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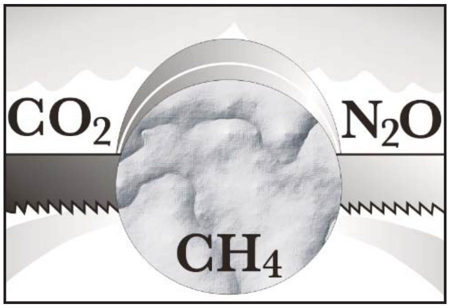

Geoscience of Climate and Energy 5. Ice Cores, Greenhouse Gases and Climate Change

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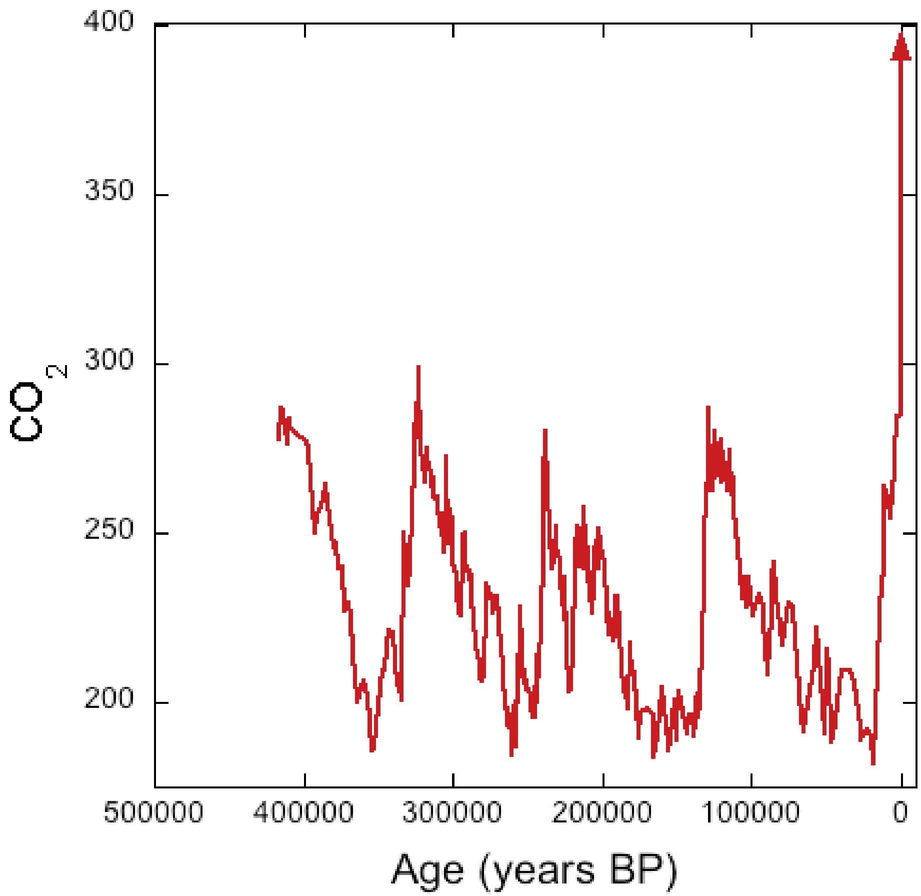

Figure 1. The CO_2 levels in the atmosphere, over the past 400 000 years, as measured in the Vostok ice core.

Ice cores are unique in that they contain not only a record of past environments, but also trap small volumes of atmosphere that directly record the levels of past greenhouse gases. Ice cores trade off temporal resolution for age via the amount of snow that falls at a given location. In places where snowfall rates are high, ice cores yield detailed temporal resolution but represent a limited time span. Annually resolved records of dust, chemical composition, accumulation and temperature via stable isotope ratios are possible in such locations along with gas records that have temporal resolutions of a few years. In places where snowfall rates are low, the temporal resolution of isotope records, for example, can be decades, and that of gases, centuries. Such records reach far back in time; currently, the longest records (from Antarctica) span more than 800 000 years (Siegenthaler et al. 2005; Lüthi et al. 2008).

In ice cores that cover the widest age ranges, records of greenhouse gases show variability on both orbital (Milankovitch) and sub-orbital time scales. Carbon dioxide (CO_2) varies by about 50% relative to its lowest glacial levels, methane (CH_4) by 100%, and nitrous oxide (N_2O) by about 40%. Carbon dioxide is readily correlated with temperature estimates from stable isotope ratios and shows little sub-orbital variability compared with CH_4 and N_2O, both of which have clear orbital variability but also vary significantly during abrupt climate changes (Loulergue et al. 2008). The strong relationship between greenhouse gases and temperature helps to scale the impact of greenhouse gases on climate, and confirms what simple radiation-balance models of the planet tell us; that greenhouse gases are a key determinant in setting global temperature. Also, they help to quickly and simply scale for the non-scientist the impacts of humans on the energy budget of the earth's surface. The total change in CO_2, for example, from peak glacial times to peak interglacial times, is about 100 ppm, from roughly 180 to 280 ppm. This change of 100 ppm has recently been matched by human activities, including fossil fuel burning and deforestation, as the atmospheric burden of CO_2 passed 380 ppm in 2007 (Fig. 1).

During the last 12 000 years (the Holocene epoch), when climate has been relatively stable, levels of greenhouse gases show less variability. Carbon dioxide has varied between 5 and 7%, as has N_2O, whereas CH_4 has varied by about 15% (Fig. 2; Fluckiger et al. 2002). The N_2O and CO_2 records are similar in that minima are observed about 7000 years ago, but the curves are different in that N_2O is slightly higher at the beginning of the Holocene than in the pre-industrial era, whereas CO_2 is higher in pre-industrial times than at any other time in the Holocene. The CH_4 concentrations are about equal at the beginning and end of the Holocene, and reach a minimum at about 5000 years ago. This pattern of correlation between N_2O and CO_2, but not CH_4, is in contrast to their respective behaviours over the past several hundred thousand years, during which time CH_4 and N_2O both exhibit similar high frequency variability, and CO_2 does not vary significantly on short time scales. The causes of Holocene variability of greenhouse gases are not fully understood; of particular interest is the determination of the time at which human impacts on greenhouse gases first become evident. For CH_4, which shows the highest variability during the Holocene, it has been suggested that anthropogenic production of methane by large-scale burning of vegetation played a role in the methane budget during the late Holocene. However, this hypothesis has not been rigorously tested and it is unknown how far back into the Holocene this influence can be detected (Ferretti et al. 2005).

Over the 2000-year period prior to 1850, atmospheric concentrations of greenhouse gases were all relatively constant, displaying a variability of only a few percent (Fig. 3). This pattern has clearly changed since 1850, when all three gases began to increase significantly: N_2O increased by 15%, CO_2 by 35%, and CH_4 over 100%, all relative to their pre-1850 values (Fig. 3). These changes are consistent with the scope of human impacts on the carbon and nitrogen cycles. It is important to note that the ice-core records, most recently updated by MacFarling Meure et al. (2006) using ice from the Law Dome area of Antarctica, merge very well with the atmospheric observations, showing the fidelity with which ice cores can record the true atmospheric composition. Small changes in greenhouse gas concentrations during the last 2000 years, prior to the Industrial Revolution, appear to correlate with climate; for example, a notable 5 to 10 ppm drop in CO_2 around 1600 AD is contemporaneous with one of the Little Ice Age coolings.

Finally, there are some recent changes in greenhouse gas concentrations that may prove instructive in understanding carbon and nitrogen cycle dynamics, both prior to, and during, the current Anthropocene. Examples of this include the current stable level of methane, which is still not fully understood and is expected to change as carbon currently frozen in Arctic regions is released via warming and melting. Another example is the 1940 to mid-1950s period, when CO_2 concentrations in the atmosphere

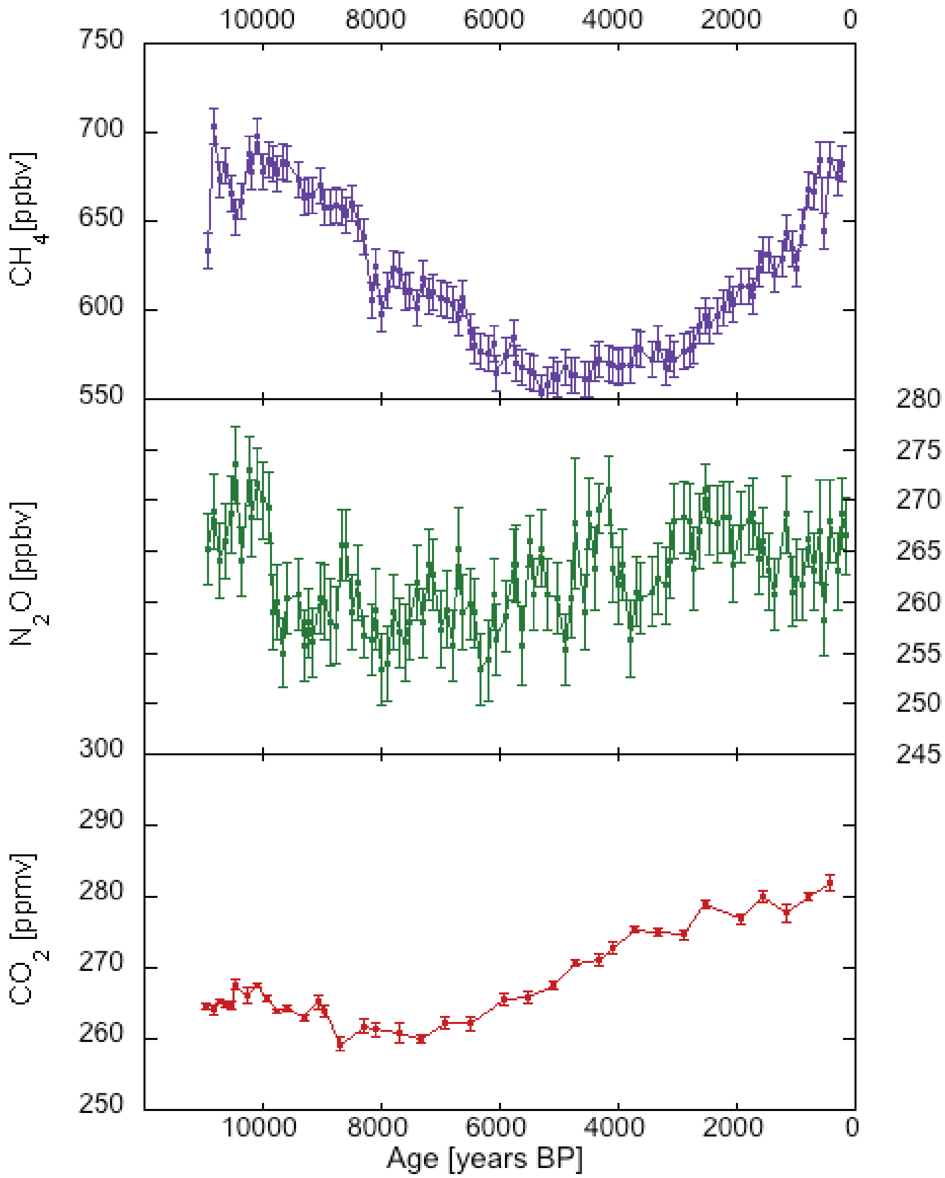

Figure 2. Variability of greenhouse gas concentrations in the atmosphere during the Holocene (Fluckiger et al. 2002).

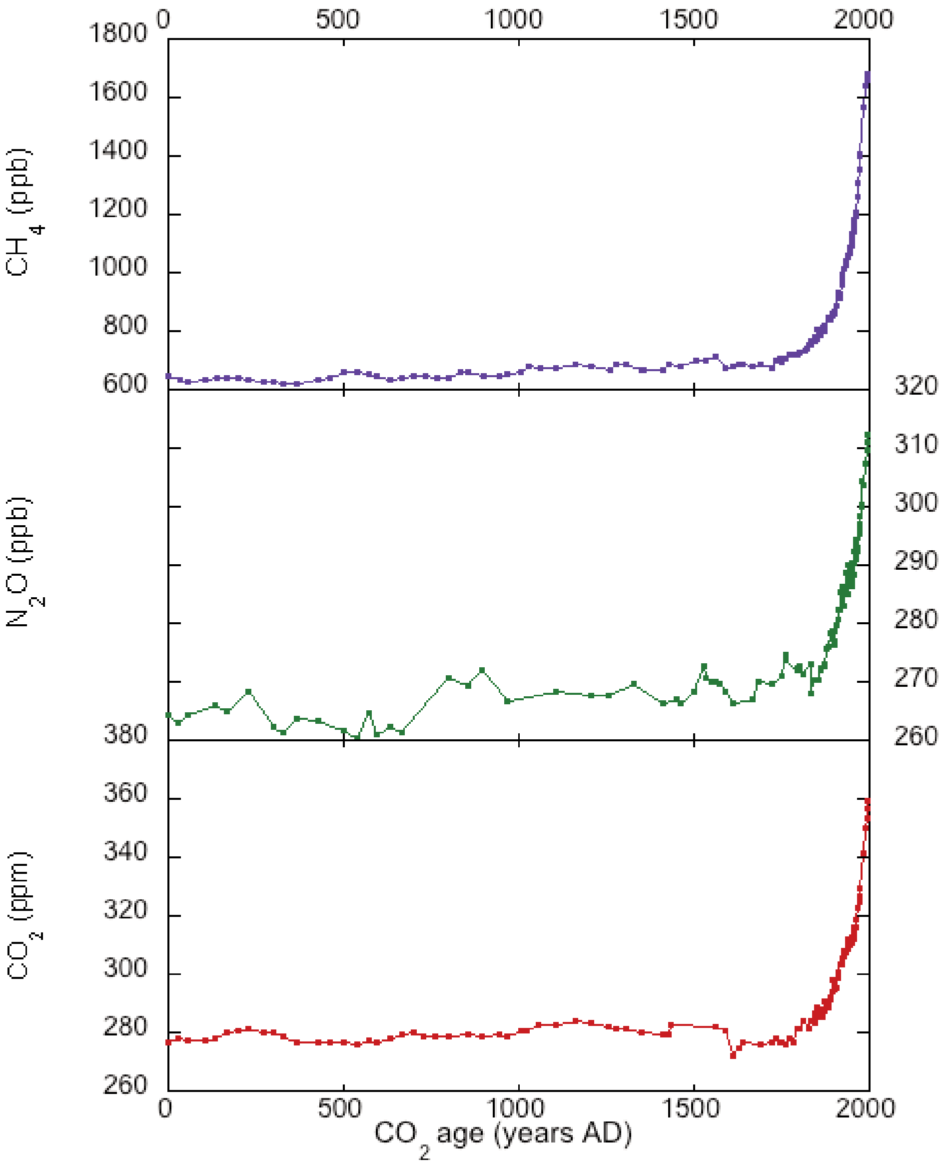

Figure 3. Time histories of greenhouse gas concentrations in the atmosphere over the last 250 years as measured (published and new data) from three Law Dome, Antarctica ice cores (DSS, DE08, and DE08-2). Atmospheric observations made at Cape Grim, Australia, are shown as well.

remained nearly constant at 311 ppm despite generally growing fossil fuel emissions over that time.

In summary, ice cores contribute important records of past greenhouse gas concentrations on time scales ranging from a million years to several decades. The general lesson drawn from these records is that, as predicted by simple radiation balance models, adding greenhouse gases to the atmosphere leads to warming of the planet. Human additions to greenhouse gases are very large compared to natural variations, therefore anthropogenically induced global climate change is a simple expectation as opposed to a surprise, and thus not a matter of serious debate. Small variations in greenhouse gases are observed to accompany small changes in climate; however, this is not always true and the threshold at which an increase in greenhouse gas necessarily prompts a change in global climate is not clear, although it is clear that we are currently past that level today.

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