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Hydrological and ecosystem response to abrupt changes in the Indian monsoon during the last glacial, as recorded by sediments from Xingyun Lake, Yunnan, China

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ABSTRACT

The Indian Summer Monsoon (ISM) is the major moisture source of precipitation in southwest China and plays an important role in regional environmental change and in economic and social development, since abrupt changes of the ISM can cause crop failures and flooding that impact the livelihood of a large population. However, with the exception of speleothem records, abrupt changes of the ISM during the last glacial are not well documented in terrestrial records. Here we present a sediment record from Xingyun Lake in Yunnan Province, southwest China, spanning the interval 36.4 ka BP to 13.4 ka BP (1 ka = 1000 cal a) which documents the occurrence of a series of millennial-scale episodes which may reflect the abrupt weakening of the ISM. Seven AMS ^{14}C dates from terrestrial wood fragments provide a robust chronology. The results demonstrate that increases in the coarse sediment fraction (>30 μm) correspond to increases in the concentration of *Pediastrum*, the grain size of magnetic minerals, carbonate content and C/N ratios, which together indicate episodes of low lake level. In addition, pollen analysis indicates that *Quercus* (oak) increased and that ferns decreased during intervals of abrupt weakening of the ISM, indicating a drier environment. Nine abrupt shifts to a low lake level are documented for the studied interval and three of them are correlative with Heinrich events 1 to 3. Our study supports the hypothesis that, in response to the cold events in the North Atlantic associated with massive iceberg influxes and the corresponding slowing down of Atlantic meridional overturning circulation, the mean latitudinal extent of the ITCZ shifted southwards. As a result of an atmospheric teleconnection there was a corresponding decrease in precipitation associated with ISM precipitation, which caused reduced fluvial runoff in Yunnan.

1. Introduction

The Indian Summer Monsoon (hereafter ISM) is the main source of precipitation for a major part of Asia. Variability of the ISM, especially abrupt changes, can have significant environmental, social and economic effects within its region of influence (Turner and Slingo, 2011; Cook et al., 2013). For example, extreme variations of the ISM can cause crop failures and flooding that impact almost two-thirds of the world's population (Webster et al., 1998). In addition, the potential effects of changes in ISM variability may be felt in other regions via atmospheric and oceanic teleconnections (Wang, 2009). In the past few decades, abrupt changes of the ISM have been inferred from marine sediments in the Arabian Sea (Schulz et al., 1998; Leuschner and Sirocko, 2000; Altabet et al., 2002; Govil and Naidu, 2010; Deplazes et al., 2013); the Bay of Bengal and the Andaman Sea (Colin et al., 1998) and speleothems from Socotra Island (Burns et al., 2003; Shakun et al., 2007), India (Sinha et al., 2005) and China (Cai et al., 2006). However, relatively few terrestrial paleoclimatic records of the ISM are from monsoon-dominated regions (Cook et al., 2013; Chabangborn et al., 2014; Dixit et al., 2014). In addition, the environmental significance of stable isotope records from stalagmites remains highly debated (Wang et al., 2001; Yuan et al., 2004; Maher, 2008; Clemens et al., 2010; Pausata et al., 2011; Liu et al., 2014; Tan, 2014). It is also noteworthy that marine paleoclimatic records can exhibit significant differences to terrestrial records; for example, Xu et al. (2013) demonstrate that terrestrial deglacial warming lagged behind marine changes by cal 3–4 ka, based on a sediment core from the Okinawa Trough. Therefore, reliable high resolution paleoclimatic terrestrial records are needed from the ISM-dominated region so that the influence of abrupt climate changes on terrestrial ecosystems can be assessed.

Yunnan, in southwestern China, is located in the heart of Monsoon Asia and is significantly influenced by the ISM (An et al., 2011; Cook et al., 2013). The availability of sedimentary records from numerous lakes makes Yunnan very suitable for reconstructing the evolution history of the ISM (X.M. Chen et al., 2014; Xiao et al., 2014). Previous

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work documents the occurrence of five episodes of lake expansion and contraction during the last 40 ka in the Xiaozhongdian Basin, Yunnan, which can be compared with the H0–H4 events recorded in the North Atlantic Ocean (Ming et al., 2011). In addition, peaks in carbonate content and a coarsening of quartz grain-size in sediments from Qilu Lake highlighted the changes from warm, moist interstadial conditions and cold, dry stadial conditions during the last glacial (Hodell et al., 1999). However, because of the limitations of the sediment dating methods and different environmental proxies used in these various studies, the timing and magnitude of the reported abrupt climatic changes are equivocal. In addition, the impacts of these abrupt climate changes on the ecosystem are unclear, especially on the lake ecosystem. For example, abrupt climatic events recorded in the Xiaozhongdian Basin were solely interpreted as reflecting a decrease of the intensity of the ISM and no ecosystem effects were discussed (Ming et al., 2011).

The study reported here of the sediments of Xingyun Lake, Yunnan, uses a combination of accelerator mass spectrometry (AMS) radiocarbon dating of terrestrial plant macrofossils and measurements of sediment grain size, carbonate content, magnetic parameters, total organic carbon (TOC), total nitrogen (TN), C/N ratios and *Pediastrum* concentration in order to: 1) identify any hydrological and ecosystem changes, especially abrupt changes potentially associated with the ISM, in southwestern China during the last glacial; and 2) explore the possible drivers of the abrupt ISM changes via regional comparisons.

2. Regional setting

Xingyun Lake, a semi-closed shallow lake, is located in the central part of Yunnan Province, southwestern China. The current lake level is 1722 m a.m.s.l. and the surface area is 34.7 km^2; the catchment area is 386 km^2. The maximum water depth is 11 m, with an average depth of 7 m (Zhang et al., 2010). Drainage into the basin is primarily via rainfall and there are more than 14 in-flowing rivers (Zhao and Zhao, 1988). The climate of the region is relatively cool from October to April (mean 8–14 °C), and warm from May to September (mean 16–20 °C) (Fig. 1C). The mean annual precipitation is about 979 mm with almost 60% falling from June to August, based on instrumental observations from Kunming Station, 80 km north of Xingyun Lake, during 1981–2010 (Fig. 1C). Thus the lake and the surrounding area are currently influenced by a typical subtropical monsoonal climate (Fig. 1B). The catchment geology includes dolomite, sandstone and sandy shale and the catchment is currently occupied by secondary coniferous forest dominated by *Pinus armandii* and *Pinus yunnanensis* (Song et al., 1994).

3. Material and methods

3.1. Sampling and sediment lithology

In 2008, we obtained a 974-cm long sediment core (XY08A) using a UWITEC sampling system from the center (24°20.08′N, 102°46.92′E) of Xingyun Lake in a water depth of 9.0 m (Fig. 1A). Here, we focus on the sediments spanning the depth interval 4.90–9.74 m of the core because immediately above there was an interval of unrecovered sediment, post-dating 5 ka (F.H. Chen et al., 2014). The lithology of the studied interval is dark grayish silty clay (Fig. 2).

3.2. Laboratory methods

Slicing the core at 2 cm intervals yielded 242 samples which were freeze-dried for storage and analysis. The grain size of all the samples was measured using a Malvern Mastersizer 2000 laser grain size analyzer. The grain size distribution was calculated for 100 grain size classes within a measuring range of 0.02–2000 μm, and the analytical error was less than 1%. Prior to measurement, the samples were pretreated with 10 ml of 30% H_2O_2 to remove organic matter and then with 10 ml of 10% HCl to remove carbonates. Then, about 100 ml deionized water was added and the samples were kept stationary for 24 h. After the supernatant was siphoned off, 10 ml of 0.05 mol/l $(NaPO_3)_6$ was added as the dispersant, and the samples were then ultrasonicated for 8 min prior to grain size measurements.

Low-frequency (0.47 kHz) magnetic susceptibility (χ_{LF}) was measured using a Bartington MS2 magnetic susceptibility meter with an MS2B dual frequency sensor (Bartington Instruments Ltd, Witney, UK). Anhysteretic remanent magnetization (ARM) was measured using a DTECH AF demagnetizer (ASC Scientific, California, USA) with a peak AF field of 100 mT and DC biasing field of 0.1 mT; it is expressed as an anhysteretic susceptibility (χ_{ARM}) by dividing by the biasing field strength. Saturation isothermal remanent magnetization (SIRM) was imparted in a 1T DC field. All remanence measurements were made using a Minispin magnetometer. All magnetic parameters are expressed on a mass-specific basis and were measured following the procedures of Walden et al. (1999).

After treatment with HCl to remove inorganic carbon, total organic carbon (TOC) and total nitrogen (TN) (from which carbon/nitrogen (C/N) ratios were calculated) were measured at an 8 cm interval using an elemental analyzer (VarioEL Cube, Elementar Analysensysteme GmbH, Germany). *Pediastrum* analyses were performed at either a 4 or a 12 cm interval using the preparation methods of Moore et al. (1991). Weight-loss on ignition was measured by igniting freeze-dried samples in a furnace for 2 h at 550 °C. Subsequently the weighed ash samples were ignited at 950 °C for 4 h, and the resulting weight lost multiplied by 1.36 to allow for the difference between the molecular weights of CO_2 and CO_3 in order to estimate the carbonate content which can then be expressed as a percentage of the dry weight (Dean, 1974). All of the above analyses were carried out in the Key Laboratory of Western China's Environmental Systems, Lanzhou University. Seven terrestrial plant macrofossils (wood fragments) were extracted from the core sediments for AMS ^{14}C dating in order to minimize the carbon reservoir effect that commonly occurs in lacustrine sediments (Zhou et al., 2009; Hou et al., 2012). The analyses were conducted at the AMS Dating Laboratory of Beijing University and by Beta Analytic, Florida, USA.

4. Results

4.1. Chronology

The ^{14}C dating results are listed in Table 1. The dates were calibrated to calendar years before present (BP, before 1950 AD) with program CALIB 6.0.1 (IntCal09 calibration data set) (Reimer et al., 2009). The age-depth model (Fig. 2) was established by fitting spline functions to the age-depth points using Clam (Blaauw, 2010) implemented by the statistical software package R. The sediment accumulation rate averages 0.45 mm yr^{-1} in the interval from the base of the core to ~616 cm, and 0.09 mm yr^{-1} from ~616–490 cm (X.M. Chen et al., 2014). These two sedimentary regimes, characterized by significantly different sediment accumulation rates, may correspond to significant differences in lake level, which are discussed in Section 5.1, below. The resulting chronology yields an average resolution of (i) ~94 yr for the magnetic susceptibility and sediment grain size data; (ii) ~371 yr for the TOC, TN and C/N data; and (iii) ~371 yr for the *Pediastrum* data. The average resolution for these three data categories from the base of the core to ~616 cm is ~47, ~181 and ~275 yr, respectively; and from ~616–490 cm the average resolution is ~225, ~967 and ~460 yr, respectively.

4.2. Variations of the environmental proxies

Comparison of the standard deviations of the different grain-size classes is a common method for identifying the grain-size intervals with highest variability within a sedimentary sequence (Boulay et al., 2003), and this approach has been used successfully in studies of marine