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Long term climate implications of 2050 emission reduction targets

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[1] A coupled atmosphere-ocean-carbon cycle model is used to examine the long term climate implications of various 2050 greenhouse gas emission reduction targets. All emission targets considered with less than 60% global reduction by 2050 break the 2.0°C threshold warming this century, a number that some have argued represents an upper bound on manageable climate warming. Even when emissions are stabilized at 90% below present levels at 2050, this 2.0°C threshold is eventually broken. Our results suggest that if a 2.0°C warming is to be avoided, direct CO_2 capture from the air, together with subsequent sequestration, would eventually have to be introduced in addition to sustained 90% global carbon emissions reductions by 2050.

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1. Introduction

[2] Since the release of the 4th Intergovernmental Panel on Climate Change (IPCC) Summary for Policy Makers from Working Group I (The Physical Science Basis) and Working Group II (Impacts, Adaptation, and Vulnerability), global warming policy has risen to the top of political agendas around the world. Both subsequent and prior to the release of the IPCC 4th assessment report (AR4), individual cities, states, provinces and countries have begun discussing, and in some case passing, legislation requiring specified greenhouse gas emissions reductions over the next several decades. One of the key targets that is emerging in policy discussions is the reduction by year 2050. Table 1 provides a list of examples from several states and countries.

[3] While there are no formal targets agreed to by the United States, three pieces of legislation have been proposed which call for cuts ranging from 65% relative to 2000 levels to 80% relative to 1990 levels (Table 1). In addition, on March 21 2006 Al Gore testified to the joint hearing by the House Energy and Commerce Subcommittee on Energy and Air Quality and the House Science and Technology Subcommittee on Energy and Environment and called for a 90% reduction in greenhouse gas levels by 2050 relative to 1990. Finally, at the G8 meeting in Heiligendamm, Germany in June 2007, leaders (including the United States) agreed to "consider seriously the decisions made by the European Union, Canada and Japan which include at least a halving of global emissions by 2050."

[4] At the same time, other international policy discussions have been framed around limiting the global mean surface temperature increase to 2.0°C relative to preindustrial times, a number that some have argued represents an upper bound on manageable climate warming. For example, on January 10, 2007 the European Commission, the executive body of the European Union, issued a communication on limiting global warming to no more than 2°C [*Commission for European Communities*, 2007; *Schnellnhuber et al.*, 2006]. This same communication was endorsed by the European unit of Greenpeace (see http://www.greenpeace.eu/issues/climate.htm). Within the communication itself, the commission concludes: "By 2050 global emissions must be reduced by up to 50% compared to 1990, implying reductions in developed countries of 60–80% by 2050. Many developing countries will also need to significantly reduce their emissions."

[5] The context for such proposed reductions is often loosely justified as comprehensive coupled atmosphere-ocean general circulation models have typically examined only the climatic consequences of specified atmospheric CO_2 concentration (as opposed to emission) stabilization pathways [*Meehl et al.*, 2007]. While the specified atmospheric CO_2 concentrations are often derived from simple off-line carbon cycle models, and so include implicit carbon cycle feedbacks, these atmosphere-ocean general circulation models do not include dynamic carbon cycle subcomponents. As a consequence, most climate model simulations have not allowed for internal carbon cycle/climate feedbacks which add up to 1.0°C 21st century warming to some of the higher proposed emission scenarios [*Meehl et al.*, 2007]. It has therefore not been possible to assess the internal consistency of proposed global emissions reductions, potential policies aimed at limiting the magnitude of warming and atmospheric levels of greenhouse gases. The purpose of this contribution is to provide a detailed analysis of the effects of specific 2050 emission reductions targets using a model which has undergone extensive evaluation as part of international model intercomparison projects [*Friedlingstein et al.*, 2006; *Stouffer et al.*, 2006; *Weber et al.*, 2006; *Meehl et al.*, 2007]. A similar approach was taken earlier by *Wigley* [1998] with respect to the climate implications of the Kyoto Protocol.

2. Experimental Design

[6] We use the University of Victoria Earth System Climate Model version 2.8 (UVic ESCM) which is a model of intermediate complexity with horizontal resolution of 1.8° × 3.6°. It consists of a vertically integrated, energy-moisture balance, atmospheric model, coupled to the MOM2 ocean general circulation model with 19 vertical levels and a dynamic-thermodynamic sea-ice model [*Weaver et al.*, 2001]. The terrestrial carbon model is a modified

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Table 1. Proposed or Legislated 2050 Emissions Reduction Targets Relative to a Particular Year

Government/NGO	2050 Reduction	Relative To
City of Toronto[a]	80%	1990
California[b]	80%	1990
Illinois[b]	60%	1990
New Mexico[b]	75%	2000
New Jersey[b]	80%	2006
Oregon[b]	75%	1990
Washington[b]	50%	1990
US Proposed (Waxman)[c]	80%	1990
US Proposed (Jeffords)[d]	80%	1990
US Proposed (Kerry)[e]	65%	2000
Canada (Conservative)[f]	45–65%	2003
Canada (Conservative)[g]	60–70%	2006
Canada (Liberal)[h]	60–80%	1990
UK[i]	60%	1990
France[j]	75%	2000
Germany[j]	80%	1990
Sweden[j]	50%	2004
Greenpeace[k]	50%	1990
Western Australia[l]	60%	2000
South Australia[m]	40%	1990
New South Wales[n]	60%	2005
Al Gore (US Senate)[o]	90%	1990
Norway[p]	100%	n/a
G8[q]	50%	2007

[a] http://www.toronto.ca/legdocs/mmis/2007/ex/bgrd/backgroundfile-2428.pdf.

[b] The Pew Center on Global Climate Change, http://www.pewclimate.org/what_s_being_done/targets/.

[c] Safe Climate Act of 2006 (H.R.5642). (http://thomas.loc.gov/cgi-bin/query/z?c109:H.R.5642:) sponsored by Representative Henry Waxman (CA-30).

[d] Global Warming Pollution Reduction Act (S.3698) (http://thomas.loc.gov/cgi-bin/query/z?c109:S.3698:) sponsored by Senator James Jeffords (VT).

[e] Global Warming Reduction Act of 2006 (S.4039) (http://thomas.loc.gov/cgi-bin/query/z?c109:S.4039:) sponsored by Senator John Kerry (MA).

[f] Government of Canada, http://www.budget.gc.ca/2007/bp/bpc3e.html.

[g] Government of Canada, http://www.pm.gc.ca/eng/media.asp?id=1683.

[h] Liberal official opposition, http://www.liberal.ca/pdf/docs/whitepaper_EN.pdf.

[i] UK Government, http://www.defra.gov.uk/environment/climatechange/uk/legislation/index.htm.

[j] France, Germany and Sweden: EEAC, 70/30 Towards European targets for Greenhouse Gas Reduction 2050 and 2020, Statement of the EEAC Energy Working Group, European Environment and Sustainable Development Advisory Councils, EEAC Office, Den Haag, Netherlands, December (2004), http://www.eeac-net.org/download/EEAC%20WG%20Energy%20Stat-70-30_13-12-04_f.pdf.

[k] Greenpeace, http://www.greenpeace.eu/issues/news.html.

[l] Western Australia, http://www.greenhouse.wa.gov.au/.

[m] South Australia, http://www.greenhouse.sa.gov.au/.

[n] New South Wales, http://www.greenhouse.nsw.gov.au/.

[o] Al Gore testimony, http://www.pbs.org/newshour/bb/environment/jan-june07/gore_03-21.html.

[p] Norway, http://dsc.discovery.com/news/2007/04/20/norway_pla.html?category=earth&guid=20070420104530&dcitc=w01-101-ae-0003; http://www.greenhouse.nsw.gov.au/.

[q] G8, http://www.g8.gc.ca/2007-chairs-summary-en.asp.

version of the MOSES2 land surface model and the TRIFFID dynamic vegetation model [*Meissner et al.*, 2003; *Matthews et al.*, 2005]. Ocean inorganic carbon is based on the OCMIP abiotic protocol. Ocean biology is simulated by an ecosystem model of nitrogen cycling [*Schmittner et al.*, 2005; *Oschlies and Garçon*, 1999]. Water, heat and carbon are conserved with no flux adjustments. The model has participated in a number of model intercomparison projects including the Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP; *Friedlingstein et al.* [2006]), the Paleoclimate Modelling Intercomparison Project (PMIP; *Weber et al.* [2006]), and the coordinated thermohaline circulation experiments [*Gregory et al.*, 2005; *Stouffer et al.*, 2006]. In addition, the model was used as an assessment tool in the IPCC AR4 [*Meehl et al.*, 2007]. The computational efficiency of the model is such that it allows us to conduct numerous sensitivity experiments which would be more difficult to perform in coupled atmosphere-ocean general circulation models.

[7] *Meehl et al.* [2007] examined the range of equilibrium climate sensitivities for models participating in the IPCC AR4. They found that a normal fit led to a central estimate of 3.3°C with a 5%–95% confidence range of 2.1–4.4°C. *Stott et al.* [2006], on the other hand, used three coupled atmosphere ocean general circulation models to develop probability distributions of transient climate response (TCR). From these they estimated a median transient climate response of 2.1°C with a 5–95% confidence range of 1.5–2.8°C. The climate sensitivity of the UVic model is 3.5°C with a TCR of 2.0°C, putting it in the middle of model-based ranges.

[8] The UVic ESCM was integrated to equilibrium under year 1800 radiative forcing (atmospheric CO_2 concentration of 283.9 ppm). The model was then integrated forward to the end of year 2005 by prescribing the observed atmospheric CO_2 profile (with 2005 having an average concentration of 379.6 ppm). The climatic effect of land-use change over the 20th century was accounted for by changing specified surface albedo in regions of pastures and croplands [*Matthews et al.*, 2003]. We did not explicitly add land use carbon emissions. Over the last year of the integration, we diagnosed the total emissions required to maintain the observed level of CO_2 from the net increase in total global carbon. The diagnosed value of 9.0 gigatons of carbon per year (GtC/year) compares extremely well with a recent estimate of total anthropogenic emissions (that includes contributions from land use change) of 9.1 GtC/year averaged over 2003–2005 [*Marland et al.*, 2006; *Houghton and Hackler*, 2002]. Our approach allowed us to calculate the highly uncertain land surface emissions consistent with the observed atmospheric CO_2 concentration.

[9] After 2005 a number of specified global emissions scenarios were applied. These scenarios all assumed that contributions to radiative forcing from sulfate aerosols and greenhouse gases other than CO_2 remained fixed throughout the simulations. An alternate way of viewing this assumption is that any increase in anthropogenic non-CO_2 greenhouse gases is balanced by an increase in sulphate aerosols (or some other negative radiative forcing). This assumption should be viewed as conservative since many future emission scenarios project decreasing sulphate emissions and increasing emissions of non-CO_2 greenhouse gases. Today, the atmospheric concentration of the six anthropogenic greenhouse gases (CO_2, CH_4, N_2O, SF_6, HFCs, PFCs) covered by the Kyoto Protocol is about 430 ppm CO_2-equivalent. The net global anthropogenic radiative forcing turns out to be close to that which arises from 380 ppm CO_2, with the difference (−50 ppm CO_2-equivalent) being attributed to all other anthropogenic effects including non-Kyoto greenhouse gases and cooling associated with sulphate aerosols.

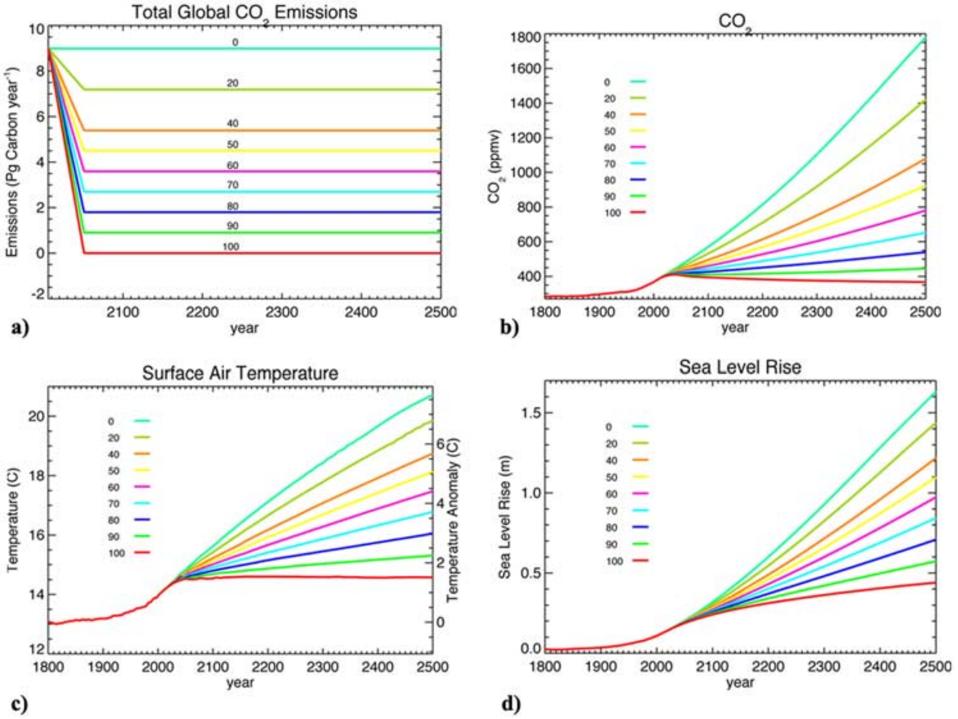

Figure 1. (a) Observed anthropogenic carbon dioxide emissions from 1800 to 2006 (red) followed by linear reductions of 0–100% of 2006 levels by 2050. From 2050 onwards emissions are held constant. Transient evolution of globally-averaged (b) atmospheric carbon dioxide, (c) surface air temperature, and (d) sea level rise due to thermal expansion for all experiments. Note that the sea-level curves have no contribution from the melting of land-based ice.

[10] In each of the 9 sensitivity experiments, we examined the effects of a hypothetical international policy option that linearly cut emissions by some percentage by 2050, and maintained emissions constant thereafter until the year 2500 (Figure 1a). Our motivation for undertaking these experiments is to try and understand the climatic consequences of the various 2050 emissions reduction targets being discussed or proposed internationally. This also allows us to develop an understanding of the future warming and sea level rise commitment as a consequence of these hypothetical reductions. We recognize that our baseline case of constant 2006 emissions is substantially more optimistic than the IPCC SRES scenarios, some of which have 2050 emissions at more than double 2006 levels. Our use of this baseline provides for an easy comparison with the level of emissions reductions currently being discussed internationally.

3. Results and Discussion

[11] The various emissions pathways lead to atmospheric carbon dioxide levels at 2050 ranging from 407 ppm to 466 ppm, corresponding to warming relative to 1800 of between 1.5°C and 1.8°C (Figure 1b, c; Table 2). As the 21st century progresses, the atmospheric CO_2 levels and warming begin to diverge between emissions scenarios, and by 2100 the range is 394 ppm to 570 ppm, with a warming of between 1.5°C and 3.6°C. None of the emissions trajectories lead to an equilibrium climate and carbon cycle at 2500, although the 90% and 100% emissions reductions have atmospheric CO_2 levels which are leveling off. Of particular note is that by 2500, the 100% emissions reduction scenario leads to an atmospheric CO_2 level below that in 2006 level, although global mean surface air temperature is still 0.5°C warmer than in 2006 (1.5°C warmer than 1800). In all cases sea level rise due to thermal expansion continues well beyond 2500. Of course, our simulations do not account for contributions from glacier of continental ice sheet melting and so sea level rise would be much greater than that simulated here.

[12] The results of our experiments underscore the conclusion of the IPCC AR4 [*Meehl et al.*, 2007] wherein the global mean climate change over the next several decades is very similar for the various emissions scenarios. That is, we find only 0.3°C less warming, 59 ppm less CO_2 in the atmosphere and 2 cm less sea level rise due to thermal expansion, when we compare the climate at 2050 in the case where emissions are maintained at 2006 levels, to the case when emissions drop to zero at 2050. Towards the end of the century, differences between scenarios begin to magnify leading to more dramatic changes as the warming and sea level commitments are slowly realized.

[13] All simulations that have less than a 60% reduction in global emissions by 2050 eventually break the 2.0°C threshold warming this century. Particularly disturbing from a policy perspective is that even if emissions are eventually stabilized at 90% less than 2006 levels globally (1.1 GtC/year), the 2.0°C threshold warming limit advocated by the European Commission is eventually broken well before the year 2500. While we recognize that other models will have slightly different responses, as noted by the IPCC AR4, differences in global mean temperature between

Table 2. Year 2006, 2050, 2100, and 2500 Emissions, Atmospheric CO_2 Concentration, Atmospheric Surface Air Temperature Increase Relative to 1800, and Sea Level Rise due to Thermal Expansion Alone Relative to 1800[a]

Year	Reduction Scenario	Emissions, GtC/year	Atmospheric CO_2, ppm	Temperature Increase, °C	Sea Level Thermal Expansion, cm
2006	—	9.0	380	1.0	9
2050	0%	9.0	466	1.8	18
2050	20%	7.2	454	1.7	18
2050	40%	5.5	442	1.6	17
2050	50%	4.6	436	1.6	17
2050	60%	3.7	430	1.6	17
2050	70%	2.8	424	1.6	17
2050	80%	2.0	419	1.5	17
2050	90%	1.1	413	1.5	17
2050	100%	0.2	407	1.5	16
2100	0%	9.0	570	2.6	30
2100	20%	7.2	532	2.4	28
2100	40%	5.4	495	2.2	26
2100	50%	4.5	477	2.1	26
2100	60%	3.6	460	2.0	25
2100	70%	2.7	443	1.9	24
2100	80%	1.8	426	1.7	23
2100	90%	0.9	410	1.6	23
2100	100%	0.0	394	1.5	22
2500	0%	9.0	1779	7.7	161
2500	20%	7.2	1421	6.8	141
2500	40%	5.4	1080	5.7	119
2500	50%	4.5	924	5.1	107
2500	60%	3.6	780	4.4	95
2500	70%	2.7	652	3.7	82
2500	80%	1.8	540	3.0	69
2500	90%	0.9	445	2.3	55
2500	100%	0.0	367	1.5	42

[a] The emissions include an implicit contribution from land-use change up to 2006. Temperature increases reflect interactive carbon cycle changes post 2006. Temperature increases include a positive carbon cycle feedback [*Meehl et al.*, 2007].

models are quite small over the next several decades. In addition, the climate sensitivity and transient climate response of the UVic model fall in the middle of estimated ranges. In the context of the present model, our analysis implies that if a 2.0°C warming is to be avoided, direct CO_2 capture from the air, together with subsequent sequestration, would eventually have to be introduced in addition to 90% global carbon emissions reduction targets for 2050.

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