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Late Holocene vegetation and climate change on the southeastern Tibetan Plateau: Implications for the Indian Summer Monsoon and links to the Indian Ocean Dipole

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ABSTRACT

The Indian Summer Monsoon (ISM) is one of the most important climate systems, whose variability and driving mechanisms are of broad interest for academic and societal communities. Here, we present a well-dated high-resolution pollen analysis from a 4.82-m long sediment core taken from Basomtso, in the southeastern Tibetan Plateau (TP), which depicts the regional climate changes of the past millennium. Our results show that subalpine coniferous forest was dominant around Basomtso from *ca.* 867 to *ca.* 750 cal. yr BP, indicating a warm and semi-humid climate. The timberline in the study area significantly decreased from *ca.* 750 to *ca.* 100 cal. yr BP, and a cold climate, corresponding to the Little Ice Age (LIA) prevailed. Since *ca.* 100 cal. yr BP, the vegetation type changed to forest-meadow with rising temperatures and moisture. Ordination analysis reveals that the migration of vegetation was dominated by regional temperatures and then by moisture. Further comparisons between the Basomtso pollen record and the regional temperature reconstructions underscore the relevance of the Basomtso record from the southeastern TP for regional and global climatologies. Our pollen based moisture reconstruction demonstrates the strong multicentennial-scale link to ISM variability, providing solid evidence for the increase of monsoonal strengths over the past four centuries. Spectral analysis indicates the potential influence of solar forcing. However, a closer relationship has been observed between multicentennial ISM variations and Indian Ocean sea surface temperature anomalies (SSTs), suggesting that the variations in monsoonal precipitation over the southeastern TP are probably driven by the Indian Ocean Dipole on the multicentennial scale.

1. Introduction

As an important component of the global climate system (An et al., 2015), the Indian Summer Monsoon (ISM) has profound societal and economic influences on the regions they affect (Cook et al., 2010). Therefore, understanding the variability and driving mechanisms of the ISM is essential not only for understanding global atmospheric circulation and climate change but also for preventing and mitigating disaster and achieving sustainable development (An et al., 2015).

Considerable effort has been made during the past two decades to improve our understanding of the ISM system. Reconstructed ISM records spanning the past millennium comprising various types of palaeoclimatic archives and proxies, including stalagmite oxygen isotopes (Berkelhammer et al., 2010; Sinha et al., 2011, 2015; Zhao et al., 2015), marine sediments (Agnihotri et al., 2002;

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Anderson et al., 2002), tree ring widths and oxygen isotopes (Cook et al., 2010; He et al., 2013) and lacustrine sediment (Bird et al., 2014; Chawchai et al., 2015; Kasper et al., 2012; Yan et al., 2011), synthetically indicate complex patterns of monsoonal variability with discrepancies in different proxies and records. These discrepancies underscore the strong spatiotemporal variabilities of the monsoon strength over different regions on multicentennial to intra-seasonal time scales (An et al., 2015). Some studies attribute the centennial oscillations of ISM to the variability of solar forcing (Agnihotri et al., 2002; Cook et al., 2010; Zhao et al., 2015), surface temperature variations of the Atlantic Ocean (Tierney et al., 2016), and the thermal contrast between the Asian continent and Indian Ocean (Anderson et al., 2002). Recently, some high-resolution studies from the monsoonal central zone have suggested that the centennial oscillations of the ISM are related to the internal dynamics governing the ISM responses to the slowly evolving changes of external boundary conditions (Berkelhammer et al., 2010; Sinha et al., 2011). The monsoon strength over the monsoonal central zone has a close relationship with the Indian Ocean sea surface temperature anomalies (SSTs) in the Arabian Sea, Bay of Bengal and Indian-Pacific Warm Pool (IPWP) (Ashok et al., 2004; Berkelhammer et al., 2010; Polanski et al., 2014; Prasad et al., 2014; Saji et al., 1999; Tierney et al., 2016; Yan et al., 2011). Thus, the centennial oscillations of the ISM might be significantly modulated by the Indian Ocean SSTs. However, more crucial evidence from monsoonal regions is required to further validate this relationship and to improve our understanding of the ISM system.

The southeastern Tibetan Plateau (TP), with its high sensitivity to global climate change (Li et al., 2016), is a typical region influenced by the ISM (An et al., 2015). Well dated dendrochronology has been used to explore the ISM variations (Cook et al., 2010; He et al., 2013). However, these results may be insufficient to understand the multicentennial variability of the ISM because of the potential loss of low-frequency climate signals in tree ring records (Yang et al., 2014). Pollen based climate reconstructions have been widely reported over the TP, based on the reliable relationships among pollen, vegetation and the climate (Lü et al., 2011; Shen et al., 2006; Yu et al., 2001). Modern pollen data indicate that the mean annual precipitation is the most significant climate variable on the TP (Herzschuh et al., 2010; Lü et al., 2011; Shen et al., 2006). Reliable pollen records of the ISM evolution during the past millennium are scarce, mainly due to a shortage of chronologies (Hou et al., 2012).

In this study, we present a high-resolution lacustrine sedimentary record from Basomtso, southeastern TP, spanning the past millennium. The age model for this core is well constrained, is based on six radiocarbon dates from different depths and is verified by varve counting in the upper sedimentary layers. We measured the fossil pollen assemblages to reconstruct the history of the regional vegetation and climate changes, and to explore the variations of the ISM and its links to the Indian Ocean SSTs.

2. Regional setting

Basomtso is located in the eastern Nyainqentanglha Mountains on the southeastern TP at 3476 m above sea level (a.s.l.) (Fig. 1). As a moraine dammed lake, Basomtso is surrounded by mountains with an altitude of 4500–5200 m a.s.l.. Basomtso is a freshwater lake with a pH of 7.2 and a salinity of 0.12 g/l. The maximum depth occurs in the western and eastern lake areas, with a depth of 120 m. The lake covers an area of 26 km^2 and has a catchment area of 1209 km^2 (Wang and Dou, 1998). Basomtso is mainly influenced by the ISM in boreal summer years. According to the closest meteorological station from Nyingchi (94°28′1.2″ E, 29°34′1.2″ N, 3001 m a.s.l.), the mean July temperature (T_{July}) is 15.9 °C, the mean January temperature (T_{Jan}) is 0.9 °C and the mean annual precipitation (P_{ann}) is 1130 mm (90% falling between April and October) (Fig. S1). Modern temperate glaciers distribute in the basin, and the lake is mainly fed by glacier melt-water via fluvial runoffs of the Basom River and Nize River and discharges into Yarlung-Tsangpo (Brahmaputra) River through Ba River and then Niyang River (Wang and Dou, 1998).

Due to the extensive altitudinal gradients and complex topography, altitudinally-controlled vegetation belts occur on the south slope of the eastern Nyainqentanglha Range (Li et al., 1985). A mixed broadleaf-conifer forest can be found between 2500 and 3200 m a.s.l., primarily comprising *Pinus* and *Quercus* (Xu and Luo, 2010). Between 3200 and 4200 m a.s.l., the modern vegetation is a subalpine coniferous forest, dominated by *Abies*, *Picea*, *Betula* and *Cupressus*. *Picea* and *Abies* are the dominant constructive species and sometimes present as pure forests, e.g., *Picea* forests between 3200 and 3600 m a.s.l. and *Abies* forests above 3600 m a.s.l. (Xu and Luo, 2010). The upper timberline stands at approximately 4200 m a.s.l., above which the forest gradually gives way to alpine shrub (mainly comprising *Hippophae*, *Rubus*, *Rhododendron* and *Salix*), alpine meadow (mainly comprising *Artemisia*, *Viola*, *Saussurea*, *Trigonotis* and *Rhodiola*) and alpine tundra with increasing altitude (Xu and Luo, 2010). At present, the vegetation around Basomtso is an alpine coniferous forest, dominated by *Picea* and *Abies*.

3. Materials and methods

3.1. Sampling and dating

In October 2012, a 4.82-m long sediment core (BSCW-1) was retrieved from Basomtso at a water depth of 120 m using a UWITEC sample system, and two short cores (22 cm) parallel to the long core were collected using a gravity corer. The sediment cores were transported to the State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, and were kept at 3.9 °C until their analysis. The long sediment core was subsampled at 1-cm intervals in the lab. BSCW-1 primarily consisted of medium-to fine-grade laminates comprising gray fine silt and clay, whereas increased contents of coarse silt and sand relating to higher sediment inputs were found at depths of 0.8–0.9 m, 1.35–1.40 m, 2.78–2.82 m, 3.18–3.22 m, 3.71–3.76 m, and 4.71–4.82 m (Li et al., 2016).

The chronology is based on accelerator mass spectrometry (AMS) ^{14}C dates from six well-preserved leaves from different depths in BSCW-1. The measurements were made by Rafter Radiocarbon Laboratory, Institute of Geological and Nuclear Sciences, New Zealand. The conventional ^{14}C dates were calibrated using CALIB 6.0 with an IntCal13 calibration dataset (Reimer et al., 2013). One of the short sediment cores was used for thin section preparation following the methods of Liu et al. (2014), and the other was sampled at 1-cm interval and used for radiometrically dating by measuring ^{137}Cs activity as a function of depth. Optical microscope analysis was performed to study the sedimentary microfacies, to count varves and to measure the varve thicknesses (Fig. S2).

3.2. Analytical method

Samples for pollen analysis were determined at 4-cm intervals and treated using standard laboratory methods (Faegri et al., 1989), including treatment with HCl (10%) and HF (50%) to remove carbonate and silicate, boiling in KOH (10%) to remove humic acid, sieving to remove the fine and coarse fractions, and mounting in silicone oil. To calculate the concentrations of pollen, tablets