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EDITORIAL

Holocene climate changes and paleoecology on the Tibetan Plateau: recent advances

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1 Introduction

The Tibetan Plateau (TP) is the largest and highest terrain on the Earth, comprising more than 80% of continents higher than 4000 m above sea level. The extremely high elevation resulted in cold and arid climate, sparse vegetation, limited available water resources, thin oxygen on TP, as well as desolated landscape, which makes it one of the most unfriendly habitable places on the Earth. However, ancient humans lived on TP as early as 200 thousand years ago (Chen et al., 2019; Zhang et al., 2020), and developed ancient civilizations, including the Tibetan Empire, Guge Kingdom in historical periods. It is essential to understand the environmental and ecological context of ancient human occupation of the high elevation TP, as well as how the mighty ancient geopolitical regimes came into power on the World's Roof.

The climate of TP is influenced by the Indian Summer Monsoon (ISM) and the mid-latitude Westerlies (Chen et al., 2008), which modulated spatiotemporal patterns of environmental changes. Previous studies showed that the monsoon could reach the northern TP in summers based on reanalysis data set in past decades (Schiemann et al., 2009). At glacial-interglacial time-scales, climate on TP was mainly influenced by the Westerlies in glacial periods, and by monsoon in interglacial periods (An et al., 2012; Zhu et al., 2015). On millennial scale, the influences of monsoon on TP generally retreated from north to south (Hou et al., 2017). TP experiences much faster warming in the context of current global changes, nearly twice of global mean temperature increases in the past decades (Zhou et al., 2020). Therefore, TP is considered as a key region to solve the Holocene temperature conundrum. Quantitative temperature records on TP would be helpful to understand the mechanisms for the Holocene temperature change.

Though the terrestrial vegetation is sparse, and their macrofossils are difficult to be preserved on TP, changes in vegetation using pollen and long-term vegetation evolution during the Holocene have been accomplished in many lakes. During the Last Glacial Maximum, extremely low total pollen concentrations are revealed from the available pollen records, suggesting the alpine desert was widely distributed on the TP with sparse vegetation (Cao et al., 2023). The total pollen concentrations rose significantly during the Last Deglaciation (with regional difference in starting time), and might infer the increase in vegetation coverage, which has also been supported by modern relationship between pollen concentration and vegetation cover (Liu et al., 2023). Widespread *Artemisia* suggested relatively dry climate 5 thousand years ago; vegetation showed strong spatial heterogeneity from the middle to late Holocene, with alpine desert in the western TP, and alpine meadow in the eastern TP (Cao et al., 2021; Xu et al., 2021). Although the natural-zoogenic or anthropo-zoogenic grazing cannot be excluded as the potential reason for the extension of alpine

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meadow during the late Holocene in the eastern TP, the recent studies revealed that grazing activity only commenced during the last few hundred years on the TP (Wang et al., 2023). It is essential to find more strong evidence to determine the contribution of human activities on vegetation changes.

2 Overview of paper in this Special Issue

When we proposed to edit a special issue for Frontiers of Earth Sciences, we aimed to solicit studies on spatiotemporal patterns of climate, environment, ecosystem, and their interactions with human activities, aiming to provide scientific basis for ecosystem management and protection on the TP. Finally, we have received more submissions than we expected. We selected 14 papers that meet the publication criteria for Frontiers of Earth Sciences. Topics of the papers include proxy verification, patterns of precipitation and hydrology on TP, quantitative temperature reconstruction from tree ring, lake sediment and loess, vegetation reconstructions using pollen, sedimentary DNA and charcoal, as well as human-environment interactions.

Wang et al. (2023, This issue) proposed the average chain length (ACL) as a proxy for precipitation, rather than temperature, vegetation, biome type on TP. The authors examined the *n*-alkane distributions of the surface sediments of 55 lakes across the TP, and found a significantly positive correlation between ACL and precipitation. Long-chain *n*-alkanes are one of the most common organic compounds in terrestrial plants and they are well-preserved in various geological archives. *n*-alkanes are relatively resistant to degradation and thus they can provide high-fidelity records of past vegetation and climate changes. Nevertheless, previous studies have shown that the interpretation of *n*-alkane proxies, such as ACL, is often ambiguous since this proxy depends on more than one variable. Both vegetation and climate could exert controls on the *n*-alkane ACL, and hence its interpretation requires careful consideration, especially in regions like TP where topography, biome type, and moisture source are highly variable.

Pu et al. (2023, This issue) sought to improve understanding of hydrological variability on decadal and centennial timescales in the source area of the Yellow River (SAYR) and to identify its general cause. The authors first determined annual fluctuations of surface area of Lake Ngoring from 1985 to 2020 using multi-temporal Landsat images, which were generally consistent with variations in precipitation, streamflow and the regional dry-wet index in the SAYR, suggesting that the water balance of the Lake Ngoring area is closely associated with regional hydroclimate changes. These records are also comparable to the stalagmite δ^{18}O monsoon record, as well as fluctuations in the Southern Oscillation Index (SOI). Moreover, an association of high TSI (total solar insolation) anomalies and sunspot numbers with the expansion of Lake Ngoring surface area is observed, implying that solar activity is the key driving factor for hydrologic variability in the SAYR on a decadal timescale. Following this line of reasoning, they compared the δ^{13}Corg-based lake level fluctuations of Lake Ngoring for the last millennium, as previously reported, with the hydroclimatic history and the reconstructed TSI record. The hydrological regime of Lake Ngoring has been mainly controlled by centennial fluctuations in precipitation for the last millennium, which is also dominated by solar activity. In general, it appears that solar activity has exerted a dominant influence on the hydrological regime of the SAYR on both decadal and centennial timescales, which is clearly manifested in the variations of lake area and water level of Lake Ngoring.

In the source region of the Yarlung Tsangpo, Sun et al. (2023, This issue) presented multiple proxy records at Gongzhu Co to study the alternating influences of the Westerlies and the ISM on the hydroclimate. The Yarlung Tsangpo, the longest river in the southern TP, has attracted much research attention aimed at understanding the factors controlling its modern hydrology and possible future discharge in the context of ongoing climate change. However, partly due to the complex regional climatic background, no consistent conclusions have been reached, especially for its upper reaches. Paleohydrological reconstructions of the source region of the Yarlung Tsangpo can potentially improve understanding of the history of humidity and its response to climatic variability. The authors used a 97-cm-long gravity core from Gongzhu Co to reconstruct the hydrology change during the late Holocene. The core was dated using AMS ^{14}C and Pb/Cs methods, and they used measurements of element contents (determined by high-resolution XRF scanning), grain size, IC/TOC, and magnetic susceptibility to reconstruct hydroclimatic changes in the source of the Yarlung Tsangpo watershed since ~4000 yr ago. Combined with a modern meteorological data set, the authors found that PC1 of the XRF data, the Ca/(Fe + Ti) ratio, and EM1 of the grain size data were indicative of changes in humidity. The records demonstrate a wet interval during ~4–1.7 ka BP (ka = 1000 yr, BP represents years before 1950 AD), followed by a dry period during since ~1 ka BP. Comparison with independent regional paleoclimatic records revealed shifts in the dominant factors controlling humidity. The wet interval during ~4–1.7 ka BP was coeval with a strengthened Westerlies, implying a dominant moisture supply from northern high latitudes. However, the extremely low values of Ca/(Fe + Ti) ratio during ~4–2.5 ka BP indicate potential glacial freshwater source, which is corroborated by the concurrent high magnetic susceptibility values and increased grain size. The rapid drying trend during ~1.7–1 ka BP suggests a switch in moisture supply from the Westerlies to the ISM. The authors attribute the drought conditions after ~1 ka BP to a weakened ISM, although a Westerlies influence and the potential effect of high temperatures on evaporation cannot be excluded.

Zhang et al. (2023, This issue) studied lake fluctuations in the central TP. Zige Tangco is a meromictic saline lake in the central TP. Two parallel cores, ZGTC A-1 and ZGTC A-2, were taken from the lake at 25 m water depth in summer of 2006. Chronology of core A-1 is established based on CIC model of ^{210}Pb and three AMS ^{14}C ages from chitin fragments. Hard water effect calibration of sediment ^{14}C age shows that the reservoir effect ranges from 1655 yr at 1950 AD to 1540 yr at 1610 AD. The hydrological variation in Zige Tangco during the past 800 yr is reconstructed using multi-proxies, including organic and carbonate content, stable isotopes of fine-grained carbonate minerals (< 38.5 μm) and grain-size distribution of the lake sediments. Between 1200 and 1820 AD, strong fluctuations of lake level and at least three dry periods at 1235–1315 AD, 1410–1580 AD, and 1660–1720 AD are recorded by high carbonate content, abrupt positive shifts of stable isotopes and high sand content. The low lake level periods during the Little Ice Age in Zige Tangco correspond to the lower δ^{18}O values in Guliya ice core, lower precipitation reconstructed from tree rings in Delingha, which demonstrates that summer monsoon on the central TP weakened whereas winter monsoon strengthened during the dry and cold periods. Relatively wetter periods or higher lake level in Zige Tangco occurred at 1580–1650 AD and at 1820–1900 AD Between 1800 and 1820 AD, negative shifts of stable isotopes are related to increased lake levels. The study also shows that the summer monsoon on the central TP is mainly controlled by solar activity during the past 800 yr.

Loess can be found across TP, which is one of the ideal archives to study dust transport and past climate change. Pan et al. (2023, This issue) studied a loess profile at Ranwu in order to explore the processes and interactions of dust transport and paleoclimate evolution in the south-eastern TP. Based on parametric grain size end-member analysis, optically stimulated luminescence (OSL) dating, and environmental proxies, the Ranwu loess profile comprises of five end members (EMs). EM1 represents the fine silt fraction transported by high-altitude westerly winds over long distances; EM2 represents the medium silt fraction accumulated by glacier winds; EM3 is the coarse silt fraction transported by local dust storms under the action of strong glacier winds; EM4 represents the very fine sand fraction transported by strong local dust storms, different wind strengths controls the relative proportion of EM3 and EM4 over time. EM5 is the coarse sand fraction formed from the product of strong weathering of gravels. OSL dating shows loess sedimentation at Ranwu started around 11.16 ka. The prevailing climate was generally warm and wet between 11.6 and 4.2 ka, with four cooling events at 10.50, 9.18, 7.85, and 6.37 ka. Extensive paleosol development between 8.2 and 4.2 ka, a change to dry and cold climate conditions was favorable for loess formation after 4.2 ka. The palaeoenvironmental changes and abrupt climate events recorded in the Ranwu loess sequence are consistent with Holocene global environmental change.

Stable oxygen isotopes are effective proxy indicators for past continental climate changes. Li et al. (2023, This issue) presented δ^{18}O records of *Tamarix* cones at Hongliujing area to study climate changes in Lop Nur during the past 200 years. The layers of *Tamarix* cones within sedimentary deposits in arid regions have significant chronological and paleoenvironmental implications. The authors first compared the δ^{18}O values of *Tamarix* cones in the Hongliujing area of Lop Nur with meteorological data for the Ruoqiang meteorological station for 1960–2019 AD. Linear regression analysis was used to reconstruct the average temperature for April and the precipitation for November in the Hongliujing area over the past 200 years. The results showed that the δ^{18}O values were significantly negatively correlated with the temperature for February, April, May, August, December, and with the annual mean temperature; significantly negatively correlated with the precipitation for February and April; significantly negatively correlated with the sunshine hours for March and May; significantly positively correlated with the sunshine hours for February, July, August, October, and December, and with the annual mean values; and significantly correlated with the relative humidity for April, July, August, September, October, and November, and with the annual mean values. Based on the δ^{18}O record of the past 200 years, the Hongliujing area experienced two warm-wet periods (1874–1932 AD and 2004–2019 AD) and two cold-dry periods (1832–1873 AD and 1933–2003 AD). Thus, the climate was characterized by alternating warm-wet and cold-dry conditions. Wavelet analysis revealed three main cycles: 45 years, 29 years, and 14 years.

Zheng et al. (2023, This issue) presented data-model comparison to understand the spatiotemporal patterns and mechanisms of moisture evolution on TP during the past 9500 years. The authors synthesized 27 paleoclimate proxy records covering the past 9500 years. The results of the rotated empirical orthogonal function analysis of the moisture variation revealed spatial-temporal heterogeneity, which was classified into 5 subregions. Proxy records were then compared with the results from the Kiel Climate Model and other paleorecords. The results showed that moisture evolution on the western-southern-central TP was controlled by the ISM. On the south-eastern TP, moisture change was affected by the interplay between the East Asian summer monsoon (EASM) and the Westerlies, as well as the ISM. With diverse patterns of circulation system precipitation, moisture changes recorded in the paleorecords showed spatial-temporal discrepancies, especially during the early to middle Holocene. Moreover, given the anti-phase pattern of summer precipitation in the EASM area under El Niño/Southern Oscillation (ENSO) conditions and the unstable relationship between the ISM and ENSO, it is reasonable to conclude that relatively strong ENSO variability during the late Holocene has contributed to these discrepancies as Asian summer monsoon precipitation has declined.

Temperature is one of the most important parameters in paleoclimate reconstruction. Li et al. (2023, This issue) presented a quantitative mean annual air temperature (MAAT) record spanning the past 4700 years based on the analysis of branched glycerol dialkyl glycerol tetraethers (brGDGTs) from a sediment core from Xiada Co, an alpine lake on the western TP. The record indicates a relatively stable and warm MAAT until 2200 cal yr BP; subsequently, the MAAT decreased by ~4.4°C at ~2100 cal yr BP and maintained a cooling trend until the present day, with centennial-scale oscillations centered at ~800 cal yr BP, ~600 cal yr BP, and ~190–170 cal yr BP. MAAT decreased abruptly at ~500–300 cal yr BP and reached its minimum for the past 4700 years. The authors assessed the representativeness of the record by comparing it with 15 published paleotemperature records from the TP spanning the past ~5000 years. The results show divergent temperature variations, including a gradual cooling trend, a warming trend, and no clear trend. The discrepancies could be caused by factors such as the seasonality of the temperature proxies, the length of the freezing season of the lakes, the choice of proxy-temperature calibrations, and chronological errors. The results highlight the need for more high-quality paleotemperature reconstructions with unambiguous climatic significance, clear seasonality, site-specific calibration, and robust dating, to better understand the processes, trends, and mechanisms of Holocene temperature changes on the TP.

Wang et al. (2023, This issue) reconstructed Holocene temperature variation using brGDGTs in a loess-paleosol sequence from the north-eastern TP. The authors worked on brGDGTs at a loess-paleosol sequence in the Ganjia Basin in the north-eastern TP to quantitatively reconstruct the MAAT over the past 12 ka. The MAAT reconstruction shows that the temperature remained low during the early Holocene (12 − 8 ka), followed by a rapid warming at around 8 ka. From 8 to 4 ka, the MAAT record reached its highest level, followed by a cooling trend during the late Holocene (4 − 0 ka). The variability of the reconstructed MAAT is consistent with trends of some annual temperature records from the TP during the Holocene. Relatively low temperatures during the early Holocene is suggested to be caused by the existence of ice sheets at high-latitude regions in the Northern Hemisphere and the weaker annual mean insolation at 35 °N. During the mid to late Holocene, the long-term cooling trend in the annual temperature record was primarily driven by declining summer insolation. This study provides key geological evidence for clarifying Holocene temperature change in the TP.

Asad et al. (2023, This issue) reconstructed summer temperature based on tree ring records in the western Himalayas of northern Pakistan over the past millennium. Using standard dendrochronological methods, an 1132-year (882 to 2013 AD) tree-ring chronology of Juniperus excelsa M. Bieb was established from the western Himalayas, northern Pakistan (WHNP). Tree growth was negatively and significantly ($r = -0.65$) correlated with the growing season (June–July) mean temperature, and positively and weakly ($r = 0.22$) associated with precipitation. This inverse relationship of tree radial growth with temperature and positive association with precipitation demonstrated that forest growth is sensitive to high temperature related drought. Utilizing a reliable STD chronology and robust reconstruction model, a 928-year (1086 to 2013 AD) mean temperature reconstruction was developed for the for the WHNP using the substantial negative correlation between the summer temperature and standard tree ring-width chronology. According to statistical validation, the reconstruction accounted for 41.6% of the climatic variation for the period of 1956–2013 AD instrumental period. Individual extreme-warm periods occurred in 1093 AD (29.42°C) and extreme cold periods in 1088 AD (26.99°C) observed during the past 928 years. The reconstruction's multi-taper method (MTM) spectral analysis reveals significant ($p < 0.05$) 2 − 3-year and 63.8-year cycles. Since the 2 − 3-year cycle occurred within the range of ENSO variation, this indicates that ENSO had an impact on the regional temperature in our studied area.

Tian et al. (2023, This issue) presented plant sedDNA metabarcoding and pollen assemblages of 27 lake surface-sediment samples collected counted pollen taxa and local plant communities in order to study the representation of vegetation communities surrounding lakes. Plant environmental DNA extracted from lacustrine sediments (sedimentary DNA, sedDNA) has been increasingly used to investigate past vegetation changes and human impacts at a high taxonomic resolution. Relative to pollen identification, sedDNA data have higher taxonomic resolution, thus providing a potential approach for reconstructing past plant diversity. The sedDNA signal is strongly influenced by local plants while rarely affected by exogenous plants. Because of the overrepresentation of local plants and PCR bias, the abundance of sedDNA sequence types is very variable among sites, and should be treated with caution when investigating past vegetation cover and climate based on sedDNA data. The sedDNA analysis can be a complementary approach for investigating the presence/absence of past plants and history of human land-use with higher taxonomic resolution.

Zhang et al. (2023, This issue) presented a high-resolution pollen record covering the last two centuries extracted from Gongzhu Co to study vegetation changes in the western TP. The records showed that alpine steppe is the predominant vegetation type in the surrounding area throughout the past 250 years with stable vegetation composition and abundance, as revealed by pollen spectra dominated by *Artemisia*, Ranunculaceae, Cyperaceae, and Poaceae. Detrended canonical correspondence analysis (DCCA) of the pollen data reveals low turnover in compositional species (0.41 SD), suggesting that the vegetation in the Gongzhu catchment had no significant temporal change, despite climate change and population increases in recent decades. DCCA analysis on ten other pollen records from the TP with high temporal resolution (1–20 years) covering recent centuries, and the results also show that compositional species turnover (0.15–0.81 SD) is relatively low, suggesting that the vegetation stability may have prevailed across the TP during recent centuries. More high-resolution pollen records and high taxonomic-resolution palaeo-vegetation records (such as 30 sedaDNA), however, are needed to confirm the vegetation stability on the TP.

Wang et al. (2023, This issue) identified and counted charcoal from topsoil samples covering the TP using the pollen methodology, and investigated its relationships with vegetation net primary production (NPP), elevation, climate (precipitation, mean temperature of the coldest month and warmest month) and human population by boosted regression trees (BRT). Results reveal that the concentration of microscopic charcoal, macroscopic charcoal, and total charcoal all increase from south-west to north-east, which is consistent with the trend that the population density on the TP is high in the east and low in the west, suggesting that an increase in human activity is likely to promote the occurrence of fire. The BRT modeling reveals that NPP, elevation, and mean temperature of the coldest month are important factors for total charcoal concentration on the TP, and the frequency and intensity of fires further increase with increasing vegetation biomass, decreasing elevation, and decreasing mean temperature of the coldest month. The spatial variation characteristics of charcoal from topsoil on the TP not only reflect well the spatial fire situation in the region, but also have a good indicative significance for vegetation, climate, and human activities.

An example of environment changes and ancient civilizations was presented by Xu et al. (2023, This issue). The discovery of Loulan ancient city (LA) in the early 20th century has important significance for understanding the history of Western regions and the Silk Road civilization. The current academic community still has disputes on whether LA was the capital of Loulan Kingdom, the time of its rise, peak and decline, and the process, rate and driving mechanism of human activity change. This study uses the radiocarbon dates (^{14}C) database of LA to reconstruct the history of the rise and fall of human activity, and finds that LA experienced more than ~500 years from its rise to its peak and then to its decline: 1) the city rose rapidly, and the population increased rapidly from ~0 to 230 AD ; 2) the city was prosperous and flourishing, and the intensity of human activity reached its peak from ~160 to 340 AD, especially in ~230 AD, when the population reached its peak; 3) the city accelerated its decline, and the intensity of human activity decreased significantly, and the population shrank rapidly from ~ 230 to 500 AD; 4) LA was completely abandoned after ~560 AD. The results of the ^{14}C dating database do not support that LA was the early capital of the Loulan Kingdom. By comparing the human activity record of LA with the existing high-resolution palaeoclimate records in the surrounding mountainous areas of the Tarim Basin and South Asia, it is found that the superposition of centennial-scale westerly circulation strength events and the ~500-year cycle of the Indian monsoon jointly controlled the precipitation and meltwater (snow) supply of the mountains in the Tarim Basin, affecting the changes of surface runoff and oasis area in the basin, which is one of the important factors causing the rise and fall of LA.

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