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Using Holo-Hilbert spectral analysis to quantify the modulation of Dansgaard-Oeschger events by obliquity

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ABSTRACT

Astronomical forcing (obliquity and precession) has been thought to modulate Dansgaard-Oeschger (DO) events, yet the detailed quantification of such modulations has not been examined. In this study, we apply the novel Holo-Hilbert Spectral Analysis (HHSA) to five polar ice core records, quantifying astronomical forcing's time-varying amplitude modulation of DO events and identifying the preferred obliquity phases for large amplitude modulations. The unique advantages of HHSA over the widely used windowed Fourier spectral analysis for quantifying astronomical forcing's nonlinear modulations of DO events is first demonstrated with a synthetic data that closely resembles DO events recorded in Greenland ice cores (NGRIP, GRIP, and GISP2 cores on GICC05 modelext timescale). The analysis of paleoclimatic proxies show that statistically significantly more frequent DO events, with larger amplitude modulation in the Greenland region, tend to occur in the decreasing phase of obliquity, especially from its mean value to its minimum value. In the eastern Antarctic, although statistically significantly more DO events tend to occur in the decreasing obliquity phase in general, the preferred phase of obliquity for large amplitude modulation on DO events is a segment of the increasing phase near the maximum obliquity, implying that the physical mechanisms of DO events may be different for the two polar regions. Additionally, by using cross-spectrum and magnitude-squared analyses, Greenland DO mode at a timescale of about 1400 years leads the Antarctic DO mode at the same timescale by about 1000 years.

1. Introduction

During the late Pleistocene epoch, climate variability was characterized by a series of strong irregular millennial-scale oscillations, termed Dansgaard-Oeschger[4] (DO) events (Dansgaard et al., 1984, 1993; Oeschger et al., 1984), with an average duration of approximately 1500 years (Grootes and Stuiver, 1997; Yiou et al., 1997). DO events were first identified in the oxygen-isotope ($\delta^{18}O$) record from the central Greenland ice cores (Dansgaard et al., 1984), and then confirmed in marine and continental archives worldwide (Bond et al., 1992; Leuschner and Sirocko, 2000; Wang et al., 2008; Wolff et al., 2010). A typical DO event exhibits a distinctive saw-tooth shape. It comprises a fast warming (up to 16 °C) within a few decades or less (Lang et al., 1999; Landais et al., 2006) and a successive slow cooling over centennial-to-millennial years, often followed by a final temperature jump back to the glacial level. A number of paleoclimatic proxies have revealed DO-like oscillations even in the recent Holocene (Bond et al., 1997; Debret et al., 2007).

Various hypotheses have been proposed for explaining DO events, including internal ice sheet-ocean-atmosphere oscillations triggered by freshwater injection (Alley, 2007; Ganopolski and Rahmstorf, 2001; Rahmstorf, 2002), dynamics of ice shelf in

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[4] Dansgaard-Oeschger is abbreviated as DO.

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coordination with sea ice (Petersen et al., 2013), and nonlinear external forcing mechanism (e.g., the solar or tidal forcing) (Braun et al., 2005; Keeling and Whorf, 2000; Lombard et al., 2010; Stuiver et al., 1997). Although the underlying mechanism (or mechanisms) of DO events is still under pursue, the intriguing saw-tooth shape of DO events implies a potential DO's linkage to the orbital forcing via the multiple stable states in the climate system (Paillard, 1998; Turney et al., 2015). This potential link between DO events and orbital forcing would undoubtedly involves nonlinear processes (Rial and Anaclerio, 2000; Thomas et al., 2011), as simple linear addition would provide no characteristic changes to DO events, even if the added orbital timescale variability may supply a changing local mean for the overlapped DO events. Using the windowed Fourier-based method, evaluation of the instantaneous amplitude of DO events has revealed that they were amplitude-modulated by the obliquity and precession (Hinnov et al., 2002). But limited by the uncertainty principle, the windowed Fourier-based method cannot achieve high resolutions in time and frequency domains simultaneously (Goswami and Chan, 2011), significantly hindering further investigation of DO events' modulation by orbital forcing. Therefore, a method for nonlinear data analysis with sufficient time-frequency resolution is required to more fully describe DO events and their mechanisms (Braun et al., 2010).

The windowed Fourier-based method is traditionally used to analyze paleoclimatic proxies (Debret et al., 2007). The method assumes that a signal's complexity can be well described by the sum of a set of sinusoidal oscillations featured by time-unvarying amplitudes and frequencies. This assumption implies that there is no cross-scale interaction between any pair of sinusoidal functions at different frequencies. An implication of this assumption for understanding paleoclimate data is that the resolved orbital timescale variability has little impact on the high frequency variability, such as DO events. Although this deficiency can be improved by analyzing instantaneous amplitude or instantaneous frequency, data are usually characterized by various combinations of instantaneous amplitude and frequency that may generate different cross-scale interactions (Huang et al., 1998; Loughlin and Tacer, 1996). Another consequence of the windowed Fourier-based method is that the resulting spectrum does not provide any time-varying information, which is inadequate for analysis of non-stationary time series, such as paleoclimatic data (Yiou et al., 1997). A sliding window can be added to alleviate this drawback of neglecting time-varying information, but the obtained Fourier spectra depends on the window size, thereby distorting the true information of variability hidden in the original time series. The first limitation also affects the wavelet transform, which uses the weighted sum of a set of packed or stretched basic wavelets to approximate the signal, therefore assuming no inter- or cross-scale interactions. Although the wavelet transform achieves time-frequency localization without needing to determine the length of the sliding window, it applies a selected wavelet function to all of the data, regardless of the variations in the localized data. In addition, wavelet transform has a poor temporal resolution for slow-varying oscillations (Goswami and Chan, 2011), such as obliquity, leaving it inadequate for clarifying the phase-preference of fast-varying components (such as DO events) in slow-varying components (such as orbital forcing).

A new method called Holo-Hilbert spectral analysis[9] (HHSA) (Huang et al., 2016) has been developed on the basis of the ensemble empirical mode decomposition[6] (EEMD) and the nested Hilbert-Huang transform[8] (HHT). Building on the multiplication principle, HHSA possesses an excellent time-frequency resolution and is thus suitable for tackling the respective drawbacks of the windowed Fourier-based and wavelet transform methods mentioned in the above. Since the HHSA was first proposed, it has been successfully applied to examine the modulation effects of low-frequency components on high-frequency components, such as wave-turbulence interactions (Qiao et al., 2016) and the inter-annual modulation of phytoplankton blooms (Zhang et al., 2017).

In this study, we take advantage of this new method and apply it to temperature proxy analysis, with a focus on understanding the amplitude modulation[1] (AM) of DO events by orbital forcing. We design a synthetic data that closely resembles Greenland DO events to verify the efficiency of HHSA. By analyzing five ice core records (including NGRIP, GRIP, GISP2 ice cores on GICC05 modelext timescales from Greenland; EPICA DOME C ice core on EDC3 age scale and VOSTOK ice core on GT4 timescale from Antarctic) with HHSA, we examine the modulation of DO events and their obliquity phase preference. We also investigate the lead-lag relationship between Greenland and Antarctic DO events, using the cross-spectrum and magnitude-squared coherence analysis. The paper is organized as follows. In Section 2, we begin with a brief description of the synthetic data and temperature proxies. In Section 3, we introduce the HHSA and discuss the method's advantages in terms of applications to the synthetic data. Section 4 presents the results of the analysis of five ice core records using HHSA. A short discussion of the analysis in Section 5 is followed by a summary.

2. The data

2.1. A synthetic time series for DO events

To test the capability of HHSA in identifying cross-scale interactions, a synthetic data designed to reflect the characteristics and potential dynamics of paleoclimatic proxies has been constructed. Comparing the obtained results with the exact information of the model demonstrates the usefulness of the HHSA method. For climate variability and change in the past 10 kyr[12] (kyr = 1000 years), it is expected that the effects of orbital forcing, such as changes of precession, obliquity, and eccentricity, may result in direct climate variability on orbital timescales (with some delays). In addition, the internal variability of the climate system may cause variability on other timescales, such as DO events, which are modulated by orbital forcing. Under the guidance of above considerations, our model contains six components:

(1) A trend resulting from eccentricity variability or other longer term changes:

$$d_6(t) = -0.0000285t^3 + 0.0084t^2 - 0.6t - 17.73, \tag{1a}$$

where t has a unit of kyr and ranges from 100 kyr. BP[13] (kyr. BP = kyr before present) to the present. The discrete time series has a temporal resolution (Δt) of 50 year;

(2) A sinusoidal component with a period of 41 kyr to mimic the direct response to obliquity variability:

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[9] Holo-Hilbert Spectral Analysis is abbreviated as HHSA.

[6] Ensemble empirical mode decomposition is abbreviates as EEMD.

[8] Hilbert-Huang transform is abbreviated as HHT.

[1] Amplitude modulation is abbreviated as AM.

[12] 1kyr = 1000 years.

[13] kyr. BP = kyr before present.