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The phase relation between atmospheric carbon dioxide and global temperature

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ABSTRACT

Using data series on atmospheric carbon dioxide and global temperatures we investigate the phase relation (leads/lags) between these for the period January 1980 to December 2011. Ice cores show atmospheric CO_2 variations to lag behind atmospheric temperature changes on a century to millennium scale, but modern temperature is expected to lag changes in atmospheric CO_2, as the atmospheric temperature increase since about 1975 generally is assumed to be caused by the modern increase in CO_2. In our analysis we use eight well-known datasets: 1) globally averaged well-mixed marine boundary layer CO_2 data, 2) HadCRUT3 surface air temperature data, 3) GISS surface air temperature data, 4) NCDC surface air temperature data, 5) HadSST2 sea surface data, 6) UAH lower troposphere temperature data series, 7) CDIAC data on release of anthropogene CO_2, and 8) GWP data on volcanic eruptions. Annual cycles are present in all datasets except 7) and 8), and to remove the influence of these we analyze 12-month averaged data. We find a high degree of co-variation between all data series except 7) and 8), but with changes in CO_2 always lagging changes in temperature. The maximum positive correlation between CO_2 and temperature is found for CO_2 lagging 11–12 months in relation to global sea surface temperature, 9.5–10 months to global surface air temperature, and about 9 months to global lower troposphere temperature. The correlation between changes in ocean temperatures and atmospheric CO_2 is high, but do not explain all observed changes.

1. Introduction

Ice core records indicate that the greenhouse gas CO_2 co-varied with the global temperature over several glacial–interglacial cycles, suggesting a link between natural atmospheric greenhouse gas variations and temperature on long time scales (IPCC AR4, 2007; Lüthi et al., 2008).

Over the last 420 kyr variations in atmospheric CO_2 broadly followed temperature according to ice cores, with a typical delay of several centuries to more than a millennium (Lorius et al., 1990; Mudelsee, 2001; Caillon et al., 2003). Atmospheric CO_2 is therefore not initiating the large glacial–interglacial climate changes, and presumably these are controlled by orbital Milankovitch cycles. It has however been suggested that the subsequent CO_2-rise may amplify or even in certain periods precede the global temperature increase initiated by Milankovitch cycles, but the interpretation of the proxy data is ambiguous with regard to this (Alley and Clarck, 1999; Shackleton, 2000; Toggweiler and Lea, 2010; Shakun et al., 2012).

The observed time lag between atmospheric temperature and CO_2 from ice cores is thought to be caused by the slow vertical mixing that occurs in the oceans, in association with the decrease in the solubility of CO_2 in ocean water, as its temperature slowly increase at the end of glacial periods (Martin et al., 2005), leading to subsequent net out-gassing of CO_2 from the oceans (Toggweiler, 1999).

Direct measurements of temperatures and atmospheric CO_2 with good time resolution are essential to understand empirically the effects of CO_2 on modern global temperature changes. The first *in situ* continuous measurements of atmospheric CO_2 made by a high-precision non-dispersive infrared gas analyzer were implemented by C.D. Keeling from the Scripps Institution of Oceanography (SIO). These measurements were initiated in 1958 at Mauna Loa, Hawaii, located at 19°N in the Pacific Ocean (Keeling et al., 1995). These data documented that not only was the amount of CO_2 increasing in the atmosphere since 1958, but also that the rise was modulated by annual cycles caused by seasonal changes in ocean surface temperature and photosynthesis in the terrestrial biosphere.

The Mauna Loa measurements were followed by other continuous *in situ* measurements at a limited number of other observation sites in both hemispheres (Conway et al., 1994; Nakazawa et al., 1997; Langenfelds et al., 2002). In the 1980s and 1990s, however, it was recognized that a greater coverage of CO_2 measurements over continental areas was required to provide the basis for estimating sources and sinks of

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atmospheric CO_2 over land as well as ocean regions, and to provide basis for calculating a good estimate of the global amount of atmospheric CO_2.

2. Modern global CO_2 and temperature

Today, an extensive network of international air sampling sites is operated by the National Oceanic and Atmospheric Administration's Global Monitoring Division (NOAA/GMD) in the USA. This organization has measured carbon dioxide and other greenhouse gases for several decades at a globally distributed network of air sampling sites (Conway et al., 1994; IPCC AR4, 2007). A global average is constructed by fitting a smoothed curve as a function of time to each site, and then the smoothed value for each site is plotted as a function of latitude for 48 equal time steps per year (IPCC AR4, 2007). A global average is calculated from the latitude plot at each time step (Masarie and Tans, 1995), based on measurements from a subset of network sites. Only sites where samples are predominantly of well-mixed marine boundary layer (MBL) air representative of a large volume of the atmosphere are considered for the global CO_2 data series (IPCC AR4, 2007). These key sites are typically at remote marine sea level locations with prevailing onshore winds, to minimize the effects of inland vegetation and industries. Measurements from sites at higher altitude and from sites close to anthropogenic and natural sources and sinks are excluded from the global CO_2 estimate. The MBL data provide a low-noise representation of the global trend and allows making the estimate directly from the data without the need for applying an atmospheric transport model (IPCC AR4, 2007).

Global monthly CO_2 data (NOAA) are available from January 1980, and is shown graphically in Fig. 1, along with the monthly global sea surface temperature (HadSST2) and the monthly global surface air temperature (HadCRUT3), using data published by the University of East Anglia and the Hadley Centre, UK. In addition, in the present study we also analyze global air temperature data from the Goddard Institute for Space Studies (GISS) in USA, the National Climatic Data Center (NCDC) in USA, and lower troposphere temperature data published by the University of Alabama (UAH), Huntsville, USA. At the end of the paper a list of URL's used to obtain the data used can be found. All these monthly data series are now sufficiently long to have collected a population of climate perturbations, and they are therefore likely to reveal essentials of the coupling between atmospheric CO_2 and temperature in modern time.

Global atmospheric CO_2 (Fig. 1) has increased steadily during the entire observation period since 1980. There is, however, a pronounced annual cyclic variation superimposed on this overall development, caused by seasonal changes in the magnitude of sources and sinks for CO_2, controlled by dynamic exchanges with oceans and vegetation (IPCC AR4, 2007). The two temperature series HadSST2 and HadCRUT3 also show an overall increase over the period, but their detailed development is more complex than for CO_2. In addition, they only show small net changes since early 2002 (Scafetta, 2011).

In general, the two temperature records are seen to vary in close concert with each other. This also applies for the three other temperature records considered in this study (GISS, NCDC and UAH), but these are not displayed in Fig. 1 to avoid visual congestion. All four temperature records display rhythmic annual variations because of the uneven hemispherical distribution of land and ocean, although this is not readily apparent from the diagram, as other short-term variations tend to dominate.

Resolving the degree of coupling between CO_2 and temperature is not visually straightforward as illustrated by Fig. 1, but obviously requires a more elaborate approach to the data series.

3. DIFF12 values

Before analyzing the monthly data, being interested in longer than annual variations, we first removed the annual cycle from the global atmospheric CO_2 data series by calculating a 12-month running average. This implies that we here consider the annual variation as noise only, and instead are looking for the underlying longer signal, the overall CO_2 increase. As the signal tends to be almost the same from one monthly observation to nearby observations and the noise does not, an average of several adjacent monthly observations will tend to converge on the value of the signal alone. The most serious

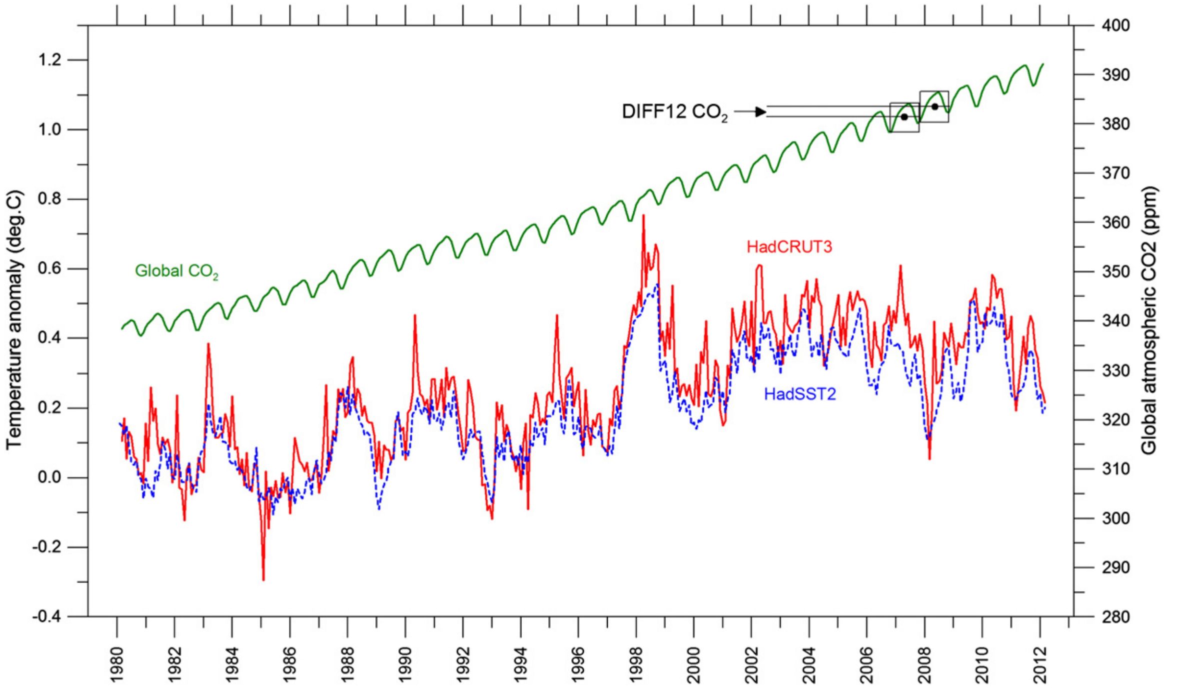

Fig. 1. Monthly global atmospheric CO_2 (NOOA; green), monthly global sea surface temperature (HadSST2; blue stippled) and monthly global surface air temperature (HadCRUT3; red), since January 1980. Last month shown is December 2011.