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Differences between the glacial cycles of Antarctic temperature and greenhouse gases

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Abstract

Ice-core measurements have indicated that the atmospheric concentrations of the greenhouse gases CO_2 and CH_4 show glacial-interglacial variations in step with Antarctic temperature. To obtain more insight into the nature of this relationship for cycles of different frequencies, measured time series of temperature, CO_2, and CH_4 are reanalysed. The results indicate that the temperature signal consists of a linear superposition of a component related to CO_2 with a period of ∼100 000 yr and a component related to variations in the obliquity of the Earth's orbital plane with a period of ∼41 000 yr. This suggests that either there operate very different feedback mechanisms at the different time scales or that CO_2 is not merely a passive follower and amplifier of the glacial-interglacial variations in Antarctic temperature.

1 Introduction

Since the discovery of ice ages in the 19th century, there has been an ongoing discussion about the origins of these climatic variations. For a long time, explanations focused on the role of variations in the Earth's orbit (Croll, 1875; Milankovitch, 1941; Hays et al., 1976). About 35 yr ago, ice-core measurements revealed that not only temperature, but also carbon dioxide was lower during the last ice age (Delmas et al., 1980). The 400 000-yr Vostok ice-core record (Petit et al., 1999) and the 800 000-yr European Project for Ice Coring in Antarctica (EPICA) measurements (Augustin et al., 2004) have since revealed robust glacial-interglacial cycles in temperature and the greenhouse gases carbon dioxide and methane exhibiting several remarkable features (Petit et al., 1999):

1. The similarity of different measured signals: over the past 800 000 yr, Antarctic temperature, CO_2, and CH_4 have varied approximately in step (Lüthi et al., 2008; Loulergue et al., 2008). The greenhouse gases CO_2 and CH_4 appear to

lag slightly behind temperature, although this is sensitive to an uncertain difference between the age of the enclosed gas and the surrounding ice (Bender et al., 2006).

2. The shape of the cycles: in particular over the last 400 000 yr, the cycles have been highly asymmetric, resembling a reversed sawtooth pattern. CO_2, CH_4 and temperature decrease over a long period of time (almost 100 000 yr) going into a glacial period and then steeply increase over a relatively short period of time (less than 10 000 yr) from glacial to interglacial. This is remarkable, since none of the Earth's orbital parameters is known to exhibit such asymmetric variations (Denton et al., 2010).
3. The period of the cycles: the dominant period of the temperature variations is 100 000 yr, with minor contributions from cycles with periods of 41 000, 23 000 and 19 000 yr (Petit et al., 1999). The latter can be interpreted as responses to orbital variations, but there is an ongoing discussion why the 100-kyr component is dominant (Imbrie et al., 2011). The eccentricity of the Earth's orbit does vary with a period of 100 kyr (Hays et al., 1976), but these cycles yield much weaker variations in insolation than other orbital cycles such as obliquity (41 kyr) and precession (23/19 kyr) (Imbrie et al., 1993).
4. The amplitude of the cycles: Antarctic temperature varies by about 10 °C between glacials and interglacials (Jouzel et al., 2007), CO_2 varies by about 90 ppmv (Lüthi et al., 2008), CH_4 varies by about 300 ppbv (Loulergue et al., 2008). It appears difficult to explain the full amplitude of these variations; in particular, the CO_2 variations pose a problem, since a large amount of carbon needs to be stored somewhere during glacial periods. Several different mechanisms could play a role: a thorough overview of potentially important mechanisms and their possible relative contributions has been provided by (Peacock et al., 2006).

Although these observed features impose rather strong constraints on any model of, or explanation for, the glacial-interglacial cycles, there is still no consensus about the dynamics underlying the cycles (Huybers, 2011). For example, the asymmetric shape and 100-kyr period of the cycles have been attributed to an oscillation of land ice (Oerlemans, 1980), sea ice (Gildor and Tziperman, 2001), and deep-water formation (Paillard and Parrenin, 2004). Furthermore, there is still no consensus about the causes of the variations in greenhouse gas concentrations and their relationship with the temperature variations, even though there appear to be approximately linear relationships between the different signals (Torn and Harte, 2006). To gain a deeper understanding, many studies have focused on explaining the striking similarity of the cycles of temperature and greenhouse gas concentrations (Broecker, 1982; Brovkin et al., 2007; Bouttes et al., 2011). Instead, I will focus here on structural differences between the time series of Antarctic temperature, CO_2, and CH_4 to further elucidate the relationships between these variables.

2 Analysis

European Project for Ice Coring in Antarctica (EPICA) data (Jouzel et al., 2007; Lüthi et al., 2008; Loulergue et al., 2008) of Antarctic temperature, CO_2 and CH_4 have been obtained from http://www.ncdc.noaa.gov/paleo/icecore/antarctica/domec/domec_epica_data.html. Petit et al. (1999) noticed remarkable differences between the Fourier power spectra of the different signals from the Vostok ice core (Petit et al., 1999). Therefore, I start here with computing Fourier spectra of the EPICA ice-core records of temperature, CO_2, and CH_4. For short time series, MTM is often considered the most appropriate method because the use of "taper" functions reduces the variance of spectral estimates (Ghil et al., 2002). On the other hand, the tapers have the tendency to distort the Fourier spectrum. In Fig. 1, I show both standard Fast Fourier Transform (FFT) (Cooley and Tukey, 1965) and Multi-Taper Method (MTM) (Huybers and Curry, 2006; Huybers and Wunsch, 2004) periodograms.

Each of the spectra of the different ice-core signals is dominated by a maximum at 100 kyr, but for temperature and CH_4, there is a clear secondary peak at the obliquity band around 41 kyr which is almost absent in the spectrum of CO_2 (as has been noticed earlier Petit et al., 1999; Masson-Delmotte et al., 2010). The differences between the Fourier spectra cannot be attributed to inadequacies of the measurements, since the reported measurement uncertainties (Lüthi et al., 2008; Jouzel et al., 2007; Loulergue et al., 2008) translate into uncertainties in the peak strengths of no more than a few per cent. Neither are the differences likely due to orbital tuning, as the same EDC3 time scale (Parrenin et al., 2007) is used for each of the time series (although with an offset to account for the difference between the ages of the gas age and the ice). Thus, even though the time series of the different signals look very similar and their degree of correlation is very high, the differences in the spectral domain suggest that there exist systematic differences in the time domain as well.

As a measure of the pattern similarity between each of the ice-core signals and obliquity, the coefficient of correlation between obliquity (Berger, 1978) (available via http://aom.giss.nasa.gov/srorbpar.html) and Antarctic temperature, CO_2, and CH_4 has been calculated. Although none of the measured time series has a particularly high correlation with obliquity, temperature appears to have the highest correlation with obliquity ($r = 0.22$), followed by CH_4 ($r = 0.18$), whereas obliquity and CO_2 have no significant correlation ($r = 0.037$, $p = 0.30$).

This indicates that temperature and CH_4 consist of a combination of a 100 000-yr cycle and a 41 000-yr cycle related to the obliquity of the Earth's axis, whereas CO_2 appears to be more representative of the “pure” 100-kyr cycle. Recently, it was noted that the temperature time series can in fact be decomposed into a contribution related to CO_2 and one related to obliquity (Masson-Delmotte et al., 2010). Here, I subtract the 100-kyr variability, represented by the CO_2 signal, from the temperature time series to filter out the 100-kyr cycle and isolate the response of Antarctic temperature to obliquity variations. First, the mean values from the temperature and CO_2 signals are subtracted and both signals are rescaled with their respective standard deviation, so that both signals have a mean value of 0 and a standard deviation of 1. These rescaled signals are shown in Fig. 2; by subtracting the rescaled CO_2 from the rescaled temperature, a residual signal is obtained that is shown in Fig. 3 along with the obliquity. The correlation between this residual signal and obliquity is higher than the correlation between obliquity and any individual signal ($r = 0.39$). If the CH_4 signal is subtracted from the temperature time series following the same procedure, a signal with a much lower correlation ($r = 0.08$) is obtained. Hence, subtracting the rescaled CO_2 time series from the rescaled time series of temperature yields a signal that is similar to obliquity, or in other words: Antarctic temperature is approximately a linear superposition of CO_2 and obliquity.

3 Discussion

Given the nonlinear nature of the climate system, it seems highly remarkable that a climatic variable could consistently be written as a simple linear superposition of two other climatic variables over a period of time spanning 800 000 yr. In my view, there are four lines of thought to explain why Antarctic temperature would be a linear superposition of CO_2 and obliquity and why the Fourier spectra of the different signals would be qualitatively different:

1. The greenhouse gases CO_2 and CH_4 are rather well-mixed across the Earth which means that the recorded variations represent a global signal, whereas Antarctic temperature is a local signal. This appears to be, at least, a viable explanation for the observation that the 41-kyr obliquity peak is somewhat stronger compared to the 100-kyr peak in the spectrum of Antarctic temperature than in the spectrum of CH_4 (Petit et al., 1999). The most important natural sources of CH_4 (tropical wetlands, tundras, boreal wetlands) (Bartlett and Harriss, 1993; Dalal and Allen, 2008) are at lower latitudes than Antarctica and atmospheric CH_4 probably responds significantly to temperature variations in these source regions. Although there appears to be a positive correlation between low-latitude temperatures and high-latitude insolation (Liu and Herbert, 2004), variations in the obliquity of the Earth's orbit are likely to have less impact at low latitudes than on Antarctica.

Therefore, obliquity can be expected to have less impact on CH_4 than on Antarctic temperature. One could explain the fact that the spectrum of CO_2 has much less power at 41 kyr than the spectra of temperature and CH_4 by postulating that atmospheric CO_2 is controlled by temperature at much lower latitudes than CH_4. However, such an interpretation would be inconsistent with the widely accepted notion that the Southern Ocean and other polar oceans play a central role in the ocean-atmosphere partitioning of CO_2 (Marinov et al., 2008; Fischer et al., 2010), even though there has been debate about whether these are the only regions where the CO_2 partitioning is determined (Archer et al., 2000; DeVries and Primeau, 2009). Furthermore, one would expect a rather strong response of CO_2 to obliquity, because obliquity variations lead to variations in the equator-to-pole insolation gradient which likely affect the Southern Ocean winds. Thus, it appears difficult to explain why Antarctic temperature would be a linear superposition of CO_2 and obliquity from this line of thought.

2. An explanation for the relatively small contribution of obliquity in the CO_2 signal could be that there exists a slow feedback process operating on a timescale longer than 41 kyr, but shorter than 100 kyr which makes CO_2 respond more strongly to cycles with a period of 100 kyr than to cycles with a period of 41 kyr. However, to the best of my knowledge, no specific feedback mechanism involving CO_2 has been proposed to act on such a timescale. A few thousand years appears to be a more logical timescale for feedbacks between climate and CO_2, given that the ocean and atmosphere equilibrate carbon on such a timescale.

3. The previous two lines of thought were based on the assumption that the CO_2 signal primarily follows temperature variations which need not necessarily be the case. Rather, the following relationship between temperature and CO_2 would be consistent with temperature being a linear superposition of the CO_2 and obliquity signals:

   (a) There exists some 100 000-yr cycle to which both CO_2 and temperature respond.
   (b) Temperature also responds to the 41 000-yr cycle in the obliquity of the Earth's orbit.

   The 100-kyr cycle to which both temperature and CO_2 respond could have its origin in sea-ice cover (Gildor and Tziperman, 2000) or the overturning circulation (Toggweiler and Lea, 2010). Land-ice dynamics does not appear to be a likely candidate, since the Fourier spectrum of benthic $\delta^{18}O$ (a proxy for land-ice volume) exhibits a rather strong component at the obliquity frequency (Lisiecki and Raymo, 2005; Köhler and Bintanja, 2008).

   At the last few glacial inceptions, temperature and CH_4 decrease much more rapidly than CO_2 (Petit et al., 1999). At first sight, this appears to suggest that CO_2 follows temperature and CH_4. However, the perspective that the temperature signal consists of a superposition of a 100-kyr cycle similar to CO_2 and a response to obliquity offers an alternative explanation. After the last few inceptions, obliquity has a minimum (see Fig. 3) and therefore, temperature reaches a minimum, even though CO_2 levels are still high. Nevertheless, the residual signal after rescaling and subtracting the CO_2 time series from the rescaled temperature time series does show large swings around the last few glacial-to-interglacial transitions.

4. In principle, also the following relationship between temperature and CO_2 would be consistent with temperature being a linear superposition of the CO_2 and obliquity signals:
   (a) There is an autonomous 100 000-yr variation in CO_2 to which temperature responds.
   (b) Temperature also responds to variations in the obliquity of the Earth's orbit.

In my view, such an explanation is attractive for its simplicity, but the implied causal relationship of temperature variations being primarily a response to CO_2 variations appears unlikely for the following reasons.

First of all, ice-core data indicate that Antarctic temperature starts to rise a bit earlier (~1000 yr) than CO_2 and CH_4 at most glacial-to-interglacial transitions (Siegenthaler et al., 2005). Nevertheless, this phasing is subject to some uncertainty. For example, there is an inherent difficulty in consistently dating temperature (for which isotopic ratios in the ice are used as proxy) and greenhouse gas concentrations (which are measured from gas bubbles enclosed in the ice) because of the difference in age between the gas in the bubbles and the surrounding ice that is estimated to be up to 7000 yr (Bender et al., 2006), much greater than the inferred 1000-yr lag. Ice densification models are commonly used to compensate for this age difference, but this approach could also give rise to systematic errors (Loulergue et al., 2007). A possible solution to this problem is the use of gas-phase proxies of temperature, such as $\delta^{15}N$ and $\delta^{40}Ar$ (Caillon et al., 2003; Landais et al., 2006). Unfortunately, there is still much uncertainty about what determines the isotopic fractionation of nitrogen and argon. Furthermore, $\delta^{15}N$ and $\delta^{40}Ar$ do not always correlate well with the widely accepted temperature proxies $\delta^{18}O$ and δD (Caillon et al., 2001; Dreyfus et al., 2010).

Second, greenhouse gas variations are considered an unlikely origin of the glacial-interglacial temperature cycles because of their relatively small radiative effect. The direct radiative effect of the glacial-interglacial variation in atmospheric greenhouse gas concentrations accounts for a global temperature variation of about 1 °C (Köhler et al., 2010) which is only $\sim\frac{1}{6}$ of the total temperature change. On the other hand, a number of feedback mechanisms are known in the climate system that could amplify a small radiative effect resulting from changes in greenhouse gas concentrations. Different studies where coupled atmosphere-ocean-sea ice models were forced with the glacial-interglacial CO_2 change and with land ice cover kept at present day have indicated that the CO_2 change with associated feedbacks can explain $\sim\frac{1}{2}$ of the glacial-interglacial temperature variation (Kim, 2004; Yoshimori et al., 2009).

4 Conclusions

To further elucidate the relationships between greenhouse gases and Antarctic temperature over glacial-interglacial cycles, I have analysed differences between the respective measured time series. The analysis indicates that Antarctic temperature has been approximately a linear superposition of CO_2 and obliquity over the last 800 000 yr. It seems difficult to explain this from the perspective that glacial-interglacial CO_2 variations are primarily a response to temperature variations; it appears easier to understand the feature, if either Antarctic temperature and CO_2 independently respond to a 100 000-yr cycle of another variable or there exists an autonomous 100 000-yr biogeochemical oscillation of CO_2, to which temperature responds. However, the latter option appears unlikely because of the inferred relative phasing of variations in temperature and greenhouse gas concentrations (Siegenthaler et al., 2005). In any case, the inference that Antarctic temperature can be written as a linear superposition of CO_2 and obliquity introduces a further constraint which must be met by any explanations for the glacial-interglacial cycles in general and explanations for the relationship between Antarctic temperature and CO_2 in particular.

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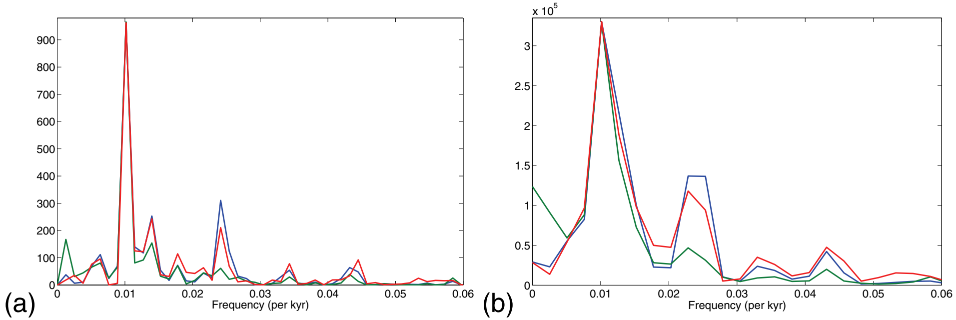

Fig. 1. Periodograms, taken over the past 800 000 yr: **(a)** FFT, **(b)** MTM of (blue) Antarctic temperature, (green) pCO_2, (red) CH_4. For the calculation, the original time series were interpolated at 770-yr intervals. For easy comparison, the spectra have been rescaled to have their respective 100-kyr peaks at similar heights.

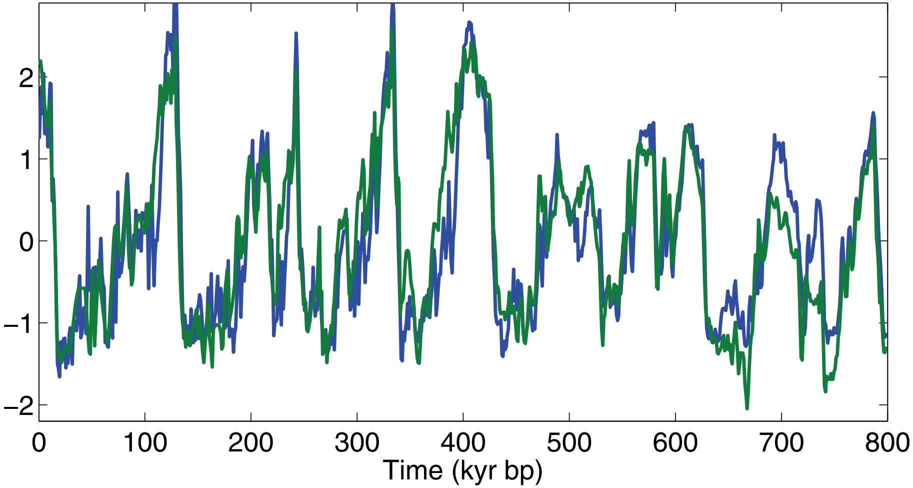

Fig. 2. Rescaled Antarctic temperature (blue) and $p\mathrm{CO}_2$ (green); the original time series is interpolated at 1000-yr intervals.

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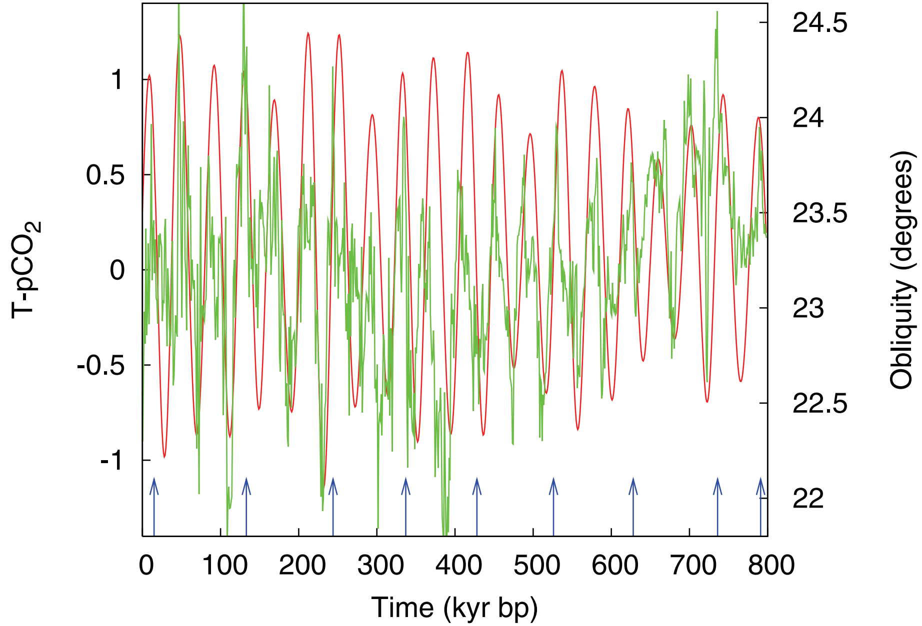

Fig. 3. Obliquity angle of the Earth's orbit (red) and residual signal after subtracting the rescaled pCO_2 from the rescaled Antarctic temperature (green); the glacial-interglacial transitions are indicated by means of blue arrows.