Positive feedback between global warming and atmospheric CO_2 concentration inferred from past climate change

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[1] There is good evidence that higher global temperatures will promote a rise of greenhouse gas levels, implying a positive feedback which will increase the effect of anthropogenic emissions on global temperatures. However, the magnitude of this effect predicted by the available models remains highly uncertain, due to the accumulation of uncertainties in the processes thought to be involved. Here we present an alternative way of estimating the magnitude of the feedback effect based on reconstructed past changes. Linking this information with the mid-range Intergovernmental Panel on Climate Change estimation of the greenhouse gas effect on temperature we suggest that the feedback of global temperature on atmospheric CO_2 will promote warming by an extra 15–78% on a century-scale. This estimate may be conservative as we did not account for synergistic effects of likely temperature moderated increase in other greenhouse gases. Our semi-empirical approach independently supports process based simulations suggesting that feedback may cause a considerable boost in warming. **Citation:** Scheffer, M., V. Brovkin, and P. Cox (2006), Positive feedback between global warming and atmospheric CO_2 concentration inferred from past climate change, *Geophys. Res. Lett.*, *33*, L10702, doi:10.1029/2005GL025044.

1. Introduction

[2] The direct effects of CO_2 and other greenhouse gases on Earth's temperature are relatively well understood. However, estimation of the overall effect of anthropogenic emissions is complicated by the existence of feedbacks in the earth system [*Kellogg*, 1983; *Lashof*, 1989; *Lashof et al.*, 1997]. An important class of feedbacks is related to the effect of temperature on greenhouse gas dynamics. Increased photosynthesis at higher CO_2 levels and temperatures implies a negative feedback, but positive feedbacks seem likely to override this effect [*Lashof et al.*, 1997; *Woodwell et al.*, 1998]. For instance, higher temperatures may lead to increased release of CO_2, methane and N_2O from terrestrial ecosystems and to increased oceanic denitrification and stratification, resulting in nutrient limitation of algal growth reducing the CO_2 sink to the ocean. Also, CaCO3 neutralization in the ocean is reduced at higher temperatures [*Archer et al.*, 2004]. Several analyses with elaborate coupled climate-carbon models that take such feedbacks into account suggest an overall amplification of the effects of anthropogenic addition of greenhouse gases to the atmosphere [*Cox et al.*, 2000; *Friedlingstein et al.*, 2001; *Prentice et al.*, 2001; *Friedlingstein et al.*, 2006]. However, we are still far from able to compute the relative strengths of the multitude of known (and unknown) relevant processes on a global scale with much precision [*Prentice et al.*, 2001; *Friedlingstein et al.*, 2003].

[3] Here, we combine information derived from reconstruction of past changes with a simple well accepted greenhouse effect model in an attempt to produce an independent estimate of the potential implications of the positive feedback between global temperature and greenhouse gases.

2. Model

[4] The essence of the problem stripped to the bare bones is that CO_2 affects global temperature, while at the same time temperature affects the CO_2 concentration. To analyze the feedback our model should include both effects. The effect of CO_2 and other greenhouse gases on global temperature is relatively straightforward. A simple logarithmic increase of global temperature (T) with concentration of, for example, CO_2 is usually assumed [*Budyko*, 1982] (see Figure 2a):

$$T = T_0 + s/\ln(2) * \ln(C/C_0) \qquad (1)$$

where $\Delta T = T - T_0$ is the temperature increase relative to a reference temperature (T_0) at a reference CO_2 concentration (C_0), and s scales the impact of CO_2 on the temperature. State-of-the-art models suggest the value of s to be somewhere between 1.5 and 4.5°C [*Intergovernmental Panel on Climate Change (IPCC)*, 2001a, 2001b, 2001c].

[5] The effect of temperature on greenhouse gases is the more difficult aspect to model. We take an empirical approach based on palaeo-reconstructions. The basic rationale is that pre-industrial CO_2 variations during glacial cycles and the little ice-age have been largely temperature driven. The relationship between CO_2 and temperature in past dynamics depends on the time-scale at which we focus, but is roughly linear in most data-sets (e.g., Figure 1) implying that for our current purpose it may be simply represented as (Figure 2b):

$$C = \alpha(T - T_0) + C_0 \qquad (2)$$

where α is the slope of change in atmospheric CO_2 against temperature, and T_0 and C_0 are reference temperature and CO_2 level respectively.

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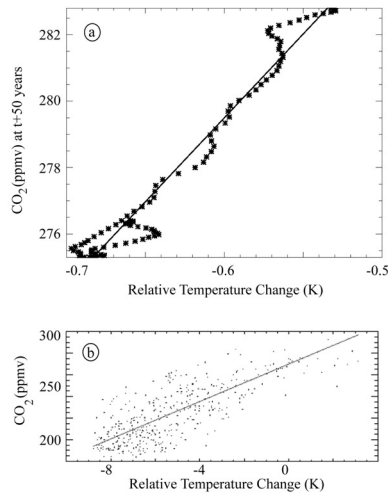[3]Centre for Ecology and Hydrology, Winfrith, Dorset, UK.

Figure 1. Relationships between past atmospheric CO_2 concentrations and reconstructed temperatures. (a) Reconstructed smoothed Northern Hemisphere temperatures over the period 1500–1600 following *Moberg et al.* [2005] plotted against CO_2 levels 50 years later as estimated from a smoothed time series from the Law Dome record [*Etheridge et al.*, 1996]. (b) A regression of CO_2 against temperature for a 400.000 years period of glacial cycles reconstructed from the Vostok ice core. Slopes of the fitted lines are 50.6 ppmv CO_2/°C for Little Ice Age (Figure 1a) and 8.7 ppmv CO_2/°C for the glacial cycles (Figure 1b).

[6] If we interpret the correlation between (pre-industrial) CO_2 and temperature (equation (2)) as representing the effect of temperature on the equilibrium atmospheric CO_2 concentrations, we can combine equation (1) which describes equilibrium temperature as a function of CO_2 with the empirically derived temperature effect on the equilibrium concentration of greenhouse gas (equation (2)), to construct a minimal interactive model which has a single stable equilibrium (Figure 2c).

[7] At first sight there may seem to be some circularity in interpreting the reconstructed times series as simply representing the effect of temperature on CO_2, as the causality between temperature and greenhouse gas concentrations goes two ways. Indeed, the correlated temperature and greenhouse gas concentrations may be considered to roughly indicate a set of possible equilibrium conditions of the interactive earth system on centennial to millennial scales

[*Woodwell et al.*, 1998]. However, it may be argued that the different CO_2 concentrations in the past have arisen largely because the equilibrium temperature curve has moved up and down over time (Figure 3) due to other mechanisms than those related to the effect of CO_2 concentrations on temperature, for example, changes in solar irradiation, which moderated the equilibrium temperatures for given CO_2 concentrations. If we assume that the CO_2 equilibrium as a function of temperature remained largely unaltered in the absence of anthropogenic emissions (or at least varied independently of the temperature isocline), the reconstructed co-variation of ancient CO_2 with temperature may be interpreted as revealing the slope of the effect of temperature on CO_2 equilibrium concentrations. This is exactly the complementary information to equation (1) needed to allow an estimate of the boost in global warming produced by the feedback of temperature to greenhouse gas dynamics.

[8] Since the equilibrium line for greenhouse gas ($C' = 0$) is not vertical (due to the feedback effect), anthropogenic emissions of fossil CO_2 and other greenhouse gases will produce a stronger increase in temperature as well as greenhouse gas concentrations than would be expected if temperature did not affect greenhouse gas concentrations (Figure 4). The magnitude of the predicted effect of warming on warming depends on the ratio of the slopes of the two equilibrium lines. The Carbon equilibrium line ($C' = 0$) is simply a straight line with slope α. The temperature equilibrium line is slightly bent (Figure 2). However, if for simplicity we linearize the temperature isocline estimating the slope δ from the projected effect of CO_2 doubling (between $3 \pm 1.5°C$ [*IPCC*, 2001a, 2001b, 2001c]), the factor with which the projected temperature rise will increase due to inclusion of the feedback follows simply from the two slopes as:

$$\Delta T_{\text{with feedback}}/(\Delta T_{\text{without feedback}}) = 1/(1 - \delta\,\alpha) \qquad (3)$$

This relationship can be deduced directly from geometrical considerations, using the ideas illustrated in Figure 4 if the temperature equilibrium curve ($T' = 0$) is approximated with a straight line.

3. Parameter Estimation

[9] There is uncertainty in the estimates of both slopes. Uncertainty about climate sensitivity to CO_2 has received
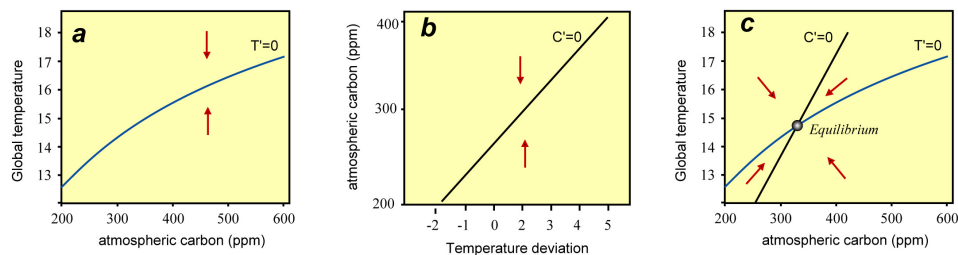

Figure 2. An illustration of how effects of atmospheric carbon on equilibrium global temperature ($T' = 0$ in Figure 2a), and effects of global temperature on the equilibrium level of atmospheric carbon ($C' = 0$ in Figure 2b) can be interpreted to lead to an equilibrium of the interactive system (dot in Figure 2c). Arrows indicate the direction of change if the system is out of equilibrium. Note that temperature change will be faster than atmospheric carbon change. Hence, arrows in Figure 2c do not show precise direction. Rather they serve to illustrate that the intersection represents a stable node.
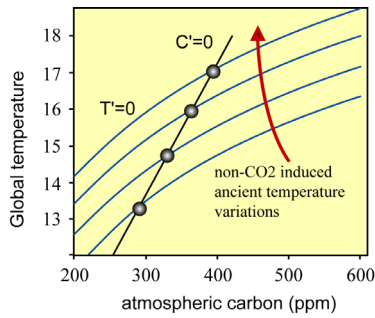
Figure 3. Orbital and other changes during glaciation cycles and the little ice age have affected the temperature-isocline ($T' = 0$, the equilibrium temperature for a given CO_2 level). If we assume that the carbon-isocline ($C' = 0$, the equilibrium CO_2 level for a given temperature), has not been altered in concert with these variations in pre-industrial times, the correlation between CO_2 levels and temperature over pre-industrial past millennia should roughly reflect equilibria aligned on the carbon isocline (dots). Therefore, past correlations as the ones illustrated in Figure 1 should reflect the feedback effect of temperature on atmospheric CO_2 levels.

much attention. Some extreme simulations suggest that temperature increase for doubling of CO_2 concentration can be as high as 11.5°C [*Stainforth et al.*, 2005] but most model experiments (excluding the feedback of temperature on CO_2 dynamics) constrain the effect of CO_2 doubling to the range from 1.5°C to 4.5°C [*IPCC*, 2001a, 2001b, 2001c]. Assuming a pre-industrial CO_2 concentration of 280 ppmv as a reference value, the variation in estimations of s implies that the slope (δ) of the line ($T' = 0$) around present-day CO_2 concentration is about 0.0107 °C/ppmv CO_2 (for the mid-range estimate of $\Delta T = 3$°C) with an uncertainty range of 0.0054 to 0.0161 °C/ppmv CO_2 (for $\Delta T = 1.5$°C to 4.5°C).

[10] The other part of the feedback, the effect of temperature on atmospheric CO_2 concentrations, is more difficult to infer. Importantly, since processes on very different time scales affect global CO_2 dynamics, the effect of temperature on atmospheric CO_2 concentration may differ strongly with the time scale of interest. A review of biospheric feedbacks on temperature [*Woodwell and Mackenzie*, 1995; *Woodwell et al.*, 1998] suggests that the effect may be small on a time-scale of years (about 3 ppmv CO_2/°C), and moderate at millennium time-scales (about 13 ppmv CO_2/°C), but large at a scale of centuries (about 20 ppmv CO_2/°C). Here we are interested in a prognosis of the expected global warming by the end of the current century. Therefore, data that give a hint of the strength of the effect on a century time-scale is what we should focus on. The most important source of information for estimating sensitivity of CO_2 to temperature on that time-scale is the temperature anomaly following the Middle Ages known as the Little Ice Age. The plotted Little Ice Age data (Figure 1a) are an illustration of how CO_2 levels have dropped (in this case with a time lag of 50 years) in response to the drop in temperature in this period. However, results differ depending on the particular temperature reconstruction and the CO_2 data used. To explore this further we fitted linear

regressions through different reconstructed drops in temperature and CO_2 observed between the years 1200 and 1700. Using the high resolution CO_2 data from Siegenthaler et al [*Siegenthaler et al.*, 2005] this yields a slope of 0.0082 ppmv/yr for CO_2 ($CO_2 = -0.0082$ yr + 282 ($R^2 = 0.45$)). The temperature drop in the same period is 0.0003°C/yr ($Temp_{NH} = -0.0003$ yr − 0.2419 ($R^2 = 0.37$)) if we use the data from the influential reconstruction of *Mann and Jones* [2003], while using data from the more recent analysis of *Moberg et al.* [2005] we obtain a decline of about 0.0010°C/yr ($Temp_{NH} = -0.0010$ yr − 0.2206 ($R^2 = 0.38$)). These estimates are for the Northern Hemisphere, and should be multiplied by 2/3 for an estimate of global temperature [*IPCC*, 2001a, 2001b, 2001c], implying an estimated drop in global temperature of 0.00020 to 0.00067°C/yr. These values roughly represent the lowest and highest estimates of temperature decline over the chosen period, given the currently available set of plausible large-scale temperature reconstructions. If we assume that the CO_2 drop during the Little Ice Age was due to the temperature drop, combining this with the estimated 0.0082 ppmv/yr drop in CO_2 we arrive at an estimated carbon sensitivity (α) to temperature of 41 (following Mann and Jones) to 12 (following Moberg et al) ppmv CO_2°C. For an estimated temperature sensitivity (δ) of 0.0107°C/ppmv CO_2 this implies a feedback effect ($1/(1 - \delta \alpha)$) of 1.15 (following Moberg et al) to 1.78 (following Mann and Jones). Note that the uncertainty in the slope of the 'IPCC greenhouse effect' (1.5−4.5°C) also translates into uncertainty of the magnitude of the feedback (estimated feedbacks become for Moberg 1.07 to 1.25 and for Mann and Jones 1.28−2.93). This highlights that it is crucial to reduce our uncertainty in the relationships needed to estimate the overall feedback effect. However, it also highlights the fact that the real system simply seems to be quite sensitive.

[11] The estimated feedback effect might be conservative, as higher temperatures are also likely to promote concentrations of methane [*Woodwell et al.*, 1998; *Petit et al.*, 1999] and N_2O [*Leuenberger and Siegenthaler*, 1992]. Although, these relationships have received somewhat less attention, the synergy implies that the overall positive effect
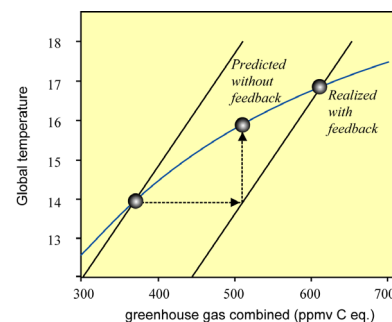

Figure 4. Inclusion of the feedback of temperature on greenhouse gases (non-verticality of the greenhouse gas equilibrium lines) can substantially affect the prediction of the effect of anthropogenic emission of greenhouse gases on temperature as well as the equilibrium concentration of greenhouse gases.

of warming on greenhouse gases is substantially larger than would be inferred from the feedback on CO_2 alone.

4. Discussion

[12] Admittedly, our approach is rather crude as we base our estimation on time series showing the lumped effects of all slow and fast mechanisms. Although we differentiate between feedback strengths inferred for different time-scales, our quasi-equilibrium approach cannot produce more than a rough estimate. Also, there are obvious differences between the period from 1200 till 1700, on which the estimate of the century scale feedback strength is based and current conditions. Some of these such as enhanced nutrient availability may tend to reduce atmospheric carbon concentrations, while others may push the balance to the other direction.

[13] The main merit of our approach as we see it, is that it allows for an estimate of the potential boost in global warming by century-scale feedbacks which is quite independent from that provided by coupled CO_2-climate models that explicitly simulate a suite of mechanisms. Like our approach these models have considerable uncertainty. Not only are the quantitative representations of the mechanisms in the models uncertain, there is also always an uncertainty related to the fact that we are not sure whether all important mechanisms have been accounted for in the models. In view of the independence of our approach it is encouraging that our estimate of a boost in global warming corresponds roughly to what was found in simulation studies [*Cox et al.*, 2000; *Prentice et al.*, 2001; *Friedlingstein et al.*, 2003]. As *Levins* [1966] once phrased it, one is more likely to accept something as the truth when it emerges "as the intersection of independent lies". Although "lies" may sound a bit too harsh for the models involved, both our approach and the large simulation models clearly have their shortcomings. Interpreting our results in this spirit, they enhance the credibility of the view that over the coming century we might see a considerable boost of global warming and greenhouse gas levels compared to recent trends.

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