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# Breakpoint lead-lag analysis of the last deglacial climate change and atmospheric $CO_2$ concentration on global and hemispheric scales

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ABSTRACT

Antarctic ice core records show that climate change and atmospheric $CO_2$ concentration ($aCO_2$) are closely related over the past 800 thousand years. However, the interpretation of their sequential, and hence the causal relationship has long been controversial. In this study, we revisit this long-standing scientific issue based on 88 well-dated high-resolution climate proxy records derived from ice cores, marine deposits, and stalagmites. We composite global and hemispheric stacks of the last deglacial climate index (DCI) using a normalization scheme instead of a more conventional area-weighting and mixing scheme to enable a better detection of temporal variations. Rampfit and Breakfit techniques are employed to detect the trend transitions in each composited DCI series and in the recently constructed centennial-scale $aCO_2$ over the period from 22 to 9 thousand years before present. We detect a clear lead of DCI change over $aCO_2$ variation on both global and hemispheric scales at the early stage of the deglaciation, suggesting that the variation of $aCO_2$ is an internal feedback in Earth's climate system rather than an initial trigger of the last deglacial warming. During the periods of the Bølling-Allerød and the Younger Dryas, the climate system appeared to have been constrained by a fast coupling mechanism between climate change and $aCO_2$ with no obvious asynchrony. The northern and southern hemispheric DCI stacks exhibit a seesawing pattern that can be linked to the influences of Atlantic meridional overturning circulation (AMOC) strength, revealing an important role of AMOC in regulating the global climate in the course of the last deglaciation.

## 1. Introduction

Multiple glacial – interglacial cycles are the major characteristics of the Quaternary climate evolution. During the period from about 20 to 10 kabp (thousand years before present, where the present is A.D. 1950), the global climate emerged from the last glaciation; the global mean temperature went up by about 4–7 K (Guilderson et al., 1994; Dahl-Jensen et al., 1998; Farrera et al., 1999; Stenni et al., 2001; Ballantyne et al., 2005; Huang et al., 2008), the large northern hemispheric ice sheets retreated (Dyke, 2004), the global sea level rose over 120 m (Fleming et al., 1998; Clark et al., 2004; Peltier and Fairbanks, 2006; Lambeck et al., 2014), and the atmospheric carbon dioxide concentration ($aCO_2$) increased by about 80 ppmv (parts per million by volume) (Neftel et al., 1988; Fischer et al., 1999; Monnin et al., 2001; Ahn et al., 2004; Marcott et al., 2014). These changes, to some degree, are similar to what the human beings are facing at the present-day. Therefore the studies with respect to the process of the last deglaciation are relevant to the understanding of the modern climate change.

Antarctic ice core studies (Neftel et al., 1988; Fischer et al., 1999; Monnin et al., 2001; Ahn et al., 2004; Marcott et al., 2014) have provided clear evidences for a close relationship between surface air temperature (SAT) and $aCO_2$ variations during the last deglaciation. However, the questions such as which one changed first, and whether $aCO_2$ was a driver of this climate transformation or it was just a feedback that had enhanced the warming, have long been subjects of debate (Wolff, 2012; Brook, 2013). Existing ice core records of Byrd (Neftel et al., 1988), Taylor Dome (Fischer et al., 1999), Dome Concordia (Monnin et al., 2001), and Siple Dome (Ahn et al., 2004) show that the rise of $aCO_2$ lagged the rise of SAT, but the timescales of ice core records are complicated by the uncertainty of the gas-ice age difference (Δage) that caused by the hysteresis of the air bubble's formation relative to the surrounding ice. In the recent years, several advanced approaches have been developed to improve the determination of Δage. For example, using $\delta^{15}N$ data as a firn column depth indicator, Parrenin et al. (2012, 2013) revised the timescale of $aCO_2$ derived from the Dome Concordia ice core, and showed that the variations of $aCO_2$ and

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SAT were almost synchronous throughout the last deglaciation within an uncertainty less than 200 years. Similarly, the recently published centennial-scale $aCO_2$ record derived from the West Antarctic Ice Sheet Divide ice core (WDC) (Marcott et al., 2014) exhibits a nearly synchronous variation with SAT.

Another obstacle in our understanding of the sequential relationship between SAT and $aCO_2$ is the global/regional representativeness of the paleoclimatic records. Although the $aCO_2$ records derived from ice cores are viewed as global average because of air diffusion, the reconstructions of SAT based on the isotope ratios (e.g., $\delta^{18}O$ and δD) of individual ice cores reflect only local information that is generally mixed with non-climatic signals. In order to overcome these drawbacks, there have been great efforts aiming at a robust reconstruction of Antarctic SAT in the past few years. For instance, based on five coastal ice core proxy records, Pedro et al. (2011) composited an Antarctic SAT stack using the fast-changing global methane gas concentrations as the time markers. Through quantitative analysis of the time-lag between the composited SAT stack and two existing $aCO_2$ records, Pedro et al. (2012) concluded that the $aCO_2$ fell behind the Antarctic SAT by less than 400 years and could not exclude the possibility of a slight lead. On larger spatial scales, Shakun et al. (2012) synthesized global and hemispheric temperature stacks from 80 proxy reconstructions using a linear interpolation and area-weighting method to show that the global warming during the last deglaciation was preceded by the increase of $aCO_2$.

Although ice core record is a well-known indicator of paleoclimate change, information of climate change in the past are also preserved well in other media. In addition to 13 polar ice core records, we include in our database 58 marine sedimentary records of sea surface temperature and 17 stalagmite isotope records of precipitation information in this study to allow for a better global/hemispheric representativeness. We totally collect and collate 88 well-dated high-resolution proxy records over the last deglaciation as the underlying paleoclimatic database of this study. Using a straightforward scheme of normalization and moving average, we reconstruct global and hemispheric stacks of the last deglacial climate index (DCI) as a composited indicator of climate change for the period from 22 to 9 kabp. To determine the sequential relationships between the reconstructed stacks and $aCO_2$, we employ the techniques of Rampfit (Mudelsee, 2000) and Breakfit (Mudelsee, 2009) to detect the breakpoints in each composited DCI series and in the centennial-scale WDC $aCO_2$ (Marcott et al., 2014) for intercomparison. Finally, we discuss the driving mechanism of the last deglacial climate change.

## 2. Data and methods

### 2.1. The paleoclimatic database

88 well-dated high-resolution paleoclimatic records derived from ice cores, marine deposits, and stalagmites are collected and collated as the underlying database of this study. Spatially, the sites of these records cover broadly the globe (Fig. 1). Temporally, the average density over the period from 22 to 9 kabp is 136 measurements per hundred years with a total of 17,699 data points. The data density over the interval from 16 to 9 kabp is even higher. The data volumes are 11,655 for the Northern Hemisphere, and 6,044 for the Southern Hemisphere, respectively (Fig. 2A). General characteristics of these 88 records are given in the companion data article (Liu et al., 2018).

#### 2.1.1. Ice core $\delta^{18}O$ and δD records

Both stable oxygen isotope ratio ($\delta^{18}O$) and stable hydrogen isotope ratio (δD) in ice cores can be analyzed to reflect glacial surface temperatures. The chronologies of ice core records depend mainly on the methods of layer-counting and glaciological models, as well as calibrations by other time markers such as methane, volcanic ash, and Beryllium-10. Our database includes 4 Greenlandic ($\delta^{18}O$) and 9 Antarctic (2 δD and 7 $\delta^{18}O$) ice core records. These records involve three representative timescales that focus on different correction methods and time markers. Therein, the chronologies of the 4 Greenlandic records, as well as the Antarctic records of Law Dome and Simple Dome, are based on the GICC05 timescale (Svensson et al., 2008), the Antarctic TALDICE, EDML, EDC, and Dome Fuji records are based on the AICC2012 timescale (Veres et al., 2013), and the Antarctic Taylor Dome, Vostok, and Byrd records are based on the Lemieux-Dudon timescale (Lemieux-Dudon et al., 2010). The average density of the ice core data is 44 measurements per hundred years with a total of 5,715 data points. The data volumes are smaller in the Northern Hemisphere than in the Southern Hemisphere (Fig. 2B).

#### 2.1.2. Alkenone $U^{K'}_{37}$ and foraminifera Mg/Ca records

Alkenone ketone unsaturation index $U^{K'}_{37}$ and foraminifera Mg/Ca ratio of marine deposits are the indicators of sea surface temperatures. Reservoir effect is an important factor that must be taken into account in the radiocarbon dating of marine paleoclimatic records (Buck and Blackwell, 2004; Nakamura et al., 2016; Wang et al., 2017). With respect to the reservoir effect of $^{14}C$ dating, Shakun et al. (2012) made careful corrections of the radiocarbon-based timescales of 32 $U^{K'}_{37}$ and 26 Mg/Ca records based on the IntCal04 standard (Reimer et al., 2004) and Monte Carlo simulations. In our database, we include these 58 corrected records as the representations of marine region. Therein, 4,351 data points in total from 22 to 9 kabp are included, showing a relatively homogeneous distribution with the average density of 33 measurements per hundred years (Fig. 2C–E).

#### 2.1.3. Stalagmite $\delta^{18}O$ records

The $\delta^{18}O$ records of stalagmites mainly reflect the information of precipitation or the intensity of monsoon. The patterns of the stalagmite-based reconstructions of precipitation and monsoon intensity have been showed to be analogous to the climate changes during the last deglaciation (e.g., Wang et al., 2001; Wang et al., 2007; Cheng et al., 2009; Cheng et al., 2013). Moreover, the accurate U-series-dating in stalagmites can provide an independent chronological constraint for the integration of the diverse paleoclimate records. In our database, all the chronologies of the 17 participant stalagmite records were derived from precise $^{230}Th$ absolute-dating. In comparison to other archives, the data density of stalagmite records with 7,632 data points exhibits a biggish fluctuation from 22 to 9 kabp and is denser in the Northern Hemisphere than in the Southern Hemisphere (Fig. 2F).

### 2.2. The WDC $aCO_2$ record

The WDC site is located in the western Antarctic (79.467° S, 112.085° W) with a high average snow accumulation rate of 22 cm/yr at the present-day. An accurate timescale since 30 kabp was established using the chronological method of annual layer counting. The Δage between the ice and the trapped gas was estimated to be 205 ± 10 years at the present and 525 ± 100 years at the last glacial maximum (Marcott et al., 2014). The high snow accumulation rate and precise chronological constraints enable a better-dated gas chronology and the reconstruction of $aCO_2$ at sub-centennial resolution.

### 2.3. Methods

#### 2.3.1. Data synthesis

Most of the existing studies on global, hemispheric, and regional scales have been based on interpolated and area-weighted assembles of climatic time series. However, such a conventional interpolation and area-weighting method is not necessarily the best choice for integration of scattered paleoclimate records derived from diverse climate proxies and different geographical settings. For example, although they are all located in the Arctic region, five paleoclimatic records used in the study of Shakun et al. (2012) that reconstructed from ice core $\delta^{18}O$,