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Holocene stalagmite oxygen isotopic record from the Japan Sea side of the Japanese Islands, as a new proxy of the East Asian winter monsoon

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ABSTRACT

Stalagmite oxygen stable isotopic records from Chinese and Japanese caves have described the intensity of the East Asian summer monsoon (EASM) in the late Quaternary. In this study, we present a stalagmite $\delta^{18}O$ record over the past 10,000 years from Fukugaguchi Cave, Itoigawa, Honshu, Japan, facing the Japan Sea. The regional climate is characteristically wet in winter and nearly 60% of the annual precipitation occurs from November to March when the East Asian winter monsoon (EAWM) brings moisture from the Japan Sea warmed by the Tsushima Warm Current. Rainwater $\delta^{18}O$ values near the cave generally decrease with the precipitation amount, indicating an amount effect. The stalagmite $\delta^{18}O$ profile has had a concurrent trend with winter precipitation observed near the cave since 1924 in addition to high-resolution records of the eolian fraction observed in China. These agreements suggest that the Fukugaguchi stalagmite $\delta^{18}O$ record reflects the EAWM intensity. In comparison of our profile with the EASM record obtained from Chinese stalagmites, inverse correlation was recognized only in the earlier interval of 10.0–5.2 ka, suggesting that the southward migration of the intertropical convergence zone intensified the EAWM. From a peak at 5.2 ka, the EAWM intensity quickly decreased and remained at a lower level between 4.5 and 3.0 ka. Since 3.0 ka, the Fukugaguchi record has high-amplitude changes of millennial time scales, including two peak intervals in 2.9–2.5 ka and 1.3–0.7 ka. EAWM-related winter precipitation might have been amplified with intensification of the Tsushima Warm Current that enhanced the land-sea thermal contrast during winter season. A co-variation presumed between the Fukugaguchi $\delta^{18}O$ record and the Chinese EAWM records implies that the thermal contrast between East Asia and NW Pacific may have influenced the winter monsoon in throughout the East Asian climate system.

1. Introduction

Stalagmite stable isotopic records are useful in reconstructing terrestrial paleoclimatic change (e.g., McDermott, 2004; Fairchild et al., 2006). Good examples are high-resolution oxygen isotope records obtained from Chinese and Japanese caves, which have been interpreted as reflecting the intensity of East Asian summer monsoon (EASM) rainfall (Wang et al., 2001, 2005; Yuan et al., 2004; Zhang et al., 2008; Shen et al., 2010). The EASM intensity with different time windows was revealed to be dominated by precessional and high-latitudinal forcings (e.g., Wang et al., 2001, 2005, 2008; Cheng et al., 2009).

In contrast to the wet summer climate, the winter climate in East Asia is influenced largely by the dry East Asian winter monsoon (EAWM) from the high-pressure cell over Siberia and Mongolia (Fig. 1A). Its intensity is not recorded by Chinese stalagmites. Instead, the intensity of the EAWM has been evaluated mainly according to eolian dust flux recorded in loess–paleosol (Xiao et al., 1995; An, 2000; Porter, 2001), lacustrine (Xiao et al., 1997, 2006; Liu et al., 2009) and marine sediments (Wang et al., 1999; Nagashima et al., 2007), which are mostly of low-resolution and dated by radiometric carbon, tephra chronology, and

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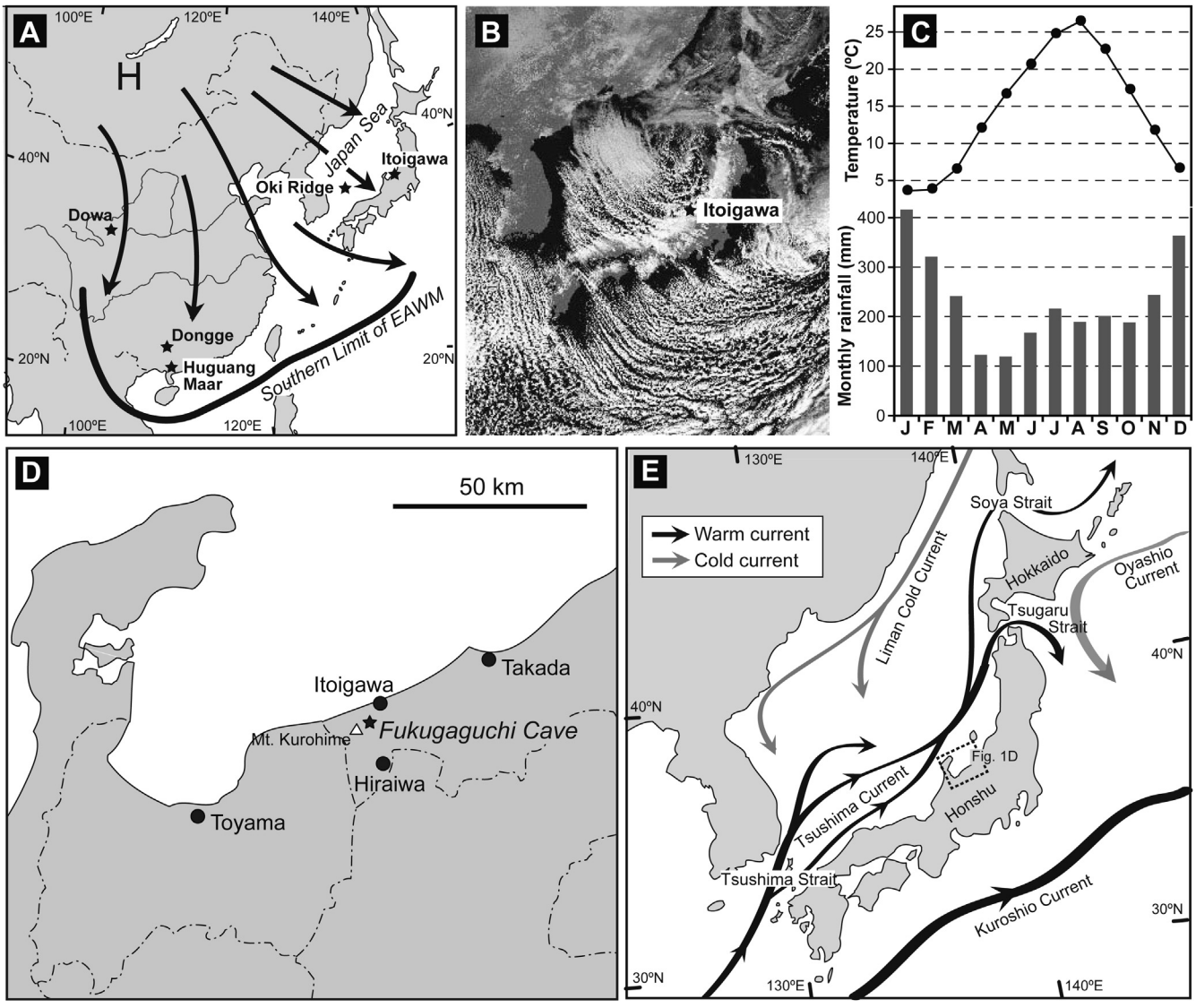

Fig. 1. Geographic and climate conditions of the study area, Itoigawa. A) The pathway and southern limit of the EAWM and localities cited in the text. B) A satellite image showing that an intense northwesterly wind generated cloud over the Japan Sea and snowfall on the Japan Sea side on 26 January 2011. C) Monthly temperature (°C) at Itoigawa (upper) and rainfall (mm) at the Hiraiwa Precipitation Observatory (lower). D) Localities cited in this study: Toyama for collecting rainwater samples, Itoigawa for temperature data (C), Hiraiwa for precipitation data of the mountainous area in southwestern Niigata prefecture (C), and Takada, where weather data have been collected since 1924 (shown in Fig. 5). E) Current system surrounding the Japanese Islands.

foraminifer $\delta^{18}O$. Over a long time window associated with glacial/interglacial change, these studies have similarly identified inverse correlation between EASM and EAWM intensities (e.g., Xiao et al., 1995). The general trend observed in these studies is that EAWM has intensified while the EASM has weakened since the early Holocene, primarily responding to the southward migration of the intertropical convergence zone (ITCZ). The ITCZ migration that resulted from decreasing summer insolation brought a broad influence to the Holocene climate and also weakened intensity of the Indian summer monsoon (ISM) represented in $\delta^{18}O$ records of stalagmites from Oman (Fleitmann et al., 2003). The Oman stalagmites show the inversed $\delta^{18}O$ trend of the Yemen stalagmites, which indicate inter monsoon (spring and autumn) rainfall of the area (Fleitmann et al., 2007).

This inverse correlation between EASM and EAWM was also suggested from the Holocene interval in lake sediments in southeast China (Yancheva et al., 2007) and Tibet (Liu et al., 2009). However, this was disputed by some previous studies on the Holocene Asian climate (Zhang and Lu, 2007; Zhou and Zhao, 2009). Insolation in the northern hemisphere (NH) has generally had reducing seasonality with decreasing summer insolation and increasing winter insolation since 9 ka (e.g., Berger, 1978; Wanner et al., 2008). Such insolation change likely increases the winter temperature on the northern continents and decreases the heat contrast with the surrounding sea, which can reduce the EAWM. Recent studies of marine sediments from the northern South China Sea indicated that the present EAWM is weaker than that in the early–middle Holocene (Steinke et al., 2010, 2011).

The EAWM brings dry wind across the Chinese continent, but receives moisture when it flows out across warm oceanic water. The moisturized EAWM brings a substantial amount of precipitation to certain regions, such as the Japan Sea side of the Japanese Islands. Here, the strong northwesterly wind generates cloud streaks, and results in heavy and frequent snowfall (and rainfall) during winter (Fig. 1B, C). Intensity of the EAWM has been quantified by the difference in the sea-level pressures between Irkutsk,