human society.

In December 2019, several CAS Members or scholars, including WU Lixin, ZHOU Weijian, WU Guoxiong, LIU Zhengyu, and I, jointly presented the initiative on climate change known as the CRossing Earth System in Time and Space (CRESTS) at the American Geophysical Union (AGU). This project integrates data on global climate and environmental changes over the past 130,000 years, particularly in the Asia-Pacific region. The integration encompasses results from studies such as data integration, transient simulation, data assimilation, and machine learning. Underpinned by theories of Earth system science, it proposes an approach that combines research on natural and anthropogenic drivers of climate change by bridging investigations between the past and present as well as Asia-Pacific with global climate change. This approach aims to conduct a comprehensive study comprising climatic observation in the past and present-numerical modeling-data assimilation-future projections to facilitate a transition from unidirectional mode towards an integrated paradigm of modern or paleoclimate research. Its objective is to adapt to global climate and environmental changes and achieve sustainable development of the society. The project has already made significant progress.

Earth System Science and Social Sustainable Development

An important objective of Earth system science is to manage the Earth in an orderly manner to promote sustainable social development. In 2000, we presented the Chinese government with the statement that the current natural environment in western China is a result of long-term historical evolution. The goal of ecological governance in this region is to restore the original natural vegetation altered by human activities while simultaneously implementing ecological construction and poverty alleviation (An *et al.*, 2013). In 2015, I proposed measures to control $PM_{2.5}$ pollution in China, advocating for policies that emphasize government leadership, scientific pollution control, and public engagement (An *et al.*, 2020). In 2018, Prof. ZHOU Weijian and I outlined a comprehensive governance strategy for the ecological environment of the Loess Plateau, which includes the "26-character strategy": "Consolidating gullies & mitigating headward erosion on the tableland, Returning farmlands to forests or grasslands on the hillslopes, Constructing dams and creating new farmlands in the valley, Stabilizing sand by restoring shrubs and grasses in the sandy land" (Zhou *et al.*, in press). Most of these recommendations have been adopted by the government.

Summary

Since the last century, Chinese scholars have gradually integrated Quaternary science with global change and Earth system science, beginning the research on Chinese loess. This integration has enhanced the global significance of Chinese loess and proposed the monsoon control theory of environmental change, emphasizing the substantial impact of interactions between Northern and Southern Hemisphere climates on global climate change.

By applying Earth system science theories, we have achieved significant progress in supporting China's sustainable development. Moving forward, we will continue to strengthen collaborations with domestic and international colleagues to investigate the patterns, development trends, and dynamics of climatic and environmental changes—including abrupt events—within the complex climate system under global warming by carrying out the project of CRESTS. We aim to innovate methods and theories in Earth system science to facilitate the orderly management of the Earth and promote sustainable social development.

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