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Precisely dated multidecadally resolved Asian summer monsoon dynamics 113.5–86.6 thousand years ago

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A B S T R A C T

We present a new ^{230}Th-dated absolute chronology of Asian summer monsoon (ASM) variability from 113.5 to 86.6 kyr BP (before 1950 AD). This integrated multidecadally resolved record, based on 1435 oxygen isotope data and 46 ^{230}Th dates with 2-sigma errors as low as ±0.3 kyr from three stalagmites collected in Sanxing Cave, southwestern China, can be a new reference for calibrating paleoclimate proxy sequences. The Sanxing δ^{18}O record follows the 23 kyr precessional cycle of insolation and is punctuated by prominent millennial-scale oscillations of the Chinese Interstadials (CIS) 25 to 22, corresponding to Greenland Interstadials (GIS) 25 to 22. The onset of CIS 25, 24, 23 and 22 is dated to 113.1 ± 0.4, 108.1 ± 0.3, 103.7 ± 0.3 and 91.4 ± 0.6 kyr BP in the Sanxing record, respectively. The end of CIS 24 and CIS 22 is constrained to 105.5 ± 0.4 and 87.7 ± 0.3 kyr BP, respectively. A centennial-scale precursor event at 104.1 ± 0.3 kyr BP preceding CIS 23 is clearly registered. These events in the Sanxing record are synchronous with those identified in stalagmites from the European Alps (NALPS), except for the onset of GIS 25 and the end of GIS 22, and differ by up to 2.3 kyr from the corresponding ones in Greenland ice core records. The high degree of similarity of the δ^{18}O records between Sanxing Cave and Greenland supports a Northern Hemisphere forcing of the ASM. The anti-phase relationship of δ^{18}O records between Sanxing stalagmites and Antarctic ice cores suggests an additional ASM linkage to the Southern Hemisphere.

1. Introduction

Millennial and sub-millennial climatic variability is a key element of glacial periods as prominently documented by ice-core records (e.g., Dansgaard et al., 1993; McManus et al., 1999; North Greenland Ice Core Project Members, 2004; Capron et al., 2010a). These abrupt and recurrent variations, known as Dansgaard-Oeschger oscillations, were first described and numbered in Greenland ice cores (Dansgaard et al., 1993), with relatively warm Greenland interstadials (GIS) and cold Greenland stadials (GS) (Rousseau et al., 2006). Polar ice cores synchronized by methane (Blunier et al., 1998, 2007; Blunier and Brook, 2001) allowed to decipher the interhemispheric dynamics (Stocker and Johnsen, 2003). A milestone in the understanding of the precise linkage between high- and low-latitude climate variability was the study of Hulu Cave stalagmites (Wang et al., 2001), which demonstrated a tight correlation between the intensity of the Asian summer monsoon (ASM) and the North Atlantic climate during Marine Isotope Stages (MIS) 4-2, i.e. from 71 to 14 thousand years before present (kyr BP) (before AD 1950; note that all subsequent dates reported and discussed in the present study refer to this datum). This and subsequent speleothem records from this region provide a precisely dated template against which ice-core and other records

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can be compared, and demonstrate a fast response of the Asian monsoon (AM) to the climate variability in Northern Hemisphere (NH) high latitudes on decadal to millennial timescales (e.g. Wang et al., 2001, 2005; Gupta et al., 2003; Yuan et al., 2004; Liu et al., 2010; Deplazes et al., 2014; Zhao et al., 2010; Duan et al., 2014; Zhang et al., 2014). However, the sub-millennial to millennial-scale climate variability prior to MIS 4 is only poorly resolved by currently available speleothem records showing low-resolution and/or relatively large dating uncertainties (Kelly et al., 2006; Wang et al., 2008; Zhou et al., 2008; Li et al., 2014).

MIS 5 (130-70 kyr BP) (Shackleton, 1987), a period of relative small ice-sheet extent, large seasonal insolation changes, and high CO_2 concentrations, was characterized by remarkable long and low-frequency GIS events compared to MIS 3 (North Greenland Ice Core Project Members, 2004). However, our knowledge of the high-to-low latitudinal climate linkage during MIS 5 is limited by the scarcity of high-resolution AM records of sufficiently precise chronology. This difficulty has been exacerbated by several recent updates of ice-core age models (e.g., Wolff et al., 2010; Capron et al., 2010b; Veres et al., 2013).

A stalagmite record from central China suggests that the teleconnection between the ASM and high-latitude NH climate was significantly weaker between 120 and 110 kyr BP, i.e. during MIS 5d (Zhou et al., 2008). Zhou et al. (2008) proposed that the glacial boundary condition with low ice volume led to a decoupling of the ASM from the North Atlantic climate. Instead, stalagmite records from Dongge and Sanbao caves in southern and central China reveal a double ASM maximum during MIS 5c, corresponding to GIS 24 and 23 (Kelly et al., 2006; Wang et al., 2008), a period of lower ice volume than during MIS 5d (Lisiecki and Raymo, 2005). The NGRIP-EPICA Dronning Maud Land (EDML) common timescale shows a strong bipolar sequence of climate events during MIS 5 (Capron et al., 2010b). Additional prominent precursor events (PEs), also present in ice-core $\delta^{18}O$ and CH_4 records, preceded GIS 23 and 21 by 100–300 yr (Capron et al., 2010a). Absolutely dated records of comparable high resolution are a prerequisite to better understand the origin of monsoon variability on millennial and sub-millennial scales during times of reduced NH ice sheets.

Recent studies suggest differences between the ASM and NH high-latitude climate on orbital to sub-millennial scales. Additional forcing by the Southern Hemisphere (SH) via the cross-equatorial flow (Cai et al., 2006; Liu et al., 2008; An et al., 2011) or climatic feedbacks in the tropical Pacific (Partin et al., 2007) are thought to modulate the AM. Based on a comparison between Hulu Cave and ice-core records, Rohling et al. (2009), however, proposed a dominant control on millennial-scale monsoon variability by SH (NH) climate change during glacial (deglacial and interglacial) times when the monsoon is weak (strong). A detailed record of the AM during MIS 5, including the last glacial inception and the early stage of last glacial, is clearly needed to advance our understanding of the role of the NH versus the SH climates in influencing the ASM.

Here we present a new multidecadally resolved oxygen isotope record, covering the interval between 113.5 and 86.6 kyr BP, i.e. the early part of the last glacial period. The record is based on three stalagmites from Sanxing Cave, southwestern China, and is anchored by high-precision U–Th dates with uncertainties of less than 0.5%. The oxygen isotopes record the evolution of the ASM between Chinese interstadials (CIS) 25 and 22 in unprecedented detail. A comparison with NH and SH temperature records supports a teleconnection to the high-latitude climate. Furthermore, the MIS 5 portion of current ice-core timescales (Wolff et al., 2010; Capron et al., 2010b; Veres et al., 2013) is compared to this well-dated stalagmite record.

2. Site, material, and methods

Sanxing Cave (107°11′E, 27°22′N) is located in Tiechang, ~70 km southeast of Zuiyi City, Guizhou Province, southwestern China (Fig. S1). This 2 km-long cave, with only one entrance at an elevation of 720 m and a mean annual air temperature of 14.5 ± 0.5 °C, is located 270 km southeastward of Dongge Cave and 600 km northeastward of Sanbao Cave (Fig. 1). The regional climate is subtropical and characterized by distinct seasons, rainy hot summers and dry cold winters. Local mean annual air temperature, recorded at the nearest meteorological station (Zuiyi, 27°42′N, 106°52′E; elevation 844 m, 70 km NW of Sanxing Cave), is 13.5 ± 0.5 °C (1950-2000), ranges from 1.6 °C in winter to 22.5 °C in summer. Mean annual precipitation is 980 ± 50 mm (1 σ; 1950-2000) (Fig. S2). The cave is overlain by approximately 30 m of Permian limestone with a thin soil cover. The well-developed vegetation above the cave is dominated by subtropical broadleaf evergreen and a deciduous mixed forest.

Three calcitic stalagmites, SX7, SX24 and SX29, were collected in June 2012, approximately 900 m from cave entrance. They are 995, 358 and 420 mm long and 80, 70, and 65 mm in diameter, respectively (Fig. S3). For U–Th dating, 46 powdered subsamples (Fig. S3), ~50 mg each, were drilled from the polished cut surfaces of the stalagmites on a class-100 clean bench in a class-10,000 clean room. The procedure for chemical separation and purification of U and Th is described in Shen et al. (2002). An isotope dilution method with a $^{229}Th–^{233}U–^{236}U$ triple-spike tracer, calibrated with U–Th standards (Cheng et al., 2013) and isotopic equilibrium carbonate (Meyer et al., 2009), was employed (Shen et al., 2012). U–Th isotopic compositions and contents were determined using a Thermo-Fisher NEPTUNE multi-collection inductively coupled plasma mass spectrometer (MC-ICP-MS) at the High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University (Shen et al., 2012). Uncertainties of ^{230}Th dates, relative to AD 1950, are calculated at the 2 σ level unless otherwise noted.

Powdered subsamples, 50–100 μg each, were obtained for $\delta^{18}O$ measurements using carbide dental burrs, 0.5 mm in diameter, by milling along the central growth axis at 1 or 2 mm intervals. A total number of 1435 subsamples were analyzed on a Finnigan MAT 253 mass spectrometer connected to an on-line, automated carbonate preparation system (Gasbench II) at the College of Geography Science, Fujian Normal University. Results are reported relative to Vienna Pee Dee Belemnite (VPDB) and standardization was accomplished using NBS-19. One-sigma reproducibility was ±0.06‰.

3. Results

3.1. U–Th dating

U–Th isotopic compositions and ^{230}Th dates are listed in Table 1. High ^{238}U concentrations ($[^{238}U]$) of 2–5 ppm and relatively low $[^{232}Th]$ of 100–1000 ppt in SX7 and SX29 result in ^{230}Th dates with precisions mostly better than ±0.5% (Table 1). The difference between corrected and uncorrected ages is less than a few tens of years, which is 5–10 times less than the age uncertainty of ±100 s yrs. This indicates that initial detrital ^{230}Th is negligible. For stalagmite SX24, $[^{238}U]$ is 384–860 ppb and $[^{232}Th]$ 96–2080 ppt. The precision of the corrected ^{230}Th dates is ±301–502 yr. All ^{230}Th ages are in stratigraphic order. The chronology for each stalagmite was established using linear interpolation between individual ^{230}Th dates. The averaged temporal resolution of the oxygen isotope data is 32 yr for SX7, 31 yr for SX24, and 13 yr for SX29.