GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L04705, doi:10.1029/2007GL032388, 2008

Stabilizing climate requires near-zero emissions

H. Damon Matthews[1] and Ken Caldeira[2]

Received 17 October 2007; revised 11 December 2007; accepted 11 January 2008; published 27 February 2008.

[1] Current international climate mitigation efforts aim to stabilize levels of greenhouse gases in the atmosphere. However, human-induced climate warming will continue for many centuries, even after atmospheric CO_2 levels are stabilized. In this paper, we assess the CO_2 emissions requirements for global temperature stabilization within the next several centuries, using an Earth system model of intermediate complexity. We show first that a single pulse of carbon released into the atmosphere increases globally averaged surface temperature by an amount that remains approximately constant for several centuries, even in the absence of additional emissions. We then show that to hold climate constant at a given global temperature requires near-zero future carbon emissions. Our results suggest that future anthropogenic emissions would need to be eliminated in order to stabilize global-mean temperatures. As a consequence, any future anthropogenic emissions will commit the climate system to warming that is essentially irreversible on centennial timescales. **Citation:** Matthews, H. D., and K. Caldeira (2008), Stabilizing climate requires near-zero emissions, *Geophys. Res. Lett.*, *35*, L04705, doi:10.1029/2007GL032388.

1. Introduction

[2] Avoiding dangerous anthropogenic interference in the climate system has been a key international policy goal since the publication of the United Nations Framework Convention on Climate Change in 1992 [*United Nations*, 1992]. Since that time, scientific and policy literature concerning climate change mitigation has been centered around stabilizing concentrations of greenhouse gases in the atmosphere [*Wigley*, 2005; *Stern*, 2006; *Meehl et al.*, 2005]. However, stable greenhouse gas concentrations do not equate to a stable global climate. Model simulations have demonstrated that global temperatures continue to increase for many centuries beyond the point of CO_2 stabilization [e.g., *Matthews*, 2006]. As such, we are committed to future warming, even with stable greenhouse gas concentrations [*Hansen et al.*, 1985; *Wigley*, 2005; *Meehl et al.*, 2005]. This implies that stabilizing global climate within the next several centuries would require decreasing, rather than stabilized, greenhouse gas levels. In this paper, we demonstrate that to achieve atmospheric carbon dioxide levels that lead to climate stabilization, the net addition of CO_2 to the atmosphere from human activities must be decreased to nearly zero.

[3] Recent research has highlighted the very long lifetime of anthropogenic carbon in the atmosphere; while approximately half of the carbon emitted is removed by the natural carbon cycle within a century, a substantial fraction of anthropogenic CO_2 will persist in the atmosphere for several millennia [*Archer*, 2005]. A recent analysis by *Montenegro et al.* [2007] found that 25% of emitted CO_2 will have an atmospheric lifetime of more than 5000 years. Studies of the climate response to declining CO_2 concentrations have generally assumed that global temperatures will decrease in response to decreases in atmospheric CO_2 [*Friedlingstein and Solomon*, 2005]. However, as we demonstrate here, because of the high heat capacity of the ocean, global temperatures may not parallel decreases in atmospheric concentrations of greenhouse gases, but rather will increase and remain elevated for at least several centuries. Thus, fossil fuel CO_2 emissions may produce climate change that is effectively irreversible on human timescales.

[4] In this paper, we present a series of idealized climate simulations to assess the centennial-scale climate response to anthropogenic CO_2 emissions, and conversely, to quantify the emissions requirements for climate stabilization. We have used the University of Victoria Earth System Climate Model (UVic ESCM), an intermediate complexity global climate model which includes an interactive global carbon cycle. We present first a series of 500-year simulations forced by CO_2 emissions, in which a specified amount of carbon was added to the atmosphere either instantaneously, or following a business-as-usual emissions scenario. The model was then run for up to 500 years without additional carbon emissions to determine the persistence of climate warming resulting from past emissions. Second, we specified hypothetical future temperature trajectories for the UVic ESCM, and controlled emissions such that the specified future temperature changes were achieved. We used this method to estimate the CO_2 emissions requirements for climate stabilization at levels between 1 and 4 degrees above pre-industrial temperatures.

2. Methods

[5] We used version 2.8 of the UVic ESCM, an intermediate complexity coupled climate-carbon model with spatial resolution of 1.8 degrees latitude by 3.6 degrees longitude. The ocean is a 19-layer general circulation model, driven by specified wind stress at the surface and coupled to a dynamic-thermodynamic sea-ice model. The atmosphere is a vertically-integrated single layer model; both temperature and moisture are transported horizontally by a combination of diffusion and advection by specified wind fields [*Weaver et al.*, 2001]. Terrestrial vegetation distributions are calculated dynamically as a function of simulated regional climatic conditions, with the result that vegetation is able to both respond to and affect simulated climate changes

---

[1] Department of Geography, Planning and Environment, Concordia University, Montreal, Quebec, Canada.

[2] Department of Global Ecology, Carnegie Institution of Washington, Stanford, California, USA.

0094-8276/08/2007GL032388$05.00

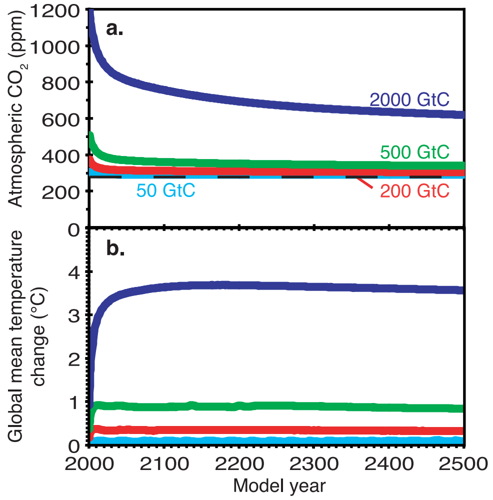

Figure 1. Climate response to an instantaneous carbon emission pulse at year zero. (a) Simulated atmospheric CO_2. (b) Simulated change in global mean surface air temperature, relative to pre-industrial.

[*Meissner et al.*, 2003]. Additionally, the UVic ESCM includes an interactive global carbon cycle [*Schmittner et al.*, 2008] which allows for the direct simulation of coupled carbon cycle and climate responses to anthropogenic carbon emissions. The version of the UVic ESCM used here does not include a sedimentary carbon model; as such we have restricted our simulations to a 500-year timescale over which time the effect of carbonate compensation on ocean carbon uptake is negligible.

[6] In forward mode, specified carbon emissions elicit climate and carbon cycle model responses. We ran the model in this mode for a series of idealized pulse-response simulations, in which emissions of 50, 200, 500 and 2000 billion tonnes (giga-tonnes of carbon: GtC) were added instantaneously to the atmosphere under pre-industrial conditions; we then ran the model with prognostic CO_2 and carbon sinks for 500 years with no additional carbon emission. In a second series of zero-emissions commitment scenarios, the model was spun-up transiently using historical CO_2 concentrations from 1800 to 2000. We then specified future business-as-usual emissions and calculated cumulative emissions relative to the year 2005. We set emissions to zero at cumulative emission levels of 0, 50, 200, 500 and 2000 GtC after 2005, and ran the model until the year 2500 with no further CO_2 emissions. In addition, we performed four simulations in which emissions were reduced linearly to zero from 2005 levels, such that total carbon emissions after 2005 were equal to 50, 200, 500 and 2000 GtC, respectively.

[7] In inverse mode, we are able to specify a desired global temperature trajectory and calculate anthropogenic carbon emissions which are consistent with this specified temperature profile. Emissions (E) were calculated at each model timestep as $E = K\,(T' - T_m)$, where T' is the desired target temperature and T_m is a running one-year global average of modelled surface air temperature. K is a constant which represents the approximate temperature response per unit of CO_2 emission, divided by the timescale of temperature response to CO_2 forcing. Emissions diagnosed in this way represent the total anthropogenic addition of carbon to the atmosphere, including both fossil fuel and net land-use change emissions.

[8] Historical temperatures were specified as an exponential curvefit to observed temperature data from 1880 to 2005. From 2005 to 2500, we constructed nine temperature profiles whereby global temperatures increased at constant rates of 0.1, 0.2 and 0.4°C/decade to stabilization levels of 1, 2 and 4 degrees above pre-industrial temperature. The transition from a fixed rate of temperature increase to temperature stabilization was smoothed using a 30-year running average.

3. Results and Discussion

[9] Figure 1 shows the climate response to an instantaneous pulse emission of carbon dioxide of between 50 and 2000 GtC. After 500 years, between 20 and 35% of the initial emission pulse remained in the atmosphere (with higher airborne fractions associated with larger emission pulses); the remaining carbon was split approximately 60/40 between ocean and land carbon sinks. The emissions pulse was followed immediately by climate warming, which then persisted for the remainder of the simulation. Averaged over the last 450 years of the simulation, temperatures increased by 0.09, 0.34, 0.88 and 3.6°C for emissions pulses of 50, 200, 500 and 2000 GtC, respectively. Historical emissions from fossil fuels and land-use change total approximately 450 GtC, which would represent about 0.8 degrees warming in the context of these pulse-response simulations. These numbers correspond roughly to a 0.175°C temperature increase for every 100 GtC emitted. This version of the UVic ESCM has an equilibrium climate sensitivity of 3.5°C for a doubling of atmospheric CO_2; as such, every 100 GtC emitted resulted in a step-wise warming of about 5% of the model's climate sensitivity.

[10] The amount of climate warming per unit of carbon emitted did not depend strongly on the timing nor duration of emissions. Figure 2 (thick lines) shows the result of a series of transient zero-emissions commitment simulations in which CO_2 emissions were set to zero when cumulative carbon emissions after 2005 reached 0, 50, 200, 500 and 2000 GtC (Figure 2a). After emissions were set to zero, simulated atmospheric CO_2 decreased as a function of time as natural carbon sinks continued to take up carbon (Figure 2b). Ocean temperatures increased throughout the simulation showing continued heat uptake, though the rate of heat uptake slowed as a function of time (Figure 2c). This slowing of ocean heat uptake balanced the decreasing radiative forcing from atmospheric CO_2; as a result, surface temperatures remained approximately constant (Figure 2d).

[11] Figure 2 also shows four additional simulations (thin lines) in which emissions were reduced to zero gradually such that total cumulative emissions after 2005 were equivalent to the thick-line zero-emissions commitment simulations. In these thin-line simulations, atmospheric CO_2 and global temperatures increased more gradually in response to gradually declining emissions; however, the final stabilization temperature was unchanged. Furthermore, the amount of additional warming that resulted per unit of carbon emitted in both sets of simulations was equivalent to the pulse-response cases shown above (approximately 5% of climate sensitivity per 100 GtC emitted), despite both higher

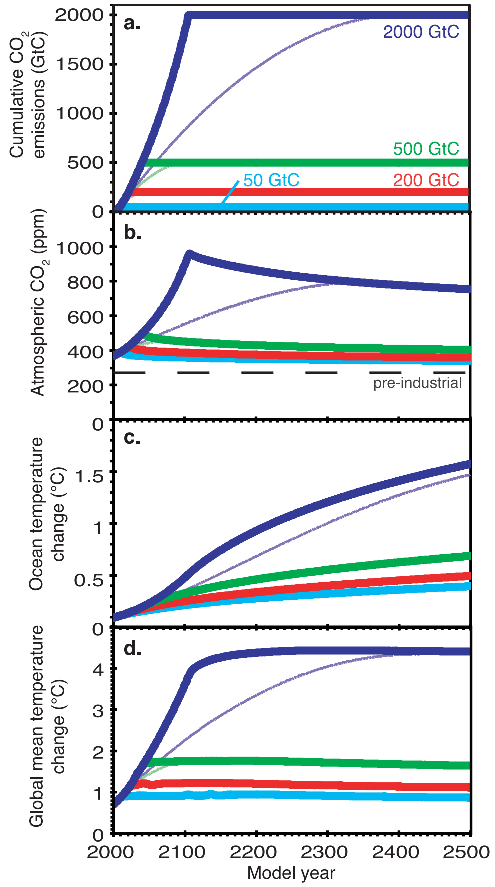

Figure 2. Climate response to transient followed by zero CO_2 emissions. (a) Specified cumulative CO_2 emissions relative to the year 2005. (b) Simulated atmospheric CO_2. (c) Simulated change in global mean ocean temperature relative to pre-industrial. (d) Simulated change in global mean surface air temperature relative to pre-industrial. Thick lines show business-as-usual followed by an abrupt elimination of emissions. Thin lines show the same post-2005 cumulative emissions but with a gradual reduction from 2005 emission levels to zero.

initial CO_2 levels in the atmosphere and the distribution of emissions over the next 10 to 100 years. This result is consistent with previous research which has shown that the declining radiative forcing per unit CO_2 increase at higher CO_2 levels is approximately counter-balanced by increased airborne fraction of emissions due to weakened carbon sinks [*Caldeira and Kasting*, 1993].

[12] The results shown here differ importantly from previous zero-emissions commitment analyses [e.g., *Friedlingstein and Solomon*, 2005], which have neglected the heat capacity of the deep ocean, and have therefore concluded that after emissions are stopped, global temperatures would decrease in response to declining atmospheric CO_2 concentrations. Our results also differ from previous studies of warming commitment which have analyzed the future warming commitment resulting from constant radiative forcing associated with stable atmospheric greenhouse gas levels [*Wigley*, 2005; *Meehl et al.*, 2005]. In contrast with these studies, our results suggest that if emissions were eliminated entirely, radiative forcing from atmospheric CO_2 would decrease at a rate closely matched by declining ocean heat uptake, with the result that while future warming commitment may be negligible, atmospheric temperatures may not decrease appreciably for at least 500 years.

[13] In the simulations described above, eliminating CO_2 emissions resulted in stable global temperatures for the following five centuries of model simulation. This result implies that stabilizing climate at a given temperature would require that anthropogenic CO_2 emissions be decreased to near-zero. We demonstrate this in a series of transient model simulations in which global temperatures in the UVic ESCM were constrained to follow a desired future climate trajectory. Results from these simulations are shown in Figure 3 for temperature stabilization levels of 1, 2 and 4°C above pre-industrial temperatures, with temperatures approaching stabilization at rates of 0.1, 0.2 and 0.4°C per decade after the year 2005. Also shown is a simulation in which climate was stabilized at year-2005 temperatures.

[14] Simulated global mean surface air temperatures for the ten temperature stabilization simulations followed closely the prescribed temperature trajectories (Figure 3a). Atmospheric CO_2 concentrations consistent with simulated temperature changes are shown in Figure 3b; in all cases, CO_2 concentrations reached a maximum value at the time of temperature stabilization, followed by a gradual decrease consistent with that shown in Figures 1 and 2. Also consistent with Figure 2, ocean temperatures increased throughout the simulation, though the rate of ocean heat uptake slowed with time after atmospheric temperatures were stabilized (Figure 3c). Cumulative CO_2 emissions from each simulation are shown in Figure 3d. At the year 2500, cumulative emissions depended only on the level of temperature stabilization, and not on the path taken to stabilization. Stabilizing climate change at 1°C above pre-industrial (approximately 0.2°C above present) required cumulative carbon emissions (from any source) after 2005 to be confined to less than 150 GtC. Stabilizing at 2 or 4°C above pre-industrial required cumulative emissions after 2005 of less than 725 and 1825 GtC, respectively. In all cases, annual emissions consistent with temperature-stabilization were reduced to nearly zero. Notably, stabilizing global temperature at present-day (year-2005) levels required emissions to be reduced to near-zero within a decade.

[15] The result shown here that each unit of CO_2 emissions results in a quantifiable step-wise increase of global temperatures, and its corollary that temperature stabilization requires near-zero CO_2 emissions, is not model specific; this same qualitative result can be demonstrated using a simple analytic model of the global climate-carbon system (see auxiliary material).[1] However, the specific amount by which global temperatures increased per unit of CO_2 emission—and correspondingly, the cumulative CO_2 emissions required to meet a given temperature target—does depend on several important model characteristics and assumptions. For example, future changes in non-CO_2 climate forcings (both natural and anthropogenic) could have an important effect on the magnitude of temperature changes associated with future carbon emissions. Furthermore, different models vary considerably with respect to both the strength of

---

[1] Auxiliary materials are available in the HTML. doi:10.1029/2007GL032388.

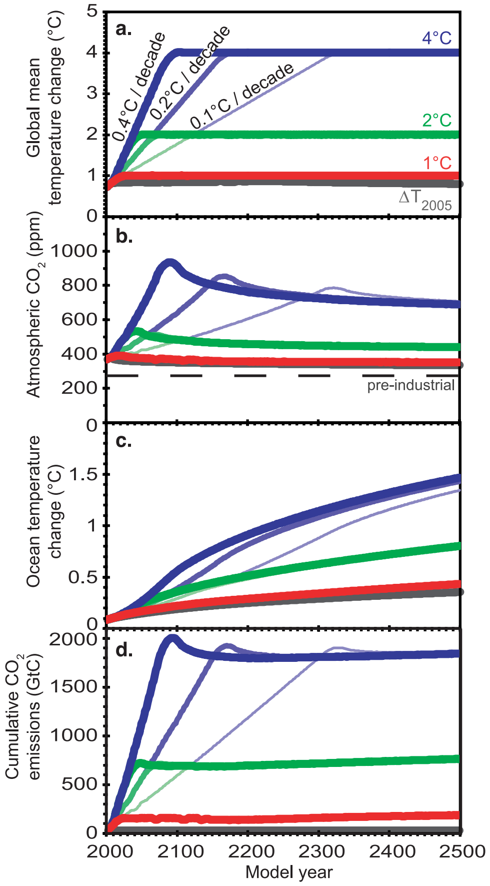

Figure 3. CO_2 emissions required for climate stabilization. (a) Simulated global mean surface air temperature relative to pre-industrial. (b) Simulated atmospheric CO_2. (c) Simulated change in global mean ocean temperature relative to pre-industrial. (d) Cumulative carbon emissions relative to the year 2005 (where near-constant cumulative emissions reflect near-zero yearly emissions). Colors indicate climate stabilization at 1 (red lines), 2 (green lines), and 4 (blue lines) °C above pre-industrial temperatures. Line styles indicate rates of warming (between 2005 and the time of temperature-stabilization) of 0.1 (thick lines), 0.2 (medium lines), and 0.4 (thin lines) °C per decade. The solid grey line shows climate stabilization at year-2005 temperatures.

carbon sinks (the carbon cycle sensitivity to CO_2 and climate changes) as well as the climate system's sensitivity to CO_2 increases (climate sensitivity).

[16] To examine the dependence of our results on the model's climate sensitivity, we repeated the temperature-stabilization simulations shown in Figure 3 with two additional versions of the model in which climate sensitivity after 2005 was approximately doubled and halved respectively by means of an adjustable temperature-longwave radiation feedback [*Matthews and Caldeira*, 2007]. Cumulative emissions from 2005 to 2500 for each of these simulations are given in Table 1. It is clear that the range of climate sensitivities explored here had a very large effect on the cumulative carbon emissions for a given temperature target. However, across all combinations of climate sensitivity and stabilization level, the rate of warming approaching a stabilization temperature had very little influence on the allowable cumulative emissions. This is consistent with the pulse-response and zero-emissions commitment experiments in which each unit of CO_2 emission produced a persistent increment of warming that was largely independent of the warming produced by other CO_2 emissions.

[17] In this study, we have made no attempt to construct economically optimal emissions scenarios for climate stabilization, but rather to quantify the climatic requirements for allowable emissions consistent with global temperature targets. It is evident that some of the temperature trajectories (and their associated emissions scenarios) illustrated here may not be economically feasible, as they require either abrupt transitions from very high to near-zero emissions, or even prolonged periods of negative emissions for combinations of high climate sensitivity and low temperature targets. It is also clear from these simulations that delays in emissions reductions now will lead to a requirement for much more rapid emissions reductions in the future in order to meet the same global temperature target. In addition, an important conclusion of our study is that if total future emissions can be constrained to within a given amount, the same long-term temperature target can be achieved by a wide range of specific emissions scenarios.

4. Conclusions

[18] International climate policies aimed at climate stabilization must reflect an understanding of the lasting effect of greenhouse gas emissions; as illustrated by a recent study, year-2050 emissions targets currently being proposed are likely insufficient to avoid substantial future climate warming [*Weaver et al.*, 2007]. We have shown here that the climate warming resulting from CO_2 emissions is not a transient phenomenon, but rather persists well beyond the timescale of human experience. In the absence of human intervention to actively remove CO_2 from the atmosphere [e.g., *Keith et al.*, 2006], each unit of CO_2 emissions must be viewed as leading to quantifiable and essentially permanent climate change on centennial timescales. We emphasize that a stable global climate is not synonymous with stable radiative forcing, but rather requires decreasing greenhouse gas levels in the atmosphere. We have shown here that stable global temperatures within the next several centuries can be achieved if CO_2 emissions are reduced to

Table 1. Effect of Climate Sensitivity on Cumulative Emissions Targets for Climate Stabilization[a]

Global temperature target (°C)	1			2			4		
Target rate of change (°C/yr)	0.01	0.02	0.04	0.01	0.02	0.04	0.01	0.02	0.04
$\Delta T_{2X} \sim 1.8$ °C	787	789	788	1970	1977	1979	4806	4801	4794
$\Delta T_{2X} \sim 3.5$ °C	149	148	150	720	723	723	1823	1808	1804
$\Delta T_{2X} \sim 7$ °C	−166	−167	−167	115	115	116	633	607	599

[a] Effect of climate sensitivity measured by ΔT_{2X}. Cumulative emissions represent total GtC emitted from 2005 to 2500.

nearly zero. This means that avoiding future human-induced climate warming may require policies that seek not only to decrease CO_2 emissions, but to eliminate them entirely.

[19] **Acknowledgments.** We would like to acknowledge and thank M. Eby at the University of Victoria for his contribution to this research in the form of development of model code which enables simulation of specified global temperature input profiles. We would also like to thank A. Weaver, C. Jones and one anonymous reviewer for their helpful comments and suggestions.

References

Archer, D. (2005), Fate of fossil fuel CO_2 in geologic time, *J. Geophys. Res.*, *110*, C09S05, doi:10.1029/2004JC002625.

Caldeira, K., and J. F. Kasting (1993), Insensitivity of global warming potentials to carbon dioxide emissions scenarios, *Nature*, *366*, 251–253.

Friedlingstein, P., and S. Solomon (2005), Contributions of past and present human generations to committed warming caused by carbon dioxide, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 10,832–10,836.

Hansen, J. E., G. Russell, A. Lacis, I. Fung, and D. Rind (1985), Climate response times: Dependence on climate sensitivity and ocean mixing, *Science*, *229*, 857–859.

Keith, D. W., M. Ha-Duong, and J. K. Stolaroff (2006), Climate strategy with CO_2 capture from the air, *Clim. Change*, *74*, 17–45.

Matthews, H. D. (2006), Emissions targets for CO_2 stabilization as modified by carbon cycle feedbacks, *Tellus, Ser. B*, *55*, 591–602.

Matthews, H. D., and K. Caldeira (2007), Transient climate-carbon simulations of planetary geoengineering, *Proc. Natl. Acad. Sci. U. S. A.*, *104*, 9949–9954.

Meehl, G. A., W. M. Washington, W. D. Collins, J. M. Arblaster, A. Hu, L. E. Buja, W. G. Strand, and H. Teng (2005), How much more global warming and sea level rise?, *Science*, *307*, 1769–1772.

Meissner, K. J., A. J. Weaver, H. D. Matthews, and P. M. Cox (2003), The role of land-surface dynamics in glacial inception: A study with the UVic Earth System Climate Model, *Clim. Dyn.*, *21*, 515–537.

Montenegro, A., V. Brovkin, M. Eby, D. Archer, and A. J. Weaver (2007), Long term fate of anthropogenic carbon, *Geophys. Res. Lett.*, *34*, L19707, doi:10.1029/2007GL030905.

Schmittner, A., A. Oschlies, H. D. Matthews, and E. D. Galbraith (2008), Future changes in climate, ocean circulation, ecosystems and biogeochemical cycling simulated for a business-as-usual CO_2 emissions scenario until year 4000 AD, *Global Biogeochem. Cycles*, *22*, GB1013, doi:10.1029/2007GB002953.

Stern, N. (2006), *The Economics of Climate Change*, Cambridge Univ. Press, Cambridge, U. K.

United Nations (1992), *Earth Summit Convention on Climate Change*, U. N. Conf. on Environ. and Dev., Rio de Janeiro, Brazil.

Weaver, A. J., et al. (2001), The UVic Earth System Climate Model: Model description, climatology and applications to past, present and future climates, *Atmos. Ocean*, *39*, 361–428.

Weaver, A. J., K. Zickfeld, A. Montenegro, and M. Eby (2007), Long term climate implications of 2050 emission reduction targets, *Geophys. Res. Lett.*, *34*, L19703, doi:10.1029/2007GL031018.

Wigley, T. M. L. (2005), The climate change commitment, *Science*, *307*, 1766–1769.

K. Caldeira, Department of Global Ecology, Carnegie Institution of Washington, 260 Panama Street, Stanford, CA 94305, USA.

H. D. Matthews, Department of Geography, Planning and Environment, Concordia University, 1455 de Maisonneuve Boulevard W., Montreal, QC, Canada H3G 1M8. (dmatthew@alcor.concordia.ca)