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Lacustrine record of centennial- and millennial-scale rainfall variability of the East Asian summer monsoon during the last deglaciation: Multi-proxy evidence from Taiwan

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ABSTRACT

Situated at the border between the Southeast Asian continent and the northwestern Pacific, Taiwan's climate is primarily influenced by the East Asian Summer Monsoon (EASM) and episodic tropical cyclones formed in the western Pacific. The lake sediments in Taiwan thus potentially archive the information of typhoon events and past monsoon variability. A high-resolution multi-proxy (total carbon, mass accumulation rate of total carbon, weight percent of wood fragments, $\delta^{13}C$ of the organic carbon, magnetic susceptibility, chemical weathering index) and well-dated lacustrine record from Dongyuan Lake (22°10′N, 120°50′E; 360 m above sea level) in southern Taiwan was used to reconstruct centennial to millennial timescale EASM oscillations specifically for the transition from the last deglaciation to the Early Holocene (17–9 ka BP). The temporal patterns of proxies on both timescales in our records broadly agree with those in the Greenland ice core, which shows enhanced EASM during the warm period and weakened monsoon during the cold period. Different from northern high-latitude climates, we found two phases in the Mystery Interval, opposite Bølling–Allerød (BA) trend with maximum monsoonal rainfall in the Allerød period and more gradual transition to Younger Dryas event in our record. Likely, other climate forcings beyond the North Atlantic climate jointly modulated the EASM. Changes of sea surface temperature in the western tropical Pacific also might have exerted synergistic control on EASM precipitation in Taiwan on the centennial timescale during the last deglaciation. In addition, several high sedimentation events accompanied by significant amounts of wood fragments were observed and coincide with the paleo-record of mass wasting events identified on various downstream floodplains in Taiwan. Since mass wasting processes were rainfall-driven and threshold-triggered, such coherence possibly indicated an intensification of typhoon activity during the early Holocene. More high-resolution lacustrine records are required to decipher the hydrological variation and climate dynamics that were co-influenced by the Intertropical Convergence Zone (ITCZ) and typhoon activity in Southeast Asia.

1. Introduction

The East Asian Monsoon (EAM) is an important component of the global climate system and plays a significant role in global hydrologic and energy cycles. The evolution of the EAM is a principal and direct factor that has influenced the past environment in East Asia, particularly the amount and distribution of precipitation on both local and regional scales that directly determines the prosperity of livelihood of tens of thousands of people who live in monsoonal regions in East Asia (An, 2000). A full understanding of the EAM variability in the past and its forcing mechanisms is vital to accurately predict its future evolution.

The history of the EAM has been explored since the early 1990s (An, 2000 and references therein). The precise timing and structure of East Asian Summer Monsoon (EASM) variability in different timescales have been well established by Chinese stalagmite records over the past decade (Cai et al., 2006; Cheng et al., 2006, 2009, 2012; Dykoski et al., 2005; Liu et al., 2008, 2013; Ma et al., 2012; Wang et al., 2001, 2005, 2008; Yang et al., 2010; Yuan et al., 2004). The East Asian monsoon is characterized by orbitally controlled cycles, punctuated by millennial and sub-millennial timescale events and synchronous with northern high latitude climate variation (e.g., Cheng et al., 2006; Liu et al., 2013; Ma et al., 2012; Wang et al., 2001, 2008). The climate variability during the last deglaciation (Termination I) is one of the most intriguing areas of paleoclimate research due to a serial abrupt climatic fluctuations including millennial scale events such as the "Mystery Interval" (MI, 17.5–14.5 ka BP, Denton et al., 2006), Bølling-Allerød Interstadial (BA, 14.5–12.9 ka BP) and Younger Dryas Stadial (12.9–11.7 ka BP) and sub-millennial scale events (i.e., Older Dryas, OD; Intra-Allerød Cold Period, IACP), which may advance our understanding of earlier abrupt

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climate change (Genty et al., 2006) and help us to assess future environmental changes under modern global warming. The consistency in the timing and duration of the millennial and sub-millennial scale events during the last deglaciation as observed in Chinese Speleothem records and Greenland temperature records provides evidence for a teleconnection between the EASM system and the climate in northern high latitudes (Dykoski et al., 2005; Ma et al., 2012; Wang et al., 2001; Wang et al., 2005; Yang et al., 2010).

However, the climatic interpretation, particularly the moisture sources, of stalagmite records still remains debatable (Maher and Thompson, 2012; Pausata et al., 2011). Recently, the variation of $\delta^{18}O$ in Chinese stalagmite records was proposed to reflect "a mean state of summer monsoon intensity or integrated moisture transport rather than local precipitation" (Cheng et al., 2012). A recent model study further corroborated this view (Liu et al., 2014). Although the authors suggested that the stalagmite $\delta^{18}O$ records in China do represent the intensity of EASM, these records do not seem to be related to the rainfall changes in southeastern China (Liu et al., 2014). Nevertheless, high-resolution and well-dated records of the EASM prior to the Holocene are almost exclusively from Chinese stalagmite studies. In addition, the correlation between EASM precipitation and the sea surface temperature in the tropical Pacific in the past remains ambiguous, although several reports have suggested the variation of sea surface temperature (SST) in the western tropical Pacific also might have important impacts on the EASM (Cai et al., 2010; Selvaraj et al., 2007, 2011; Zhong et al., 2015). Thus, more independent high-resolution natural archives, especially for the low latitude regions, are urgently needed to fully understand the EASM variability, particularly the magnitude, frequency and forcing mechanisms of the EASM during the last deglaciation.

Taiwan Island is located off the southeastern coast of mainland China and sits along the front edge of the East Asian monsoon range; therefore, it is geographically suitable for exploring past monsoon variability through its natural archives such as lake sediment and peat deposits (Lee et al., 2010, 2014; Li et al., 2013; Liew et al., 2006a, 2006b, 2014; Selvaraj et al., 2007, 2011, 2012; Wang et al., 2014, 2015; Yang et al., 2011, 2014). The climate of Taiwan is mainly influenced by the East Asian monsoon system superimposed by episodic tropical cyclones (typhoons). On average, 3–4 typhoons make landfall during late summer and early fall every year (Chen and Chen, 2003). The total rainfall of Taiwan is very high (3300 mm) and tropical cyclones account for as high as 47.5% of the total (Chen et al., 2010). In addition to typhoon rain, a strong seasonality can be observed with warm and wet seasons during the boreal summer (May–September) and relatively cool and dry seasons during the winter (October–April). Because of typhoon-induced high precipitation (and thus high erosion and sedimentation rates) and strong tectonic activities, Taiwan Island has the world's largest physical weathering rate (Kao and Milliman, 2008; Li, 1976); therefore, the lacustrine sediment records in Taiwan are generally younger than the last glacial period except for a few longer records (e.g., Liew et al., 2006a; Yang et al., 2011). The ~14.5-m-long core TYP-B retrieved from Dongyuan Lake in southern Taiwan fortunately covered the last 21 ka. Previously, palynological records and sedimentary organic matter have been published in low temporal resolution to infer vegetation change and monsoonal rainfall evolution (Lee and Liew, 2010; Yang et al., 2011). Due to their relatively lower sampling resolution, the fine structures and mechanisms of the climate oscillation variability during the last deglaciation and Early Holocene have not been revealed and discussed. In this study, we present a multi-proxy record (total carbon, mass accumulation rate of total carbon, weight percent of wood fragments, $\delta^{13}C$ of the organic carbon, magnetic susceptibility and chemical weathering index) with high sampling resolution for the period of the last deglaciation from Dongyuan Lake in southern Taiwan. The fine structures of climate oscillation variability are thus reconstructed, which facilitates a comparison with other records from mainland China and the North Atlantic region to examine different climatic responses at centennial to millennial scale.

2. Geographical setting and modern climate

Dongyuan Lake (22°10′N, 120°50′E; 360 m above sea level), is located along the northern edge of a hilly basin in southern Taiwan, near the head waters of Mudan River (Fig. 1). At present, the lake has a surface area of 2×10^4 m^2. The lake level is less than 2 m and the drainage area covers approximately 94×10^4 m^2 and ranges from 360 m to 500 m a.s.l. The surrounding catchment of Dongyuan Lake is covered by lowland subtropical evergreen forest (Lee and Liew, 2010). According to instrumental records from a nearby meteorological station, the contemporary average monthly air temperatures in the study area vary between 20.7 °C and 28.4 °C with an annual mean temperature of 25.1 °C (Fig. 1C). The annual precipitation is greater than 2000 mm, and approximately 90% of the precipitation occurs during the summer when southwesterly monsoon prevails and typhoons frequently pass. Over half of the summer rainfall comes from tropical typhoons which commonly bring intensive rainfall (>100 mm/d) for a few days (see spiky daily rainfall in Fig. 1D).

3. Sampling and methods

Core TYP-B was retrieved from the center of Dongyuan Lake in 2004. Yang et al. (2011) previously used 16 AMS ^{14}C dates on organic materials of wood and plant debris to establish the chronology of the entire core (14.5 m). For this study, we focused on the middle part of this core from 8.5 to 13.2 m, which is comparable to the last deglaciation and the Early Holocene. We added 12 radiocarbon dates for this specific period to obtain a better age model. To obtain higher temporal resolution analyses, we subsampled at 1-cm intervals so that a total of 460 sub-samples were obtained from this segment with an average temporal resolution of approximately 16 calendar years, which is adequate to reveal multi-decadal to centennial scale variations in paleoclimate.

For total carbon analysis, an aliquot of freeze-dried, ground bulk sediments was analyzed with a HORIBA model EMIA-220 V C/S analyzer at 1350 °C. Note that, there is a certain amount of wood debris present in some sections of this core, thus, we picked out and weighed these wood debris before the measurements. Here, we analyzed the total carbon content instead of organic carbon as a paleoclimate proxy because the concentrations of TOC and TC were highly correlated (Fig. 2, $r^2 = 0.97$, $n = 95$). On the other hand, independent analysis on clay minerals revealed that the core contained only a trace amount of carbonate (Yang et al., 2011). Thus, we use TC hereafter in this study.

Magnetic susceptibility (MS) was measured with a Bartington MS2 Susceptibility System mounted on an ASC auto-tracking rail. Samples were also taken at 1-cm intervals.

The isotopic compositions of organic carbon were measured at 2–5 cm intervals by using an elemental analyzer (EA2100 Carlo Erba) coupled with a Thermo Finnigan Deltaplus Advantage isotope ratio mass spectrometer (IRMS), as detailed in Kao et al. (2006, 2008). All the isotopic values are presented in standard δ-notation in per mil (‰) with respect to Pee Dee Belemnite (PDB) carbon. The reproducibility of the carbon isotope measurements is better than 0.2‰.

Major elements (Al, Na, Ca and K) were taken at 5-cm intervals and analyzed by using an ICP-OES (Optima 3200DV, Perkin-Elmer™ Instruments, Waltham, Massachusetts, United States) to assess the state of chemical weathering. The total digestion method has been reported by Hsu et al. (2003). The major element contents were converted into their stoichiometric oxides for further calculation.

The total sediment accumulation rate (SAR) and mass accumulation rate (MAR-TC) of total carbon were calculated by using the following formula:

$$\mathrm{SAR}\ (\mathrm{g\ cm^{-2}yr^{-1}}) = \mathrm{DBD}\ (\mathrm{g\ cm^{-3}}) \times \mathrm{LSR}\ (\mathrm{cm\ yr^{-1}}) \quad (1)$$

$$\mathrm{MAR\text{-}TC}\ (\mathrm{g\ cm^{-2}yr^{-1}}) = \mathrm{SAR} \times \mathrm{TC}(\%) \quad (2)$$