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Glacial cycles and carbon dioxide: A conceptual model

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[1] The correlation between Antarctic temperature and atmospheric carbon dioxide concentration is a key feature of Quaternary climate cycles. The cycle is characterised by pronounced temporal asymmetry; with rapid increase in both temperature and CO_2 at the glacial termination. Here I compare observed climate cycles with results from a simple model which predicts the evolution of global temperature and carbon dioxide over the glacial-interglacial cycle. The model includes a term which parameterises deep ocean release of CO_2 in response to warming, and thereby amplifies the glacial cycle. In this model, temperature rises lead CO_2 increases at the glacial termination, but it is the feedback between these two quantities that drives the abrupt warming during the transition from glacial to interglacial periods. **Citation:** Hogg, A. M. (2008), Glacial cycles and carbon dioxide: A conceptual model, *Geophys. Res. Lett.*, *35*, L01701, doi:10.1029/2007GL032071.

1. Introduction

[2] The earth's climate over the last million years is punctuated by a 100,000 year cycle of ice ages and warm interglacials. Air temperature over Antarctica, as determined from ice core data, goes through four glacial cycles in the past 430,000 years (Figure 1, reproduced from *Petit et al.* [1999, 2001]). At the end of each glaciation (the glacial termination) temperature increases rapidly, as does CO_2, producing a sawtooth pattern.

[3] The primary candidate for the mechanism controlling the timing of ice ages is the 100,000 year variation in the eccentricity of the earth's orbit [*Hays et al.*, 1976]. However, the amplitude of glacial cycles cannot be explained by orbital cycles alone [*Wunsch*, 2004] implying that temperature is modified by feedbacks within the earth's system. For example, it is possible that the albedo of ice sheets provides a positive feedback mechanism, implying that glacial terminations may be triggered by maxima in northern hemisphere radiation [e.g., *Ruddiman*, 2006a; *Hansen et al.*, 2007], most likely due to variations in the orbital obliquity cycle. Alternatively, it is argued that the global carbon cycle enhances the orbital eccentricity variations [e.g., *Shackleton*, 2000].

[4] In this paper I outline the development of a minimum complexity model which allows one to investigate key aspects of the glacial-interglacial cycle. The model relies on the hypothesis that the glacial cycle is triggered by variations in the earth's orbit which alter the incoming solar radiation to the earth. These orbital cycles are amplified by limited positive feedback between CO_2 (and other greenhouse gases) and temperature. Assuming that Antarctic temperature can be used as a proxy for mean global temperature, I construct a simplified set of equations for greenhouse gas concentration and global temperature. These equations are solved numerically to demonstrate how feedbacks between greenhouse gases and temperature may operate to produce the observed temporal asymmetry in the glacial-interglacial cycle (as shown in Figure 1).

2. Earth's Radiative Balance

[5] The simplest possible radiative balance of the earth can be written as

$$\overline{S} = \sigma \overline{T}^4, \tag{1}$$

where $\overline{S}$ is the mean incoming solar radiation, $\sigma = 5.67 \times 10^{-8}$ W/m^2/K^4 is the Stefan-Boltzmann constant and $\overline{T}$ the mean global temperature [*Peixoto and Oort*, 1992]. If the standard value of $\overline{S} \approx 240$ W/m^2 is used, the solution of equation (1) gives $\overline{T} \approx 255$ K (which is about 33K lower than present day temperatures). The primary reason for this anomaly is that greenhouse gases act to trap outgoing radiation [*Ramaswamy et al.*, 2001]. This effect can be written as an extra source term in the radiative balance:

$$\overline{S} + \overline{G} = \sigma \overline{T}^4, \tag{2}$$

where $\overline{G}$ is the greenhouse warming term. A value of $\overline{G} \approx 150$ W/m^2 is sufficient to give $\overline{T} \approx 288$ K.

[6] A time dependent version of equation (2) can be written as

$$c\frac{dT}{dt} = S + G - \sigma T^4. \tag{3}$$

where c is the specific heat capacity of the ocean (we use 1.7×10^{10} J/m^2/K), and the use of un-barred quantities indicate that S, G and T are now permitted to vary in time, but remain global averages. In this equation, a slow variation in S (with G kept constant) will produce oscillations in T which are almost in phase with the radiation perturbations. Incoming radiation is modelled as

$$S(t) = \overline{S} + \sum_i S_i \sin\left(\frac{2\pi t}{\Gamma_i}\right) \tag{4}$$

where S_i is the amplitude of insolation perturbations and Γ_i is the period of variations in the earth's orbit. If we force equations (3)–(4) with orbital eccentricity forcing ($S_1 = 0.25$ W/m^2 [*Hansen et al.*, 2007]; $\Gamma_1 = 10^5$yr [*Berger and Loutre*, 1991]) we find that the thermal response has an

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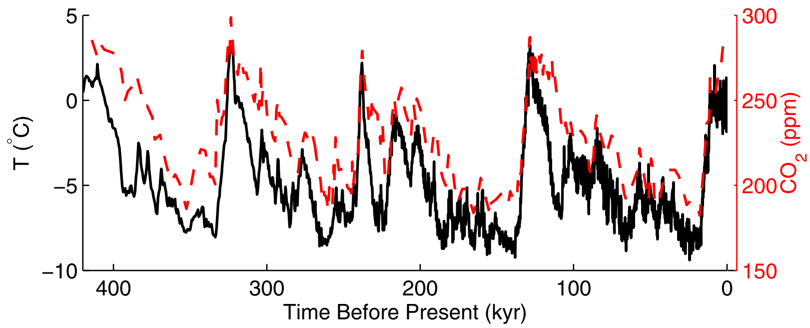

Figure 1. Temperature anomaly and CO_2 (dashed line) inferred from the Vostok ice core data [*Petit et al.*, 1999, 2001]. There is a pronounced temporal asymmetry; temperatures and greenhouse gas forcing both increase rapidly with deglaciation.

amplitude of only 0.1°C. This demonstrates the small direct effect of the 100 kyr orbital cycle.

3. Feedbacks Between CO_2 and Temperature

[7] The model in equation (3) is modified to allow for variation in the greenhouse gas forcing [*Ramaswamy et al.*, 2001],

$$G(t) = \overline{G} + A \ln\left(\frac{C(t)}{C_0}\right), \quad (5)$$

where $C(t)$ is the atmospheric concentration of CO_2 and C_0 = 280 ppm the preindustrial concentration [*Ramaswamy et al.*, 2001]. The constant A represents the effect of CO_2 on the radiation budget, and can be measured as 5.35 W/m^2 [*Ramaswamy et al.*, 2001]. However, in the climate system, other greenhouse gases co-vary with carbon dioxide, and there is a positive feedback between water vapour and warming which amplifies the direct effect of CO_2. Estimates from global climate models [*Knutti et al.*, 2002] and from paleoclimate proxies [*Royer et al.*, 2007] predict a climate sensitivity of 2.6°C to a doubling of CO_2, which is analogous to using A = 20.5 W/m^2.

[8] The model includes a global carbon cycle which acts to amplify radiative forcing [*Shackleton*, 2000]. Given that carbon storage at the glacial maximum is smallest on the land [*Crowley*, 1995] and maximal in the deep ocean [*Hodell et al.*, 2003] it is likely that release of CO_2 at the glacial termination is derived from the deep ocean [*Toggweiler*, 1999]. Ventilation may result from reduced stratification [*Paillard and Parrenin*, 2004; *Watson and Garabato*, 2006], reduced surface buoyancy flux leading to decreased upwelling [*Watson and Garabato*, 2006], a shift of the Southern Ocean westerly winds [*Toggweiler et al.*, 2006] or a chemical switch in the ocean [*Toggweiler*, 2007]. Existing models of these effects assume the existence of a glacial-interglacial switch [*Paillard and Parrenin*, 2004; *Toggweiler*, 2007] which depends upon the model state, or assume ice-albedo feedback dominates [*Ruddiman*, 2006b]. Here I introduce the notion that greenhouse gases may be released in response to warming (i.e. it depends upon the rate of change rather than the model state), producing a positive feedback. This feedback is parameterised in an equation for the evolution of C,

$$\frac{dC}{dt} = V - (W_0 + W_1 C) + \beta(C_{\max} - C)\max\left(\frac{dT}{dt} - \epsilon, 0\right). \quad (6)$$

Here the first term on the right represents a constant source of CO_2 from volcanoes, which is estimated at between 130–230 Mtonnes/year (or 0.018–0.03 ppm/yr) [*Gerlach*, 1991]; we use 0.028 ppm/yr. The second term represents a weak CO_2 sink. It is assumed that on long timescales the primary sink is the weathering of silicate rocks; and that this carbon is contributed to the ocean through river runoff, thus default values are W_0 = 0.013 ppm/yr and $\frac{1}{W_1}$ = 12 kyr after *Toggweiler* [2007]. The final term represents a release of CO_2 with significant warming, i.e. when $\frac{dT}{dt} > \epsilon$, and is limited to a value of $C_{\max}$ (governed by the amount of oceanic CO_2 readily available). I set $C_{\max}$ = 400 ppm and the scaling parameter β = 0.38°C^{-1} to simulate observed glacial-interglacial ranges [*Petit et al.*, 1999; *Augustin et al.*, 2004], while ϵ is dependent upon the timescale of the orbital forcing.

[9] Equations (3)–(5) may be written as a single equation,

$$c\frac{dT}{dt} = \overline{S} + \sum_i S_i \sin\left(\frac{2\pi t}{\Gamma_i}\right) + \overline{G} + A\ln\left(\frac{C}{C_0}\right) - \sigma T^4. \quad (7)$$

leaving a pair of coupled ordinary differential equations (6 and 7) describing the climate system. This extremely simple model can transparently demonstrate some important elements of the glacial cycle.

[10] Evolution of the system is strongly dependent upon the choice of parameters for equation (6). However, for a wide range of parameters, CO_2 concentration and global temperatures interact to amplify the imposed orbital forcing. An example is shown in Figure 2a, where only the 100 kyr eccentricity variation in forcing is included (S_1 = 0.25 W/m^2). CO_2 concentration interacts with warming to produce an asymmetric amplification of the global temperature signal which qualitatively resembles the Vostok record for Antarctic temperature (Figure 1). The size of glacial variation is increased to over 2°C, which is smaller than the Vostok record, but is consistent with the theories that ice–albedo

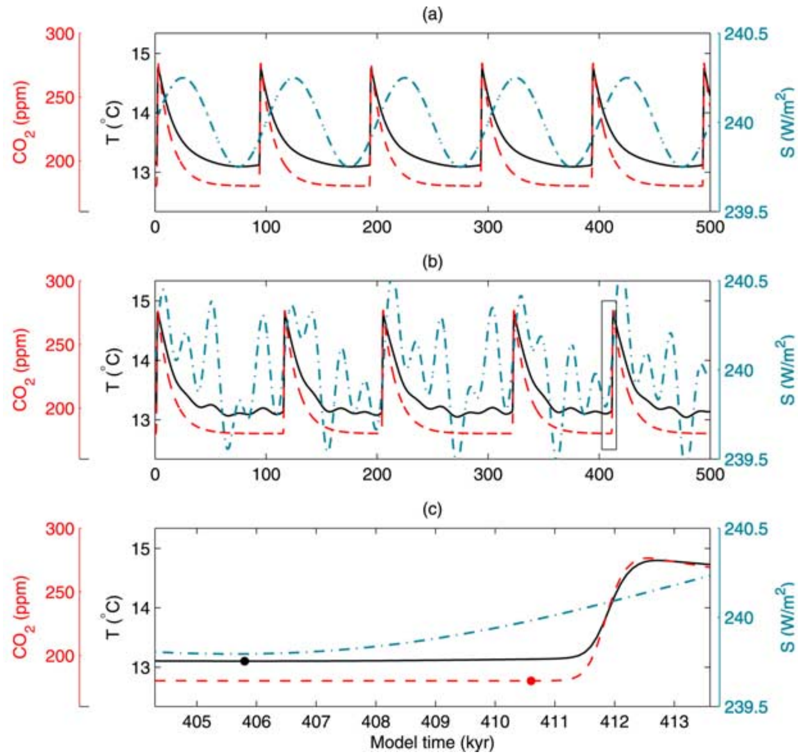

Figure 2. (a) Variation of temperature and CO_2 (dashed line) due to orbital eccentricity forcing (dash-dot line). Feedback amplifies the thermal response and introduces temporal asymmetry. (b) Model result for case with 23, 41, and 100 kyr forcing. (c) A close-up of the thermal and CO_2 minima which occur at 408 and 411 kyr respectively.

feedback further amplifies the glacial cycle [*Hansen et al.*, 2007], and that variations in polar temperatures are likely to exceed the global average [*Cubasch et al.*, 2001].

[11] The cycle shown in Figure 2a is consistent with the notion that orbital eccentricity controls the timescale of glacial cycles. However, shorter orbital cycles – the obliquity at 41 kyr and the precession at 23 kyr – may also control glacial terminations. These cycles change the relative location of insolation (rather than total insolation) but modulate the net global radiative forcing via spatial variation in the earth's albedo. This net forcing is crudely parameterised in this model by imposing the three orbital harmonics with the same amplitude (S_i = 0.2 W/m^2). The results are shown in Figure 2b, for a case where the CO_2 feedback threshold has been increased from $\epsilon = 2.4 \times 10^{-6}$°C/yr to 13×10^{-6}°C/yr (to allow for increased rates of heating caused by higher frequency orbital harmonics). For this parameter set approximate 100 kyr cycles persist, but glacial terminations are less regular.

[12] An important feature of Figures 2a and 2b is that the onset of cold periods occurs slowly, but they are terminated suddenly; a similar asymmetry is observed in records of the glacial-interglacial cycle. The temporal asymmetry in the model is caused by limited positive feedback between rising temperatures and CO_2. The relative timing of temperature and CO_2 increases at the glacial termination is examined more closely in Figure 2c. Here we zoom up to a temperature minimum which occurs at 406 kyr. The CO_2 minimum occurs 4500 years later. The lag between global temperature and CO_2 is greater in this model than in observations [*Caillon et al.*, 2003], but any higher frequency modes or noise are likely to shorten this lag. The termination itself lasts 2000 years, which is similar to observed terminations.

4. Model Sensitivity

[13] A major weakness with this model (and other models of paleoclimate) is that parameter choices are not well constrained. However, the advantage of such a simple model, with relatively few parameters, is that we are able to investigate the effects of parameter choices. Thus, this modelling approach is a valuable tool to help distinguish between proposed mechanisms for glacial climate variability. We start by investigating the role of the CO_2-dependent sink, the parameter W_1. The default parameter value, based on *Toggweiler* [2007], is equivalent to a timescale of 12 kyr for the decay of atmospheric carbon. However, it could be argued that a much shorter timescale, representing the meridional overturning of the ocean, may control the carbon sink [*Paillard and Parrenin*, 2004]. Reducing this timescale to 5 kyr (Figure 3a) generates a higher frequency glacial cycle, and much shorter interglacials. On the other hand, lengthening the timescale to 50 kyr (Figure 3b) produces lower frequency cycles. This result demonstrates that, under the model considered, the timescale of the carbon sink controls the frequency of interglacials, rather than orbital forcing alone.

[14] Two other poorly constrained parameters are the rate of volcanic CO_2 emissions, V, and the CO_2 feedback threshold ϵ; the effect of these two parameters on the

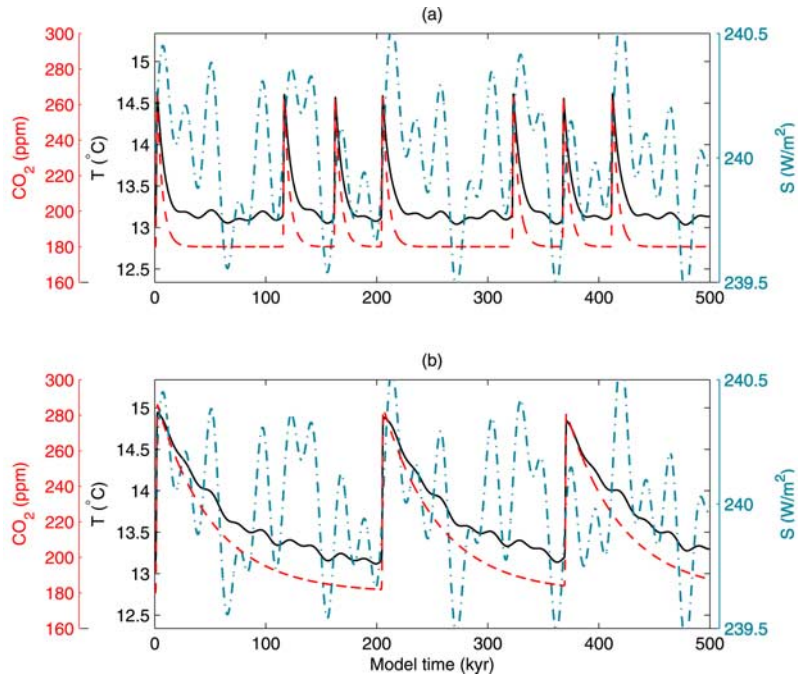

Figure 3. As for Figure 2b but with (a) faster carbon uptake ($\frac{1}{W_1}$ = 5 kyr); (b) slower carbon uptake ($\frac{1}{W_1}$ = 50 kyr).

temperature curve is shown in Figure 4. Volcanic emissions are constrained to lie between 0.018–0.03 ppm/yr [*Gerlach*, 1991] and are balanced by the weathering rate. Without CO_2 feedback the balance $(V - W_0)/W_1$ sets the lower level of CO_2 concentration in this model (this differs from *Toggweiler* [2007] where it is assumed that the volcanic–weathering balance sets the mean CO_2 concentration). Therefore, for the simulations shown in Figure 4a, we alter

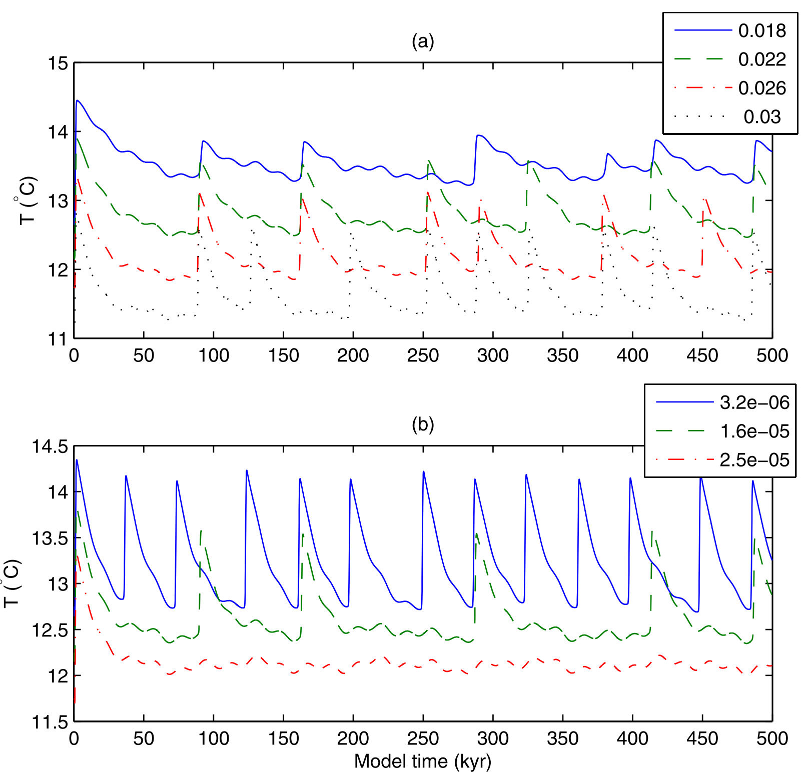

Figure 4. Variation of temperature time series (offset by 0.5°C) with (a) volcanic rate V (ppm/yr); and (b) CO_2 feedback threshold ϵ (°C/yr).

volcanic emissions, subject to the constraint that $W_1 = (V - W_0)/180$. Under this constraint we find that higher volcanic emissions leads to more frequent interglacials (primarily because W_1 increases) and larger amplitudes. On the other hand, increasing V without altering W_1 decreases the amplitude of cycles without altering the frequency (result not shown).

[15] The model is dependent on rapid CO_2 outgassing at the glacial termination. There are a number of candidates for the cause of outgassing, from biological [*Shackleton*, 2000] or chemical [*Toggweiler*, 2007] switches to physical switches [*Watson and Garabato*, 2006; *Toggweiler et al.*, 2006]. Moreover, *Toggweiler et al.* [2006] makes no assumption about global temperature; instead local temperature changes in Antarctica are sufficient to drive the transition. The formulation presented here does not assume which of these theories is dominant, but instead is designed simply to generate feedback, and is sensitive to the threshold rate of change above which outgassing occurs (ϵ). This sensitivity is exhibited in Figure 4b: if the threshold is small it is exceeded for every small perturbation, if it's large it cannot be exceeded and no interglacials occur. Sensitivity to this parameter should help to provide constraints on the range of possible mechanisms which may trigger glacial termination.

[16] The above sensitivity tests show that small changes in parameters can switch the model to shorter glacial cycles. For example, faster carbon uptake, higher volcanic emissions or a more sensitive feedback threshold are sufficient to invoke 41 kyr glacial cycles, which dominated earths climate between 2.75 and 0.9 million years ago.

5. Conclusions

[17] The simple model described here is designed to quantitatively investigate the hypothesis that CO_2–temperature feedback plays a role in the earth's climate system. The model has some features in common with observed temperature records: the temperature range far exceeds that due to global mean insolation alone, and the temporal response is asymmetric due to a large outgassing of CO_2 produced by warming. This effect is a limited positive feedback triggered by the insolation cycle. In addition, warming at the end of an ice age begins before carbon dioxide increases. This modelling approach is proposed as an important tool in distinguishing between proposed mechanisms for control of glacial cycles.

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