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SUMMARY REPORT

A STRATEGY FOR CLIMATE CHANGE STABILIZATION EXPERIMENTS WITH AOGCMs AND ESMs

Aspen Global Change Institute 2006 Session
Earth System Models: The Next Generation

(Aspen, Colorado, July 30-August 5, 2006)

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Aspen Global Change Institute (AGCI) 2006 Session Participants

(numbers correspond to placement in group photo on facing page)

1. Ron Stouffer, GFDL, Princeton, NJ
2. Nebojsa "Naki" Nakicenovic, Vienna University of Technology and IIASA, Vienna and Laxenburg, Laxenburg, Austria
3. Phil Rasch, NCAR, Boulder, CO
4. Kathy Hibbard, NCAR, Boulder, CO
5. Claire Granier, CNRS, Paris, France
6. David Kicklighter, Woods Hole, MA
7. Guy Brasseur, NCAR, Boulder, CO
8. David Rind, NASA Goddard Institute for Space Studies, New York, NY
9. Masahide Kimoto, Univ. of Tokyo, Tokyo, Japan
10. Michio Kawamiya, Frontier Research Center for Global Change, Yokohama, Japan
11. Peter Cox, Exeter University, U.K.
12. Olivier Boucher, Hadley Centre, Exeter, U.K.
13. John Katzenberger, AGCI Director, Aspen, CO
14. Norm McFarlane, Univ. of Toronto, Toronto, Canada
15. George Hurtt, Univ. of New Hampshire
16. Richard Moss, UN Foundation and Univ. of Maryland, College Park, MD
17. Steve Smith, PNNL and Univ. of Maryland, College Park, MD
18. Dave Bader, PCMDI, Livermore, CA
19. Gerald Meehl, NCAR, Boulder, CO
20. Dave Lawrence, NCAR, Boulder, CO
21. Jean-Francois Lamarque, NCAR, Boulder, CO
22. Linda Mearns, NCAR, Boulder, CO
23. Peter Gent, NCAR, Boulder, CO
24. Sue Bookhout, AGCI, Aspen, CO
25. Michelle Masone, AGCI, Aspen, CO

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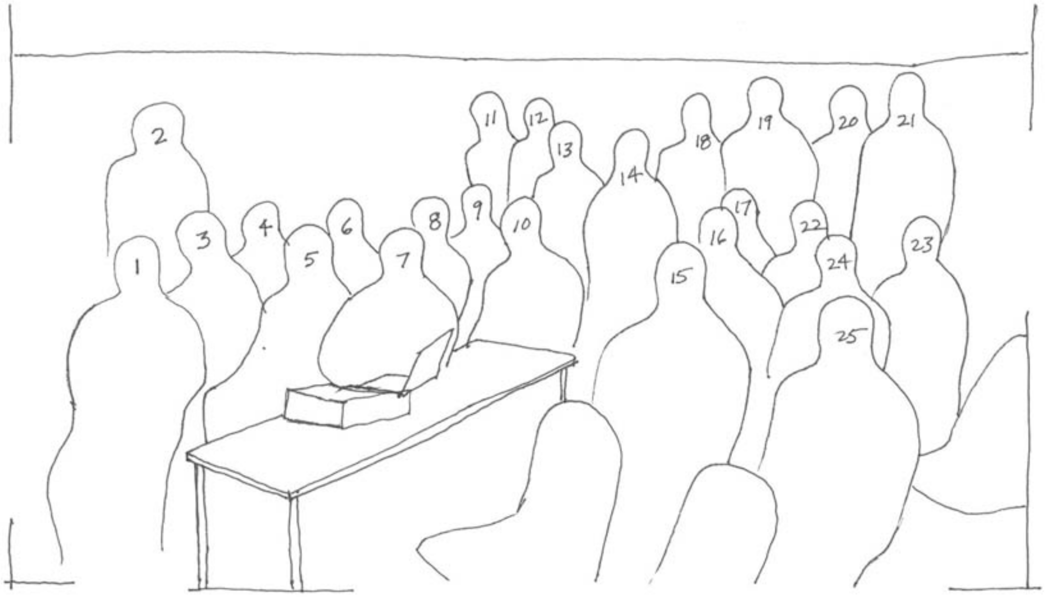
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A Strategy for Climate Change Stabilization Experiments with AOGCMs and ESMs

Aspen Global Change Institute 2006 Session: Earth System Models: The Next Generation

Report from Aspen Global Change Institute session, July 30-August 5, 2006 and joint
WGCM/AIMES Steering Committee Meeting 27 September,2006

Gerald A. Meehl and Kathy Hibbard
(and session participants—see list inside front cover)
June 3, 2007

Executive summary

We are now on the threshold of including Earth system model (ESM) components in "standard" global coupled climate models used for climate change projections. At present, these standard models (referred to generically as atmosphere-ocean general circulation models, or AOGCMs) include components of atmosphere, ocean, land and sea ice. Some modeling centers have incorporated simple carbon cycle models into AOGCM's (e.g., Cox et al. 2000, Friedlingstein et al. 2006), and additional candidate components include aerosols, chemistry, and dynamic vegetation (Figure 1), as discussed below.

Modeling groups are now making decisions on what form their next generation models will take to be used for climate change projections as well as a possible IPCC Fifth Assessment Report (AR5). The integrated assessment modeling community and others continue to develop new emission scenarios (e.g. mitigation/adaptation, also referred to as stabilization). The 25th IPCC Session (April 2006) recommended that the following four elements be addressed in the development of new scenarios: (1) Consistency between scenarios used for studying climate change, climate change impacts and adaptation and mitigation, (2) Comparability of scenarios by using comparable definitions and assumptions (the content of the definitions and assumptions should be entirely defined by the scientific community itself), (3) Transparency and openness of the development process; and (4) Substantive involvement of experts from developing countries and economies in transition in the scenario development process. The climate modeling community, however, does not have the expertise to evaluate and choose the appropriate subset of scenarios to run. Therefore, it has become evident that a new set of experiments be designed as part of a coordinated research strategy to address the climate changes associated with possible stabilization of atmospheric CO_2 concentrations. The experimental design proposed in this report reflects a coordinated effort between the climate modeling and integrated assessment communities to address the first three recommendations, with an extra effort needed towards the fourth. The new scenarios will come to bear on coordinated climate change projection experiments for possible assessment in the IPCC AR5 with the new emerging Earth system models.

There has therefore been a confluence of activities in climate model and scenario development that must be communicated and coordinated across various groups and scientific communities in a timely fashion to begin a next assessment process. To this end, a session of the Aspen Global Change Institute was convened from July 30-August 5, 2006, to address four major objectives:

1. Identify new components that are currently under implementation or will be ready in the next six months for inclusion as first generation Earth System Models in Atmosphere-Ocean General Circulation Models (AOGCMs).
2. Establish communication through WCRP, IGBP, IPCC, the climate impacts community, and integrated assessment (IA) modeling teams to coordinate activities in preparation for climate change simulations that will be performed with this next generation of climate system models for a possible IPCC AR5.
3. Propose an experimental design for 21st century climate change experiments with these models (near term and longer term time frames).
4. Specify the requirements for these new models in terms of time series of constituents from new stabilization scenarios (particularly with regard to impacts, mitigation, and adaptation).

Updates for emerging Earth system models regarding current status of new components, along with scientific issues involved with coupling these components were discussed. The status of carbon cycle and dynamic vegetation to be incorporated in AOGCMs include:

- Empirical evidence indicates that the carbon cycle responds to climate change, and first generation coupled carbon cycle models indicate the possibility of a large positive carbon cycle feedback to global change (Cox et al. 2000, Fung et al., 2005, Friedlingstein et al. 2006, Meehl et al. 2007a). This makes the challenge of achieving any particular stabilization target more difficult to achieve. Therefore, the community is moving towards including aspects of the terrestrial and ocean carbon cycle and dynamic vegetation in the next generation Earth system models.

- Some models already include a closed carbon cycle, but none have yet consistently included the impacts of land use change, land management, and wildland fires. These dynamics are under development in some groups and will be a priority.

- We also expect some models to include a representation of ocean biology.

- Although all models won't include other potentially important processes such as micronutrient limitations on ocean ecosystems, ocean bottom chemistry, nutrient limitations on terrestrial ecosystems (e.g., nitrogen), impact of anthropogenic management on fires and increases in tropospheric ozone, it is anticipated that some models may be implementing some or all of these.

- Modeling groups are also implementing various strategies for biogeography and successional processes.

Summary points for aerosols and chemistry to be incorporated in AOGCMs include:

- Aerosols and chemistry need to be considered in Earth system models for a number of reasons, including aerosol composition, effect of pollution on the biosphere and air quality. Indeed, a new consideration is the ability of the ESM to provide insight into air quality trends, for use by impacts and scenario communities.

- Most models will have a representation of the indirect effect of aerosols. However, mixed phase and ice phase cloud-aerosol interactions are likely to be handled rather crudely and are a subject of ongoing research.

- The representation of aerosols and chemistry is likely to be more comprehensive for near-term (2005-2030) than for long term (2100 and beyond) experiments partly due to computational resource limitations and computing demands. In addition, the climate effects of aerosols and chemistry are expected to be particularly important over the near-term time frame.

Another important new component under development relates to prognostic interactive ice sheet models. However, these components, though likely to be included in some next generation models, will not be part of the coordinated experiments discussed here.

Taking into account the state-of-the-art of these new components, session participants (who represented relevant communities involved with WCRP, IGBP, the former Task Group on New Emissions Scenarios (TGNES), and IPCC Working Groups I, II and III), proposed an experimental design for coordinated community climate change experiments that would be relevant to a next IPCC assessment. Subsequent to the AGCI session, a joint meeting between WGCM and AIMES in September, 2006 further discussed the proposed experimental design for the community climate change experiments that fell into two timescales involving different scientific problems, policy considerations, scenario issues, and model configurations. This report summarizes the experimental design proposed at the Aspen Global Change Institute session and further developed during the joint meeting.

Proposed AR5 Experimental Design for Coordinated Climate Change Projections

1. Near term (2005-2030)

The primary goal of projections for the next 25 years is to provide better guidance as to the likelihood of changes in extremes on the regional scale. This depends on scientific questions involving understanding the physical processes that produce such extremes related to the hydrological cycle, and relevant atmospheric and oceanic processes operative on that timescale. To produce such regional scale predictions could require finer resolution models (at least ½ to 1 degree latitude/longitude in the atmosphere, but other resolutions are possible, as well as increased vertical resolution and domain) with the inclusion of simple chemistry, aerosols, and dynamic vegetation, but an interactive carbon cycle is not required on this timescale. Both improved process representation and higher resolution are important and compromises will be required to make the simulations computationally feasible.

To determine the significance of regional changes, especially those of 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, mid-range scenario is anticipated to be used in model predictions for this near-term timescale. For this time frame, the relatively small magnitude of climate change will make signal to noise discrimination even more difficult. The number of ensemble simulations to be performed is somewhat uncertain, but a minimum of 10 ensemble members for each case should be performed and discriminating changes in hydrologic processes that contribute to precipitation extremes may require even more.

Two options for additional experiments were identified: (1) Several scenarios for pollutants (aerosols and short-lived gases) to study their effects on weather could be provided for low, medium and high emission projections as perturbations around the standard scenario, and (2) Testing geo-engineering hypotheses (e.g., 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. This would require accurate representation of, for example, ocean salinity data and soil moisture which are currently problematic due to sparse observations, and improved initialization datasets of sea ice may be required. Simulations should start during the latter half of the 20th century in order to incorporate past climate forcings to account for: (1) radiative imbalances that produce short-term committed climate change, (2) facilitate model verification and evaluation; and (3) the logistics involved with the coupled assimilation/initialization process.

2. Long term (2005-2100 and beyond)

The goal for longer term projections is to quantify the various feedbacks in the climate system involving Earth system components related to climate outcomes for different scenarios that could be affected by various socio-economic and policy considerations (e.g., stabilization). Therefore, coupled initialization would not be recommended for long term runs (e.g., 1850-2100/2300) as the model initial conditions for a time in the late 1800s are from pre-industrial control runs. A lower resolution AOGCM (roughly 2^o) could be used with a more conventional pre-industrial spin-up, followed by a 20th century experiment with natural and anthropogenic forcings (at least 10 member ensembles would be required for detection/attribution studies), leading to an A1B-type mid-range 21st century experiment as a single member. This set-up would correspond to what was done for the IPCC AR4 and would provide a reference to earlier experiments, as well as supply a multi-model ensemble of a mid-range scenario for analysis. Two benchmark stabilization scenario experiments would then be performed:

1. high forcing, perhaps A2-type stabilization scenario
2. low forcing, perhaps B1-type stabilization scenario

At least one ensemble member would be run for each, with carbon cycle and biogeography active, and prescribed, transient chemistry and aerosols. Initially the experiments would be run to 2100, then concentrations stabilized after 2100 following the prescribed concentration scenario, and the models run out to 2300. Two experiments from 2005 to 2100 would be run for each scenario:

Experiment 1: ***Long term benchmark stabilization***. Both AOGCM and AOGCMs coupled to the carbon cycle (ESMs) run with a time series scenario of prescribed CO_2 concentrations. In this run, the climate system is allowed to respond to prescribed CO_2 concentrations. Coupled carbon cycle-climate ESMs produce time series of CO_2 fluxes from the land-atmosphere and ocean-atmosphere that do not enter the atmosphere or impact the climate system response. The internally calculated land/ocean CO_2 fluxes plus the prescribed increase in atmospheric CO_2 produce an implied CO_2 emission rate (F1(t)) and are provided to WG3 and IA modeling groups to derive mitigation policies to achieve those allowed emissions. Non-ESM groups (standard AOGCMs) without a carbon cycle component can also run this experiment to derive climate system response to changing CO_2 concentrations as occurred in the AR4.

Experiment 2: ***Carbon cycle response to increasing concentrations***. This experiment evaluates the carbon cycle response to increasing CO_2 concentrations without climate change feedbacks. It is similar to Experiment 1, with the exception that the atmospheric CO_2 concentrations are held constant at pre-industrial levels for radiative calculations in the atmosphere, but the 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. .

Experiment 3: Emissions driven carbon cycle/climate. Though not finally determined, a couple of options for a third experiment are proposed that involve an emissions-driven carbon cycle/climate simulation driven by emissions rather than concentrations to quantify the climate response with an active carbon cycle. One option would be for this experiment, to be compared to the 1% per year CO_2 increase experiments which are now standard for AOGCMs, is to quantify the transient climate response (TCR), or the globally averaged surface air temperature increase at the time of CO_2 doubling. This experiment would then use an emission time series comparable to 1% per year CO_2 concentration increase, and then run with fully interactive carbon cycle feedbacks that can change the atmospheric CO_2 concentrations. The difference between this experiment and the 1% per year CO_2 increase experiment would give the magnitude of the carbon cycle feedback in terms of the climate response (e.g. temperature). Such an experiment would provide a direct connection to the C_4MIP experiments (e.g., Friedlingstein et al. 2006) as well as to the standard idealized 1% per year CO_2 increase experiments run with AOGCMs. 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.

This experimental design has a number of desirable features as well as requirements:

- Different timescales of climate change projections require different approaches in terms of model configurations and scientific and policy problems of interest.

- Relatively few future climate projection simulations would be required of the ESMs using two new benchmark stabilization scenarios (for high and low forcing). For the AR4 there were three future climate projection simulations. For the proposed new coordinated experiments, there would be a minimum of three simulations for groups with ESMs, and two for groups with AOGCMs. If it is desired to run an intermediate stabilization scenario as well, that would be one more additional experiment.

- Non-ESM results can be directly compared with the ESM results for the physical climate system (modeling groups without new Earth system components (e.g., no carbon cycle) can still participate by running either the near-term projection, the longer term projection (just Experiment 1), or both.

- Using benchmark stabilization concentration scenarios allows the WG3 community to provide these scenarios to the WG1 community in a timely manner without the WG1 community having to evaluate and choose individual scenarios, this being outside their area of expertise. The development of a complete new set of scenarios would take several years and WG3 have assessed revised SRES and some new scenarios (from the literature) that are available immediately. Based on these revised SRES and corresponding stabilization scenarios, WGI supplies emission time series back to WG3 scientists, who derive socio-economic constraints to achieve those emissions stabilization pathways. This is the reverse of what has typically been done up to now (i.e. with socio-economics as the starting point, generating emissions, concentrations, climate response, impacts analysis). Impacts are analyzed from the climate response experiments as before. WG3 will therefore evaluate socio-economic assumptions to achieve stabilization.

- The process involved with this experimental design establishes pathways for necessary interactions between WG1 and WG3 communities. Community groups that can coordinate activities across their respective communities (e.g. the WCRP Working Group on Coupled Models (WGCM) for the AOGCMs, the IGBP Analysis, Integration and Modeling of the Earth System (AIMES) for biogeochemistry and biogeography) need to be formed for WG2 and WG3 to allow better overall coordination of these types of activities.

Overall Recommendations:

- An integrated effort is needed to produce past/current/future emissions of aerosols and ozone precursors that would ensure the use of consistent and documented data relevant to climate/carbon cycle/aerosol/chemistry communities.

- To assess regional climate change effects will require gridded emission data for aerosols and short-lived trace gases. A concerted effort will be necessary to produce these datasets.

- In order to use more up to date model projections for impacts results reported in IPCC WG2 assessment, model simulations need to be made available to impacts modelers several years before the production of the WG2 report. This could be done by either staggering the WG1 and WG2 reports or by producing new climate change simulations as soon as possible (about 2009-2010).

- There is a need for a PCMDI-equivalent for WG2 and WG3 communities where relevant climate model output can be collected, archived, and tailored for use by scientists in these communities. This could include an expanded role for the IPCC Data Distribution Center. A WGCM-type community organization mechanism is also needed for the WG2 and WG3 communities.

- WG2 and WG3 scientists need to have input to the selection of fields to be archived for analysis in the new integrations for the AR5, in particular a list of fields related to the carbon cycle.

1. Introduction

In IPCC Fourth Assessment Report (AR4), a common or core set of integrations was performed by sixteen climate modeling groups (Meehl et al. 2007b). These integrations allowed the assessment of model response uncertainty to changes in the radiative forcing. The simulation of past climate changes led to identification of model errors in the simulation of present day climate and improved estimates of the human impact on climate. The future climate projections sampled the range of uncertainty associated with the various scenarios used to drive the climate models, and the uncertainty associated with the model response to the imposed forcing changes.

In the AR4 common set of integrations, three future scenarios were used by most modeling groups: the draft or marker SRES A2, A1B and B1 scenarios. Twenty-three different climate models were used to make the future climate projections. The range of model responses for a given scenario represents a measure of the model response uncertainty.

An Earth System Model (ESM) simulates processes in the climate system involving the major components of atmosphere, ocean, land and sea ice, and also includes forcings and feedbacks involving the biosphere, and composition and chemistry of the atmosphere and ocean of potential importance to the physical climate (e.g. carbon cycle, aerosols, chemistry, and dynamic vegetation) (Figure 1). Such ESMs can be used as tools to study climate impacts which are dependent on climate change, to inform climate mitigation strategies such as avoiding dangerous climate change (e.g. Amazon dieback) or verifying plausibility and providing consistency with scenarios (e.g. air quality control policy, food production, biofuels, and costs of adaptation). The ultimate ESM would include every known process in the physical and biogeochemical earth system. Clearly at this stage we are not yet at that point, so we will be discussing ESM-type configurations with simplified biogeochemical components. For simplicity, we will refer to these models as “ESMs”.

The current status of modeling the Earth system is characterized by sophisticated global coupled climate models of the physical climate system including components of atmosphere, ocean, land surface and sea ice (Fig. 1, upper left). These are often referred to simply as atmosphere-ocean general circulation models or AOGCMs. The climate modelling community is now considering expanding these already complex models to encompass chemical and biological aspects of the Earth System. In particular, AOGCMs are now beginning to implement detailed sub-models, or components, of atmospheric chemistry, the carbon cycle, aerosols, and dynamic vegetation (Fig. 1, lower left).

Ice sheet models are also being considered for inclusions in ESMs by some groups, though their implementation has lagged somewhat the other components. Thus, though some form of dynamic ice sheet models will be included in some versions of the next generation ESMs, they remain as elements of purpose-driven experiments to test the responses of ice sheet dynamics and will not be encompassed in the coordinated experiments proposed here.

Currently, output from AOGCMs can either used to produce information on climate change impacts on line if the impact is dependent on the weather that is being simulated (e.g. heat waves), or if the impact feeds back on climate (e.g. soil moisture changes). If the impact is just dependent on the climate being simulated, the impacts can be determined separately or offline using various types of impact models or methodologies (Fig. 1, right). These can include models directly using AOGCM or ESM output (e.g. crop models) or, if higher resolution information is required, statistical downscaling or embedded regional models driven by output from the AOGM can be employed.

Earth System Models of Intermediate Complexity (EMICs) offer a complementary approach for long-term simulations. EMICs span a wide range of a hierarchy of more simplified models, but usually include coupled processes in a reduced domain (e.g. two dimensional), and can capture some of the essential feedbacks while using far less computer resources than a typical AOGCM or ESM. EMICs can therefore be used to run many more scenarios for much longer time periods than typical AOGCMs or ESMs, and can provide first order information on global temperature and sea level response (but not information on changes of variability or extremes). More holistic, exploratory models are being developed for the investigation of the interaction of human societies with the other components of the Earth System.

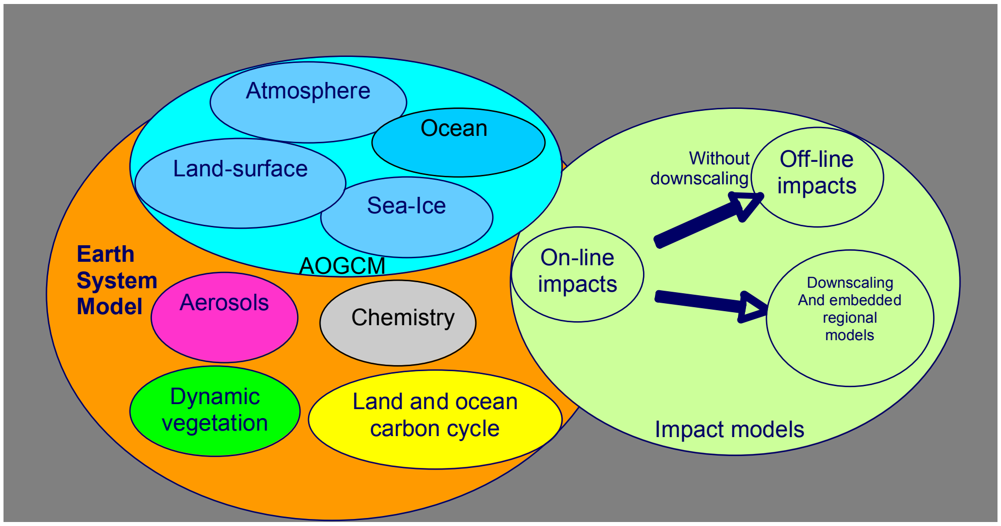

Figure 1: Schematic diagram of an AOGCM (oval at upper left), and Earth System Model (encompassed by orange oval), and various types of impact models (right).

We are entering a crucial period of climate model development where several communities now have functioning components, beyond the traditional global coupled model components of atmosphere, ocean, land surface and sea ice, that could be included in global coupled ESMs. These new components include carbon cycle, dynamic vegetation, aerosols and atmospheric chemistry. Developments across these disparate communities have been rapid, and it is urgent that these communities communicate closely regarding the form the next generation ESMs will take, with particular application for a possible IPCC Fifth Assessment Report (AR5).

Scientists working in these fields as well as members of a number of international panels representing these various communities met in July 2006 at an Aspen Global Change Institute (AGCI) session. Participants represented the Working Group on Coupled Models (WGCM) and Stratospheric Processes and their Role in Climate (SPARC) from the World Climate Research Program (WCRP), and Analysis, Integration and Modeling of the Earth System (AIMES) and the International Global Atmospheric Chemistry program (IGAC) from the International Geosphere-Biosphere Program (IGBP). In addition, representatives from the emissions scenario (IPCC WG3 and the now-disbanded Task Group on Next Emission Scenarios (TGNES)), climate change impacts (IPCC WG2, and Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA)), and the integrated assessment communities were present. The purpose of this workshop was to define a roadmap to accelerate progress in ESMs at the international level. Several scientific issues were considered at this workshop, for example, aerosol/ cloud/ climate coupling, and vegetation/ ocean/ biogeochemistry/ climate feedbacks. The central question for the workshop was: what should be the strategy to improve our ability to model with more certainty these processes, what form will these processes take in the next generation of earth system-type models, and what would be an experimental design to address future climate change in these models with new scenarios?

The outcomes and recommendations from the joint AGCI session provided fuel for discussion at a joint WGCM/AIMES meeting in September 2006 as well as the Earth System Science Partnership (ESSP) Open Science Conference in Beijing in November 2006. The objective of the workshop was to establish a coherent approach through WCRP and IGBP (jointly), and to "distribute" the responsibilities and tasks between the different IGBP and WCRP Projects in preparation for climate change simulations that would be performed by this next generation of models for the IPCC AR5. The workshop had four general objectives:

1. Identify new components that are currently under implementation or will be ready in the next six months for inclusion in AOGCMs
2. Establish communication through WCRP, IGBP, IPCC, the climate impacts community, and integrated assessment (IA) modeling teams to coordinate activities in preparation for climate change simulations that will be performed with this next generation of climate system models for the IPCC AR5
3. Propose an experimental design for 21st century climate change experiments with these models (near term and longer term time frames)
4. Specify the requirements for these new models in terms of time series of constituents from new stabilization scenarios (particularly with regard to impacts, mitigation, and adaptation).

This report outlines a strategy for the new AOGCM/ESM modeling components in terms of aerosols/atmospheric chemistry and carbon cycle/dynamic vegetation components that are under development and implementation in ESMs that involves a proposed experimental design that integrates impacts and scenarios (represented in IPCC WG2 and WG3, respectively) and physical climate science (WG1). We summarize with a suite of recommendations for the joint

WGCM, AIMES and IPCC communities. An abbreviated version of this white paper has already appeared (Hibbard et al., 2007).

2. New ESM components for inclusion in AOGCMs

Aerosols and Chemistry

Aerosols are important to the climate system for many reasons. They have a direct effect on heating and photolysis rates in the atmosphere by scattering and absorbing radiation. They influence the climate system indirectly by modulating cloud drop size, cloud lifetime, and precipitation, and there are other processes such as the "semi-direct" effect involving subtle modulations of the dynamical and physical processes of the atmosphere. Aerosols also act on other components of the climate system by reducing energy reaching the surface, and by transporting nutrients from one place to another. There are well documented changes in aerosol distributions due to mankind during the last few hundred years and some more changes are anticipated in the future.

There are also many photochemical processes taking place in the atmosphere which are affected by mankind. These processes influence aerosol formation and properties, and affect the climate system directly. The changes in the chemistry of the troposphere are of concern for a variety of reasons. Air quality near the Earth's surface affects humans and ecosystems. Many aerosols are formed or influenced by chemistry (the oxidation of precursor gases to sulfate, nitrate, and secondary organic aerosols is an obvious example).

Simulating the chemistry of the atmosphere, the interactions with aerosols, and the interactions of these components with other components of the climate system are enormously complex, and computationally very costly. These components cannot be represented comprehensively in today's AOGCMs. Simplifications must be made, and many aspects of their interactions must be ignored to be able to include them in the emerging ESM-type models. We recognize that complexity could be different for short- (up to 2030) and long-term simulations (to 2100 and beyond). In this section, we discuss some of the properties of aerosols and chemistry of the climate system which we believe are needed for the next generation of ESMs, and identify the simplifications that are appropriate in their treatment.

1. The radiative forcing by tropospheric ozone is believed to be globally small, however, it is not negligible regionally. Some representation for this effect should be employed. One way to implement this is through "time slice" photochemistry, where a reasonably comprehensive photochemical model is occasionally employed off line (e.g. a one year simulation performed once every 10 years). There may be other alternative efficient methods of producing photochemical information in the model.

2. One simplification to represent tropospheric O_3 that is frequently used in today's ESMs is the use of prescribed oxidant distributions (OH and O_3 for example in the oxidation of SO_2 to sulfates). Alternatively, extreme simplifications to the photochemistry can be employed (the chemistry of peroxides in the oxidation of SO_2 to SO_4 in clouds). While limited treatment of most aerosols can be achieved though the use of these off-line

oxidants, it is clear that an improved treatment may be required for the formation of secondary organic aerosols.

3. A number of climate feedbacks should be explored more thoroughly for the climate change problem including, but not limited to:
    - Temperature => isoprene emission => ozone => temperature
    - Temperature => monoterpenes emission => SOA => temperature
    - Climate change => DMS= > sulfates=> temperature
    - Climate change => lightning, fires, wetlands=> O_3, CH_4, aerosols
    - Climate change => vegetation cover => dust emissions => climate
    - Preliminary studies indicate however that these feedbacks are likely to be not very strong; but many are positive and may add up to something larger.

4. Aerosols and some reactive chemical species (mostly ozone, carbon monoxide and nitrogen oxides) are important for impact assessments of air quality as they have a large impact on human health and crop (and more generally vegetation) yield. The occurrence of ozone episodes and nitrogen deposition can strongly impact the carbon cycle. These species should be considered in this context for the present proposed modeling strategy.

5. Interactive modeling of stratospheric ozone would alleviate the current difficulties of merging independent characterizations of ozone from tropospheric and stratospheric chemistry at the tropopause.

6. It is estimated that air quality controls may result in additional heating over the next two or three decades (because of the removal of cooling aerosols). These controls may also have an impact on precipitation over the same time scales. Feedbacks involving the vegetation (mostly ozone poisoning and nitrogen deposition) operate over multi-decadal to century timescales. Overall, the consideration of aerosol and chemistry in the next set of coordinated climate change simulations will require more interaction with the integrated assessment modeling community. For this effort to be successful, consistency with assumptions made in emission scenarios (including land use) will also be required.

A. Representing aerosols and chemistry in the near- and longer-term

In many climate modeling centers, the capability for simulating aerosols exists but the computational cost of additional tracers and processes is an issue that limits their applicability to climate assessment exercises. This is becoming even more of an issue when more complex aerosol formulations are being considered. Furthermore, it is important to keep in mind that the knowledge of driving inputs (e.g. characterizing the number of primary aerosol particles emitted, individual VOC species emissions, and the vertical profiles of emissions) might be insufficient to run the most complex versions over the historical or future periods. It is unclear at this point if the full complexity is required for IPCC-type simulations. Therefore simplified versions are currently under investigation. For instance (1) bulk versus modal approach for aerosols, (2) simplified versus comprehensive gas-phase chemistry, and (3) asynchronous versus full reactive chemistry coupling.

An evaluation of these different alternatives is well underway through the participation of the various modeling groups who are involved in intercomparison exercises such as AEROCOM, CCMval, ACCENT, and the new Atmospheric Chemistry and Climate (AC&C) initiative under the auspices of SPARC and IGAC. However, it is recognized that there is a need for more coordinated intercomparison studies and common diagnostics. This should lead to more insight into what should be included in the next generation of ESMs.

The following table summarizes the status of the developments planned within the various groups represented at the Aspen workshop with respect to the aerosol and chemistry packages that will most likely be included in the core version of their climate models to be used for the next set of coordinated climate change experiments. *This is only a subset of the total number of modeling groups making plans for such experiments*, but this list is representative of the activities at the larger number of modeling groups.

	Model Center:/Aerosols	Chemistry
Within about 1 year (ready to run for next IPCC)	GISS: Sulfate / BC / OC / dust / sea-salt Hadley: bulk, sulfate /BC / OC / dust driven from DGVM / sea-salt / SOA climatology NCAR: Both bulk and modal approaches are available and being considered MPI: A seven-category modal approach predicting total number and species mass in each category (M7) Limited ability to represent aerosol indirect effect processes, especially in mixed phase, ice and convective clouds.	Cost is under evaluation for all groups. At least snapshots / asynchronous coupling will be done with full chemistry (tropospheric and stratospheric) with a coupling every 5/10/20 years?
Beyond AR5	Full aerosol scheme Comprehensive mixed and ice phase cloud microphysics	Full chemistry

In summary, most models will have a representation of the indirect effect of aerosols and the considered aerosol schemes will be much more comprehensive than in AR4, including more species, and treating their temporal change from past to the future. The representation of chemistry has to be more comprehensive for the near-term (2005-2030) than for the long-term (2100 and beyond) experiments. Beyond the next set of coordinated experiments, it is expected that all modeling centers will have access to enough computer power to be able to have a full representation of aerosols (for both mass and number) and gas-phase chemistry.

B. Aerosol and chemistry considerations for an experimental design

For the simulation of aerosols and chemistry, a critical item is the knowledge of historical and future emissions, which have to be consistent. In particular, because of the developments in the simulation of aerosols, it is necessary to build and assess historical emissions beyond sulfur. These include black carbon and primary organic carbon (with some information on size if possible) and ozone precursors. The more comprehensive chemistry schemes will also require the development of a detailed speciation of volatile organic compounds (VOC) emissions. For both gaseous species and aerosols, the knowledge of emissions for different sectors is needed as emission factors and speciation depend on the emission type. In all cases, the knowledge of injection heights (smoke stacks, airplanes, biomass burning, etc.) is an important additional piece of information.

Recent studies of the carbon cycle indicate that over the past 100+ years, as a result of fire suppression policies, large areas of the western US and Canada (and possibly other parts of the world) have experienced a large decrease in fires and open burning, in contradiction with the usual assumption of an increasing number of fires over the industrial period made in previous studies. The negative trend in fire emissions at mid-latitudes could have very significant impact on the present estimate of the radiative forcing of ozone and biomass burning over the pre-industrial to present-day period. In addition, the intensity of contemporary wildland fires, because of fire suppression practices, are not representative of historic low-to-moderate intensity, but rather, are becoming more catastrophic in nature for many forested systems. These higher intensity fires have different characteristic injection and emissions profiles than either pre-industrial or experimental and prescribed burns. In addition, the knowledge of historical and future land use (incl. ecosystem knowledge) is necessary for the representation of past dust and biogenic emissions.

Because of the existence of a variety of historical emissions, it is unclear what the appropriate level of guidance could or should be for defining whether a single set of emissions should be used and, if so, which one. In order to minimize the amount of simulations of interest to a variety of communities (IPCC, CLRTAP), a strong effort will be required to ensure consistency in the used past/present/future emissions.

There is a strong and urgent need for an increased dialogue and collaboration between the observation, measurement, modeling and scenarios communities that utilise past and current emissions relevant to gas-phase chemistry, aerosols and carbon cycle (e.g., GEIA and IGAC). An integrated assessment or a synthesis document discussing these emissions and providing expert evaluations would be extremely useful. Such a process should be coordinated at the highest level (IPCC, IGBP, WCRP, IHDP, CLRTAP), which would ensure the existence of a consistent set of input data usable by all the communities interested in climate change science and impacts over the historical and future periods.

C Computer cost

<u>Very rough estimates</u> of the additional cost (with the atmospheric model using the same model resolution serving as a reference) of a fairly simple aerosol scheme range from 30% (Hadley Center) to 100% (NCAR). For tropospheric chemistry the overhead ranges from 50 % (for simple chemistry version of the GISS model) up to a factor of 3 (NCAR) or 4 (Hadley) increase

compared to the atmosphere model. It is clear that computer cost depends on how the atmospheric model is optimized and on the type of platform. In the case of NCAR, it has been estimated that, for transport only and ignoring other costs, there is an additional cost of 2-3% per added tracer.

D. Recommendations for implementing aerosols and chemistry components

- Aerosols and chemistry need to be considered in ESMs for a number of reasons. A new consideration for a coordinated experimental design is the ability of the ESM to study air quality trends, and to be used by the impact (WG2) and the scenarios (WG3) communities.
- For this next generation of models, most will have a representation of the indirect effect of aerosols using more comprehensive schemes than in AR4, and will treat their temporal change from past to the future.
- The representation of aerosols and chemistry is likely to be more comprehensive for the near-term (2005-2030) than for the long-term (2100 and beyond) experiments partly due to computational limitations.
- The expectation is that effects from aerosols and chemistry would be particularly important over this near-term time frame.
- Mixed phase and ice phase cloud-aerosol interactions are likely to be handled rather crudely in these new simulations. This is a subject of on-going research.
- An integrated effort to produce past/current/future emissions of aerosols and ozone precursors would ensure the use of consistent and documented data relevant to climate/carbon cycle/aerosols/chemistry communities.

Dynamic Vegetation and the Carbon Cycle

A. Model Strategies

“Core” components of the carbon cycle in new ESMs

The majority of major global models are expected to include several additional components into their carbon cycle modeling strategy. Taken together, these components “close” the global carbon cycle (i.e. allow calculation of the net land-atmosphere and ocean-atmosphere exchanges of CO_2 online within the ESM):

- Ocean biogeochemistry including simple ocean ecosystem (e.g. Nutrient–Phytoplankton–Zooplankton–Detritus (NPZD)) models.
- Terrestrial carbon cycle model (typically without nitrogen limitations) that simulates the water, energy, and carbon fluxes at the land surface.
- Vegetation dynamics – re-growth following disturbance including age class succession with limited Plant Functional Types (PFTs) (e.g. 5-15 PFTs) and in some cases dynamic biogeography (i.e. the ability to change the geographical distribution of PFTs).
- Anthropogenic land-use change (transient) with corresponding translation into net carbon fluxes including wood harvest.
- Land management – agricultural activity on cropland (e.g. irrigation, tilling), pasture and forestry.
- Fire - wildfire including affects on vegetation and soil carbon stocks.

It is important to stress that the response (and sensitivity) of the terrestrial carbon cycle depends heavily on the simulated precipitation and temperature of the climate model. A short set of climate metrics that need to be met in order for a meaningful simulation of the carbon cycle to be possible should (and in some cases have already) be identified and delivered to developers of the physical model as early in the model development cycle as possible. The Köppen and/or Holdridge classifications may be useful diagnostic tools to help identify inconsistencies between the simulated temperature and precipitation regimes and the expected vegetation class. In the case where a solution to a temperature or precipitation bias that is detrimental to the vegetation distribution simulation cannot be found, it is preferable to avoid tuning the land or dynamic vegetation model to get the correct vegetation types (e.g. rainforest in the Amazon) and consider the resulting problems during analyses.

While many groups have already implemented, or are developing the above model components, there are technical and philosophical challenges when it comes to integrating the components. Coupling of the components should also occur relatively early in the development cycle to identify and counter unforeseen problems (e.g. programming errors, model instabilities).

Not all modeling groups will incorporate all of the DGVM and carbon cycle components in time for the planned coordinated climate change experiments. We may therefore wish to provide prescribed fields (e.g. of the CO_2 fluxes from land-use change), that will allow these models to participate in an intercomparison. Careful design of the model experiments are critical in this respect (see text on "*Proposed Experimental Design*").

"Vanguard" components of the carbon cycle in ESMs by the time of IPCC AR5

The following "vanguard" elements are not likely to be incorporated into the majority of carbon cycle models but may be present in some models, and will therefore be used in "research-type" model experiments:

- Nitrogen cycling and nitrogen limitations on the terrestrial carbon cycle.
- Anthropogenic impacts on fire (including ignitions, suppression).
- More sophisticated ocean ecosystem models, with resolution of more phyto- and zooplankton functional groups.
- River biogeochemistry (especially dissolved organic carbon (DOC) fluxes from land-to-ocean).
- Micronutrient limits (e.g., Fe) on ocean biogeochemistry.
- Ocean bottom carbon chemistry, calcite formation (only important on 300-1000 yr timeframe, e.g. for stabilization scenarios)
- Interactive biogenic fluxes of methane, VOCs etc. (for coupling to atmospheric chemistry).
- Advanced vegetation dynamics with improved succession based-on more PFTs and possibly explicit dispersal mechanisms (the latter is only applicable in high-resolution ESMs).
- Multiple agriculture (crop x management) PFTs and associated local/regional land use practices
- Transient urban fractional cover.

- Improved spatial resolution of the land-surface based on either a higher resolution regular-grid and/or an irregular land-grid defined by river-catchments.
- Impact of tropospheric ozone on vegetation.
- Improved treatment of organic soils including carbon dynamics and links to thermal and hydraulic impacts of peatlands.

Coupling frequency

The land-atmosphere carbon fluxes need to be determined at every land-model timestep (typically 30 minutes) to ensure consistency with energy and water fluxes. Ocean-atmosphere fluxes will typically be calculated on the timestep of the ocean model and increment atmospheric CO_2 (in runs with prescribed emissions) on every ocean-atmosphere coupling period (typically 1 hour to 1 day). The terrestrial and ocean carbon cycle models will therefore be coupled synchronously, although a hierarchy of timescales are often used within the DGVM component (daily to weekly for phenology, monthly to yearly for dynamic biogeography).

Timescale of feedback

Although global carbon cycle feedbacks may not be readily apparent for 30 or so years, the biophysical response (e.g., albedo) to disturbances (fire, drought, timber harvest, etc) is detectable on much shorter timescales, e.g. annual, timescales.

B. Computer resources

The cost of adding the terrestrial carbon cycle may be around 20% of the atmosphere-land model (3-5% (GFDL); and as high as 30% (NCAR's CCSM)), with most of this associated with the calculation of CO_2 fluxes on each timestep of the land model. By contrast, vegetation dynamics will be computationally cheap because it only needs to be updated fairly infrequently (monthly to yearly). Storage requirements for the land model increase significantly due to large increase in number of prognostic variables, but this increase is likely to be fairly insignificant in the context of the ESM as a whole.

Ocean biogeochemistry is likely to require a 2- to 5-fold increase to the computational cost of the ocean model due to a large increase in the number of tracers. Storage requirements will also increase considerably.

It is important to note that to bring the carbon cycle into equilibrium, computational requirements for a coupled carbon cycle model development and spin-up will significantly increase over those for a standard AOGCM.

C Scenarios requirements and new requirements from the atmosphere model

- Global mean CO_2 concentrations for 1850-2100 (for runs with prescribed CO_2 but diagnosed anthropogenic emissions , see *"Proposed Experimental Design").*
- Global anthropogenic CO_2 emissions from fossil fuel burning plus cement production for 1850-2100 (for runs with interactive CO_2).
- Global net CO_2 emissions from land-use change for 1850-2100 (for runs with interactive CO_2 in models that do not calculate land-use fluxes internally).

- Gridded land-use and land management information, including consistent disturbance history and future disturbance. It is critically important that the history and scenarios of land-use are consistent (i.e. without a discontinuity in going from past to future!).
- Gridded fire history reconstruction including area burned (disturbance) and emissions to the atmosphere from fires.
- National-level CO_2 emissions for the carbon cycle validation period (say 1960-2000). These emissions will be used in the coupled climate-carbon cycle models to assess their ability to reproduce seasonal changes and latitudinal gradients of atmospheric CO_2 concentration.
- Gridded nitrogen deposition fields for 1850-2100.
- Gridded near-surface ozone concentration fields for 1850-2100.

D. Validation and Model Improvements

A number of missing observational datasets can be readily identified that would speed-up and augment the carbon cycle model development. These include satellite measurements of column integrated CO_2, soil moisture, and vegetation structure as well as a general increase in the southern hemisphere data (e.g. carbon stocks, land use/management, surface ocean-atmosphere CO_2 fluxes).

The representation of agriculture (crop types, crop phenology, management including irrigation and tiling) and fire can clearly be identified as a weak point of many current models and requires further development.

Historical reconstructions of globally gridded land-use change including crop, pasture, shifting cultivation, and wood harvest have recently been completed for use in this class of models. A major need is the development of future global gridded-land use change products that are consistent with both the gridded historical reconstructions, and the future scenarios developed by scenario teams.

More constraints on the simulated carbon cycle are required to validate the models. These constraints could include observations or other methods (e.g. the Tracer Transport Model (TransCom) and Ocean Carbon Model Intercomprison Project (OCMIP) modeling strategies).

Ocean flux of CO_2 at the air-sea interface is likely to improve as eddies are resolved or as eddy mixing parameterizations are improved (e.g., through the use of ARGO float density, salinity and temperature information to validate models). In general, and as noted above, it is critical that the carbon cycle modelers identify critical aspects of the physical models that require further attention before realistic carbon cycle simulation can be achieved.

3. Proposed Experimental Design

The pathways of model development over the next ten years will not be parallel across groups. There are specific questions that will require high-resolution (in space, time, complexity) model runs, and those that will need to address longer-term questions with regard to impacts and mitigation. Therefore, we propose an experimental design that leverages near-term and longer-term model runs with appropriate classes of model complexity to address specific science questions.

I. Near-Term Experimental Design – Climate Change to 2030

A. Scientific Questions and Relevant Models

It is anticipated that model capability is now sufficient to provide some regional guidance as to the effects of climate change out to 2030. Of particular interest are regional changes in water availability (soil moisture), affected by changes in precipitation, evaporation and melting of the snow pack. Also of interest are local daily and seasonal temperature changes. With regard to societal impacts, it is the changes in extremes in both of these categories - floods, droughts, extended heat waves, hurricane frequency and intensity are primary concerns. Effects of climate change on human health, through alterations in air pollution (aerosols, ozone) or the migration and adaptation of disease vectors (e.g., carried by insects) could have significant societal impact. Many of these changes have ramifications for agriculture; in addition, climate change will also impact fishery industries. Conversely, the (unintended) consequences of large-scale conversion of forested and pastures to biofuels production on the coupled climate system are largely unkown. Stratospheric ozone recovery from chlorine loading will also impact the climate system during this time frame. In addition, an assessment of historical and near-term aerosol forcing, compared with on-going aerosol and temperature observations, may allow us to better understand aerosol climate forcing, and hence climate sensitivity.

Both AOGCM and ESM models will be useful for near-term simulations, although development of each requires significant computational and manpower resources. How to divide those resources remains an issue.

At one extreme, AOGCMs run at relatively high resolution (on the order of 0.5° for latitude and longitude) would allow for a better regional assessment of climate change and is necessary to simulate the statistics of observed storm systems that affect regional processes (Jung et al., 2006) as well as improved simulation of precipitation extremes (M. Wehner, personal communication), although additional downscaling to even finer resolution might be required for some climate change impact studies. Most AOGCMs currently have about 2° resolution. An increase of spatial resolution by a factor of 4 would increase computational time by close to a factor of 60. Additional increases in the vertical resolution, to optimize the dynamical advantages of the finer horizontal resolution, would bring the computational burden to greater than 100 times (i.e., two orders of magnitude). Such an approach would strongly inhibit the inclusion of additional physics to explore alternate aspects of the Earth system, some of which (aerosols, ozone, vegetation health) would be having direct effects on regional climate that would be omitted.

At the other extreme, ESMs could be run at close to the current resolution but with expanded physics packages for aerosol, atmospheric chemistry and dynamic vegetation. These additions likewise require significant computing time. Aerosol and atmospheric chemistry calculations can each double the computational time or add even more, depending on the sophistication of the routine. Simulations of stratospheric ozone chemistry could require greater resolution in the stratosphere and a higher top of the model. Their inclusion would allow for a more complete assessment of the physics of climate change, but would not provide more regional discrimination.

As a compromise approach, it is suggested that models for this time period utilize a somewhat finer horizontal resolution (on the order of 0.5º to 1° latitude/longitude) along with simplified aerosol and chemistry packages. Dynamic vegetation would be included to assess the health of the vegetation and possible in-place succession. Other longer-time scale processes, such as ocean biogeochemistry, land ice and ecosystem migration would be omitted or performed off-line since their feedbacks related to climate change operate on a longer timescale. A crude estimate is that for the various simulations suggested, even this model version would require some 4 dedicated computer-years using current computer capabilities, and developing finer resolution models is itself a non-trivial task. While the Japanese experience has been that their model parameterizations did not have to be changed (just tuned), and climate sensitivity was relatively invariant when going to significantly finer horizontal resolution, this has not been the experience of, say, GFDL, and may not be true with much finer vertical resolution. Developing this new model may require significant time and resources prior to its use in these proposed experiments.

B. Relevant Emission Scenarios

Given that the different scenarios for well-mixed gases do not vary greatly prior to 2030, it is suggested that only one such scenario be employed. For aerosols and short-lived gases, several emission scenarios (including a low and a high estimate) should be provided. For example, consistent global, gridded data for reactive gases (CH_4, NO_x, major classes of NMVOCs, CO, NH_3), aerosol precursors (SO_2), and aerosols (BC, OC) are needed. The ideal emissions input data set would:

1. Extend continuously from historical to future projection years
2. Be gridded at the finest resolution being considered (*e.g.* 0.5 degrees)
3. Exhibit appropriate spatial changes over time
4. Resolve appropriate injection heights (ground, 100m, aircraft)
5. Resolve large seasonal effects (biomass burning in particular)

Decisions on exactly what emissions are required will need to be made by the Earth system modelers, and providing these emissions will be the responsibility of Integrated Assessment modelers.

Some shorter-term projections (e.g. GAINS, RAINS, Streets et al.) produce emissions at a temporal and spatial scale that may be consistent with most of the ideal requirements listed. The integrated assessment models (IAMs) used to produce long-term emissions scenarios (up to 2100) generally produce emissions at a large spatial scale. The SRES exercise produced long-term emissions that were gridded at a level of four meta-regions, with a fixed pattern within each meta-region.

However, in general, producing consistent and globally gridded historical, near-term, and long-term input data sets is not a capability that exists at present. A first step toward this capability would be to conduct a census of available inventories and projections, their characteristics, and level of detailed data availability. Using this information, the actions and capabilities that would be needed to produce the necessary emissions data sets could be detailed.

The next generation of ESMs will also require scenarios of anthropogenic land use changes as input data. Gridded input data sets of land-use conversions (changes from one category to another) and management (agriculture, perhaps specific crops or classes of crops, forestry, pasture, etc.) will be needed. Methodologies to convert the output of IAMs to land-use change data sets that are consistent with the historical land-use change data sets used in the ESMs can carbon cycle models will also need to be developed. Ideally, biogenic emissions of VOCs would be produced by the ecosystem component of the ESM. In this manner, the effect of anthropogenic land-use and vegetation changes would be reflected in biogenic emissions. The same is true for methane, although this will likely remain in the research domain for the near future.

Additional experiments could be done to investigate suggested geoengineering attempts at mitigating climate warming. For this time frame, one option being discussed is that of injecting sulfur into the atmosphere, either into the stratosphere or troposphere, to help cool the climate. The climate consequences of such injections could be explored in ESMs; unintended consequences might be harder to ascertain.

C Experimental Design and Ensembling/Scenario Simulations

Assuming the 'compromise' modeling approach is adopted, the attempt would be to provide the most realistic predictions possible for the regional scale. While the predictions would extend from the present to 2030, climate change over this time period is affected by what has happened in the past due to the committed warming in the system. The past decades will also provide the possibility of hind-casting, or evaluating the model for historic to current regional scale projections. These simulations will be affected by the initial conditions at the start of the experiment, particularly in the ocean (temperature, salinity) but also on land (soil moisture, ground temperature). Ocean initial conditions could conceivably be provided by ocean data assimilation exercises currently underway, and ideally using coupled initialization, but lack of observed salinity data sufficient for such a data assimilation exercise remain a significant problem. Additionally, there is no direct way to provide soil moisture or ground conditions at this time. The potential errors induced by incorrect initial conditions should become less important in later years but could still be evident through the course of these simulations. If model simulations are started prior to the availability of the ocean initial conditions, the model ocean would have to be 'nudged' toward the observed values; how strongly this should be done, and what it implies about energy conservation are research issues that will have to be explored. There is also the science question of whether or not starting the model with something close to the present observed initial state matters, both in terms of decadal predictability, regional signal to noise, and climate change commitment.

In addition, as noted above, gridded emission data for aerosols and short-lived gases would need to be provided on this same fine regional scale, for both the historical times of concern as well as future projections. The "natural forcings" would be handled conservatively. The total solar irradiance for this time period could either remain unchanged, or specify an average observed 11-year cycle. The mean value for volcanic aerosol loading over the past 25 years could be employed, or a stochastic occurrence of major volcanoes, based on the last 100 years of data might be added.

To determine the significance of regional changes, especially those of extremes, will require numerous simulations in an ensemble approach. For this time frame the relatively small magnitude of climate change will make signal to noise discrimination even more difficult. We therefore propose that there could be one base-case scenario for the well-mixed gases along with low, medium, and high air pollution estimates (i.e., aerosol and short-lived gas emissions). The number of simulations to be performed is somewhat uncertain, but it should be at least 10-15 for the base case in order to discriminate changes in hydrologic extremes and to assess regional signal to noise for climate changes.

D. Initialization and Model Spinup Considerations

While historical simulations for spin-up and model evaluation are necessary, there are various factors to consider regarding the starting date for these runs. The atmosphere is in better radiative balance starting in 1950 than at later times, so starting the coupled initialization then should provide a better cumulative state of climate change commitment in the system. Ocean data initialization is currently being done from 1970 onward, although it is better in more recent years due to a larger number of observations; and emissions data improves greatly after 1980. The addition of the ARGO float data provide a better three-dimensional structure for ocean salinity after about 2004. However, the earlier the start time, the greater the computational burden being assumed. This may already be a problem (even without considering the longer-term simulations anticipated), and so the starting time may have to be 1980 for practical computing considerations.

II. Longer-Term Experimental Design – 2100 and Beyond

Longer-term runs provide an opportunity to contribute a policy perspective on avoiding the consequences of climate change in terms of stabilization strategies. In addition, experiments would provide a basis for evaluating the feedbacks and contributions of the carbon cycle to the climate system. The recommended experimental design indicates that WG1 and WG3 be staggered in time. The long-term simulations would be with lower resolution AOGCM and ESM's (roughly 2^o) with a pre-industrial spinup including a 20th century forced experiment that consists of natural and anthropogenic forcings. Two, possibly three greenhouse gas (GHG) and aerosol concentration scenarios would be supplied by WG3: (1) a high radiative forcing stabilization (e.g., A2-type), (2) a low radiative forcing stablization (e.g., B1-type); and possibly (3) mid-range scenario (A1B-type) to provide a swath of possible outcomes. At least one ensemble member for each scenario would be considered, and the models would include as core, the terrestrial and ocean carbon cycle, biogeography and successional processes as implemented. Chemistry and aerosols would be prescribed to 2100 and stabilized after 2100 until 2300, although a few models may run interactive aerosols and chemistry as well. The first two experiments are considered 'core' for all groups to participate in, with a third, optional carbon cycle feedback calibration experiment. WG3 would provide time series of concentrations of GHGs for these experiments.

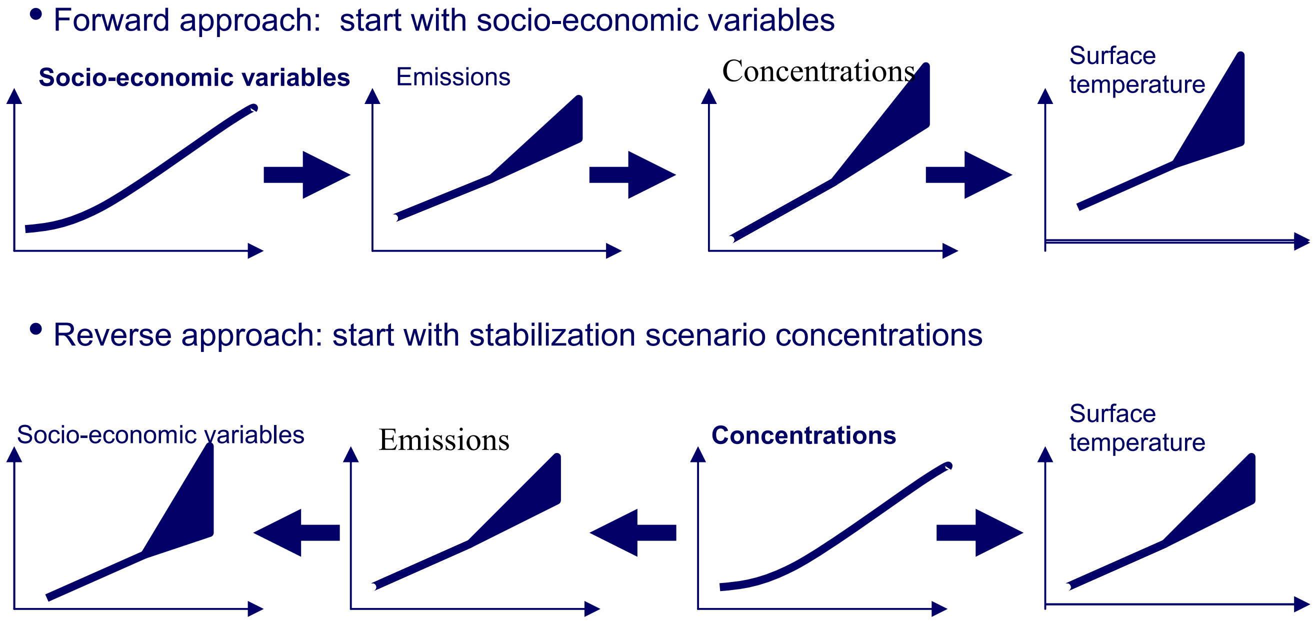

Figure 2: Schematic of traditional forward approach starting with socio-economic variables to derive emissions, concentrations and then temperature and other climate changes from climate models (top), and new proposed methodology where the starting point is concentrations run in climate models, that are used to derive emissions and then socio-economic factors to achieve those emissions. Traditionally, the forward approach is characterized by uncertainty (indicated by the wedge-shaped ranges for future climate) growing in the direction of the response of the climate system (i.e. left to right). The reverse approach, where anthropogenic emissions are equal to the difference between prescribed concentrations and simulated Earth system CO2 fluxes shows uncertainty growing in the direction of the socio-economic factors required to achieve the concentration targets (i.e. right to left).

As noted in Fig. 2, using benchmark concentration scenarios as the starting point is different from the more traditional starting point of socio-economic variables used to derive emissions, and then concentrations that are run in the models (left to right in the top part of Fig. 2). However, by using benchmark concentration scenarios that are then applied to derive emissions and then socio-economic factors to achieve them (right to left in lower part of Fig. 2), WG1 does not have to evaluate socio-economics before running scenarios in climate models, and WG3, who have expertise in socio-economics, can determine the factors that would produce the emissions from the concentrations that have an associated climate change outcome. There will be multiple socio-economic pathways leading to the concentrations resulting in a rich ensemble of WG3 scenarios.

It is important that any proposed set of integrations be easily integrated by non-ESM (AOGCM) models. This will allow groups who do not have an ESM to participate in these experiments. The number of proposed integrations is also important. Due to the large amount of computer resources required to time integrate ESMs, it is important to prescribe only a few required integrations. Groups are always free to integrate other scenarios and other models (e.g. including ice sheet models), but these would be for research and not part of the common set.

A second type of constraint involves the scenarios used to drive the ESMs. Policymakers are increasingly focused on stabilization scenarios and the ways to achieve climate stabilization. All proposed scenarios assume stabilization after 2100. To implement this strategy, experiments are proposed which use given benchmark concentration scenarios that represent a high and a low radiative forcing.

***Control Simulation (required)*:** This is a long-term control run for diagnosing model drift in terms of climate and carbon fluxes.

***Experiment 1: Long-term benchmark stabilization*:** An AOGCM or ESM is run with time series of specified benchmark concentrations provided by WG3. The idea is to use prescribed concentrations of the GHGs and aerosols (Note: Aerosol concentrations will depend on spatial emissions patterns, these will have to be specified for the scenarios, as was the case in SRES. How these are developed and by whom needs to be determined; In the case of SRES this was a joint WG1 and WG3 effort). Each scenario would also include the prescribed changes in the future land use in accordance with the scenario characteristics. The ESMs would be initialized in a manner similar to what was used in AR4. After the model is developed, the radiative forcing constituents are set to “pre-industrial” (usually mid-1800s) conditions. The model is allowed to come into a quasi-equilibrium state with those radiative conditions (usually after several centuries of integration). At some point in this integration, the start of the pre-industrial control is declared (i.e. year 1 of the pre-industrial control). One evaluation criterion to be used for the fidelity of the carbon components will be the rate of drift of the carbon system in this control (e.g. some modelling groups try to achieve long-term mean land-atmosphere and ocean-atmosphere fluxes of CO_2 within 0.2 GtC/yr of zero net flux). However, the 10% level of the current sink is not totally relevant here. The main point is that the long term mean of the sum of land and ocean fluxes should be close to zero (0.1 to 0.2 GtC/yr). The sum is what really matters for 2 reasons: a) in the ‘real world’, there is a net CO_2 flux from the land to the ocean through rivers, this means that the net atmosphere-land flux is a sink and the net atmosphere-ocean flux is a source, but the sum of the two is zero; b) emissions will be function of the sum of the ocean and land fluxes, and any long term imbalance in the land+ocean flux will translate to a non-zero emission. As in the AR4 exercise, it would be good to have a long control run from the ESMs in order to estimate the carbon drift, and remove it from the inferred emissions for a given scenario if necessary.

At various points in the pre-industrial control, historical integrations of 20th century climate can be started to generate an ensemble. This ensemble is useful for detection/attribution studies and other comparisons to the observed climate changes. The inputs needed for this type of integration are the time series of anthropogenic (GHG, ozone, and aerosol concentrations and land use changes) and natural (solar and volcano) forcings. This is similar to what was done for the coordinated integrations assessed by the IPCC AR4.

The future projections start from the end of the historical integrations. The concentrations of GHGs (including CO_2) and aerosols and the future land use changes are prescribed according to the input scenario (see below for details). The prescribed atmospheric CO_2 concentrations are used in the radiation calculation and to compute the carbon fluxes from the land and ocean. This prescription allows non-ESM models to be forced in a manner similar to the ESMs and allows for easier intercomparison of the physical climate response among all the models in the common set.

The ESMs that include an interactive carbon cycle will calculate land and ocean CO_2 fluxes which are the response to the prescribed CO_2 concentration scenario and the climate change as a result of those changing concentrations. These CO_2 fluxes do not enter the atmosphere, so the atmospheric temperature responds only to the prescribed concentrations. The CO_2 fluxes are saved and, in combination with the prescribed CO_2 concentrations, are used to calculate the "permissible CO_2 emissions" time series using an approach already adopted applied to some first generation coupled climate-carbon cycle models (Jones et al., 2006):

$$E(t) = dCO_2/dt + F_{A\text{-}O} + F_{A\text{-}L}$$

where E(t) is the time series of anthropogenic emissions calculated from the prescribed rate of carbon dioxide concentration increase dCO_2/dt, and the modelled atmosphere-land and atmosphere-ocean fluxes of CO_2 are $F_{A\text{-}O}$ and $F_{A\text{-}L}$ respectively. This applies to models not computing land use change fluxes, so, e.g. carbon fluxes from deforestation would be lumped in with those from fossil fuel burning. Other models could estimate carbon fluxes from imposed land use changes as part of the last term on the right, and the residual would be only from fossil fuel. The profile of permissible emissions diagnosed from each ESM can be used by IPCC WG3 to determine the policy measures consistent with the prescribed concentration scenario and the particular model projection. In some cases the permissible emissions may not be feasible, or could be inconsistent with the assumptions implicit in the concentration scenario (e.g. by assuming land-use changes that are inconsistent with the implied net CO_2 emissions). Here a WGIII-WGI-WGIII iteration could be desirable to derive achievable stabilization scenarios. Related guidance on the realism or otherwise of stabilization scenarios will be very useful information for policymakers. That is, the rate of change of CO_2 concentration (which is prescribed) is $dCO_2/dt = F_{emissions} - F_{o\text{-}a} - F_{l\text{-}a}$, or, the change in CO_2 with time = emissions minus CO_2 fluxes from the ocean-atmosphere and land-atmosphere. The WG3 scenarios group would also provide prescribed concentrations for other gasses as well as aerosols that would be used by the models.

The stabilization concentration scenario produces climate change with either an AOGCM or an ESM, whereas diagnoses for the carbon cycle and compatible emissions are performed by either an ESM or offline carbon cycle model.

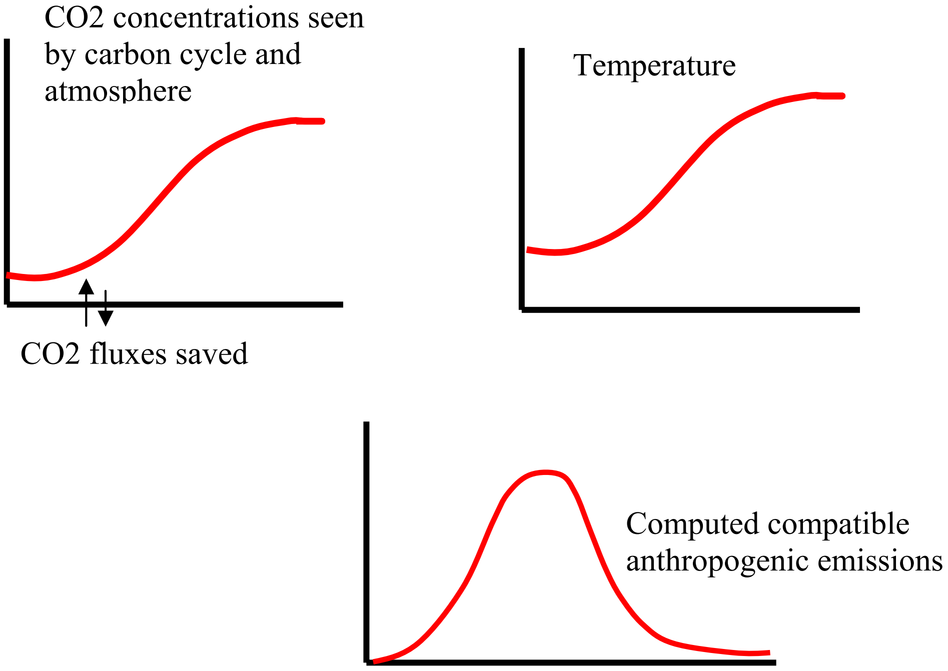

Figure 3. Schematic of Experiment #1. The carbon cycle sees increasing CO_2 concentrations and resulting changes in temperature. The land and ocean CO_2 fluxes are saved to derive emissions for WG3 scientists. The land and ocean CO_2 fluxes are saved for that purpose and do not enter the atmosphere to influence the atmospheric concentrations. Computed compatible anthropogenic emissions are equal to the prescribed atmospheric CO_2 concentration changes plus Earth system (land + ocean) CO_2 fluxes. Since the concentration changes are prescribed and the fluxes are computed in the model, the experiment allows the calculation of the model-dependant compatible anthropogenic emissions

Experiment #2: Carbon cycle response to increasing concentrations: A second integration is designed to evaluate the impact of the changes in prescribed atmospheric CO_2 on the carbon cycle response. For this experiment, atmospheric CO_2 is fixed for the radiation code in the atmospheric model only. That is, the atmosphere sees a constant CO_2 concentration throughout the experiment. Therefore, no forced climate change occurs, and the temperature response to that constant CO_2 will remain about the same throughout (except for internal climate variability and climate change commitment). However, the CO_2 concentrations from Experiment 1 are seen by the carbon cycle component, and the resulting CO_2 fluxes are saved as they were in Experiment 1, but the carbon cycle only responds to the increasing CO_2 since the temperature remains about the same. Consequently, the CO_2 fluxes from the carbon cycle (along with the specified concentrations) can be used to derive emissions, and the difference between the two derived time series of emissions in experiments 1 and 2 is a measure of the carbon cycle feedback in terms of emissions (emissions consistent with a given concentrations scenario). The CO_2 concentrations from Experiment 1 are very important, since the impact of emissions on stabilization at a given level for a given benchmark scenario provides WG3 with information regarding which socio-economic options would be required to reach that level of stabilization. The derived emissions likely will be noisy, and WG3 will have to fit, or smooth the time series of emission pathways.

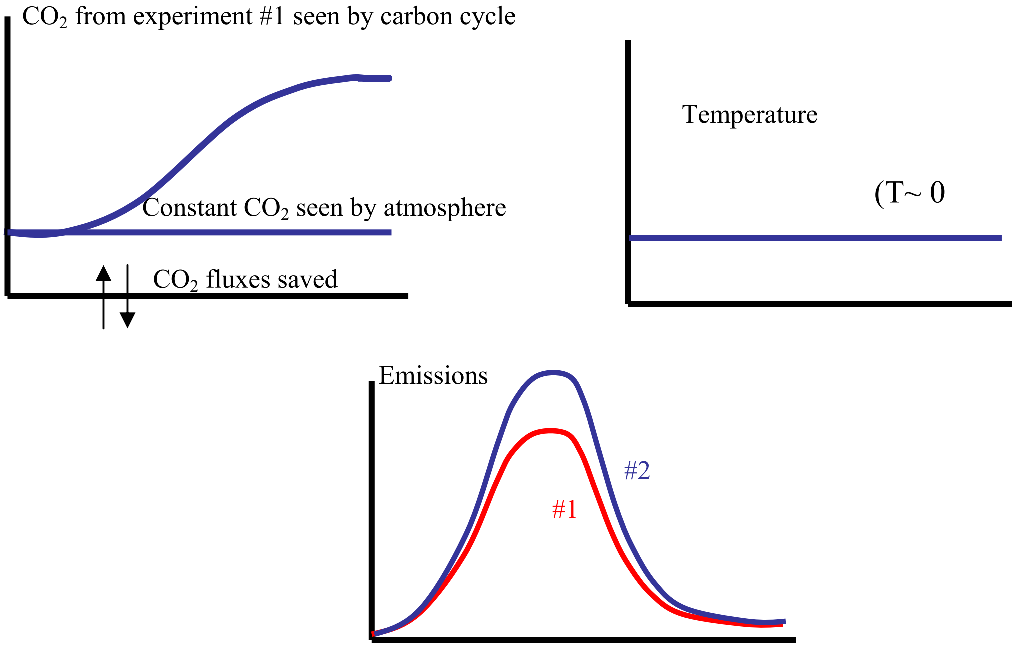

Figure 4. Schematic of Experiment #2. The carbon cycle (land and ocean) sees CO_2 concentrations from Experiment #1 (top left). Atmospheric CO_2 is held constant for the radiation calculation so there is little temperature change (top right). Earth system (land and ocean) CO_2 fluxes are saved to derive emissions (lower) for the integrated assessment modeling groups. The land and ocean CO_2 fluxes are NOT radiatively interactive with the atmosphere. Anthropogenic emissions from experiment 2 (blue line in lower panel) are calculated as in experiment 1 (red line in lower panel) where the change in anthropogenic emissions is equal to the prescribed atmospheric CO_2 changes plus Earth system (land + ocean) CO_2 fluxes. Calculation of carbon cycle fluxes and compatible emissions are simulated by ESMs or offline carbon cycle models. The difference in emissions between experiment 2 and experiment 1 represents the effect of carbon cycle feedbacks on compatible emissions for a given stabilization concentration scenario.

A minimum of two stabilization concentration scenarios are required to be integrated by the models: a high and a low case, with the possibility of a medium range case. As noted above, these are all GHG stabilization scenarios. The high case could stabilize near 700 ppm CO_2 (or about 950 ppm in terms of equivalent CO_2) concentration in the atmosphere corresponding to about 6.5 W/m2 radiative forcing relative to present day. The low case could stabilize near 400 ppm CO_2 (or about 500 ppm equivalent CO_2) concentration corresponding to about 3 W/m2. Each scenario would take into account land use changes changes (and other driving forces) consistent with the GHG emission profiles.

Experiment 3: Emissions-Driven Carbon Cycle/Climate: Though still under discussion, this simulation is designed to evaluate ESM response to climate change that is driven by emissions rather than concentrations. One option for this experiment would be to prescribe a standard emissions time series (comparable to the idealized 1% per year CO_2 increase experiments run with AOGCMs) with a fully interactive carbon cycle. Each model will produce a slightly different concentration trajectory and result in different climate changes that represent the carbon cycle feedback compared to the standard 1% per year CO_2 increase experiment in terms of quantities like temperature. This would provide a direct connection to simulations from the C_4MIP experiments as well as to the standard idealized 1% per year CO_2 increase experiments run with AOGCMs. 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.

If a modeling group has only an AOGCM (i.e. no carbon cycle), the near-term and/or the long term Experiment 1 could still be run to obtain climate change outcomes, thus widening the participation. This experimental design also provides consistent analyses across models such that caveats of model-specific inputs will not have to be documented later. Results from AOGCMs can be directly compared with the ESMs for the physical climate system response. WG3 scientists would supply the benchmark concentration scenarios to the modeling groups. In turn, WGI modeling groups would supply emission time series back to WG3 to derive socio-economic considerations to achieve those emissions stabilization pathways.

These experiments are designed to be community-coordinated, and do not rule out different experiments with different scenarios and different model formulations that could be run by individual modeling groups. This experimental design allows an ESM to diagnose the feedback of the carbon cycle in terms of emissions from Experiments 1 and 2, and Experiment 3 explores the quantification of the carbon cycle feedback in terms of climate change. This experimental design also provides consistent analyses across models such that caveats of model-specific inputs will not have to be documented later.

Avantages of a three-phase long-term stabilization approach include:

1. Relatively few future climate projections required of the ESMs. In AR4, three future integrations were integrated by most groups. The two required benchmark integrations per scenario with two required scenarios yield four future integrations (with the optional fully

coupled carbon cycle feedback experiment 3, and a possible mid-range scenario experiment). Modeling groups that have only an AOGCM would have only two required future integrations.

2. AOGCM results can be directly compared with ESM results for the physical climate system as in AR4.

3. Using benchmark scenarios allows the WGIII community to supply new scenarios to the WGI community in a timely manner. The development of a complete new set of scenarios would take place in parallel to the climate modeling groups running the benchmark concentration scenario experiments. At the same time, WGII and III can use the climate outcomes of benchmark scenarios to better assess the resulting impacts and possible mitigation and adaptation measures and policies. All of this together can help improve the integrated assessment models.

4. The process involved with this experimental design establishes pathways for the necessary interactions between the WGI, WGII and WGIII communities and shortens the time frame required for developing new scenarios and climate projections.

5. Overall Recommendations

- The development of Earth System Models (ESMs) prompts addressing a new set of scientific questions with a coordinated set of experiments that could also be assessed as part of a possible Fifth IPCC Assessment (AR5). Here we view this generation of ESMs to include components of the terrestrial and ocean biology to close the carbon cycle. The ESM may include other components such as atmospheric chemistry, prognostic aerosol components or dynamic vegetation. The input scenarios should supply information (emissions or concentrations) so that models of varying sophistication can be integrated. Gridded land use changes must also be incorporated. Ice sheet components will likely be included in experimental versions of the models but are not included in the coordinated experiments.

- An integrated effort is needed to produce past/current/future emissions of aerosols and ozone precursors to ensure the use of consistent and documented data relevant to climate/carbon cycle/aerosol/chemistry communities.

- To assess regional effects in short-term predictions will also require gridded emission data for aerosols and short-lived trace gasses as well as land use. A concerted effort will be necessary to produce these datasets.

- For longer-term runs, ideally the WG2 and WG3 IPCC reports need to be lagged about 2 years behind a WG1 report. At present, the WG2 and WG3 reports use relatively outdated (up to six years) model simulations from the previous assessment while WG1 uses relatively outdated emissions scenarios. It would be more desirable if all three working groups are using as close to current generation model projections as possible. An alternative would be for the modeling groups to make new climate change projections with benchmark concentration scenarios as soon as possible (about the 2009-2010 timeframe), and delay the next full assessment by about 2 years (to 2015).

- There is a need for a PCMDI equivalent for WG2 and WG3 communities, or an expanded role for the IPCC DDC, and a WGCM-type community organizing mechanism for WG2 and WG3.

- WG2 and WG3 need to have input to selection of fields to be archived for analysis in the new integrations, in particular a list of fields related to the carbon cycle.

- Earth System Models of Intermediate Complexity (EMICs) could be used to interpolate between the benchmark scenarios, or to run many more stabilization scenarios that will be generated by the IA modeling groups.

6. Emerging Issues

After the joint WGCM/AIMES meeting in Victoria, B.C., Canada in September, 2006, a number of issues were raised, first where there was agreement with the strategy posed so far, and where there were science questions related mainly to the short-term experiment:

Agreement so far for long term experiments:

a. A "reverse approach" for scenarios with WG3 supplying a few benchmark concentration scenarios, and WG1 supplying emissions back to WG3 to derive socio-economics.

b. Experiments 1 and 2 for long term climate to get carbon cycle feedback in terms of emissions, and carbon cycle calibration experiment

c. Option for AOGCMs and ESMs to participate

Science Questions for short term experiments:

a. Does a coupled initialized observed state matter? (i.e. Is there decadal predictability from an observed initial state that would improve projections for the 25 year time frame?)
b. What is signal to noise for climate changes on the regional space scale for the 25 year time scale? Would such changes be detectible?
c. Is time-evolving chemistry necessary or time slice, and/or how important is time-evolving chemistry/aerosols for regional climate change?
d. Is it better for more ensemble members and lower resolution, or fewer ensemble members and higher resolution?
e. What about details of land use change (e.g. need to coordinate land use changes in IA models, carbon cycle models, and ESMs)?
f. In lieu of chemistry, specified stratospheric ozone?

Current status:

a. An abbreviated summary version of this white paper has been published in EOS (Hibbard et al., 2007), and this white paper includes more detailed descriptions and discussions. The EOS article and this white paper are to receive wide distribution throughout the WCRP and IGBP communities, and comments are being solicited from the modeling community regarding the proposed experimental design.

b. The proposed strategy will be considered over by the relevant communities, and research will occur to address issues raised by the science questions involved with the strategy
c. The approaches and issues involved with ESMs are new to the WCRP community and need time to consider; therefore revisit this plan and revise/alter as needed at the next WGCM meeting (September, 2007, Hamburg)
d. Research activities: short term regional signal/noise quantification; coupled initialization and decadal predictability; EMICs used to test feasibility of experimental design, with possible low resolution ESM experiments to follow.
e. Currently, there are several venues where this strategy will be further discussed and developed:
    i. An Integrated Assessment Model Scenarios meeting early August, 2007 to coordinate land-use datasets with WG1,
    ii. An IPCC Expert Scenarios Meeting: 'Towards New Scenarios for Analysis of Emissions, Climate Change and Response Strategies'. The meeting will be held in Noordwijkerhout, The Netherlands, 19 -21 September 2007, and will be hosted by the Dutch Government. The objective of this meeting is to identify requirements and plans for the development of new scenarios of emissions, climate change, and adaptation and mitigation (including underlying socio-economic conditions that shape emissions and vulnerability), and to recommend the benchmark concentration scenarios for use in the experimental design described in this report. The scenarios will be of interest to the research and user communities, and will assist in the coordination of research assessed in a possible IPCC Fifth Assessment Report (AR5). The meeting will provide a unique forum for various groups and scientific communities to meet and discuss plans and coordination requirements for new scenario development.
f. There is probably a need for a similar activity to engage WG1 and WG2 scientists as well as the observing network communities that addresses lessons learned from the AR4 towards reducing uncertainties in the climate system observations and projections. A joint WCRP/GCOS and IGBP workshop will be held in Sydney, early October to establish future observing system and climate change research requirements based on gaps and uncertainties identified from the IPCC Fourth Assessment Report's (AR4); to determine observation and research requirements that lead to better climate change risk analyses and adaptation measures; and result in lower vulnerability and impacts to a changing climate; and to outline observation and research priorities for possible input into future IPCC assessments with regard to risk management/vulnerability issues.

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