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# Droughts in the East Asian summer monsoon margin during the last 6 kyrs: Link to the North Atlantic cooling events

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## ABSTRACT

Teleconnections to the high latitudes, forcing by the tropical oceans and solar variability have all been suggested as dominant factors in the sub-millennial global climate changes, yet there is little consensus as to the relative importance of these factors for the East Asian summer monsoon (EASM) variability. This study presents the results of high-resolution analyses of Ca and Mg concentrations, Mg/Ca ratio, $\delta^{18}O$ and $\delta^{13}C$ values of endogenic calcites from a sediment core from Dali Lake in the EASM margin, in order to investigate the sub-millennial EASM variability and its possible driving forces during the last 6 kyrs. Increases in these chemical proxy data were interpreted as drought events in the region due to the intensive evaporation losses overwhelming the water input to the lake. The chemical proxy data in this study combined with multi-proxy indicators including grain size component and total organic carbon concentrations from the same sediment core imply that declines in the EASM intensity may have played a dominant role in triggering the drought events during the last 6 kyrs. The results indicate that the EASM intensity significantly declined at the intervals of 5.8–4.75, 3.2–2.8, 1.65–1.15 and 0.65–0.2 kyrs BP. Large declines in the EASM intensity during the last 6 kyrs correspond in time to occurrences of ice-rafted debris in the North Atlantic, indicating that millennial-to-centennial scale changes in the EASM intensity were mainly controlled by climatic processes occurring in the northern high latitudes. These data imply that persistent global warming may be favorable for the strengthening of the EASM circulation and for the transportation of more rainfall to the semi-arid regions of northern China on sub-millennial scales.

## 1. Introduction

The East Asian summer monsoon (EASM) is an integral component of the global climate system, and plays a key role in transporting heat and moisture from low to high latitudes (An, 2000). On the regional scale, the large variability of the EASM can cause calamitous flooding or severe drought that impacts more than a quarter of the world's population. In recent years, more and more attention has been paid to the effect of future global warming on the EASM (IPCC, 2013). However, there is little consensus as to this highly contested issue because the dominant factors forcing the variability of the EASM at sub-millennial time scales are still unclear (Held and Soden, 2006; Li et al., 2010; Broecker and Putnam, 2013).

Several studies indicated that solar variability was the main cause of global climate change at centennial time scales (Stuiver, 1980; Yu and Ito, 1999; Staubwasser et al., 2003). Solar forcing could change the position of polar front and subtropical jets through its influence on the stratospheric ozone and temperature (Shindell et al., 2001). However, several other studies argued that there was no significant relationship between the paleoclimatic records in tropical low latitudes and the atmospheric $\Delta^{14}C$ records (Russell et al., 2003; Russell and Johnson, 2005), which partly reflect the solar variability (Stuiver, 1980). These studies suggested

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that the variability within the tropical oceans may be the dominant forcing of global climate change. Camberlin et al. (2001) found that changes in tropical Pacific sea surface temperatures during modern El Niño events could exert a direct influence on equatorial African rainfall through changes in atmospheric and oceanic circulation in Indian and Atlantic Oceans. Nelson et al. (2011) suggested that changes in the El Niño Southern Oscillation in the tropical Pacific could have a great impact on the precipitation variability in the Pacific Northwest. In addition, some studies suggested that the significant sub-millennial cooling events that occurred in the North Atlantic during the Holocene could have global impacts (Bond et al., 2001). General circulation models pointed out that cooling in the North Atlantic could cause anomalous Atlantic trade winds and cross-equatorial moisture transport, thereby shifting the Inter-tropical Convergence Zone southward (Vellinga and Wood, 2002; Lohmann, 2003) and leading to significant decreases in the precipitation in the northern subtropics (Wang et al., 2005, 2008; Chen et al., 2016). Despite mounting evidence for these factors affecting the global climate, the relative importance among them is still a controversial issue. Therefore high-resolution, well-dated paleoclimatic records from middle latitude regions are needed to be compared with the climatic processes in high and low latitudes, in order to detect the dominant factors controlling the regional climate change.

Dali Lake is located at the transition from semi-humid to semi-arid regions in the northern middle latitudes, where the regional precipitation is mainly controlled by the EASM (An, 2000). Endogenic carbonates precipitated in lakes in semi-arid regions can provide direct information on past changes in the regional climate (Talbot and Allen, 1996). This study presents ~50-yr resolution records of elements and stable isotopes of endogenic calcites from the Dali Lake sediments in order to reconstruct a prominent feature of the EASM variability during the last 6 kyrs, and improve our understanding of the dominant driving forces of the EASM variability. These data would provide insights into how the EASM may respond to the global warming in the future.

## 2. Regional setting

Dali Lake (43°13′–43°23′ N, 116°29′–116°45′ E) is located in the northern margin of the E–W-extending Hulandaga Desert Land, 70 km west of Hexigten Banner, Inner Mongolia (Fig. 1), in an inland fault-depression basin that was formed in the Pliocene to Pleistocene (Li, 1993). The lake has an area of 238 km$^2$, a maximum water depth of 11 m, an elevation of 1226 m above sea level (Fig. 1), and is hydrologically closed. Hills surround the lake to the north and west, and lacustrine plains are present along the eastern shore. Two permanent rivers, the Gongger and Salin Rivers, enter the lake from the northeast and two intermittent streams, the Holai and Liangzi Rivers, enter from the southwest (Fig. 1); however, there are no outflowing rivers. The Gongger River, the major inflow, rises in the southern terminal part of the Great Hinggan Mountains, where the elevation reaches 2029 m, and has a drainage area of 783 km$^2$ and a total channel length of 120 km (Li, 1993). Hydrological observations indicate that the discharge of the Gongger River is as large during spring floods in April as during summer floods in July, because of significant melt water runoff from the snow/ice packs covering the mountains (Li, 1993).

Dali Lake is located at the transition from semi-humid to semi-arid regions of the middle temperate zone. The climate of the region is mainly controlled by the East Asian monsoon (An, 2000). In region, mean annual temperature is 3.2 °C with a July average of 20.4 °C and a January average of −16.6 °C (Fig. 2). Mean annual precipitation is 383 mm, and ~70% of the annual precipitation falls from June–August (Fig. 2). Mean annual evaporation reaches 1632 mm, which is more than 4 times the annual precipitation (Fig. 2). The lake is covered with ice from early November to late April (Li, 1993).

## 3. Materials and methods

### 3.1. Water sampling and hydrochemical analyses

Water in the Dali Lake was sampled using a PURITY stainless steel depth-setting water sampler (Model WB-SS) from the central-northwestern, central-northeastern and central-southern parts of the lake in June 2010, while water from the four inflowing rivers was sampled in April and August 2011, respectively. Temperature and pH measurements were taken on site using a HANNA portable multi-parameter water quality analyzer (Model HI9828). Ion concentrations and isotope composition were measured in laboratory. Concentrations of major cations of $Ca^{2+}$, $Mg^{2+}$, $K^{+}$ and $Na^{+}$ in the water were determined with an IRIS Intrepid II XSIP Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES), and the relative standard deviation was less than 5%. Concentrations of anions of $SO_4^{2-}$ and $Cl^{-}$ were determined with an ICS-1000 Ion Chromatograph Spectrometer, and the relative standard deviation was less than 5%. In addition, concentrations of $CO_3^{2-}$ and $HCO_3^{-}$ were determined by titration, and the repeated measurement error was less than 1%. Water salinities were calculated by using the sum of total major ion ($Ca^{2+}$, $Mg^{2+}$, $K^{+}$, $Na^{+}$, and $CO_3^{2-}$, $HCO_3^{-}$, $SO_4^{2-}$, $Cl^{-}$) concentrations, while alkalinities were calculated by the sum of $CO_3^{2-}$ and $HCO_3^{-}$ concentrations and expressed in $CaCO_3$ g/L. The $\delta^{18}O$ (VSMOW) values of the water and the $\delta^{13}C$ values of the water's dissolved inorganic carbon ($\delta^{13}C_{DIC}$) (PDB) were determined with a Finnigan Delta S Mass Spectrometer, and the precision was better than 0.1‰ for both $\delta^{18}O$ and $\delta^{13}C_{DIC}$ values. The $\delta^{2}H$ ($\delta D$) (VSMOW) values were determined with a Finnigan MAT 252 Mass Spectrometer, and the precision was better than 1‰.

### 3.2. Sediment sampling and lithology

Sediment coring was conducted at a water depth of 10.8 m in the depocenter of Dali Lake in February 2004, when the lake surface was frozen (Fig. 1), using a TOHO drilling system (Model D1-B) (Toho Chikakoki Co., Ltd, Japan). Incremental sediment cores were extracted to a total depth of 11.83 m beneath the lake floor and were designated DL04 (43°15.68′ N, 116°36.26′ E) (Fig. 1). The cores were collected in polyethylene tubes using a piston corer of the drilling system, and sediment recovery was close to 100%. All of the sediment cores were split, photographed and described on site, and then cut into 1-cm segments for samples. There was no indication of any sedimentary hiatuses (Fig. 3).

The upper 6.39 m of the DL04 core was used for the present study (Fig. 3). The sediments of the upper 6.39 m were composed of homogeneous clayey silt and silt, and could be divided into four main sedimentary units (Fig. 3), as follows: 6.39–6.34 m greenish-grey massive silt with occasional blackish-grey bands; 6.34–5.98 m blackish-grey banded clayey silt; 5.98–4.94 m greenish-grey laminated clayey silt; 4.94–0 m blackish-grey massive clayey silt. $CaCO_3$ contents in the sediments of the upper 6.39 m of the DL04 core were generally higher than 10% with an average of 20% and a maximum of 41%. Below the core depth of 6.39 m, the $CaCO_3$ contents were close to zero in most horizons (Fig. 3). The upper 6.39 m of the DL04 core was sampled at 3- to 6-cm intervals, yielding a total of 114 samples for laboratory analyses.

### 3.3. Radiocarbon dating

Eleven bulk samples were collected at 50- or 100-cm intervals