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Stabilization and Global Climate Policy

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Stabilization and Global Climate Policy

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Abstract

Academic and political debates over long-run climate policy often invoke "stabilization" of atmospheric concentrations of greenhouse gases (GHGs), but only rarely are non-CO_2 greenhouse gases addressed explicitly. Even though the majority of short-term climate policies propose trading between gases on a global warming potential (GWP) basis, discussions of whether CO_2 concentrations should be 450, 550, 650, or perhaps as much as 750 ppm leave unstated whether there should be no additional forcing from other GHGs beyond current levels or whether separate concentration targets should be established for each GHG. Here we use an integrated modeling framework to examine multi-gas stabilization in terms of temperature, economic costs, carbon uptake, and other important consequences. We show that there are significant differences in both costs and climate impacts between different "GWP equivalent" policies and demonstrate the importance of non-CO_2 GHG reduction on timescales of up to several centuries.

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1. INTRODUCTION

The stated goal of Article 2 of the UN Framework Convention on Climate Change (UN FCCC) is the "stabilization of greenhouse gas concentrations in the atmosphere" at a level that would "prevent dangerous anthropogenic interference with the climate system." The 1997 Technical Paper III of the Intergovernmental Panel on Climate Change (IPCC) attempted to clarify the Convention's stabilization goal (Schimel *et al.*, 1997). Sensitivity to small deviations in other GHG emissions was evaluated and the study revealed that in the short term these deviations could have significant impact. The Technical Paper also noted that since pre-industrial times the contribution of these 'other' substances to radiative forcing is comparable to that of CO_2. But in academic papers, control of other gases is at best usually relegated to footnotes or asides (Dai *et al.*, 2001a; Nordhaus, 2001; Arnell *et al.*, 2002; Hoffert *et al.*, 2002; O'Neill and Oppenheimer, 2002). Question 6 of the Synthesis Report to the IPCC Third Assessment Report (TAR) asks what the consequences are of stabilizing concentrations in carbon dioxide equivalents, but the text then only addresses CO_2, and the stabilization scenarios are analyzed with only one projection of other greenhouse gases, namely the unconstrained SRES A1B

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scenario (Watson and Core Writing Team, 2001). The U.S. National Assessment Report on Climate Change Impacts relies heavily on the CGCM1 and HADCM2 models, both of which use CO_2 as a surrogate for other greenhouse gases (National Assessment Synthesis Team, 2001).

While most stabilization proposals only explicitly address carbon dioxide stabilization, shorter term climate policies often include the possibility of trading among greenhouse gases by using the global warming potentials (GWPs) established by the IPCC in order to reach more economically efficient solutions than relying on CO_2 reduction alone would allow. Indeed, the Kyoto Protocol allows for precisely this sort of trading across greenhouse gases, using a 100-year GWP as the 'exchange rate.'

Trading schemes that rely on constant GWPs will not generate stabilization of concentrations or radiative forcing, as trading a reduction of a gas with a short lifetime for an increase of a long-lived gas will inherently lead to reductions in radiative forcing in the near term and increases in radiative forcing in the long term (and vice versa). Stabilizing radiative forcing would require trading concentration levels of one GHG for another, which would imply that in terms of emissions, emissions paths for each GHG be specified over at least the lifetime of the longest lived of the two. Other studies equate a CO_2 stabilization level with a forcing value, such as a recent Hadley Centre analysis (Mitchell *et al.*, 2000). These studies model varying CO_2 concentrations and assume the concentrations of all other gases stay constant, but acknowledge that, in reality, society might choose a different allocation among other GHGs and CO_2 that add up to the same total forcing level.

For a given CO_2 equivalent stabilization target, the actual level at which CO_2 will need to be stabilized is therefore likely to be significantly lower and, moreover, such studies provide no direct guidance on the emissions paths that would be consistent with stabilization of radiative forcing. The question of stabilization of multiple greenhouse gases is inevitably linked to the issue of comparison among them, and thus the inadequacy of GWPs (*e.g.*, Reilly *et al.*, 1999). One approach is to set a specific climate or radiative forcing target and endogenously estimate the optimal control path of different gases (*e.g.*, Manne and Richels, 2001). Work in this vein has relied on highly stylized climate and atmospheric chemistry relationships because that assures that the mathematical system has a single optimal path or that it is numerically feasible to solve for it. Absent in these efforts are important relationships among methane, the hydroxyl radical, and tropospheric ozone (and its precursors).

In this study we use the MIT Integrated Systems Model (IGSM) to examine several different ways in which a stabilization target might be interpreted. Economic projections were made under different policy constraints to develop emissions scenarios and also to examine economic impacts. The IGSM's internal earth systems model was used to determine the climate impacts of the various emissions scenarios. The inclusion of chemistry, terrestrial ecosystem, and other components in the coupled natural system model enables examination of processes such as ozone generation and the carbon cycle on both 100-year and several century timescales. Previously, different components of the MIT IGSM have been used to examine the economics of non-CO_2 gas abatement (Hyman *et al.*, 2003), the Kyoto protocol (Prinn *et al.*, 1999; Reilly *et al.*, 2002), and the climate impacts of reductions in non-CO_2 gases (Reilly *et al.*, 2003). The unique contribution of this study is an examination of the complex relationships among physical climate system components as they affect stabilization. By extending the IGSM to consider periods well beyond 2100, we examine the limits of the 2100 horizon often used in the literature for stabilization discussions. More generally, this study is designed to bring the definitional issues involved in stabilization policy discussions into sharper focus. While the results of the model runs depend on several assumptions, comparisons between the various policies do provide an indication of the economic and climatic importance of these definitions.

2. MODEL OVERVIEW

The MIT IGSM has recently been described in Webster *et al.* (2003). To summarize, the IGSM includes: (a) the MIT Emissions Prediction and Policy Analysis (EPPA) model which is designed to project emissions of climate relevant gases and the economic consequences of policies to limit them; (b) a two-dimensional (2D) zonally-averaged land-ocean resolving atmospheric model coupled to an atmospheric chemistry model; (c) a 2D ocean model; (d) the Terrestrial Ecosystem Model (TEM 4.1) (Tian *et al.*, 1999); (e) a reduced form urban air chemistry model; and (f) a Natural Emissions Model (NEM).

Climate system properties were chosen as the median of distributions used in the works of Forest and Webster (Forest *et al.*, 2002; Webster *et al.*, 2003). Namely, ocean diffusivity (K_v), a parameterization for diffusion of heat into the deep ocean, was set to 9.2 cm^2/s, climate sensitivity (S), a parameter for cloud feedback that determines the sensitivity of the model, was set to 2.4 °C, and an aerosol forcing constant (F_{aer}), a measure of forcing from a given aerosol loading, was set to -0.61 W/m^2, corresponding to loading for the 1980s.

3. RESULTS

We considered several ways that a stabilization goal might be achieved. Two primary targets were considered—550 ppm and 650 ppm—using the MIT IGSM, which includes an economic model capable of estimating the cost of multiple greenhouse gas control (Prinn *et al.*, 1999; Babiker *et al.*, 2001; Hyman *et al.*, 2003). The CO2ONLY scenarios restrict CO_2 but no other gases. In these scenarios, emissions paths were designed to control CO_2 starting in 2005 with a global carbon price that rose at 5% per year and to achieve their target CO_2 stabilization level sometime after 2100 given the median climate parameters described above. Reductions in other GHGs occurred only as side effects of the CO_2 quotas. The GHGTRADE scenarios used the appropriate CO2ONLY scenario as a baseline, and then allowed trading of other GHGs as weighted by their GWPs in order to achieve identical GWP emission profiles. A third case, PROPRED, assumes the same CO_2 quotas as the CO2ONLY scenarios, but imposes proportional reductions from the baseline path of the other GHGs. Finally, a fourth case, GHGCONST, uses the same CO_2 emissions pathway but holds all other GHG emissions constant at their 2005 levels.

Each of these scenarios is a plausible interpretation of a stabilization goal but we find very different temperatures changes and economic costs on the century timescale (**Table 1**) (Babiker *et al.*, 2001). In the reference (no policy) case the temperature increase was 2.8 °C by the end of the century. For 550 (650) ppm stabilization, the CO2ONLY case reduced the temperature by roughly three quarters (one-half) a degree at a cost of 1.2% (0.4%) of net present value of consumption (final consumption being a measure of societal welfare in the EPPA model, discounted at 5% per year over the century). The GHGTRADE cases were at least 50% more effective in temperature reduction on the century timescale than the CO2ONLY scenarios, at less than half the cost. The PROPRED case achieved nearly twice the temperature reduction compared to the CO2ONLY case but at a 40% increase in cost.

In general, these costs are likely to be low because optimal reduction through time assumes the most cost effective approach to emissions reduction (Wigley *et al.*, 1996). Our policies also assume participation by all countries from the start, and thus include the most cost-effective reductions in all parts of the world. In contrast, when we simulated the economic cost of an extended Kyoto policy where the Kyoto reductions in 2008-2012 are gradually deepened in the industrialized world and then later extended to developing countries in such a way as to achieve approximate stabilization of CO_2 at 550 ppm, the net present consumption loss due to this policy was 2.0%, higher than in any of the present 550 stabilization cases (Reilly *et al.*, 1999).

To consider the extent to which 2100 conditions were consistent with stabilization, we ran the earth system components of the MIT IGSM beyond 2100. We considered stabilization at 550 ppm in the CO2ONLY case. To achieve long-term stabilization of CO_2 we imposed continued emissions reductions at 1% per year from 2100 to 2300. This simple extrapolation of the emissions path was used because the EPPA model was designed to run only through 2100.

Table 1. Results of Different Policies on Temperature and Costs

	CO2ONLY	**GHGTRADE**	**PROPRED**	**GHGCONST**
650 ppm				
ΔT from BAU[a]	0.47	0.86	0.86	1.02
NPC loss[b]	0.4%	0.2%	0.5%	0.6%
2005 C-equiv Price[c]	$23	$1	$0 to $23	$0 to $23
550 ppm				
ΔT from BAU[a]	0.75	1.18	1.46	1.34
NPC loss[b]	1.2%	0.5%	1.7%	1.4%
2005 C-equiv Price[c]	$50	$4	$0 to $50	$0 to $50

[a] ΔT from BAU: Difference in decadal global mean temperature in 2100 between the policy case and the no policy ("business as usual") case (with warming of 2.8 °C).

[b] NPC loss: Percent reduction in net present consumption through 2100 given a 5% discount rate.

[c] C-equiv Price: The carbon-equivalent price is the price that would clear a permit market in emissions given the emissions constraint imposed on the model in 2005. Note that in the PROPRED and GHGCONST cases there is no trading between gases, so there are different prices for each gas, but the non-CO_2 gases have near zero prices in early periods.

For the remaining cases, we decreased CO_2 emissions at the same rate as in the CO2ONLY case and maintained all other gases at their 2100 emissions levels. We note that the CO2ONLY case does *not* stabilize radiative forcing, which is still rising at 0.01 W/m^2 per decade at the end of the extended period. Radiative forcing in the GHGTRADE case, which continues to be GWP equivalent to the CO2ONLY case, is rising at the much faster rate of 0.1 W/m^2 per decade in 2300. The GHGCONST case has nearly stabilized radiative forcing despite continued emissions of long-lived gases, and radiative forcing is actually decreasing at 0.01 W/m^2 per decade in the PROPRED case.

For the CO2ONLY scenario (**Figure 1**) CO_2 emissions (orange), which were declining at a rate of 0.1 GtC/yr in 2100, still have not yet reached zero in 2300. Emissions of CH_4 and CO are significant sources of CO_2 and must be included in the eventual stabilization plan (purple). In order to stabilize concentrations, CO_2 emissions must continue to decrease, eventually approaching zero (Hoffert *et al.*, 2002), but even out to 2300 there remains some positive ocean uptake (see Figure 1) mainly due to the ocean's slow mixing processes. Uptake by the ocean in the 550 ppm CO2ONLY stabilization scenario peaks at 4.2 GtC in 2070 and drops to 1.6 GtC in 2300 and is still declining thereafter. Terrestrial uptake peaks at 1.7 GtC in 2050 and is nearly zero by 2300. The strength of these sinks at any point in time and their overall response depend

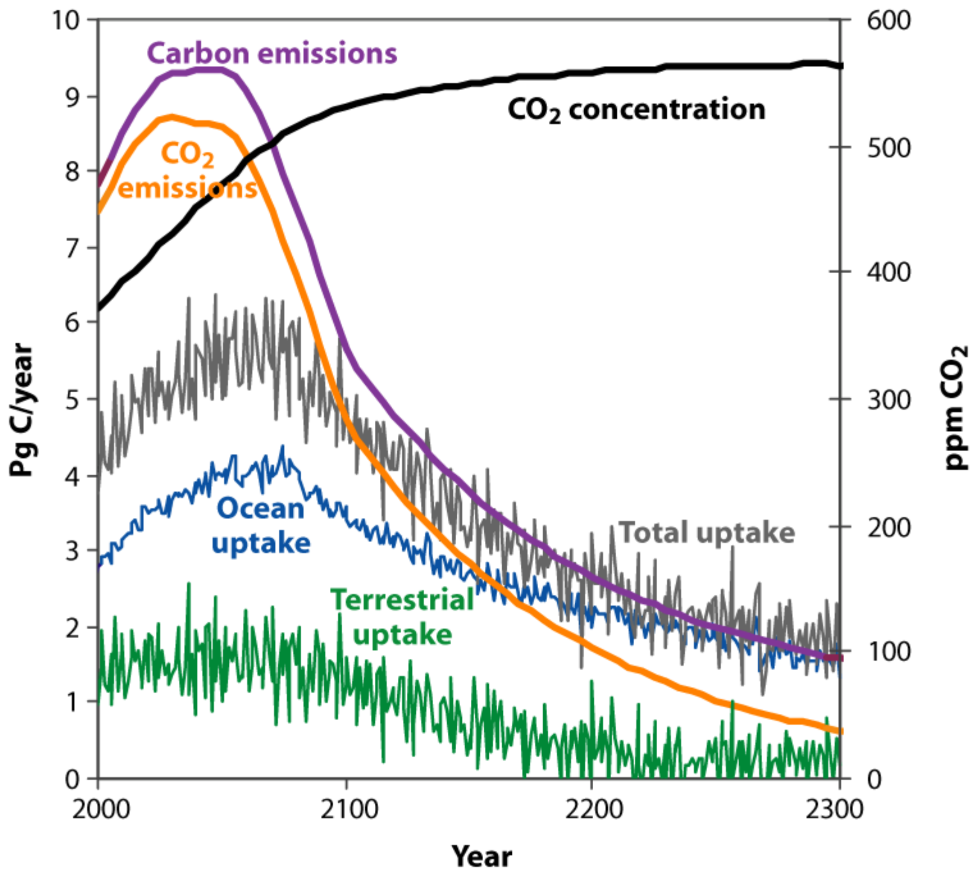

Figure 1. Components of carbon-cycle budget and CO_2 concentrations for the CO2ONLY 550 ppm stabilization case. Annual average uptake, emissions, and concentrations are shown.

strongly on the properties controlling the climate system response (S and K_v) and on the features of the terrestrial ecosystems model in the IGSM (Webster *et al.*, 2003). For the CO2ONLY case in 2100, the 95% bounds on CO_2 concentration due to S and K_v uncertainty alone range from 500 to 585 ppm. With declining anthropogenic emissions, atmospheric concentrations of CO_2 begin to stabilize, allowing the terrestrial ecosystem to reach equilibrium with the atmosphere. The ocean mixed layer also approaches equilibrium, and further ocean uptake is then limited by diffusion into the deep ocean. Furthermore, there are temperature effects on both terrestrial ecosystem and oceanic uptake rates.

In the trading cases, more of the reductions come from CH_4 than from CO_2 because of the relative opportunities for least cost emissions reductions. Because CO_2 is longer-lived than CH_4, this means that the GHGTRADE cases show greater reductions in temperature from the reference case in the short term than the CO2ONLY cases. But, with more long-lived CO_2 accumulating in the atmosphere, the GHGTRADE cases should eventually become warmer. Analysis of the 550 ppm scenarios (**Figure 2**) shows that the temperature rise under GHGTRADE exceeds the CO2ONLY case after 2240, when the CO_2 concentration in the former case is 780 ppm. The 'short term' benefits of CH_4 reduction thus remain for a surprisingly long period. Due to inertial effects, sea level rise in the two cases is comparable only after about another 100 years (2330), when the rise is 1.1m above present in both cases. The comparison between the GHGTRADE and CO2ONLY cases again raises the question of whether GWPs are an appropriate 'exchange rate' in trading GHG reductions (Reilly *et al.*, 1999; Smith and Wigley, 2000; Manne and Richels, 2001; Sygna *et al.*, 2002). If the rate of temperature change is an important factor in designing a

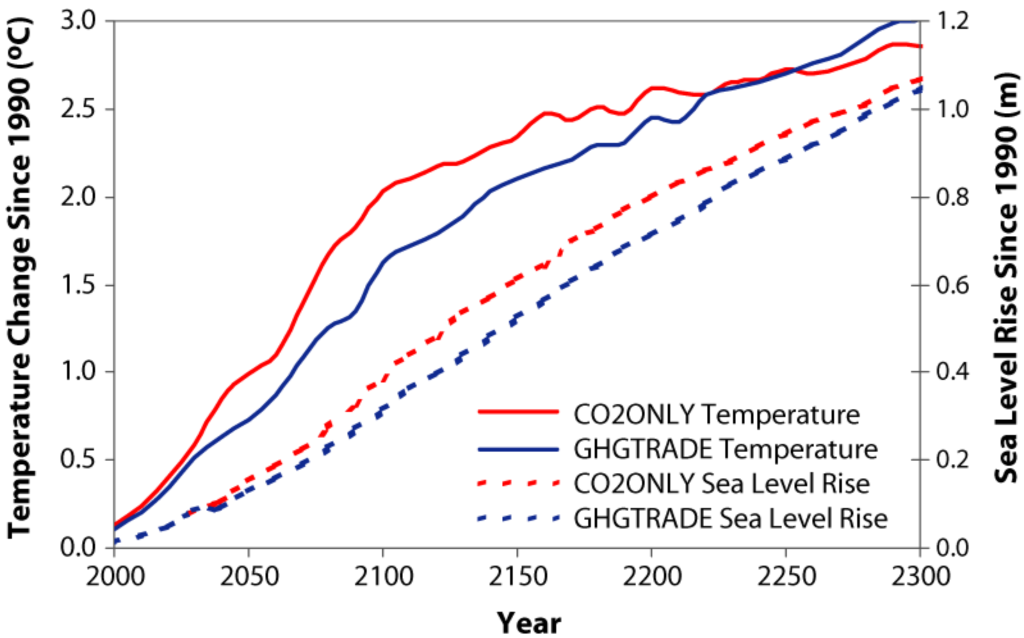

Figure 2. Decadal global mean average temperature and sea level rise results for the CO2ONLY and GHGTRADE 550 ppm scenarios.

policy, as studies on thermohaline circulation collapse suggest (Schneider, 2003), then non-CO_2 greenhouse gases are being undervalued by GWP measures, whereas if long-term radiative forcing stabilization is the criteria of interest, then gases such as methane are being overvalued. In addition to timescale issues, the implications of non-CO_2 GHGs for atmospheric chemistry such as the impact of methane on ozone levels (**Table 2**) might also be important for air quality and for changing the lifetimes of other greenhouse gases. Because the GHGTRADE scenario has both superior temperature and cost characteristics, our study shows that adhering to a definition of stabilization that emphasizes CO_2 is likely to miss win-win opportunities (Reilly *et al.*, 2003).

These results depend on the specific reference emissions projections which, for CO_2, at a cumulative level of 1700 GtC, falls into the "medium-high" range for the IPCC's SRES scenarios, but considerable uncertainty exists in future emissions of CO_2 and perhaps even more so for the other GHGs (Webster *et al.*, 2002). The projections of non-CO_2 emissions and concentrations in our reference scenario clearly have an impact on the results. By the end of the century, the EPPA model reference scenario projects methane emissions of 860 Tg (comparable to the A2 SRES scenario of 889 Tg), and N_2O emissions of 22 Tg (which is slightly higher than the 20 Tg of the upper range of the SRES scenarios). The resulting methane concentration is, however, significantly higher than the SRES projections. The MIT IGSM includes stratospheric chemistry, natural emissions of methane and N_2O, and a more complex tropospheric chemistry model than the single box model used by the TAR, which likely contributes to the much higher atmospheric concentration results in this study, even though methane emissions are comparable.

Table 2. Greenhouse Gas Concentrations in Year 2100[a]

	CO_2 (ppm)	**CH_4** (ppm)	**N_2O** (ppb)	**O_3** (ppb)	**Δ Radiative Forcing**[b] (W/m^2)
No Policy, 2100	822	5.42	483	51	7.4
650 ppm cases, 2100					
CO2ONLY	608	4.09	473	46	5.0
GHGTRADE	673	2.12	410	45	4.4
PROPRED	606	2.23	418	45	4.0
GHGCONST	605	2.12	414	46	3.8
550 ppm cases, 2100					
CO2ONLY	529	3.80	466	45	4.0
GHGTRADE	592	1.96	402	44	3.5
PROPRED	527	1.48	393	41	2.7
GHGCONST	527	2.14	413	45	3.0
550 ppm cases, 2300					
CO2ONLY	562	3.58	676	44	5.0
GHGTRADE	868	1.85	514	43	6.3
PROPRED	540	1.14	444	44	2.8
GHGCONST	550	2.12	510	45	3.6

[a] HFCs and SF_6 are also included in the model though the numbers are not shown here due to their comparatively smaller contributions to net forcing.

[b] Change in radiative forcing since 1990 of all GHGs, not including sulfate aerosols.

The feedbacks and uncertainties involved in the response of natural emissions of CH_4 and N_2O to climate change, like the uncertainty in CO_2 uptake, add to the complexity of designing climate policies. Yet another emission uncertainty has to do with non-GHG climatically important substances that may be controlled by non-climate related policies (Dai *et al.*, 2001b). Our SO_2 emission projections also differ from those of the SRES scenarios. Further exploration of these uncertainties and those of climate system parameters is warranted, but the first step towards a study of stabilization under uncertainty is an examination of what stabilization means for a single set of reference conditions.

4. CONCLUSIONS

Stabilization of concentrations is a long-term goal of climate policy, and while exact consensus on its meaning may not be needed to proceed with mitigation efforts in the near term, we have shown that different interpretations of how other greenhouse gases are considered in a stabilization target have a substantial affect on how much warming is avoided. As stated by Hasselmann, *et al.* (2003), successful climate policies should take into account both short term policies and long term goals. Judgments about the adequacy of climate policy in light of a long term target, whatever it might be, will need to consider just what is meant by stabilization and how, in terms of the mix of GHG reductions, a target will be achieved. As seen in the heated debates over forest and agricultural sinks in the Kyoto Protocol negotiations, settling on definitions may ultimately be a political matter, but these debates can only benefit from being placed in a framework that elucidates the discussions (Watson and Intergovernmental Panel on Climate Change, 2000). Our results suggest that any policy measure that does not take into account all greenhouse gases will be both more expensive and less effective through the next century and beyond.

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