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Editorial preface to special issue: Cenozoic climate change in Asia in honour of Prof. Zhengtang Guo

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ABSTRACT

The Asian monsoon has progressively become a megamonsoon system since the early Cenozoic. To improve our understanding of the complex nature of the Asian monsoon system, involving strong interactions between atmospheric, oceanic and terrestrial systems across different timescales, we present this special issue, entitled *Cenozoic climate change in Asia*. The special issue is dedicated to Prof. Zhengtang Guo in honour of his distinguished contributions as Editor-in-Chief of *Global and Planetary Change* to our understanding of the long-term evolution of the Asian monsoon system. The special issue consists of nineteen papers, grouped into three categories, that address Cenozoic climate change, mainly in Asia. The first category focuses on the plate tectonic-scale and considers how changes in palaeogeography and palaeotopography have shaped climate evolution. The second category addresses orbital- to suborbital-scale climate change and, in particular, explores the links between low-latitude insolation, high-latitude ice sheets and the Asian climate. The third category addresses millennial- to decadal-scale climate changes. In addition, past human-environment interactions are also discussed. These studies provide important insights into our understanding and prediction of both natural variability and human-induced climate changes in Asia and their linkages with global climate within the Earth System.

1. Introduction

Cenozoic climate has experienced several stepwise changes from Hothouse, Warmhouse, Coolhouse to Icehouse climates over 66 million years (Zachos et al., 2001; Westerhold et al., 2020), and some of these ancient climate modes may provide useful analogues for our future climate. With its unique tectonic evolution, Asia provides an ideal natural laboratory for investigating these climate changes, especially the complex interactions between the terrestrial and oceanic realms and between Earth's interior and surface processes.

Strongly linked with Eurasian continental evolution, the Asian monsoon has evolved since early Cenozoic times and now comprises a complex megamonsoon system (Guo, 2017). It traverses from equatorial low to middle northern latitudes, forming the most extensive regional monsoon system on the planet. The Asian monsoon is a complex system involving strong land-air-sea interactions across different timescales. During the Cenozoic era, collisions between continents and terranes, reorganizations in palaeogeography, orogenesis generating large mountain belts, fluctuations in the Earth's orbital parameters, waxing and waning of continental ice sheets, large variations of greenhouse gases concentration, as well as many other processes have profoundly shaped the Asian monsoon system.

1.1. A tribute to Prof. Zhengtang Guo

This Virtual Special Issue (VSI), entitled *Cenozoic Climate Change in Asia*, is in honour of Prof. Zhengtang Guo and recognizes his outstanding contributions to our understanding of the long-term evolution of the Asian monsoon system. Zhengtang is a research professor at the Institute of Geology and Geophysics of the Chinese Academy of Sciences in Beijing. He served as an Editor-in-Chief for *Global and Planetary Change* for nine years until 2022, developing it into a leading journal for Earth System Science. He is an internationally recognized Cenozoic geologist and paleoclimatologist, with exceptional expertise in the study of loess and paleosol sequences. He has published >300 scientific papers. His research has revealed the connections between Asian monsoon

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development and Asian tectonic and continental evolution, the Earth's orbital elements, and the polar climate system. His expertise also lies in biogeochemistry, past human-environment interactions, and planetary paleoclimate.

The early work of Zhengtang focused on the glacial-interglacial cycles in the Chinese loess and he was among the very first to demonstrate a close link of the East Asian monsoon to North Atlantic Heinrich events (Guo et al., 1996), North Atlantic deep-water formation (Guo et al., 1998), and strong hemispheric climate asymmetry (Guo et al., 2009). His landmark paper, *Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China* (Guo et al., 2002), marks a significant milestone in our understanding the evolution of monsoon-arid environments in Asia and its relationship with the uplift of the Himalayan-Tibetan complex. Zhengtang's subsequent studies have shown a major reorganization of Asian climate from a zonal planetary-wind-dominated to a nonzonal monsoon-dominated pattern during the late Oligocene to early Miocene (Guo et al., 2008; Guo, 2017).

More recently, Zhengtang's research has expanded into the relationship between continental evolution and the Earth's monsoon system since the assembly of supercontinent Pangea from a global perspective (Guo, 2017). He and his colleagues have confirmed that continental configuration (continental area, latitudinal location, and fragmentation) plays a primary role in shaping the global monsoon system (Hu et al., 2023). His research area has also expanded into planetary paleoclimate (Liu et al., 2023; Qin et al., 2023). In particular, Zhengtang has been committed to leading data/model-enabled Earth System Science, integrating Earth interiors and surface tectonic-climatic processes across both timescales and Earth-spheres (Guo, 2015; Guo, 2019; Zhao et al., 2023; Wang et al., 2024b).

In addition, Zhengtang has also actively served the scientific community and society. He was elected to the Chinese Academy of Sciences and the World Academy of Sciences (TWAS). He served as a Vice President of the International Union for Quaternary Research (INQUA), President of the China Association for Quaternary Research (CHIQUA), member of the PAGES scientific steering committee, and co-leader of the Australasian Pole-Equator-Pole international project (PEP-II). His leadership in these scientific organizations has fostered international effort and collaborations in the research of Cenozoic geology, paleoclimate and global enviroments. He has been instrumental in promoting Cenozoic research in China and building strong relationships between the Chinese Cenozoic community and the international community. He is now still serving several important national and international scientific journals, e.g., Editor-in-Chief for *Quaternary Sciences*, Associate Editor-in-Chief for *Science China Earth Sciences*, Section Editor for *National Science Review*, and Editor for *Climate of the Past*.

1.2. Scope of special issue

This special issue features nineteen papers, mostly contributed by former and current students of Zhengtang and his colleagues, covering various timescales of Cenozoic paleoclimatic change mainly in Asia (Fig. 1). These studies provide valuable insights into the understanding and prediction of the natural climate variability and human-induced changes in the region, as well as their linkages to global climate and the Earth system. In the following sections of this preface, we summarize the major findings presented in this special issue under three headings:

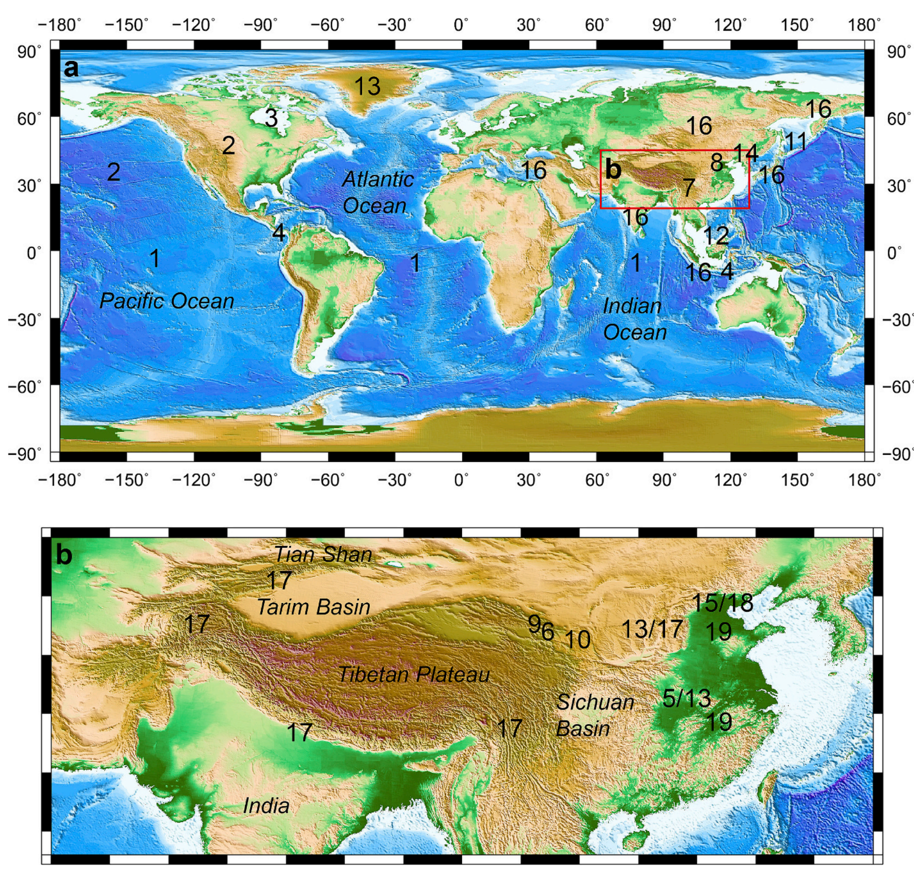

Fig. 1. Topographic map showing the locations of the studied areas/sites.
The base map is generated online at https://www.odsn.de/hg/. Numbers refer to the articles in this VSI and roughly indicate the study regions considered in each article: 1) Zhang et al. (2024a); 2) Li et al. (2024b); 3) Wu et al. (2023); 4) Tan et al. (2024); 5) Zhang et al. (2024b); 6) Zhang et al. (2023); 7) Li et al. (2024a); 8) Xie and Liu (2023); 9) Xiao et al. (2023); 10) Hao et al. (2024); 11) Wang et al. (2024a); 12) Zhao et al. (2024); 13) Rousseau et al. (2023); 14) Zhou et al. (2024); 15) Shi et al. (2023); 16) Xu et al. (2024); 17) Fang et al. (2024); 18) Ge et al. (2024); 19) Yu et al. (2024).

variability at the plate tectonic-scale, orbital- to suborbital-scale variability, and millennial- to decadal-scale variability.

2. Variability at plate tectonic-scale

2.1. Global climate from model simulations

Tectonic-scale climate variability is mainly controlled by land-sea-topography distribution patterns (Zachos et al., 2001; Ruddiman, 2014; Guo, 2015). Zhang et al. (2024a, this VSI) evaluate the impacts of plate reference frames (mantle reference frame and paleomagnetic reference frame) on simulated climates. In addition, paleoclimate modeling results are presented on the Pacific-North American teleconnection (PNA) in the Cenozoic (Li et al., 2024b, this VSI) as well as the effects of high-northern-latitude Hudson Bay closure (Wu et al., 2023, this VSI) and the closure of tropical seaways (Tan et al., 2024, this VSI) on global and regional climate.

Paleogeographic maps, crucial boundary conditions for deep-time paleoclimate simulations, can be reconstructed using different plate reference frames, possibly causing potential divergence in simulated climates. Investigating how paleogeographic maps influence simulated deep-time climates is of vital importance. Two reference frames are often used in plate reconstructions: the mantle reference frame reconstructing plates' positions relative to the mantle and the paleomagnetic reference frame reconstructing plates' positions relative to the spin axis. Although some studies suggest that the paleomagnetic reference frame is more suitable for climate simulations due to its constraint on paleolatitudes, most published Eocene simulations use paleogeographic maps based on the mantle reference frames, and the Deep-Time Model Intercomparison Project (DeepMIP) community predominantly employs the mantle reference frame. Previous works have revealed significant disparities in ocean circulations when different reference frames were employed for the 38-Ma palaeogeography. However, the impacts of different plate reference frames on simulated deep-time climates and atmospheric circulations are still unclear. With the Norwegian Earth System Model, utilizing three early Eocene paleogeographic maps, Zhang et al. (2024a, this VSI) document the impact of reference frames on simulated climates, focusing on atmospheric circulations. Their simulations reveal notable disparities in general climatic characteristics, particularly in the Pacific region. For instance, compared to the mantle reference frame, the paleomagnetic reference frame simulates a narrower and stronger Pacific Walker Circulation, asymmetrical Hadley Circulations, and a stronger subtropical high in the North Pacific. Zhang et al.'s (Zhang et al., 2024a, this VSI) study shows that different plate reference frames lead to clear divergences in the simulated deep-time climates. It emphasizes the importance of paleogeographic boundary conditions for paleoclimate simulations and motivates modelers to carefully consider the choice of reference frames for deep-time simulations.

Climate variations in the tropical Pacific through the PNA significantly impact North America. However, whether the PNA-like mode existed in the deep-time climate and how it evolved remain unknown. Li et al. (2024b, this VSI) study the evolution of the PNA in the Cenozoic, using simulation results with coupled Community Earth System Model version 1.2.2. Their study shows that the PNA existed during the Cenozoic but had different strengths and pathways. Simulations show that the strength of the PNA patterns became stronger from 70 Ma to the pre-industrial period when the global climate became colder and that the PNA pathway has been distorted northward. Further analysis indicates that warmer climates in the early Cenozoic were associated with weaker meridional temperature gradients on the surface and at the lower and middle troposphere, especially in the subtropics. The weaker meridional temperature gradients caused weaker subtropical westerly jet streams. Consequently, the wave guide was weaker in the early Cenozoic than at present, thus the weaker PNA. Their findings highlight the huge effect of geological atmospheric temperature on the evolution of PNA, which will help us understand and predict future changes in PNA in a warming world.

Hudson Bay is one of the largest inland seas in the world, and it greatly affects regional and global climate. During the Quaternary, it switched between closed and open conditions due to the advance and retreat of the northern American ice sheet. However, the effect of this change in Hudson Bay on local and global climate is unclear. Based on the sensitivity experiments using the model LOVECLIM1.3, Wu et al. (2023, this VSI) investigate the influence of Hudson Bay closure on global and local climate under glacial conditions with different astronomical configurations. Their results show that the closure of Hudson Bay leads to an intensification of the Atlantic Meridional Overturning Circulation, mainly caused by the increased evaporation minus precipitation over the Labrador Sea. The strengthening of the Atlantic Meridional Overturning Circulation leads to a warming in the Northern Hemisphere, a cooling in the Southern Hemisphere, and a northward shift of the Inter-tropical Convergence Zone. At a regional scale, strong cooling occurs over Hudson Bay due to the change from ocean to ice-covered land over this region. In addition, more sea ice export from the Arctic to southeastern Greenland, driven by northeasterly wind anomaly, also leads to a cooling in southeastern Greenland. The model results also show that the effect of Hudson Bay closure is dependent on background climate conditions. Wu et al. (2023, this VSI) highlight the importance and necessity of appropriate treatment of the land-ocean mask over Hudson Bay in paleoclimate simulations.

The closure or narrowing of the Central American Seaway (CAS) and the Indonesian Seaway (INDO) have been recognized as significant factors influencing climate during the Pliocene epoch. Notably, tropical climate and vegetation underwent considerable transition during this period, particularly in East Africa. However, studies on how the closure/constriction of tropical seaways affects the tropical climate system are still sparse and not systematic. Previous studies have linked the constriction of INDO to the aridification over East Africa and discussed the role of CAS closure in affecting the moisture supply over South America, but the underlying mechanism and combined effect of both tropical seaways have not been well studied. Tan et al. (2024, this VSI) systematically evaluate the impacts of tropical seaways' closure/constriction and distinguish the relative roles of CAS and INDO on climate in tropical Africa and South America by using the NorESM-L Atmosphere-Ocean General Circulation Model (AOGCM) and a dynamic vegetation model (LPJ-GUESS). Their results indicate that the closure of the CAS primarily induces aridification and expansion of savannas in northeastern Brazil, while the narrowing of the INDO primarily leads to increased aridification and the contraction of tropical forests across tropical East Africa. The closure/narrowing of the two tropical seaways results in a superposition of the individual seaway's effect, particularly over the northeastern Brazil region, which exhibits enhanced aridification compared to the closure of the CAS alone. These modeling results align well with the reconstructed sea surface temperature over the Indian Ocean and pollen records in East Africa. The study of Tan et al. (2024, this VSI) strengthens that seaway changes are pivotal for the evolution of climate and vegetation over East Africa and northeastern South America to contemporary conditions.

2.2. Paleogene-Neogene climate transition in East Asia

The most drastic paleoenvironmental change during the Cenozoic in Asia is the transition from a subtropical aridity pattern to a mid-latitude inland aridity pattern during the late Paleogene to early Neogene (Guo et al., 2002; Guo et al., 2008; Guo, 2017), which profoundly reshaped the monsoon-arid environments and biodiversity patterns in central-eastern Asia. Zhang et al. (2024b, this VSI) highlight the significance of differentiating the Paleogene zonal climate pattern from the Neogene nonzonal climate pattern in eastern Asia. In addition, Zhang et al. (2023, this VSI) document that the Oligocene climate in the northeastern Tibetan Plateau was characterized by a transition from arid to humid. Li et al. (2024a, this VSI) present a revised chronostratigraphic framework for Cenozoic sedimentary basins in the southeast margin of the Tibetan Plateau, which shows that most of the Paleogene sedimentary successions in the region ended during the late Eocene to early Oligocene and were unconformably overlain by Middle-Late Miocene sediments.

The classical paradigm for understanding the Cenozoic climate evolution in China depicts a shift from a Paleogene zonal pattern to a Neogene nonzonal pattern. During the Paleogene, a broad and zonal arid climate spanned from western to eastern China, as evidenced by the widespread occurrence of evaporites and other indicators of arid environment. This zonal pattern is called the planetary-wind-dominated climate pattern. Later, during the Neogene, a wet climate emerged in eastern China, while arid conditions persisted in western China. This nonzonal pattern, resembling the modern climate, is called the monsoon-dominated climate pattern. The shift from a zonal to a nonzonal climate pattern signifies the establishment of a modern-like monsoon climate in East Asia around the boundary of the Paleogene and the Neogene. Although this classical paradigm has been established for ~60 years in China, it has been questioned by recent studies. Zhang et al. (2024b, this VSI) emphasize the importance of considering orbital-scale climate oscillations to better understand and reassess the paradigm. They first examined the halite and mudstone sequence in the Jianghan Basin. The pronounced oscillations between halite and mudstone appeared between ~43–33 Ma in the Eocene but gradually diminished between ~33–30 Ma in the Oligocene. After ~29 Ma, the occurrence of halite layers ceased, indicating the disappearance of arid climates on orbital time scales and a shift to a wetter mean climate on tectonic time scales. They further conduct numerical experiments using the Norwegian Earth System model. Their results show that the simulated Eocene climate was more sensitive to Earth's orbital forcings, with strong oscillations between relatively humid and arid conditions in eastern China, which agree with the occurrence of halite-mudstone sequence from the Jianghan Basin. They further propose the concept of a "green Yangtze" phenomenon, which utilized orbital-scale climate oscillations to reconcile the wet and dry environmental indicators in eastern China during the Paleogene. Zhang et al. (2024b, this VSI) highlight that it is essential to differentiate the Paleogene climate, characterized by intense orbital-scale wet and arid oscillations, from the Neogene monsoon-dominated climate. Though influenced by tropical monsoon circulation, the Paleogene climate in eastern China is not a typical monsoon-dominated climate. The classic paradigm remains valuable in understanding the long-term mean environment, albeit without capturing the orbital-scale details.

The Oligocene climate in the northeastern Tibetan Plateau is of significant interest for understanding the climate evolution in the arid Asian interior. Zhang et al. (2023, this VSI) report a high-resolution paleoclimate record from the northeastern Tibetan Plateau using clay mineral assemblages and geochemical proxies of clay fraction (<2 μm) for the Oligocene strata from the Xining Basin. Using these data and climatic data from surrounding basins, Zhang et al. (2023, this VSI) reconstruct the Oligocene climatic evolution of the northeastern Tibetan Plateau. Three characteristic climatic periods are recognized as follows: the late Eocene-early Oligocene characterized by arid climate, the early-late Oligocene (32–25 Ma) being warmer and more humid, and the terminal Oligocene (25–23 Ma) with reduced humidity. Zhang et al. (2023, this VSI) suggest that the relatively warm and humid climate conditions since 32 Ma were likely caused by enhanced transport of water vapor in response to relatively warm temperatures, as the high topography of the northern and northeastern parts of the Tibetan Plateau had not developed during the Oligocene. Zhang et al.'s (Zhang et al., 2023, this VSI) reconstruction of the Oligocene climate in the inland arid region of China reveals that the Oligocene climate in the northeastern Tibetan Plateau was characterized by a transition from arid to humid.

The southeast margin of the Tibetan Plateau not only provides a meaningful constraint on the geodynamic evolution of the Tibetan Plateau but also serves as an exemplar to understand the various interactions among surface uplift, drainage network reorganization, climate change, and biodiversity. Li et al. (2024a, this VSI) synthesize high-resolution magnetostratigraphy, detrital zircon geochronology, and isotopic dating of interbedded bentonite layers obtained during the past two decades. Using these data, Li et al. (2024a, this VSI) build a revised chronostratigraphic framework for Cenozoic sediments in the southeast margin of the Tibetan Plateau and use this updated temporal framework to contextualize regional tectonics and climate change. The new chronostratigraphic framework shows that many of the sedimentary basins in the region previously assigned a Neogene age based on plant fossils and inter-basin lithostratigraphic correlation were actually formed in the late Eocene and early Oligocene and that most of the Paleogene sedimentary successions in the region ended at the late Eocene-early Oligocene and were unconformably overlain by Middle-Late Miocene sediments. The updated age framework, together with analyses of depositional environment and sedimentary basin structures, suggests that the southeast margin of the Tibetan Plateau underwent rapid deformation and uplift following the continent-continent collision during the early Eocene between India and the Tibetan Himalaya terrane (Yuan et al., 2021, 2022), and achieved its near-present elevation at around the Eocene-Oligocene transition (Su et al., 2019). The updated geochronologic framework also supports previous assertions that the modern Asian biodiversity hot spots were already becoming established during the late Eocene to early Oligocene (Linnemann et al., 2018; Su et al., 2019).

3. Orbital- to suborbital-scale variability

The cyclic changes of insolation that are related to the astronomical periods of eccentricity, obliquity, and climatic precession (Berger, 1978) have been widely accepted as the primary forcing mechanism of global climate over the Cenozoic (e.g., Zachos et al., 2001; Westerhold et al., 2020). Besides, the cyclicity of the East Asian climate was believed to be modulated by the uplift and expansion of the Tibetan Plateau and the presence of marginal seas in the western Pacific (e.g., Wang et al., 2017; Zhao et al., 2020; Jian et al., 2022).

Xie and Liu (2023, this VSI) present new modeling results to show that the precipitation in East Asia exhibits complex spatiotemporal variation patterns due to multiple origins of water vapor sources. Xiao et al. (2023, this VSI) document the cyclicity of regional climate over the past 420 kyr recorded in alpine loess of the northeastern Tibetan Plateau. Hao et al. (2024, this VSI) suggest that Marine Isotope Stage (MIS) 8 exhibits an unusual weakening trend of the East Asian winter monsoon over the last 880 kyr based on grain-size variations of Chinese loess and further ascribe the behavior to the shrinking of Arctic ice sheet during MIS 8.

The precipitation in East Asia exhibits complex spatiotemporal variation patterns due to originating from multiple water vapor sources. Xie and Liu (2023, this VSI) investigate contributions of terrestrial and oceanic moisture sources to orbital-scale precipitation changes in the northern East Asian monsoon region (NEA, 35–45°N, 105–120°E) by conducting a transient simulation lasting 300,000 years using a climate model equipped with a water tagging capability. Their results reveal that the orbital-scale variation in annual NEA precipitation was mainly characterized by a significant 23-kyr cycle and a weak 100-kyr cycle, with a dominant terrestrial moisture contribution of 57.6% to annual NEA precipitation, followed by the Pacific Ocean source contributing 20.9%. A notable finding is that synchronized terrestrial and oceanic moisture fluctuations drive the dominant 23-kyr cycle of the precipitation, while a weak 100-kyr precipitation cycle is attributed to their asynchronous changes of the terrestrial and oceanic moistures. Their study further highlights the control effect of precession-induced Northern Hemispheric summer insolation variations and the modulatory role of global ice volume on the precipitation variability by regulating the contribution rates of land and Pacific moisture sources. By unraveling the linkage between the precipitation and external forcings through the water vapor sources, Xie and Liu's (Xie and Liu, 2023, this VSI) research provides new insights into the temporal-frequency characteristics and physical mechanisms of orbital-scale East Asian monsoon precipitation variations from a water vapor source perspective, enriching our comprehension of the regional climate rhythms and patterns.

The northeastern Tibetan Plateau is one of the most ecologically vulnerable areas, with large expansion and retreat of desert areas since the Last Glacial Maximum. Although the long-term history of desertification in this area and its mechanisms are of great importance for China's future policies and actions on desertification control, they are still unknown due to the lack of long-term and well-dated records. Xiao et al. (2023, this VSI) report the sand particle content (a proxy of local materials) and detrital zircon ages from a highly resolved loess-paleosol section spanning the past 420 kyr in the Menyuan Basin, the northeastern Tibetan Plateau. Their results show that the provenance of loess units (formed in glacial periods) was strongly influenced by local desertified materials mainly produced by alpine glaciers surrounding the basin, significantly different from the paleosol units (formed in interglacial periods). The strong signals of ~100-kyr and ~ 20-kyr cycles in the content of local materials suggest that the desertification of the Menyuan Basin was controlled by both the late Quaternary ~100-kyr ice age and the ~20-kyr precession cycles. The strong ~20-kyr cycle in the Menyuan Basin suggests that the alpine glaciation activities in the northeastern Tibetan Plateau were driven by local summer insolation. Xiao et al.'s (Xie and Liu, 2023, this VSI) results allow us to characterize the long-term natural variability of desertification in the northeastern Tibetan Plateau.

A fundamental aspect of marine benthic foraminiferal $\delta^{18}O$ records of the last one million years is their "saw-tooth" pattern, characterized by gradual cooling to full glacial conditions followed by very rapid glacial terminations. Understanding the mechanism of this pattern is crucial for understanding ice age dynamics. However, it is less clear whether the ice volume changes in the Arctic region had such a uniform "saw-tooth" pattern due to complex climatic interpretation of marine $\delta^{18}O$ records and the lack of continuous records of Arctic ice sheets older than the last interglacial. Hao et al. (2024, this VSI) present a record of grain-size variations in the Chinese Loess Plateau — a proxy of variations in the strength of the East Asian winter monsoon — and show that MIS 8 exhibits an unusual weakening trend over the last 880 kyr. They argue that the unusual weakening trend of the East Asian winter monsoon indicates the shrinking of Arctic ice sheets during MIS 8. This aligns with a compilation of global paleoclimate records showing a mild climate in middle to high northern latitudes and a cold climate in high southern latitudes during late MIS 8. They further suggest that an increase in benthic foraminiferal $\delta^{18}O$ value during MIS 8 is a signal of ocean bottom water cooling of Antarctic origin rather than Arctic ice sheet volume. This is supported by the unusual orbital configuration during this glacial. Thus, MIS 8 provides a window for understanding ice age dynamics in terms of distinguishing the role of the two polar regions and understanding the operation of Earth's climate under an unusual orbital configuration and decoupled ice sheets in the two polar regions.

In addition, Wang et al. (2024a, this VSI) document sediment provenance variations over the past 110 kyr in the high-northern-latitude Okhotsk Sea, which were believed to be mainly governed by the interplay between sea ice and ocean circulation. Zhao et al. (2024, this VSI) report silicate weathering evolution over the last 21 kyr in the low-northern-latitude southern South China Sea, which were believed to be regulated by sea level and monsoon rainfall. The two findings contribute to a better understanding of high- and low-latitude climate processes in East Asia.

The Okhotsk Sea, situated at the southernmost boundary of the sea ice influence in the Northern Hemisphere, is characterized by a diverse array of sediment sources due to intricate interactions between the ocean and land, the dynamics of sea ice, and ocean circulation. This makes it an ideal natural laboratory for studying the source-to-sink pathways of sediments. Previous studies have demonstrated that sea ice, along with surface and intermediate-depth ocean currents, significantly influences the variations in sediment provenance within the Okhotsk Sea. However, there is a scarcity of research differentiating the relative impacts of these factors on sediment provenance changes over geological timescales in this unique area. Wang et al. (2024a, this VSI) investigate the provenance changes over the past approximately 110,000 years by analyzing the strontium-neodymium (Sr—Nd) isotopic compositions of detrital components in surface sediments and sediment core LV55–40-1 from the southwestern Okhotsk Sea. Their findings suggest that the primary sources of sediments in the Okhotsk Sea, constituting approximately 60–80%, were the Amur River and Sakhalin Island, with the Okhotsk-Chukotka volcanic belt and the southern Kuril Islands/Hokkaido contributing around 20–40%. Moreover, they observe an overall increase in εNd values, marked by a sharp rise in the early Holocene and secondary cyclic fluctuations during MIS 5–2. These variations in provenance were mainly governed by the interplay between sea ice drift, driven by atmospheric circulation patterns, and changes in ocean circulation. Wang et al. (2024a, this VSI) present the first comprehensive record of Sr—Nd isotopes over the last glacial cycle in the Okhotsk Sea, shedding light on the complex relationship between sediment sources and the interplay of sea ice and ocean currents in the region.

Silicate chemical weathering sequesters atmospheric CO_2 in weathering products, regulating the atmospheric and oceanic carbon balance. Weathering products in the deep sea are commonly used to reconstruct silicate weathering evolution. Zhao et al. (2024, this VSI) report major element results of a deep-sea core from the southern South China Sea since the last glaciation, and use the chemical index of alteration and SiO_2/Na_2O ratio as chemical weathering proxies to analyze the variation of chemical weathering records and its controlling factors. The values of the proxies are higher during the last glaciation than during the Holocene. They attribute this to the provenance shift caused by sea level change. The Malay Peninsula and Sumatra were the primary sediment sources for the study region during the last glacial sea-level lowstand, while the Indochina Peninsula was the major source during the Holocene sea-level highstand. Accordingly, the weathering evolution analysis reveals increased physical erosion in the Malay Peninsula and Sumatra during enhanced East Asian summer monsoon rainfall while increased chemical weathering in the Indochina Peninsula during the intensified monsoon rainfall. Therefore, they propose that the chemical weathering records of the deep-sea sediments in the southern South China Sea were regulated by sea level and monsoon rainfall. They emphasize that higher weathering values of deep-sea sediments during the last glaciation could be related to the provenance variation rather than to enhanced chemical weathering in the same provenance.

4. Millennial- to decadal-scale variability

4.1. Millennial-scale climate variability

Millennial- to decadal-scale climate changes are of great significance in paleoclimatology due to their profound impacts on future climate scenarios (e.g., Yin et al., 2021). Rousseau et al. (2023, this VSI) apply the augmented Kolmogorov–Smirnov test (Bagniewski et al., 2021) to detect abrupt transitions in loess grain size and speleothem $\delta^{18}O$ records. Their results highlight the potential of abrupt changes as robust tie points for synchronizing different proxy indicators on a global scale. Specifically, Zhou et al. (2024, this VSI) argue a low-latitude forcing of the 4.2 ka event in the East Asian monsoon region. Shi et al. (2023, this VSI) present, for the first time, continuous calibrations of modern plant *n*-alkane carbon isotopes ($\delta^{13}C_{alk}$) responses to climate at the same place next to a meteorological station and reveal the potential of leaf $\delta^{13}C_{alk}$ in paleoclimate studies. They further reconstruct the pCO_2 during the Paleocene-Eocene Thermal Maximum (PETM) by eliminating the impact of precipitation changes on $\delta^{13}C_{alk}$.

Although best documented in ice cores and marine sediments, abrupt climate changes are also recorded in different archives on the land, among which Chinese loess and speleothem records effectively document orbital-to-millennial monsoon variability during the Pleistocene. Such millennial fluctuations can be of varying amplitudes and either more or less abrupt depending on the type and proxies of these records. The abruptness usually depends on the sedimentation rates and sampling resolution in the loess and speleothem records. However, it can also be refined by comparing multiple physicochemical and isotopic proxies. Rousseau et al. (2023, this VSI) apply the augmented Kolmogorov–Smirnov test (Bagniewski et al., 2021) to detect abrupt changes in loess grain size and speleothem $\delta^{18}O$ records. Firstly, they compared two reference records (i.e. the NGRIP ice-core (Rasmussen et al., 2014) and the Hulu speleothem $\delta^{18}O$ records (Wang et al., 2001, 2008)) of abrupt climate change to verify the robustness of the method in detecting the well-recognized abrupt events during the last glaciation. Secondly, the method is employed to compare two high-resolution loess grain-size stacks (i.e. the CHILOMOS (Yang and Ding, 2014), and the LGS640 datasets (Sun et al., 2021)) with the Chinese speleothem composite record built from Hulu and Sanbao records (Cheng et al., 2016). Although visually observed rapid grain-size variations were previously interpreted as representing millennial-scale variations. Their statistical results suggest that whether these abrupt climate changes can be robustly identified is highly dependent on the time resolution of the proxy records. They then detected abrupt transitions in the MGSQ grain size stack over the last 3.6 million years, implying that both winter and summer monsoons co-varied at glacial-interglacial to millennial timescales. Their statistical analysis confirms a three-stage evolution of monsoon intensity: (1) from 3.6 Ma to 2.6 Ma, (2) from 2.6 Ma to 1.2 Ma, and (3) from 1.2 Ma to present. These results finally show that the identified abrupt climate events can be employed for synchronizing climate records on a global scale.

The pronounced global climatic and cultural impacts of the 4.2 ka event have positioned it as the formal boundary to separate the Middle and Late Holocene. However, the forcing mechanism of the 4.2 ka event is still in debate, with current evidence being divided between high-latitude and low-latitude forcings. The Asian climate system consists of strong summer and winter monsoon circulations, originating from low and high latitudes, respectively. Therefore, the Asian monsoon region is ideal for studying the transmission of climatic signals. Zhou et al. (2024, this VSI) present a 5000-yr high-resolution and well-dated pollen record from a crater lake in the higher latitudes of the Asian monsoon region. The broadleaf tree pollen percentage decreased distinctly around 4.2 ka, suggesting a decrease in summer monsoon rainfall. By synthesizing well-dated high-resolution pollen, stalagmite $\delta^{18}O$, and winter monsoon records, Zhou et al. (2024, this VSI) find that most of the pollen records, linked to summer monsoon changes, showed significant changes during the 4.2 ka event, while no apparent change was found in winter monsoon records. Meanwhile, the changing amplitude in stalagmite $\delta^{18}O$ records was generally greater at the lower latitudes than at the higher latitudes in the Asian monsoon region. Their results suggest that the 4.2 ka event signal was transmitted to the Asian monsoon region through low-latitude processes, thus corresponding to a low-latitude forcing.

Calibration of modern plant *n*-alkane carbon isotopes ($\delta^{13}C_{alk}$) responses to climate is a prerequisite for interpreting the climate information recorded by $\delta^{13}C_{alk}$ in archives, thereby facilitating climate prediction. The previous calibrations were typically conducted by collecting plants along a spatial environmental gradient, which could not effectively eliminate the interference of geographic factors on the $\delta^{13}C_{alk}$ impact, leading to uncertainty in these calibrations. Shi et al. (2023, this VSI) present the first continuous calibration at the same place next to a meteorological station, which excludes errors in the commonly used spatial calibrations, resulting in robust calibrations. Furthermore, Shi et al. (2023, this VSI) conduct a greenhouse study to provide evidence for the observations under natural conditions. Their results show that $\delta^{13}C_{alk}$ is negatively related to precipitation but not temperature, and that $\delta^{13}C_{29}$ is most related to precipitation. The greenhouse study shows that moisture negatively influenced $\delta^{13}C_{alk}$ and accounted for ~97% of its variance. Finally, Shi et al. (2023, this VSI) reconstruct the pCO_2 during the PETM by eliminating the impact of precipitation changes during that period on the isotopes using the obtained $\delta^{13}C_{alk}$-precipitation coefficient. In the scenario where methane hydrates were the primary carbon source responsible for PETM warming, the estimated $pCO_{2\,(initial)}$ and $pCO_{2(excursion)}$ were 201–275 ppm and 911–985 ppm, respectively, whereas, in the scenario where volcanic CO_2 emissions were the primary carbon source, they were 398–505 ppm and 1708–1815 ppm, respectively. Shi et al.'s (Shi et al., 2023, this VSI) results suggest that $\delta^{13}C_{alk}$ is a good indicator of precipitation, especially $\delta^{13}C_{29}$, and has the potential to yield more robust reconstructions of precipitation.

4.2. Decadal-scale climate variability

To expound the finer details of the decadal-scale variability of Asian climate, Xu et al. (2024, this VSI) present a synthesis of tree-ring oxygen isotope research in Asia, and show that the tree-ring oxygen isotope series of monsoonal Asia reveal summer hydroclimate variations at seasonal to millennial timescales. Fang et al. (2024, this VSI) further suggest that the Indian summer monsoon drives synchronous interdecadal hydroclimate changes in the Tibetan Plateau and surroundings.

Tree-ring oxygen isotope, a powerful proxy that has become increasingly important in paleoclimatology, ecology, and archaeology over the past five decades, has significantly enhanced our understanding of Asian climatic and ecological systems. Xu et al. (2024, this VSI) provide a retrospective review of the progress made in tree-ring oxygen isotope research in Asia based on 220 papers. This yields several valuable insights, including details on the study areas, the utilized tree species, the experimental methods employed, the climatic implications, and long-term climate trends. Tree-ring oxygen isotope research thrives across diverse Asian climates, utilizing existing tree species. Its progress has been further bolstered by the development of the novel plate method for faster and more efficient cellulose extraction. Currently, there are 96 chronologies >200 years. Notably, Japan boasts a 4354-year annual record, while the northeastern Tibetan Plateau holds the longest Asian record at 6700 years (1–5 year resolution). Monsoon Asia's tree-ring oxygen isotope series reveal summer hydroclimate variations (seasonal-millennial scales). Additionally, contrasting trends have emerged since 1850: monsoon regions (upward trend) suggest drying, while westerly regions (downward trend) indicate increased moisture. Xu et al. (2024, this VSI) present a comprehensive analysis of tree-ring oxygen isotope research in Asia, highlighting significant advancements in the development and interpretation of oxygen isotope chronologies. It also explores promising avenues for future research, including applying these techniques in understanding climatic variations, reconstructing past climates, and uncovering ecological relationships.

The interdecadal relationship between the Indian Summer Monsoon (ISM) and arid climate dynamics in the Tibetan Plateau and surrounding areas is pivotal for understanding the Asian hydroclimate system and its implications on regional water resources and ecosystems. Extensive tree-ring-based climate reconstructions have been conducted in the Tibetan Plateau and its adjacent regions. Yet the relationships between the ISM and arid climate over the Tibetan Plateau and surroundings remain contentious on interdecadal scales. Fang et al. (2024, this VSI) employ a composite chronology development method that is particularly efficient in revealing robust climate signals on interdecadal scales to address this gap. They assemble a comprehensive tree-ring network from 242 moisture-sensitive sites in three regions over ISM and three regions over arid areas across the Tibetan Plateau. Their findings demonstrate synchronous hydroclimate variations on interdecadal timescales throughout the common period from 1517 to 2003. The co-varying hydroclimate exhibits the strongest correlations with the ISMdominated Himalayan region, indicating ISM-driven synchronous changes. Furthermore, the synchronous interdecadal hydroclimate changes display positive associations with solar irradiance. This study clarifies the overall in-phase hydroclimate changes on interdecadal scale in the Tibetan Plateau and its surroundings and the mechanisms related to the ISM. It also provides valuable insights for predicting future interdecadal changes, given their quasi-periodic nature, and highlights the significant role of solar irradiance in driving these changes.

4.3. Past human-environment interactions

Climate change and its effects on terrestrial ecosystems may have profoundly shaped human evolution (e.g., Levin, 2015; Bae et al., 2017). Exploring past human–environment interactions helps to understand their interactions in the present day and in the future. Ge et al. (2024, this VSI) document that the population shift during the late Pleistocene in temperate northern China, which is significantly modulated by East Asian monsoon fluctuations, corresponds to the major wave of Out-of-Africa modern humans. Yu et al. (2024, this VSI) explain the impact of climate changes on asynchronous Holocene human population changes in temperate northern and subtropical southern China.

The timing and mechanism of modern human dispersal and occupation into northern China, especially cultural interactions between exogenous Paleolithic populations and those indigenous to East Asia during the Late Pleistocene are of great interest. *Homo sapiens* dispersed eastward into Siberia and Northeast Asia after ~45 ka (e.g., Bae et al., 2017; Wang et al., 2022; Yang et al., 2024). When anatomically modern humans crossed the Mongolian steppe/desert and dispersed further across East Asia, encounters between allochthonous modern humans and indigenous hunter-gatherers inevitably occurred, possibly leading to population replacement and geographical shifts. How they colonized and interacted with autochthonous Paleolithic populations in East Asia remains ambiguous. Ge et al. (2024, this VSI) dated two Paleolithic sites from the vicinity of Tianjin, northern China, characterized by simple core and flake technology. They then analyzed spatio-temporal variations in Late Pleistocene human populations during the last glacial in Northeast Asia, revealing an “ebb and flow” migration pattern for exogenous Initial Upper Paleolithic “blade” populations and indigenous “core-flake” populations corresponding to the advance and retreat of the East Asian monsoon regime. Their dating results attest to the population shift during the late Pleistocene corresponding to the major wave of Out-of-Africa modern humans, and reveal an “ebb and flow” demographics of human occupation in northern China during 70–10 ka, which is significantly modulated by East Asian monsoon fluctuations. Their study thus provides a potential scenario to testify to the simulation of human dispersal and monsoonal environmental change in East Asia.

Clarifying the level and intensity of animal resource utilization is critical to understanding the process of human population change in northern and southern China during the Holocene, as domestic and wild animal resources were essential components of ancient human food sources. Currently, agriculture development has always been taken as the key driver of the Holocene population changes, and previous studies have revealed that dispersal of cultivation led to population growth, and changes in cultivation types also affected fluctuations of population. However, the contribution of animal resource utilization to changes in regional population is still unclear. Yu et al. (2024, this VSI) quantitatively reconstruct the spatiotemporal changes in Holocene population, and domestic and potential wild animal resources in northern and southern China, based on the combination of a large number of archaeological sites and a process-based terrestrial resource model. Potential connections among changes in population, animal resources, and climate are further discussed. Asynchronous population changes occurred in northern and southern China during 10–2 ka BP, which were correlated with regional domestic and potential wild animal resource utilization. In northern China, more significant population growth corresponded to a greater increase in domestic animal ratios and a sharp decline in potential wild animal resources after 8 ka BP. In southern China, less significant population growth was accompanied by a slower increase in domestic animal ratios and stable variations of potential wild animal resources. Yu et al. (2024, this VSI) suggest that different changes in potential wild animal resources in northern and southern China contributed to spatial variations in survival pressure, utilization level of domestic animals, and population growth, which expands the understanding of the driving mechanism of population evolution. Changes of precipitation further determine potential wild animal resources, thus, the study explains the impact of climate changes on the population from a new perspective.

5. Concluding remarks

The Asian monsoon has progressively become a megamonsoon system since early Cenozoic times due to the addition of India to the enlarging megacontinent of Eurasia and the ensued progressive closure of tropical ocean basins and seaways, the uplift and expansion of the Himalayan-Tibetan complex, and the westward retreat of the Paratethys Sea during the presently ongoing supercontinent cycle. The nineteen papers presented in this special issue address Cenozoic climate change mainly in Asia on multi-timescales and their linkages with global climate. The findings achieved by these studies contribute to a better undestanding of the complex nature of the Asian monsoon system involving strong land-air-sea interactions across timescales.

CRediT authorship contribution statement

Chenglong Deng: Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing. **Zhongshi Zhang:** Conceptualization, Writing – original draft, Writing – review & editing. **Qiuzhen Yin:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data availability

No data was used for the research described in the article.

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