



## Sensitivity of ocean acidification to geoengineered climate stabilization

H. Damon Matthews,<sup>1</sup> Long Cao,<sup>2</sup> and Ken Caldeira<sup>2</sup>

Received 26 January 2009; revised 31 March 2009; accepted 20 April 2009; published 28 May 2009.

[1] Climate engineering has been proposed as a possible response to anthropogenic climate change. While climate engineering may be able to stabilize temperatures, it is generally assumed that this will not prevent continued ocean acidification. However, due to the strong coupling between climate and the carbon cycle, climate engineering could indirectly affect ocean chemistry. We used a global Earth-system model to investigate how climate engineering may affect surface ocean pH and the degree of aragonite saturation. Climate engineering could significantly re-distribute carbon emissions among atmosphere, land and ocean reservoirs. This could slow pH decreases somewhat relative to the non-engineered case, but would not affect the level of aragonite saturation due to opposing responses of pH and aragonite saturation to temperature change. However, these effects are dependent on enhanced carbon accumulation in the land biosphere; without this, climate engineering has little effect on pH, and leads to accelerated declines in aragonite saturation. **Citation:** Matthews, H. D., L. Cao, and K. Caldeira (2009), Sensitivity of ocean acidification to geoengineered climate stabilization, *Geophys. Res. Lett.*, 36, L10706, doi:10.1029/2009GL037488.

### 1. Introduction

[2] The past decade has seen rapidly accelerating climate changes and ever-increasing global emissions of greenhouse gases. Concern over the current pace of change and the slow progress on international climate mitigation efforts have prompted some scientists to call for increased research into alternate measures of climate control [Crutzen, 2006; Wigley, 2006]. Geoengineering can be defined as the deliberate large-scale modification of the environment to counteract anthropogenic climate warming [Keith, 2000]; in this paper, we use the term “climate engineering” to refer specifically to the modification of incoming shortwave radiation. There have been many different proposed climate engineering schemes, but most attention has been given to the suggestion that we may be able to mimic the cooling effect of large volcanic eruptions by injecting reflective aerosols into the stratosphere [e.g., Crutzen, 2006].

[3] A number of recent studies have begun to evaluate the climatic response to geoengineered reductions in incoming solar radiation. Most have shown that it may be possible to stabilize global temperatures, but with the possibility of undesirable impacts on the hydrological cycle, stratospheric ozone formation and the rate of climate change [Matthews

and Caldeira, 2007; Trenberth and Dai, 2007; Bala et al., 2008; Tilmes et al., 2008; Lunt et al., 2008]. These studies invariably include the caveat that even in the case of successful temperature stabilization, geoengineering will not ameliorate the problem of ocean acidification owing to high levels of CO<sub>2</sub> in the atmosphere [Crutzen, 2006; Wigley, 2006; Trenberth and Dai, 2007; Bala et al., 2008; Robock, 2008; Lunt et al., 2008]; however, there has not been any scientific study to formally support this claim. Matthews and Caldeira [2007] showed that geoengineering can have a significant effect on the global carbon cycle as a result of the strong coupling between global temperatures and the rate of CO<sub>2</sub> uptake by carbon sinks. As a result, geoengineered changes to the global radiative budget could result in secondary effects on the rate of ocean acidification.

[4] Here we present an analysis of the possible effect of geoengineering combined with unmitigated CO<sub>2</sub> emissions on the extent of ocean acidification over the next century. We used a global Earth system model, with coupled representations of spatial climate and carbon cycle processes, to show the response of ocean pH and calcium carbonate saturation levels to CO<sub>2</sub> and climate changes in an idealized geoengineering experiment. In addition, we discuss the extent to which the redistribution of carbon under geoengineered climate stabilization is dependent on the response of the land biosphere to elevated CO<sub>2</sub> and show the sensitivity of ocean chemistry to this land carbon response.

### 2. Methods

#### 2.1. Earth System Model

[5] In this study we used the University of Victoria Earth System Climate Model (UVic ESCM) version 2.8, an intermediate-complexity global model of the coupled climate-carbon system. The climate component consists of a three-dimensional ocean general circulation model coupled to a dynamic-thermodynamic sea-ice model and a two-dimensional atmospheric energy-moisture balance model [Weaver et al., 2001]. The carbon cycle includes a dynamic vegetation and biogeochemical carbon cycle model on land [Meissner et al., 2003], as well as a three-dimensional inorganic and organic carbon cycle in the ocean [Schmittner et al., 2008]. Version 2.7 of the UVic ESCM (which did not include the organic carbon cycle component) was included in the inter-model comparison of coupled climate-carbon cycle models (C4MIP) [Friedlingstein et al., 2006], as well as the long-term climate and carbon cycle projections performed by intermediate-complexity models as part of Chapter 10 of the recent Intergovernmental Panel of Climate Change Fourth Assessment Report [Meehl et al., 2007].

#### 2.2. Simulations

[6] We performed a series of five transient model simulations of 21st century climate change, as described in Table 1.

<sup>1</sup>Department of Geography, Planning and Environment, Concordia University, Montreal, Quebec, Canada.

<sup>2</sup>Department of Global Ecology, Carnegie Institution of Washington, Stanford, California, USA.

**Table 1.** UVic ESCM Experiments

Experiment	Description
A2	Prescribed SRES A2 CO <sub>2</sub> emissions
A2+eng	Prescribed CO <sub>2</sub> emissions with climate engineering after 2010
A2A+eng	Prescribed atmospheric CO <sub>2</sub> concentrations from experiment A2 with climate engineering after 2010
A2nb	Neutral biosphere: Prescribed CO <sub>2</sub> emissions with no land-atmosphere CO <sub>2</sub> exchange after 2010
A2nb+eng	Neutral biosphere: Prescribed CO <sub>2</sub> emissions with climate engineering and no land-atmosphere CO <sub>2</sub> exchange after 2010

All simulations began from multi-thousand year stable pre-industrial equilibrium simulation, which was integrated to present-day under observed fossil-fuel and land-use change CO<sub>2</sub> emissions. Future CO<sub>2</sub> emissions were specified until the year 2100 from the fossil-fuel intensive SRES A2 scenario, with no other specified climate forcings. Climate engineering was implemented at the year 2010 of the simulation as a uniform reduction of incoming solar radiation, following the methodology of *Matthews and Caldeira* [2007]. The “neutral biosphere” experiments differ only in that the land biosphere did not exchange carbon with the atmosphere after the year 2010.

### 2.3. Ocean Chemistry Analysis

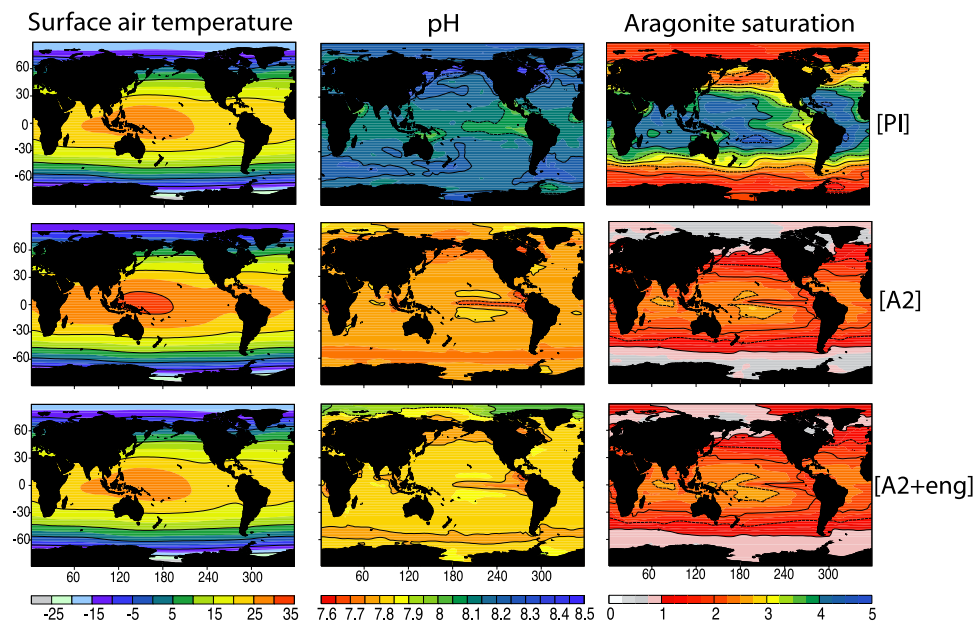
[7] We analyzed ocean chemistry in terms of pH and the saturation state of calcium carbonate. We calculated the degree of saturation with respect to aragonite ( $\Omega_{aragonite}$ ) as the ion product of the concentrations of calcium and carbonate ions divided by the stoichiometric solubility product [*Feely et al.*, 2004]. These chemistry fields were

calculated from the UVic ESCM’s simulated dissolved inorganic carbon (DIC), alkalinity (ALK), temperature, and salinity using the chemistry routine from the OCMIP-3 project (<http://www.ipsl.jussieu.fr/OCMIP/phase3>). In our calculations, model-predicted perturbations in temperature, salinity, nutrients, DIC and ALK relative to the mid-1990s were added to gridded data sets derived from modern observational data [*Key et al.*, 2004].

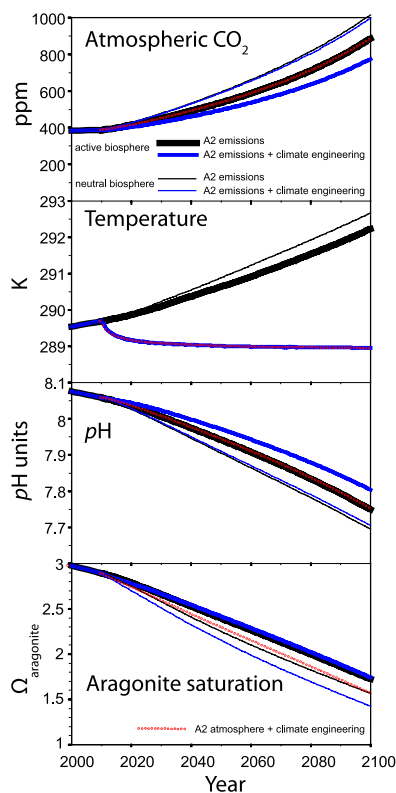
### 3. Results

[8] Figure 1 shows spatial patterns of temperature, pH and aragonite saturation state under pre-industrial climate and CO<sub>2</sub>, and at 2100 from the prescribed emissions scenario (A2), and the prescribed emissions scenario with climate engineering (A2+eng). In both A2 and A2+eng, pH and aragonite saturation were substantially reduced due to increased atmospheric CO<sub>2</sub> concentrations and subsequent higher DIC concentrations in the surface ocean. Climate engineering led to slightly higher pH values at 2100 compared to the non-engineered case, but had an almost negligible effect on changes in aragonite saturation state.

[9] These trends can also be seen in Figure 2, which shows the time-dependent changes in atmospheric CO<sub>2</sub>, temperature, pH and  $\Omega_{aragonite}$ . Climate engineering was effective in decreasing atmospheric temperatures to close to pre-industrial values; in addition, climate engineering led to lower atmospheric CO<sub>2</sub> as a result of colder temperatures leading to increased carbon uptake by natural carbon sinks. The combination of lower atmospheric CO<sub>2</sub> and lower temperatures slowed pH decreases, leading to 0.05 units higher pH at 2100. In contrast,  $\Omega_{aragonite}$  values were virtually unaffected with only a 1% difference between A2 and A2+eng  $\Omega_{aragonite}$  values at 2100.



**Figure 1.** Simulated spatial fields of (left) surface air temperature, (middle) ocean pH, and (right) the ocean surface aragonite saturation state ( $\Omega_{aragonite}$ ) at (top) pre-industrial [PI] and at 2100 for (center) the case with A2 emissions [A2], and (bottom) the case with A2 emission and climate engineering [A2+eng]. Climate engineering led to surface air temperatures at 2100 that were comparable with pre-industrial temperatures. pH values at 2100 were slightly higher in A2+eng compared to A2, but aragonite saturation state was largely unaffected by climate engineering.



**Figure 2.** Simulated changes in atmospheric CO<sub>2</sub>, globally-averaged surface air temperature, pH and aragonite saturation state ( $\Omega_{\text{aragonite}}$ ). Black lines show cases with A2 emissions without climate engineering. Blue lines show cases with A2 emissions and climate engineering. Thick lines show the cases with an active land biosphere and the thin lines show cases with a neutral biosphere (i.e., no net atmosphere/biosphere carbon fluxes after 2100). The dotted line shows results for a climate engineering case in which atmospheric CO<sub>2</sub> was specified to be the same as the non-engineered simulation.

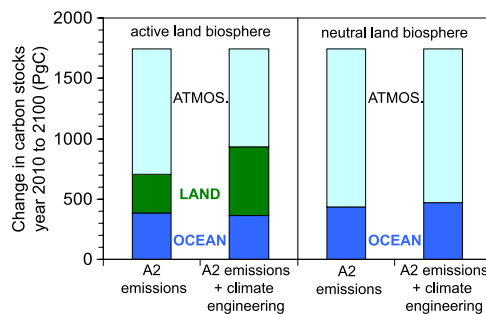
[10] In these simulations, climate engineering modified ocean chemistry through changes to CO<sub>2</sub>, temperature, salinity, DIC, and alkalinity (globally-averaged values at 2100 are listed in Table S1 of the auxiliary material).<sup>1</sup> As a result of climate engineering, decreased atmospheric CO<sub>2</sub> caused lower surface DIC, but this effect was mediated by decreased temperature which tends to increase surface DIC due to increased CO<sub>2</sub> solubility. In addition to modifying CO<sub>2</sub> solubility, changes in temperature affected the carbonate acid dissociation constant; at a fixed DIC concentration, lower temperature increases pH, but decreases aragonite saturation state, resulting in a decoupled response of pH and  $\Omega_{\text{aragonite}}$  to temperature change [Cao *et al.*, 2007] (see also Figure S1 and associated discussion in the auxiliary material). Climate engineering also affected surface alkalinity due to an increase in CaCO<sub>3</sub> production by marine organisms with warmer temperatures [Schmittner *et al.*, 2008]. Alkalinity changes led to an additional—and likely model specific—modification of pH and aragonite saturation state,

which may be particularly important at regional scales. At the global scale, the response of ocean chemistry to climate engineering is primarily determined by the direct effect of atmospheric CO<sub>2</sub> and temperature changes.

[11] The relative effect of atmospheric CO<sub>2</sub> and temperature on ocean chemistry can be separated in the simulation with prescribed atmospheric CO<sub>2</sub> (from A2) and climate engineering (A2A+eng). With equivalent atmospheric CO<sub>2</sub> levels, the effect of climate engineering on ocean pH was much smaller. In this case, surface ocean DIC was higher in the climate engineering run (due to enhanced temperature-driven CO<sub>2</sub> solubility); higher DIC by itself would have decreased pH, but this decrease was balanced by a direct temperature-driven pH increase, leading to almost no net pH change. In contrast,  $\Omega_{\text{aragonite}}$  in A2A+eng decreased faster in response to climate engineering; in this case, both DIC changes and colder temperatures served to accelerate the decline in aragonite saturation state, leading to 9% lower  $\Omega_{\text{aragonite}}$  values at 2100 (from 1.72 in A2 to 1.58 in A2A+eng). Again, we emphasize here the different responses of pH and  $\Omega_{\text{aragonite}}$  to engineered temperature stabilization: colder temperatures led to slightly higher pH values, but resulted also in lower values of  $\Omega_{\text{aragonite}}$ .

[12] As can be seen by comparing simulations A2+eng and A2A+eng, the effect of climate engineering on ocean chemistry shown here depends on how climate engineering affects atmospheric CO<sub>2</sub> levels. The primary cause of the decreased atmospheric CO<sub>2</sub> in response to climate engineering is demonstrated in the two neutral-biosphere simulations (A2nb and A2nb+eng, thin lines in Figure 2). Both runs simulated more rapid rates of atmospheric CO<sub>2</sub> increase, as a result of the absence of any future terrestrial carbon sink. More importantly however, the effect of climate engineering on atmospheric CO<sub>2</sub> concentrations was much smaller with a neutral biosphere; atmospheric CO<sub>2</sub> was 111 ppm lower in A2+eng than in A2, but only 19 ppm lower in A2nb+eng than in A2nb.

[13] In the case of an active land biosphere, the draw-down of atmospheric CO<sub>2</sub> under climate engineering was entirely due to increased land carbon storage (249 GtC, or 10% more land carbon at 2100 in A2+eng than in A2), whereas total ocean carbon storage at 2100 in A2+eng was 18 GtC lower than A2 due to lower atmospheric CO<sub>2</sub> concentrations (Figure 3). This indicates that the primary carbon cycle response to climate engineering was due to



**Figure 3.** Simulated changes in global carbon stocks (atmosphere, ocean, and land) from 2010 to 2100 in response to climate engineering, for the case (left) with and (right) without land carbon exchange with the atmosphere.

<sup>1</sup>Auxiliary materials are available in the HTML. doi:10.1029/2009GL037488.

enhanced terrestrial primary productivity and decreased plant and microbial respiration carbon losses as a result of cooler atmospheric temperatures. When the response of the terrestrial biosphere was removed, the primary carbon cycle response to climate engineering was a small increase in ocean carbon uptake brought about by cooler ocean water temperatures and consequent enhanced carbon dissolution (total ocean carbon storage at 2100 in A2nb+eng was 40 GtC higher than in A2nb). Consequently, the effect of climate engineering in the neutral biosphere simulations mirrored that of the prescribed-CO<sub>2</sub> simulation (A2A+eng). In A2nb+eng, surface temperatures were colder, and ocean DIC was higher than in A2nb; as a result, pH changes were unaffected by climate engineering, whereas the aragonite saturation state was further decreased relative to the non-engineered case.

#### 4. Discussion and Conclusions

[14] Future changes in ocean chemistry are of significant concern to ocean ecosystems due to both direct influences of pH on marine organisms [e.g., Siebel and Walsh, 2001] as well as the effect of lower aragonite saturation on the ability of calcifying organisms to form shells and skeletons [e.g., Feely et al., 2004; Orr et al., 2005]. Ocean acidification has also been the subject of several recent modelling studies which have aimed to estimate the implications of atmospheric CO<sub>2</sub> and climate changes for ocean pH, aragonite saturation state and ocean ecosystems [e.g., Caldeira and Wickett, 2003, 2005; Orr et al., 2005; Cao et al., 2007; Cao and Caldeira, 2008]. Most such studies have studied the effect of CO<sub>2</sub> changes alone using ocean-only models, ignoring the second-order effects of climate change. Our results are consistent with those of Cao et al. [2007] in that changes in temperature due to climate engineering have secondary effects on pH and aragonite saturations, compared to anthropogenic CO<sub>2</sub> emissions.

[15] In addition, we have shown that both the sign and magnitude of the effect of climate engineering on ocean chemistry are dependent on the response of the terrestrial biosphere to future CO<sub>2</sub> increases and climate changes. The extent by which terrestrial carbon uptake may be enhanced by elevated CO<sub>2</sub> concentrations and/or suppressed due to climate warming is one of the leading uncertainties in current projections of future climate change. Our simulation of enhanced terrestrial carbon uptake due to colder temperatures is consistent with the analysis of carbon cycle feedbacks carried out as part of the coupled climate-carbon cycle model intercomparison project [Friedlingstein et al., 2006]; however, there was considerable variation between models in the magnitude of terrestrial climate-carbon feedbacks, as well as in the direct effect of elevated CO<sub>2</sub> on terrestrial carbon uptake. Our “active” and “neutral” biosphere simulations represent reasonable bounds on the uncertain terrestrial carbon response to elevated CO<sub>2</sub> and climate, and it is notable that the effect of climate engineering on ocean chemistry in these two contrasting cases is both qualitatively and quantitatively different.

[16] In this study, we have shown that future ocean acidification is not independent of the effect of climate engineering due to coupled climate and carbon cycle changes over the next century. To first order, we have

confirmed previously unsupported statements that climate engineering will not help ocean acidification [Crutzen, 2006; Wigley, 2006; Trenberth and Dai, 2007; Bala et al., 2008; Robock, 2008; Lunt et al., 2008]. However, we have also identified important second-order interactions between climate engineering, the global carbon budget and ocean chemistry, which may either slightly decrease or slightly increase the rate of ocean acidification, depending on uncertain future changes in terrestrial carbon sinks.

[17] It is worth noting, however, that in addition to the interactions shown here between climate engineering and natural carbon fluxes, it is possible that there may be additional interactions between climate engineering and anthropogenic carbon emissions. It is difficult to predict how socio-political systems will respond to the prospect of anthropogenic climate control; however, if climate engineering is perceived to be a viable solution to avert climate warming, and this perception results in delayed CO<sub>2</sub> emissions reductions, this could lead to an additional indirect impact of climate engineering on ocean chemistry. The results of this paper support the view that climate engineering will not resolve the problem of ocean acidification, and that therefore deep and rapid cuts in CO<sub>2</sub> emissions are likely to be the most effective strategy to avoid environmental damage from future ocean acidification.

[18] **Acknowledgments.** We would like to acknowledge A. Ridgwell and D. Lunt for helpful comments and suggestions on earlier version of this manuscript. HDM would like to thank S. Turner for support during the writing of this work, as well as acknowledge financial support from the Canadian Foundation for Climate and Atmospheric Sciences and the National Science and Engineering Research Council of Canada.

#### References

- Bala, G., P. B. Duffy, and K. E. Taylor (2008), Impact of geoengineering schemes on the global hydrological cycle, *Proc. Natl. Acad. Sci. U. S. A.*, *105*, 7664–7669.
- Caldeira, K., and M. E. Wickett (2003), Anthropogenic carbon and ocean pH, *Nature*, *425*, 365.
- Caldeira, K., and M. E. Wickett (2005), Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean, *J. Geophys. Res.*, *110*, C09S04, doi:10.1029/2004JC002671.
- Cao, L., and K. Caldeira (2008), Atmospheric CO<sub>2</sub> stabilization and ocean acidification, *Geophys. Res. Lett.*, *35*, L19609, doi:10.1029/2008GL035072.
- Cao, L., K. Caldeira, and A. K. Jain (2007), Effects of carbon dioxide and climate change on ocean acidification and carbonate mineral saturation, *Geophys. Res. Lett.*, *34*, L05607, doi:10.1029/2006GL028605.
- Crutzen, P. J. (2006), Albedo enhancement by stratospheric sulfur injections: A contribution to resolve a policy dilemma?, *Clim. Change*, *77*, 211–219.
- Feely, R. A., C. L. Sabine, K. Lee, W. Berelson, J. Kleypas, V. J. Fabry, and F. J. Millero (2004), Impact of anthropogenic CO<sub>2</sub> on the CaCO<sub>3</sub> system in the oceans, *Science*, *305*, 362–366.
- Friedlingstein, P., et al. (2006), Climate-carbon cycle feedback analysis, results from the C<sup>4</sup>MIP model intercomparison, *J. Clim.*, *19*, 3337–3353.
- Keith, D. W. (2000), Geoengineering the climate: History and prospect, *Annu. Rev. Energy Environ.*, *25*, 245–284.
- Key, R. M., A. Kozyr, C. L. Sabine, K. Lee, R. Wanninkhof, J. L. Bullister, R. A. Feely, F. J. Millero, C. Mordy, and T.-H. Peng (2004), A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP), *Global Biogeochem. Cycles*, *18*, GB4031, doi:10.1029/2004GB002247.
- Lunt, D. J., A. Ridgwell, P. J. Valdes, and A. Seale (2008), “Sunshade World”: A fully coupled GCM evaluation of the climatic impacts of geoengineering, *Geophys. Res. Lett.*, *35*, L12710, doi:10.1029/2008GL033674.
- 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., et al. (2007), Global climate projections, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate*

- Change*, edited by S. Solomon et al., pp. 747–845, Cambridge Univ. Press, Cambridge, U. K.
- 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.
- Orr, J. C., et al. (2005), Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms, *Nature*, *437*, 681–686.
- Robock, A. (2008), Whither geoengineering?, *Science*, *320*, 1166–1167.
- 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<sub>2</sub> emission scenario until year 4000 AD, *Global Biogeochem. Cycles*, *22*, GB1013, doi:10.1029/2007GB002953.
- Siebel, B. A., and P. J. Walsh (2001), Potential impacts of CO<sub>2</sub> injections on deep-sea biota, *Science*, *294*, 319–320.
- Tilmes, S., R. Müller, and R. Salawitch (2008), The sensitivity of polar ozone depletion to proposed geoengineering schemes, *Science*, *320*, 1201–1204.
- Trenberth, K. E., and A. Dai (2007), Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering, *Geophys. Res. Lett.*, *34*, L15702, doi:10.1029/2007GL030524.
- 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.
- Wigley, T. M. L. (2006), A combined mitigation/geoengineering approach to climate stabilization, *Science*, *314*, 452–454.
- 
- K. Caldeira and L. Cao, 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 West, Montreal, QC H3G 1M8, Canada. (dmatthew@alcor.concordia.ca)