Missing feedbacks, asymmetric uncertainties, and the underestimation of future warming

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[1] Historical evidence shows that atmospheric greenhouse gas (GhG) concentrations increase during periods of warming, implying a positive feedback to future climate change. We quantified this feedback for CO_2 and CH_4 by combining the mathematics of feedback with empirical ice-core information and general circulation model (GCM) climate sensitivity, finding that the warming of 1.5–4.5°C associated with anthropogenic doubling of CO_2 is amplified to 1.6–6.0°C warming, with the uncertainty range deriving from GCM simulations and paleo temperature records. Thus, anthropogenic emissions result in higher final GhG concentrations, and therefore more warming, than would be predicted in the absence of this feedback. Moreover, a symmetrical uncertainty in any component of feedback, whether positive or negative, produces an asymmetrical distribution of expected temperatures skewed toward higher temperature. For both reasons, the omission of key positive feedbacks and asymmetrical uncertainty from feedbacks, it is likely that the future will be hotter than we think.

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1. Introduction

[2] The uncertainty reported for GCM projections of climate change stems largely from the treatment of ice-albedo, water vapor, and cloud feedbacks in the climate system [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001]. Among the sources of uncertainty not yet included in the models are a suite of feedbacks generated by terrestrial and marine biogeochemistry [*Lashof et al.*, 1997]. In these feedbacks, a change in climate affects the sources and sinks of GhG, resulting in a change in atmospheric GhG concentrations that feeds back to amplify or dampen the initial temperature change.

[3] The Vostok ice core record clearly suggests that feedbacks involving atmospheric carbon dioxide and methane concentrations are positive, not negative [*Lorius et al.*, 1990; *Cuffey and Vimeux*, 2001; *Köhler et al.*, 2005]. To see this, note that the timing of glacial-interglacial cycles is triggered by cycles in the amount of sunlight reaching the earth, but the magnitude of warming and cooling cannot be explained by the solar variations alone. Rather, the temperature change is explained by the strong variation in atmospheric carbon dioxide and methane concentrations, both of which co-vary with temperature (Figure 1). The close correlation of GhG concentrations with temperature over repeated glacial-interglacial cycles and the absence of any known independent source of variability in their concentrations suggest that the changes in their levels were caused by changes in climate [*Shackleton*, 2000]. Thus there is a positive feedback in the earth climate system: a small initial warming (for example caused by a change in solar input) causes carbon dioxide and methane concentrations to rise, which in turn causes more warming, and so on. This positive feedback has the reverse effect (in other words, enhanced cooling) when the driving term, the solar-input, is decreasing.

2. Approach and Results

[4] The strength of a feedback can be described by the overall gain in the system—the amplification or dampening of an initial perturbation ΔT_0, as calculated in equation (1):

$$\Delta T_F = \Delta T_0 \times 1/(1-g) \quad (1)$$

where ΔT_F is the final change in temperature; ΔT_0 is the initial temperature perturbation before any feedback; and g is the feedback gain, the sum of independent feedbacks.

[5] Is the magnitude of the greenhouse gas-temperature feedback big enough to worry about? The answer is a definite "yes." We have estimated the feedback gain using new, deuterium-corrected temperature records for the ice cores [*Cuffey and Vimeux*, 2001], climate sensitivity calculated by GCM, and an equation for quantifying gain[1] [*Lashof et al.*, 1997] (equation (2)):

$$g_{CO_2} = \frac{\partial T}{\partial CO_2}\frac{\partial CO_2}{\partial T} \quad (2)$$

The first factor on the right-hand side (RHS) of this expression is the climate sensitivity to atmospheric carbon dioxide, calculated without CO_2-mediated feedback to temperature. We estimate this from GCM predictions of equilibrium change in global mean surface temperature, following a doubling of atmospheric CO_2 concentration equivalent. An increase in atmospheric CO_2 concentration from 275 to 550 ppm is expected to increase radiative forcing by about 4 W m^{-2}, which would lead to a direct warming of 1.2°C in the absence of feedbacks or other

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[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005gl025540.

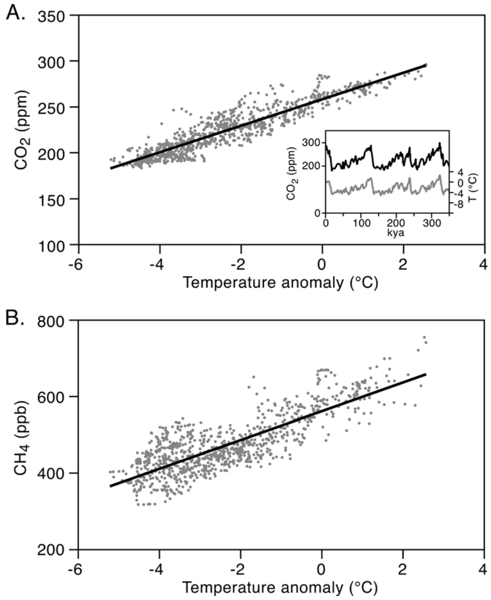

Figure 1. Vostok ice core data for the past 360,000 years, from data originally published by *Petit et al.* [1999]. The temperature data were deuterium excess-corrected to generate Southern Hemisphere temperature equivalents [*Cuffey and Vimeux*, 2001], and all other quantities (CO_2, CH_4, and isotopes) were filtered by *Cuffey and Vimeux*, [2001] with a center-weighted filter with nominal filtering length 1000 y, which eliminated the high-frequency part of the isotope signals with minimal effect on the gas concentration signals used here. The inset shows CO_2 concentration and temperature anomalies over the past 360,000 years. (a) Atmospheric CO_2 concentration versus temperature anomaly. The slope of the regression line is 14.6 ppm/°C (r^2 = 0.85). For the local Vostok temperature, the slope is 9.1 ppm/°C (r^2 = 0.85). The slope for the warming of the past 20,000 years is 17 ppm/°C. (b) Atmospheric CH_4 concentration versus temperature anomaly. The slope of the regression line is 37.4 ppb/°C (r^2 = 0.67). For the local Vostok temperature, the slope is 23.7 ppb/°C (r^2 = 0.68).

responses of the climate system [*IPCC*, 2001]. (Due to feedbacks involving water vapor, clouds, ice-albedo, the predicted climate warming is 1.5–4.5°C for a doubling in CO_2, with the range deriving from uncertainties in those feedbacks.) This estimate is consistent with *Hegerl et al.* [2006]; it is conservative because the direct climate sensitivity during the past glacial-interglacials was likely higher than this value for the modern era for several reasons, including saturation of IR-absorbing wavelengths as GhG concentrations increase.

[6] The second factor on the RHS of equation (2) is the change in GhG concentration with temperature, which we derive from ice core data. The slope of the regression of CO_2 or CH_4 concentration on temperature gives the amount of change in GhG concentration per unit change in temperature [*Jouzel et al.*, 2003]. We report results for two relevant temperature records, local (Antarctic) and hemispheric: the local record is better studied but the hemispheric temperature is more relevant to large-scale ecosystem feedbacks. The latter has a steeper slope (in other words, more change in GhG per change in temperature) because for the same increase in GhG forcing, there should be more warming at the poles than at the equator. As a result, the hemispheric record suggests a larger feedback. The covariance between CO_2 and temperature has been reported [*Cuffey and Vimeux*, 2001] with $r^2 >$ 0.84. Although not reported in that study, the regression slopes are quite steep. For CO_2, the regression on local temperature (equation (3)) gives 9.1 ppm/°C, and for the Southern Hemisphere (equation (4)) gives 14.6 ppm/°C. Equation (1) can now be evaluated:

$$g_{local,CO_2} = \frac{\partial T}{\partial CO_2}\frac{\partial CO_2}{\partial T} = \frac{1.2^oC}{275ppm(CO_2)}\frac{9.1ppm(CO_2)}{^oC} = 0.040 \tag{3}$$

$$g_{hemispheric,CO_2} = \frac{\partial T}{\partial CO_2}\frac{\partial CO_2}{\partial T} = \frac{1.2^oC}{275ppm(CO_2)}\frac{14.6ppm(CO_2)}{^oC} = 0.064 \tag{4}$$

The same approach can be used to estimate the feedback to warming generated by CH_4. In the ice core record, the regression slope is 23.7 ppb/°C for the local temperature and 37.4 ppb/°C for the Southern Hemisphere (Figure 1b). Although methane climate sensitivity is not explicitly reported in the IPCC comparison of GCMs, it can be estimated by considering that, to first order, climate sensitivity to a change in forcing is independent of the GhG species causing the change in forcing [*IPCC*, 1995]. Therefore, we can use the climate sensitivity of GCMs to CO_2, with a substitution for the per-molecule forcing of CH_4 (CH_4 has 21× the radiative forcing of CO_2 per molecule, so if *Y* moles atmospheric CO_2 cause *Z* increase in temperature, then *Y*/21 moles CH_4 will have the same effect). The resulting feedback strength generated by methane is 0.0022 (local temperature, equation 5) and 0.0034 (Southern Hemisphere, equation (6)).

$$g_{local,CH_4} = \frac{\partial T}{\partial CH_4}\bullet\frac{\partial CH_4}{\partial T} = \left[\frac{1.2^oC}{275ppm(CO_2)}\bullet\frac{21mole(CO_2)}{1mole(CH_4)}\bullet\frac{ppm}{1000ppb}\right]\bullet\frac{23.7ppb(CH_4)}{^oC} = 0.0022 \tag{5}$$

$$g_{hemispheric,CH_4} = \frac{\partial T}{\partial CH_4}\bullet\frac{\partial CH_4}{\partial T} = \left[\frac{1.2^oC}{275ppm(CO_2)}\bullet\frac{21\ mole(CO_2)}{1\ mole(CH_4)}\bullet\frac{ppm}{1000ppb}\right]\bullet\frac{37.4ppb(CH_4)}{^oC} = 0.0034 \tag{6}$$

The summed contributions to the feedback gain, *g*, from these greenhouse gas feedbacks is $g_{local} \sim 0.042$ and $g_{hemispheric} \sim 0.067$. The range in *g* derives from the choice of paleo temperature records, as indicated by the subscripts to *g*. Use of the local, more commonly cited record gives less feedback strength than does the data set used to estimated hemispheric temperatures.

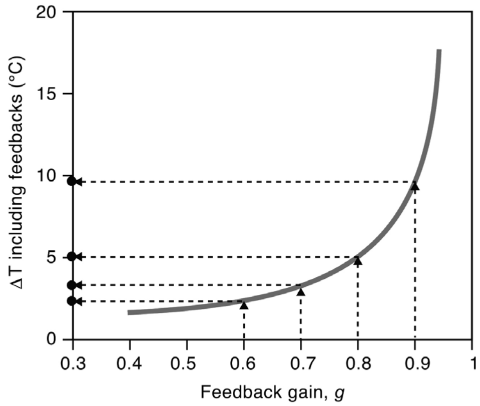

Figure 2. The impact of feedbacks on expected temperature response to elevated CO_2 concentrations. The direct effect of doubled CO_2 (1.2°C) is amplified by a variety of feedbacks. The gain from the feedback processes currently included in GCMs varies from 0.2 to 0.73 depending on the model, amplifying the total warming to 1.5–4.5°C. This graph of equation (1) illustrates the property that a change or uncertainty in the feedback has an asymmetric effect. In the example shown here, the direct warming is 1°C, nominal g = 0.7 and nominal warming = 3.3°C. An additional 0.1 negative feedback (g = 0.7 − 0.1 = 0.6) results in a warming of 2.5°C (0.8°C lower than the nominal case), whereas the same magnitude of change or uncertainty in the positive direction (g = 0.7 + 0.1 = 0.8) results in a 5°C warming (1.7°C higher). The positive feedback we estimate in the Vostok record (g_{GhG} = 0.067 based on the hemisphere record) would lead to an addition 1.5°C warming, for a total of 6.0°C for doubled CO_2.

[7] We calculate the new, total feedback gain in the system by adding the GhG feedbacks estimated above to the gain currently in GCMs reported by *IPCC* [2001]. The feedbacks currently in those GCMs—mainly water vapor, cloud, and ice-albedo processes—amplify the direct effect of doubled-CO_2 (1.2°C) to a total warming of 1.5–4.5°C [*IPCC*, 2001]. Using equation (2), the baseline gain implicit in these models (i.e., without CO_2 or CH_4 feedbacks) is 0.20–0.73. At the upper end of sensitivity, the baseline gain is large and adding the GhG feedback gives a new total feedback gain of ∼0.78 to 0.8, strongly amplifying any climate perturbation. At the lower end, the new gain is 0.24–0.27. The range in each case comes from adding the local or hemispheric temperature-derived g to 0.2 or 0.73 baseline g.

[8] Conceptually, this additional feedback takes place because anthropogenic GhG emissions cause warming, which alters earth system processes, resulting in additional atmospheric greenhouse gas loading and additional warming. Thus, the feedback greatly increases the warming commitment engendered for any given anthropogenic emission scenario. In fact, the gain calculated above implies that human activities that would, in the absence of GhG feedback, double CO_2 and cause ∼1.5–4.5°C warming, would actually result in 1.6–6.0°C warming at equilibrium, or up to 1.5°C warmer temperatures than currently predicted for an initial perturbation of 2 × CO_2. According to IPCC Special Report on Emissions Scenarios, atmospheric forcing may increase beyond 550 ppm CO_2 equivalent forcing in the next 100 years. The GhG feedback quantified above suggests that the upper value of warming that is projected for the end of the 21st Century, 5.8°C [*IPCC*, 2001], could be increased to 7.7°C, or nearly 2°C additional warming.

3. Discussion

[9] Even if there were equal probability of positive and negative feedback, the consequences of uncertain feedback are tilted toward more warming, for two reasons. First, the range of possible impacts from positive and negative feedbacks is not symmetric. Warming of 5, 10, or 20°C is theoretically possible due to positive feedback, while negative feedback cooling can only span from the initial warming (such as 3.3°C mean warming [*IPCC*, 2001]) to no (zero) warming. Second, the same magnitude of feedback strength causes a much larger change in temperature if it is positive (e.g., g = +0.1) than if it is negative (e.g., g = −0.1). This can be seen from equation (1), which expresses the change in temperature as a function of g, and is graphed in Figure 2. Specifically the second derivative (equation (7)) is always positive because g < 1, which means that a positive Δg increases the slope in equation (1) ($\Delta T/\Delta g$) more than a negative Δg decreases it.

$$\frac{\partial^2}{\partial_g^2}\Delta T_0(1-g)^{-1} = 2\Delta T_0(1-g)^{-3} \qquad (7)$$

The asymmetry obtains whether Δg represents a change in feedback gain (i.e., from including an additional feedback) or represents uncertainty in g. An uncertainty bound around a positive feedback, even if a symmetrical uncertainty in the feedback gain, poses an asymmetrical risk weighted toward higher warming.

[10] In risk theory, the risk of an outcome is the product of the consequence and the probability of occurrence. Thus our argument that the uncertainty from feedbacks creates a risk of larger-than-expected climate change rests on two legs: a positive feedback has a bigger consequence (temperature change) than a negative feedback of same magnitude, and there is a higher probability of net positive greenhouse gas feedback than of negative feedback.

[11] What mechanisms gave rise to the CO_2 and CH_4 feedbacks in the ice core record, and what can this tell us about the future? For the warming following the last glacial maximum (LGM), oceanic mechanisms proposed include CaCO3 dissolution and thermal- and circulation-driven release of oceanic CO_2 [*Kohfeld et al.*, 2005; *Archer et al.*, 2004]. On land, several studies suggest that revegetation led to a net C sink by terrestrial ecosystems (forming negative feedback) after the LGM [*Köhler et al.*, 2005], but another concludes that soil C released during deglaciation was sufficient to form net positive feedback [*Zeng*, 2003]. There is evidence that many of these processes could operate on the century time scale [*Barnola et al.*, 2005].

[12] Experimental and modeling evidence is accumulating that terrestrial ecosystems could form positive feedbacks with global warming in the next century [*Angert et al.*, 2005; *Ciais et al.*, 2005; *Fung et al.*, 2005], through

changes in, for example, primary productivity, soil carbon storage, and methane emission due to the influence of climate on, for example, length of growing season, soil moisture, and permafrost, respectively. All 10 simulations in the recent coupled climate carbon cycle model intercomparison (C4MIP) show positive feedback by 2100 due to ecosystems [*Friedlingstein et al.*, 2006].

[13] As an analogy to anthropogenic climate change, do long-term paleo data, such as ice cores from glacial-interglacial cycles, under- or overestimate biosphere feedbacks to warming over the next century? The answer depends in part on the relative importance of slow or lagged processes versus those that saturate or arise rapidly. Data from long-term climate change include more processes, processes with time lags, and slower processes compared to data from rapid climate change. Feedbacks involving plant species distribution (such as shifts in the ranges of forest biomes) and ocean carbonate [*Archer et al.*, 2004] are two examples of slower processes. If slow processes drove the net positive feedback evident in Vostok data, then the long-term record could overestimate the centennial-scale response. In contrast, biosphere response on short time scales can reveal processes that saturate/exhaust quickly (for example, if warming accelerates decomposition only until the labile pool of soil organic matter is exhausted) or that are driven by disturbance or the rapid pace of change itself [*Scheffer et al.*, 2006; *Harte et al.*, 1992]. If these are dominant, then the ice core data may underestimate the climate response.

[14] An additional reason that long-term ice core data may underestimate the magnitude of future positive biosphere feedbacks is that certain negative feedbacks that occurred during or after the LGM may not occur in the near future. Specifically, while the future redistribution of plant biomass cannot be predicted with certainty [*Cox et al.*, 2000; *Dufresne et al.*, 2002], it is unlikely there will be a modern equivalent of the negative feedback from re-vegetation that occurred during deglaciation. Yet a positive feedback from accelerated decomposition of global soil C is expected. Thus, there are several reasons why regressions of long-term climate data sets may underestimate the magnitude of positive feedbacks under global warming.

[15] Although global temperatures have risen more than 0.5°C in the past 150 y, it is difficult to determine if this warming has caused an increase in GhG levels via feedback because the magnitude of anthropogenic inputs, presumably the main cause of rising GhG, are highly uncertain, particularly from 1750–1900 (15). GCM simulations of the recent 0.5°C warming of the 20th century, or of past glacial cycles, are successful without including these feedbacks because they are driven by exogenous GhG concentrations. While avoiding these problems, there are important limitations to inferring future feedbacks from ice core records. Doing so means extrapolating to temperature and GhG levels that are higher than those spanned by the 420,000 y record. However, these feedback mechanisms had a consistent effect over multiple climatic cycles, and give even tighter correlations between temperature and methane or CO_2 during the recent Holocene warming. We have no reason to assume that they are not still operative [*Cuffey and Vimeux*, 2001; *Petit et al.*, 1999].

[16] Perhaps because the causes of the rise in atmospheric CO_2 and CH_4 concentrations from the LGM to their pre-industrial values are not understood, the significance of these feedbacks to us, today, has not been highlighted in the policy debate about global warming. Both ice core data and contemporary experiments indicate that relevant response times can be of the order decades to centuries. Thus, the significance of these positive feedbacks for climate change is clear. If the mechanisms underlying them were incorporated in our climate models, we would be predicting a significantly greater increase in global warming than is currently forecast over the next century and beyond. Uncertainty in climate change predictions has been used as a rationale for inaction against the threat of global warming, based on a prevailing view that the uncertainties give equal support to climate "optimists" (who think it will be a small problem) and "pessimists" (big problem). This view stems in part from the reporting of uncertainty in climate change predictions as symmetric errors around the mean. A rigorous investigation of the uncertainties in climate change prediction reveals that there is a higher risk that we will experience more severe, not less severe, climate change than is currently forecast.

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