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Temperature and seawater isotopic controls on two stalagmite records since 83 ka from maritime Japan

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A B S T R A C T

Millennial-scale interstadial Dansgaard-Oeschger (D-O) cycles and Heinrich (H) stadial events are pronounced paleoclimatic features during the last glacial period, which were first demonstrated in the North Atlantic region. These stadial and interstadial events are expressed in marine and terrestrial high-resolution records elsewhere in the world, but the magnitude and mode of the regional climate changes are still poorly quantified. Here we present new replicated stalagmite $\delta^{18}O$ profiles from two caves in central Japan, which extend back to 83.4 ka. The records clearly display the H7 to H3 events, but not D-O cycles. An important feature of the two Japanese stalagmites is the small difference (~2.9‰) in $\delta^{18}O$ values between the mid-Holocene and the Last Glacial Maximum (LGM). Long-term trends of the stalagmite $\delta^{18}O$ values at the more maritime site generally follow that of the $\delta^{18}O$ record of seawater, which is responsible for ~1.1‰ of the ~2.9‰ difference between mid-Holocene and LGM. The remaining 1.8‰ in the difference can be accounted for by +9 °C of warming between the LGM and mid-Holocene and -3 °C cooling at H events, which are comparable with the previous estimates of land paleotemperature in the Japanese Islands. The attenuated isotopic signal associated with D-O interstadials indicates that the warming in the Atlantic did not significantly transfer to the maritime Japan. These unique features of the isotopic records of the Japanese stalagmites are due to the geographic position at the vicinity of the moisture source, Kuroshio warm current.

1. Introduction

A series of millennial-scale Heinrich stadial events (H events) and Dansgaard-Oeschger (D-O) interstadials events are conspicuous features of many climate records from the last glacial period. These events were closely related to variations in the Atlantic meridional overturning circulation (AMOC) (e.g., Rahmstorf, 2002; Knutti et al., 2004). The H events were triggered by large freshwater discharges from the North American ice sheet into the North Atlantic, causing long-lived cold intervals recorded in the Greenland ice-sheet (Dansgaard et al., 1993; NGRIP, 2004; Hodel et al., 2008). Researchers invoke a variety of causes for these millennial-scale changes, such as inherent ice-sheet instability (Alley et al., 2007) and changes in the solar activity (Braun et al., 2005) or ocean structure (Shaffer et al., 2004; Kim et al., 2012).

The climate signals temporally coinciding with the D-O stadials and interstadials have been reported in paleoclimate records from elsewhere in the Northern Hemisphere (NH) including areas surrounding the Japanese Islands (e.g. Tada et al., 1999; Nagashima et al., 2007; Iwamoto and Inouchi, 2007; Urabe et al., 2014). The inter-regional teleconnection of these millennial-scale changes has been clearly demonstrated in speleothem records from south China where H-events and the D-O interstadials correspond to elevated

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and lowered $\delta^{18}O$ values, respectively (Wang et al., 2001, 2008). Stalagmite $\delta^{18}O$ records from south China are primarily interpreted as an intensity index of East Asian summer monsoon (EASM) (Wang et al., 2001, 2005; 2008; Zhao et al., 2003; Cheng et al., 2006, 2009; Liu et al., 2014) owing to the effect of rainfall amount, a major controlling factor on meteoric $\delta^{18}O$ values in monsoonal regions (Harmon et al., 1978; Rozanski et al., 1993). However, others have suggested that changing moisture source is the main cause of variations in $\delta^{18}O$ values in stalagmite records from south China (Maher, 2008; Clements et al., 2010; Tan, 2014; Caley et al., 2014; Liu et al., 2015; Chen et al., 2016), a balance between ^{18}O-depleted vapor from the Indian Ocean and ^{18}O-enriched vapor from the Pacific (Pausata et al., 2011; Wang et al., 2014; Yang et al., 2014).

Stalagmites from the Japanese Islands potentially provide a valuable perspective on the hydrodynamic response to the millennial-scale climate events in East Asia, because of their maritime location at the fringes of the East Asian monsoon area and outside the influence of the Indian monsoon. Moisture transport during the summer monsoon season also differs between Japan and South China: summer moisture over China is transported by southwesterlies from the South China Sea, whereas summer moisture in Japan originates in western Pacific and is mainly carried by the southerlies along the western edge of the Bonin High where the Kuroshio warm current flows along the southern coast of Japan (Kurita et al., 2015). Such differences in hydrological features can be recorded on the stalagmite records. In this study, we present stalagmite $\delta^{18}O$ profiles covering the last 83.4 kyr from two caves in central Japan; Kiriana cave located on the Pacific coast, and Ohtaki cave from a more inland area (Fig. 1). We will examine the patterns of millennial-scale changes in these cave records and propose an interpretation for the stalagmite $\delta^{18}O$ not involving changes in rainfall amount.

2. Materials and methods

2.1. Cave settings, climate and field collections

Kiriana cave [34°37′ N, 136°46′ E; altitude: 620 m above sea level (masl) at the entrance] is located in middle Mie Prefecture in central Honshu (Fig. 1B). The regional climate is characterized by dry winters and wet spring to fall months (Fig. 1C). The nearest meteorological observatory at Kayumi (altitude: 120 m) recorded annual average rainfall of 2095 mm/yr during 2000–2014, 20.3% in spring (March–May), 33.2% in summer (June–August), 36.8% in autumn (September–November), and 9.6% in winter (December–February). The largest monthly rainfall of 421 mm was recorded in September (Fig. 1C) when typhoons often pass through this area. The 15-yr mean annual temperature is 14.9 °C, ranging from 4.0 °C in the coldest January to 26.1 °C in August. Considering the altitude difference between Kayumi and Kiriana (500 m) and a temperature gradient of 0.6 °C/100 m, the average temperature at Kiriana cave can be estimated at 11.9 °C.

The 2-km-long and 200-m-deep Kiriana cave is developed in the Triassic limestone bedrock of the southern Chichibu Terrane (Kashiwagi et al., 2007; Suzuki et al., 2015). Stalagmites occur at several locations along horizontal passages that are located below the vertical hole 50 m deep. One 97 mm-long stalagmite KA03 was collected in a chamber with humidity of 95–100%, 120 m from the cave entrance. KA03 is currently inactive without any drip water supply, but drip water was collected at six other sites in Kiriana cave, in March, June, September, and December of 2015. Sampling of drip water of >0.5 mL typically took less than 1 h. We also sampled 181 rain events from March 2014 to December 2017 at nearby Taiki Town (altitude: 120 m), 7 km northwest of the cave. Taiki is located downwind of Kiriana along the major route of moister transportation. Here, we defined rainfall as an “event” if it was separated by a rainless period of at least 6 h, as recorded at the nearby weather observatory at Kayumi.

Ohtaki cave (35°44′ N, 136°59′ E; 400 masl at the entrance) is located 150 km north-northeast of Kiriana cave in middle Gifu Prefecture, also in central Honshu but 100 km farther from the Pacific Coast than Kiriana cave (Fig. 1B). At Nagataki (altitude: 430 m), a nearby meteorological station, the annual average rainfall is 3081 mm during AD 2000–2014. It is wet year-round: 22.8% in spring (March–May), 34.8% in summer (June–August), 23.9% in autumn (September–November), and 18.5% in winter (December–February). The largest monthly rainfall was recorded in July (487 mm; Fig. 1C), when the interaction of cold northerly and warm southerly air masses induces wet weather in central Japan. The 15-yr mean annual average temperature is 11.6 °C, from −0.5 °C in January to 24.0 °C in August.

Ohtaki cave is > 1000 m in the total length and reaches 110 m below the surface (Yura, 2011) into the Permian limestone of the Mino Terrane (Kajita et al., 1971). Of the three cave levels, stalagmites are best developed in the middle level. The cave, modified by construction of tunnels that connect between galleries in 1970, is currently open for tourism. A 140 mm-long stalagmite OT02 was collected 200 m from the cave entrance. Drip water was collected at three sites including one at the stalagmite OT02 in 13 different periods from July 2013 to November 2015. Sampling of drip water of >0.5 mL typically took less than 2 h. We also collected 137 separate rain events (defined as previously) from November 2013 to September 2015 at Ohgaki City (altitude 10 m), located 60 km southwest from the cave (Fig. 1B). Ohgaki is located upstream of Ohtaki along the major route of moister transportation.

2.2. Laboratory methods

The two stalagmites, KA03 and OT02, were cut along the growth axis, polished, and dated using U-Th dating methods at the High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), National Taiwan University (Shen et al., 2002, 2012). A powdered sample of ~0.1 g of each horizon was gently dissolved in 7N nitric acid, and spiked with a ^{229}Th-^{233}U-^{236}U tracer for U-Th chemistry. U and Th fractions were purified using anion-exchange chromatography after removing Ca^{2+} by a co-precipitation step. Isotopic measurements were performed on a multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS), Thermo NEPTUNE. U-Th ages [thousand years ago (ka), expressed as years before AD 1950] were calculated using an off-line data reduction program and half-lives of U-Th nuclides given in Cheng et al. (2013). Isotopic and age errors given are two standard deviation of the mean and two standard deviation, respectively, unless otherwise noted. The age model of the stalagmites was constructed by statistics of Bayesian inference using the software Bacon ver. 2.2 (available at http://chrono.qub.ac.uk/blaauw/bacon.html).

Stalagmite oxygen isotopes were measured on a gas-source mass spectrometer, Thermo Finnigan Delta Plus, installed with a gas separation system, GASBENCH II, at the Kyushu University. Subsamples of 0.2 mg were extracted at 0.1-mm intervals for KA03 and 0.2-mm intervals for OT02 along the central growth axis on a polished half-cut surface using a dental drill. Seven coeval subsamples drilled from five depths, 13.0, 31.0, 47.5, 68.5 and 86.0 mm, of KA03 and eight depths, 9.0, 28.0, 56.0, 60.0, 80.0, 109.0, and 127.0 mm, of OT02 were drilled to perform the Hendy Test (Hendy, 1971) for evaluating kinetic effects. $\delta^{18}O$ values of carbonates are expressed relative to the Vienna Pee Dee Belemnite (VPDB). Repeat measurements of laboratory standards, Solnhofen limestone ($\delta^{18}O = -5.04‰$) calibrated against NBS-19 confirmed that the standard deviation (1σ) was < ±0.1‰ (Hori et al., 2009).