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A Strategy for Climate Change Stabilization Experiments

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Climate models used for climate change projections are on the threshold of including much greater biological and chemical detail than previous models. Today, standard climate models (referred to generically as atmosphere-ocean general circulation models, or AOGCMs) include components that simulate the coupled atmosphere, ocean, land, and sea ice. Some modeling centers are now incorporating carbon cycle models into AOGCMs in a move toward an Earth system model (ESM) capability. Additional candidate components to include in ESMs are aerosols, chemistry, ice sheets, and dynamic vegetation [e.g., *Cox et al.*, 2000; *Friedlingstein et al.*, 2006].

In this article, we discuss a new strategy for using climate system models as part of a coupled biophysical-climate and integrated model assessment approach. The motivation is to develop a next-generation experimental design that follows on the scenario approach where concentrations and their derived emissions based on story lines were used in the development of the Intergovernmental Panel on Climate Change (IPCC) third and fourth assessment reports. We specifically address recent developments in climate system models that can shed light on greenhouse emissions scenarios. Complementary aspects of ongoing model development (e.g., observations and paleoclimate experiments) are important components of a much larger research strategy of which the modeling approach proposed here is one part.

Modeling groups are now making decisions as to what form their next-generation climate models will take with the consideration of how new climate change experiments may be evaluated in a next IPCC assessment. The experiments proposed in this article regarding stabilization scenarios warrant community experiments to address this issue even if there is not another IPCC assessment. Additionally, new emissions scenarios developed by the integrated assessment community reflect recommendations of the 25th IPCC session (held in April 2006 in the Republic of Mauritius). These advances in both the climate modeling and scenarios communities provide an opportunity for increased communication and collaboration that could recommend plausible action toward assessing human mitigation of changing climate.

This confluence of activities in model and scenario development needs to be communicated and coordinated across various groups and scientific communities. To this end, a strategy for the next-generation climate simulations should (1) identify new components in preparation for inclusion in AOGCMs;
(2) establish communication for coordination through the World Climate Research Programme (WCRP), the Integrated Geosphere-Biosphere Programme (IGBP), and the Integrated Assessment (IA) modeling teams such as those involved with IPCC Working Group III (WGIII); (3) propose an experimental design for 21st-century climate change experiments; and (4) specify the requirements for new stabilization scenarios (particularly with regard to impacts, mitigation, and adaptation).

Empirical evidence and first-generation coupled carbon cycle model results indicate the possibility of a large positive carbon cycle feedback to the climate system, which challenges any particular stabilization target [*Cox et al.*, 2000; *Fung et al.*, 2005; *Friedlingstein et al.*, 2006]. While some models include a carbon cycle, none has consistently incorporated nutrient and/or micronutrient limitations, land use, fire, succession, ocean bottom chemistry, and tropospheric ozone dynamics. Taking into account the state of the art of these new components, a strategy involving an experimental design addressing two timescales is proposed for community coordinated climate change projection experiments.

Near-Term Experimental Design (2005–2030)

A major goal for 25-year model projections is to provide better guidance about the likelihood of changes in climate extremes at regional scales. Meeting this challenge will depend on scientific questions that address understanding the processes that produce extremes related to the hydrological cycle,

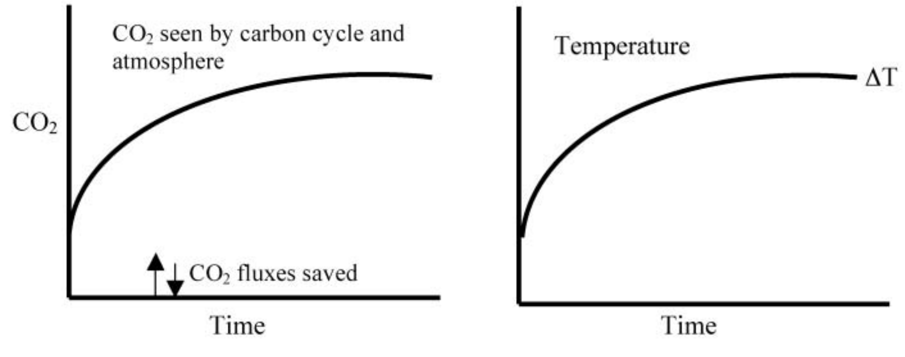

Fig. 1. Schematics of experiment 1. The carbon cycle responds to (left) increasing CO_2 concentrations and (right) changes in temperature. The land and ocean CO_2 fluxes are saved to derive emissions for Integrated Assessment (IA) modeling teams such as those involved with IPCC Working Group III (WGIII) scientists. The land and ocean CO_2 fluxes are not radiatively interactive with the atmosphere.

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and on understanding relevant atmospheric and oceanic processes that operate on appropriate timescales. Regional-scale predictions will require finer-resolution spatial models (e.g., atmospheric model components reduced to at least 0.5°–1° latitude and longitude grid cells, as well as increased vertical resolution) that incorporate simple chemistry, aerosols, and dynamic vegetation. On this short timescale, carbon cycle feedbacks would be small and a carbon cycle component would not be included. Both improved process representation and higher resolution are important, though compromises will be required to make the simulations computationally feasible.

Determining the significance of regional changes, and especially those of climate extremes, will require numerous simulations in an ensemble approach. Given that scenarios of long-lived greenhouse gases do not differ substantially prior to 2030, a single, midrange scenario will be used here for model predictions. Near-term experiments will produce relatively small magnitude climate change; however, the signal-to-noise discrimination will be more difficult. While an exact number of ensemble simulations required is uncertain, a minimum of 10 for each case should be performed, and even more may be required to discriminate changes in hydrologic extremes.

On this short timescale, additional experiments are possible with higher-resolution models. For example, several scenarios for pollutants (aerosols and short-lived gases) to study their effects on weather could be provided for low, medium, and high emissions projections as perturbations around the standard scenario, and hypotheses could be tested (e.g., targeted emissions reduction or overshoot strategies, injecting sulfur into either the stratosphere or troposphere) with model experiments to mitigate climate change. Interactions and feedbacks to the climate system would nevertheless need to be explored with ESMs to try and ascertain unintended consequences on other Earth system model components such as ecosystems and atmospheric chemistry.

These near-term simulations could use a coupled initialized state close to the present-day state of the climate system, though the utility of this approach is still being explored by the modeling communities as a research problem. This would require accurate representation of, for example, ocean salinity data and soil moisture, which is currently problematic due to sparse observations. It would also require improved initialization data sets of sea ice. After spin-up, simulations would begin with the latter half of the twentieth century. This strategy will incorporate past climate forcings to account for (1) radiative imbalances that produce short-term committed climate change, (2) the facilitation of model verification; and (3) the logistics involved with the coupled assimilation/initialization process.

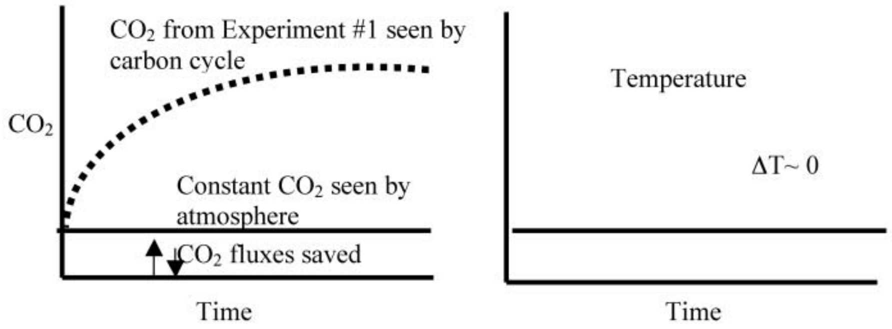

Fig. 2. Schematics of experiment 2. The carbon cycle (land and ocean) responds to (left) CO_2 concentrations from experiment 1. Atmospheric CO_2 is constant for the radiation calculation so there is (right) little temperature change. Land and ocean CO_2 fluxes are used to derive emissions by IA modeling teams. The land and ocean CO_2 fluxes are not radiatively interactive with the atmosphere.

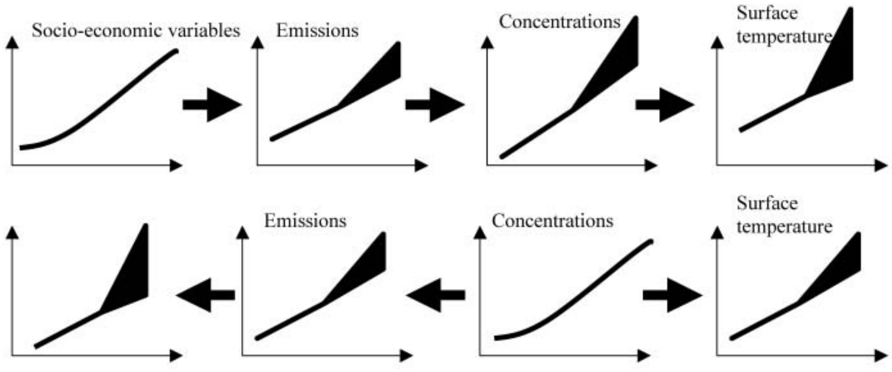

Fig. 3. (top) Traditional progression of derived emissions to climate system response starting from socioeconomic variables, emissions, concentrations, and climate change. (bottom) New strategy starts with benchmark concentration scenarios from IPCC WGIII scientists to modeling groups, from which emissions are calculated, and supplied to WGIII scientists to derive socioeconomic variables consistent with emissions stabilization pathways. The climate system response is still generated from concentrations (arrow from concentrations to temperature).

Long-Term (2005–2100 and Beyond)

Longer-term projections quantify feedbacks in the Earth system related to climate outcomes that could be affected by various socioeconomic and policy considerations (e.g., stabilization). These types of experiments would utilize a lower-resolution AOGCM (roughly 2°) with a conventional preindustrial spin-up, or initialization, followed by a twentieth-century experiment with natural and anthropogenic forcings that would provide a reference to earlier experiments and a comparison with observations. Carbon cycle feedbacks are important on this timescale and would be included for these long-term experiments, though atmospheric chemistry and aerosols would be calculated simply or prescribed. Three experiments are proposed:

1. Long-Term Benchmark Stabilization: In this experiment, both AOGCMs and ESMs are run with a scenario of prescribed CO_2 concentrations leading to stabilization (Figure 1). ESMs produce time series of standard climate variables, as well as CO_2 fluxes from the land-atmosphere and ocean-atmosphere consistent with the increasing concentrations and the consequent modeled climate change. It is important to note that for this experiment, the carbon cycle feedbacks do not affect atmospheric concentrations (as concentrations are prescribed). These internally calculated land/ocean CO_2 fluxes plus the prescribed increase in atmospheric CO_2 concentration are combined to calculate an implied CO_2 emission time series that is provided to IA modeling groups to derive mitigation policies to achieve those allowed emissions. This experiment provides a quasi-inverse estimate of fossil and land use emissions in the context of feedbacks between the carbon cycle and climate for prescribed time-evolving concentrations. The modeling groups that will not have coupled carbon cycle components can still participate by simply running the concentration scenarios in their AOGCMs.

2. Carbon Cycle Response to Increasing Concentrations: This experiment is similar to experiment 1, with the exception that the atmospheric CO_2 concentrations are held constant at preindustrial levels for radiative calculations in the atmosphere, but other ESM components respond to the increasing CO_2 concentrations from experiment 1 (Figure 2). The derived emissions from experiment 2 represent the carbon cycle feedback

reacting only to the prescribed increasing atmospheric CO_2 concentrations. Comparing the derived emissions from experiments 1 and 2 provides an indicator of the magnitude of the carbon cycle/climate feedback in terms of those different emissions.

3. Emissions-Driven Carbon Cycle/Climate: This experiment is driven by emissions rather than by concentrations. Each ESM calculates the concentrations resulting from an idealized prescribed standard emissions time series (e.g., 1% per year for CO_2) with a fully interactive carbon cycle. This experiment provides a direct connection to simulations from the Coupled Carbon Cycle Climate Model Intercomparison Project (C^4MIP) experiments [e.g., *Friedlingstein et al.*, 2006]. Similarly, the AOGCMs will still perform the standard 1% increase per year CO_2 concentration experiments (from the Coupled Model Intercomparison Project (CMIP)) for comparison with the previous generation of models. Another possibility being discussed for this experiment would be to take the emissions used to derive the benchmark concentration scenarios in experiment 1, run the fully coupled ESMs with those emissions, and compare the climate response to experiment 1 to assess the magnitude and nature of the climate feedbacks involved with the carbon cycle.

Previously, scenarios have started with socioeconomic considerations evolving to emissions scenarios, and then concentrations were derived and the models were run to produce climate changes that were used by IPCC Working Group II (WGII) scientists for climate impact studies. The proposed strategy for climate change stabilization experiments instead begins with concentrations and goes back to socioeconomics. This approach is being discussed by members of the IPCC working groups, and the IPCC Scenarios Consortium is considering examining the approach at a September 2007 IPCC Expert Meeting. Impacts are analyzed from the climate response experiments as before (Figure 3).

Overall Recommendations for Future Climate Change Experiments

An integrated and synergistic effort is needed to produce past, current, and future emissions scenarios that would ensure the use of consistent and documented data relevant to the global change communities. In addition, Earth system models of intermediate complexity (EMICs) capture essential feedbacks while using far less computer resources than a typical AOGCM or ESM. Also, EMICs can be used to run more scenarios over much longer time periods (including paleo) and can be used to test the feasibility of the experimental design. For impacts reported by WGII scientists, up-to-date model projections need to be made available to impact modelers several years before the production of the WGII report. This could be done by staggering the WGI and WGII reports or by producing new climate change simulations as soon as possible. There is a need for a Program for Climate Model Diagnosis and Intercomparison (PCMDI) equivalent for WGII and WGIII communities where relevant climate model output can be collected, archived, and tailored for use by these scientists. This could include an expanded role for the IPCC Data Distribution Center. An international community organization mechanism is also needed for the WGII and WGIII communities. Finally, an assessment of regional climate change effects will require gridded emissions data for aerosols and short-lived trace gases.

The strategy proposed in this article involves a number of unresolved science questions that need to be addressed, including but not limited to (1) how to initialize short-term model experiments, (2) how to archive time-evolving chemistry/aerosols for regional climate change, (3) how to resolve the number of ensembles versus resolution with regard to signal-to-noise in detecting projected near-term climate changes, (4) how to develop and implement land use change data sets and information, (5) how or if to specify stratospheric ozone, (6) what additional methods might be useful for quantifying carbon cycle feedbacks, and (7) when and/or how to incorporate ice sheet components in ESMs.

Regarding this last point, a number of groups are in the process of including dynamical ice sheet models of some form in their AOGCMs. However, given the early stages of development of these models, it may currently be too early to assess ice sheet changes in a coordinated fashion. Since the experimental design proposed here applies only to coordinated experiments across modeling groups, each individual group, of course, will still be able to perform other experiments that take into account other factors such as ice sheets.

We welcome comments and ideas on the proposed strategy for the experimental design and related issues for the research questions above. This input can be provided through the WCRP (http://wcrp.wmo.int/AP_Greenhouse.html) Working Group on Coupled Models (WGCM; e-mail for cochair Gerald Meehl: meehl@ucar.edu) or the IGBP (http://www.igbp.kva.se/) Analysis and Integration of Models of the Earth System (AIMES; http://www.aimes.ucar.edu; e-mail for project scientist Kathy Hibbard: kathyh@ucar.edu).

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