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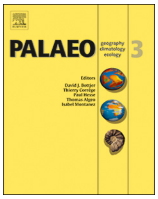

Carbon dioxide precedes temperature change during short-term pauses in multi-millennial palaeoclimate records

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ABSTRACT

In Antarctica, ice-core temperature has traditionally been regarded as a leading variable to carbon dioxide, CO_2 during the last 400,000 years before present (B.P.). This finding is in contrast to most reports on global mean surface temperature and atmospheric CO_2 for the last 150 years. However, previous techniques for establishing leading or lagging (LL) relations between paired global warming variables have required that the time series show constant frequency (stationarity). Herein, we show that on orbital and multi-millennial time scales, the Vostok Antarctic ice core displays 9 periods of 8.7 kyr ± 5 kyr during which CO_2 becomes a leading variable to temperature. Six of the 9 periods were associated with short-term pauses occurring during 4 major glaciation-deglaciation periods. We find that CO_2 also leads temperature during short pauses in the major cyclic pattern of the Greenland time series. In the latter series, there are also two contrasting cycle developments. In the first contrasting cycle developments, lasting from 103.5 to 79 ka, there is an in-phase relation between CO_2 and temperature, with a slope of 0.75. In the second contrasting cycle developments, lasting from 61.5 to 43.5 ka, there is an out-of-phase relation with a slope of −0.67. In addition, the latter shows a see-saw pattern between Arctic and Antarctic temperatures.

1. Introduction

The question of whether increasing CO_2 will lead or lag global warming is relevant for the interpretation of candidate factors that cause changes in the global mean temperature. It is relevant on the palaeontological 100,000 year scale, the millennial scale, and the present 100-year time scale (Cuffey and Vimeux, 2001; Barker et al., 2011; Seip and Grøn, 2017a, 2017b). Here, we examine leading and lagging (LL) relations on the orbital and multi-millennial time scales.

Antarctic temperature appears to have been a leading or synchronous variable to CO_2 during the last 800 kyr (Cuffey and Vimeux, 2001; Monnin et al., 2001; Stips et al., 2016). On a millennial, global scale, CO_2 appears to be a leading variable to temperature on average during the last deglaciation period but not at its onset (Shakun et al., 2012).

An important issue is whether it is possible to find the mechanisms that trigger deglacial warming (Imbrie et al., 1993; Shakun et al., 2012; He et al., 2013). These studies suggest that Milankovitch cycles may induce global warming (≈3 °C), which initiates ice melting and subsequent increases in CO_2 concentrations that further provide means for global deglaciation. The present study gives a more detailed picture of LL relations between temperatures, CO_2, and CH_4 during the four recent glaciation-deglaciation cycles.

We apply a local method for identifying LL relations. The method distinguishes itself from alternative methods in that it can be used to calculate LL relations for three consecutive observations in paired time series and makes it possible to find significant LL relations at the 95% level for 9 consecutive observations. The method does not require observations to be equally spaced or that the series show constant frequency (showing stationarity), but the observations in the paired series have to be sampled at the same time steps (being synoptic).

Since both CO_2 and global mean temperature time series appear to result from several cyclic phenomena, it may be that there are cycles that result from interactions between global surface temperature (GST) and a series of dynamical systems: i) the Solar system (He et al., 2013; Ma et al., 2017), ii) the atmosphere (Knutson et al., 2015), iii) the oceans, including ice–sheets (Barker et al., 2011; He et al., 2013; DeVries et al., 2017) and biogenic carbonate and ocean fertilization (Tang et al., 2016), iv) the Earth's core, e.g., directly through magma migration (Stevens et al., 2016) or through volcanic activities (Huybers and Langmuir, 2009; Huybers and Langmuir, 2017) that affect the CO_2 emissions, and v) anthropogenic substances that are brought into the atmosphere. Since CO_2 and temperature are either synchronous or show

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LL relations between them, identifying common patterns may also help in identifying common governing mechanisms.

In the present study, we examine and compare LL relations between CO_2 and global temperature anomalies (TEMP) for three datasets: i) a 400 kyr dataset from the Vostok ice core in Antarctica, ii) a 120 kyr dataset from the NGRIP ice core in Greenland, and iii) a composite 20-kyr dataset, which represents a global mean for the last deglaciation period constructed by Shakun et al. (2012). There are several recent potential improvements to the records, e.g., those reported by Buizert et al. (2015) and Parrenin et al. (2013). To test the robustness of our results, we repeat selected calculations with the dataset of Parrenin.

Our *first* hypothesis to be tested is that CO_2 changes may sometimes lead and at other times lag temperature changes in the time series. The rationale is that we believe cycles in the series are caused by interactions within the oceans or between the oceans and the atmosphere so that there will be net sequestering of CO_2 during some periods and net emissions of CO_2 during other periods, e.g., "Tang et al. (2016)". Sequestering and emissions of CO_2 may not be a direct function of ocean temperature but may be indirect effects of winds set up by regional temperature differences. Other mechanisms may also be important, e.g., those discussed in Patra et al. (2005) and Johnston and Alley (2006). Furthermore, we hypothesize that the time windows when CO_2 leads temperature can be associated with characteristic events in the temperature series.

Our *second* hypothesis to be investigated is that the relation between the LL patterns that we find for the four-glaciation periods in Antarctica will also be found for the glaciation-deglaciation period in the Arctic and in the global deglaciation pattern identified by Shakun et al. (2012).

Third, we examine if there are anti-phase or see-saw patterns on the multi-millennial scales. The rationale is that such patterns have been found on millennial (Stocker, 1998) and decadal (Chylek et al., 2010) scales.

The rest of the paper is organized as follows. In Section 2 we present the material, and in Section 3 we provide an outline of the method used to identify leading, lagging and synchronous relations between paired cyclic time series. In Section 4 we show results for the sets of time series for Antarctica, the Arctic, and the globe. In Section 5 we discuss the results, and our results are summarized in Section 6.

2. Materials

Herein, we examine time series for Antarctica, the Arctic represented by Greenland and a synthetic series set for the globe. The first series describes four glaciation periods in Antarctica. The data were retrieved from "https://www.ncdc.noaa.gov/paleo-search/study/15076", and we used the "http://www1.ncdc.noaa.gov/pub/data/paleo/icecore/antarctica/aicc2012icecore-data.xls" data file with δD (‰) based on Petit et al. (1999). The temperature data span the period 400 ka–3 ka and were based on analyses of the Vostok ice core. The median value for the time steps was 85 years. The CO_2 data were retrieved from https://www.ncdc.noaa.gov/paleo-search/study/15076 as well and are due to Luthi et al. (2008), transferred on AICC2012. The period for the CO_2 values was from 350 years (B.P. 1950) to 798.6 ka. The data were unequally spaced, with time steps ranging from 0 to 6.01 kyr and median value of 590 years. The time intervals are shown as histograms in Supplementary material 1. The data were linearly interpolated to a 500-yr resolution. Carbon dioxide and temperature data for Antarctica from Parrenin et al. (2013) were retrieved from the article's Supplementary material. We did not use the time series from 800 ka to 400 ka because the time resolution is much coarser for those data. The methane data were retrieved from "Petit et al. (1999)". These data correspond well with data retrieved from the EDC record for the last 420 kyr (Loulergue et al., 2008). The period for the CH_4 values was from 6.6 ka to 403.7 ka. The data for CH_4 were also unequally spaced, with a median time step of 404 yrs. The data were linearly interpolated to the 500-yr resolution.

The second series describes a glaciation-deglaciation period in Greenland. The data were retrieved from https://www.ncdc.noaa.gov/paleo-search/study/15076. The temperature data span the period 120 ka to −30 yr (B.P.). The time steps were unequally spaced, with time steps ranging from 14 to 25 years and median time step of 20 years. The $\delta^{18}O$ ice (‰) values ranged from 46.5 yr to 32.1 yr, with a median value of 40 yr. There are no CO_2 records for Greenland because CO_2 cannot be measured with accuracy in ice-cores from Greenland (Barnola et al., 1995). In addition to the temperature records, there is also a record for methane from Petit et al. (1999) that starts at 119.673 years (B.P.) and ends at 89.453 years (B.P.). However, there is a vacancy in the series from 100.201 years (B.P.) to 62.960 years (B.P.). The data were transformed to synoptic series using linear interpolation with a 500-yr resolution.

The third series describes the last global deglaciation period. The data were supplied by Shakun (personal communication) but can be found in http://www.nature.com/nature/journal/v484/n7392/full/nature10915.html. The data span the period 22 ka–6.5 ka and were calculated as the area-weighted mean of 80 globally distributed temperature records with median resolution of 200 yr. The resulting series was linearly interpolated to a 100-yr resolution to agree with Shakun et al. (2012) and to the 500-yr resolution to be consistent with the other series. The sets we used for Antarctica and the Arctic are shown as raw series in Fig. 1A and as smoothed series in Fig. 1B. Fig. 1C and D will be discussed later.

The temperature data were obtained from the stable isotope compositions of water in the ice cores (δD or $\delta^{18}O$) used as a proxy. Because we only examined LL relations between the temperature, CO_2 and CH_4, we normalized all the time series to unit standard deviation and thus did not convert the proxies to temperatures. However, we use the terms temperature, or TEMP, CO_2 and CH_4 to ease reading. We adopt the term "short-term pauses" when the time series on orbital or multi-millennial scale appear to show a pause, although there may still be small amplitude oscillations. We use the Greek letter β for the slopes between x- and y-variables.

3. Methods

Several methods are available to establish cause and effect relations (Granger, 1969; Sugihara et al., 2012; Stips et al., 2016). However, causality requires that the cause comes before the effect, and several studies restrict the topic to potential causality and require physical, chemical and biological plausibility for support. Kestin et al. (1998) provide an overview of methods, and Huang et al. (1998) describe the identification of moving frequencies. Alley et al. (2002) discuss advantages of identifying maxima or minima in contrast to midpoints in global warming time series. We adopt a method developed by Seip and Grøn (2017a, 2017b), which determines LL relations for paired synoptic series of three consecutive observations.

3.1. The leading-lagging (LL) method

The method consists of 5 steps that are explained below with reference to Fig. 2. This explanation follows closely the description given in Seip and Grøn (2016). The first part of the method, step 2 below, has a counterpart in electrical engineering in Lissajous curves, see, e.g., https://en.wikipedia.org/wiki/Lissajous_curve. The second part, step 3 and Eq. (1), has a counterpart in the calculation of magnetic fields around a wire, e.g., https://en.wikipedia.org/wiki/Biot%E2%80%93Savart_law.

In step 1, we centralize and then normalize the data to unit standard deviation. In this step, we also smooth the series to avoid singularities in the subsequent calculations. With smoothing, we also see trends in the data more clearly (see the Detrending and smoothing section below).