# *Earth System Models: The Next Generation*

Report from Aspen Global Change Institute session, July 30-August 5, 2006
Gerald A. Meehl and Kathy Hibbard (and session participants—see list at end)
August 31, 2006 (draft)

## Executive Summary

It has been recognized that 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 at atmosphere-ocean general circulation models or AOGCMs) include components of atmosphere, ocean, land, sea ice. New candidate components for inclusion in these models include carbon cycle, aerosols, chemistry, and dynamic vegetation. Including these components would transition AOGCMs to first generation earth system models. However, these components will introduce new feedbacks that will need to be understood through the analysis of sparse observations related to our limited understanding of how these components function in the climate system. These could include, for example, aerosol/cloud/climate feedbacks, vegetation/ocean/biogeochemistry/climate feedbacks.

Assuming the IPCC AR5 publication date is early 2013, modeling groups are making decisions this year (2006) on what form their next generation models will take (to be used for climate change projections). The IPCC Task Group on New Emission Scenarios (TGNES) and other groups have been discussing new emission scenarios (e.g. mitigation/adaptation, also referred to as stabilization). These scenarios will come to bear on climate change projections performed for assessment in the IPCC AR5 with the new emerging earth system models. Thus there has been a confluence of activities in model development and scenario development that must be communicated and coordinated across various groups and scientific communities this year. Therefore, a session of the Aspen Global Change Institute was convened from July 30-August 5, 2006, to address four major objectives:

1) Identify what new components are ready now or will be ready in the next six months for inclusion in AOGCMs
2) Establish communication through WCRP, IGBP and TGNES to coordinate activities in preparation for climate change simulations that will be performed with this next generation of models for the IPCC AR5
3) Propose an experimental design for 21st 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 regarding current status of four new components for earth system models were discussed, along with scientific issues involved with coupling these components into emerging ESMs. Summary points for the status of carbon cycle and dynamic vegetation to be incorporated in AOGCMs included:

- 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 warming. This makes the challenge of achieving any particular stabilization target more difficult to achieve. Therefore, the community is moving towards including aspects of the carbon cycle and dynamic vegetation in emerging earth system models.

- Some models already include a closed carbon cycle, but none have yet consistently included the impacts of land use change and land management, wildland fires, and this will be a priority for models to be used for the AR5.

- We also expect models to include some simple representation of ocean biology for the AR5.

- Although all models won't include other potentially important processes such as micronutrient limitations on ocean ecosystems, ocean bottom chemistry, nitrogen limitations on terrestrial ecosystems, 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, and re-growth.

Summary points for the status of aerosols and chemistry to be incorporated in AOGCMs included:

- Aerosols and chemistry need to be considered in earth system models for a number of reasons. A new consideration for IPCC is the ability of the ESM to study air quality trends, to be used by impacts and scenario communities.

- For the AR5, most models will have a representation of the indirect effect of aerosols. Using more comprehensive schemes than for the AR4, and they will treat the temporal change from the past to the future.

- 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 limitations (demands?).

- The expectation is that effects from aerosols and chemistry will 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 the AR5 simulations. This is a subject of ongoing research.

Taking into account the state-of-the-art of these new components, session participants (who represented relevant communities involved with WCRP, IGBP, TGNES, and IPCC Working Groups I, II and III), formulated a proposal for an experimental design for community coordinated climate change projection experiments for assessment in the IPCC AR5. These fell into two timescales involving different scientific problems, policy considerations, scenario issues, and model configurations.

## *Proposed Experimental Design for Coordinated Climate Change Projections for the AR5*

### *1. Near term (2005-2030)*

A prime 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. A research task will be to determine the feasibility of this goal.

To produce such regional scale predictions will require finer resolution models (desire at least _ to 1 degree in the atmosphere, but other resolutions are possible, and increased vertical resolution and domain) with the inclusion of simple chemistry, aerosols, and dynamic vegetation. Both improved process representation and higher resolution are important and compromises will be required to make the simulations computationally feasible.

Such simulations will also require accurate ocean data initialization which is currently problematic, particularly the lack of observed salinity data. Improved initialization datasets incorporating observed soil conditions and sea ice may be required.

Given that scenarios of long-lived greenhouse gases do not differ substantially prior to 2030, only one such mid-range scenario is anticipated to be used in model predictions for this time period.

To provide statistically significant assessments on the regional scale will likely require ensemble simulations of at least 10 members for each scenario.

To incorporate past climate forcings, for model verification, and for the coupled assimilation/initialization process, simulations should start some time during the latter half of the 20th century.

Two additional options were identified: a) A number of scenarios for pollutants (aerosols and short-lived gases) could be provided for low, medium and high emission projections as perturbations around the standard scenario, or b) testing geo-engineering questions and hypotheses with model experiments.

### *2. Long term (2005-2100 and beyond)*

A prime 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 is not required, and a lower resolution AOGCM (roughly 2 degree) could be used with a more conventional pre-industrial spin-up, a 20th century experiment with natural and anthropogenic forcings (at least 10 member ensemble 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 could provide a reference to earlier experiments, as well as supply a multi-model ensemble of a mid-range scenario for analysis. Then two new GHG and aerosol benchmark stabilization concentration scenarios would be supplied by WG3:

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

At least one ensemble member would be run for each, with carbon cycle and biogeography/succession active, and chemistry and aerosols prescribed and time-evolving. Initially the experiments would be run to 2100, then concentrations stabilized after 2100, and the models run out to 2300.

Two experiments from 2005 to 2100 would be run for each scenario:
***Experiment 1***: ESM-type model run with the time series of specified concentrations, and climate system responds to those concentrations; coupled carbon cycle produces time series of CO2 fluxes that are saved—this CO2 does not enter the atmosphere or impact climate system response to specified concentration time series (these CO2 fluxes are used to derive emissions, and provided to WG3 scientists to derive mitigation policies to achieve those emissions); groups without a carbon cycle component can also run this experiment to get climate system response as in the AR4.
***Experiment 2***: Fix atmospheric CO2 at a constant value so the atmospheric temperature remains about the same throughout the experiment, and specify CO2 concentrations from the carbon cycle response derived from exp 1. The resulting CO2 fluxes do not enter the atmosphere, but are saved to diagnose emissions in the following way:
CO2 concentration change = emissions – CO2 fluxes
These derived emissions will be noisy, and WG3 will fit them to smoother emission pathways. Comparing experiments 1 and 2 will provide and indicator of the magnitude of the carbon cycle feedback in terms of the different emissions.

In addition, a third experiment could be run to quantify the climate response (e.g. temperature) to inclusion of the new feedbacks involved with the carbon cycle:
***Experiment 3 (optional)*****:** Derived emissions from Experiment 2 are implimented in an Experiment 1-type simulation but with full interactive carbon cycle. The difference in temperature response between experiments 1 and 3 is the magnitude of the carbon cycle feedback in terms of the climate system response.

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 are four for groups with ESMs, and two for groups with AOGCMs.

- Non-ESM results can be directly compared with the ESM results for the physical climate system (i.e. modeling groups without new earth system-type 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. The development of a complete new set of scenarios would take several years and WG3 have developed revised SRES scenarios that are available immediately. Based on these revised SRES scenarios, WGI supplies emission fields 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) need to be formed for WG2 and WG3 to allow better overall coordination of these types of activities.

***Recommendations included***:

- 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.

- The WG2 and WG3 IPCC reports need to be lagged about 2 years behind the WG1 report. At present the WG2 and WG3 use relatively outdated (up to six years) model simulations from the previous assessment. 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 projection simulations as soon as possible (about the 2009-2010 time frame), and delay the next full assessment by about 2 years (e.g. target publication in 2015).

- 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 a number of climate modeling groups (about 17). 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. More than 20 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). 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 types of models as “ESMs”.

The current status of modelling 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). 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.

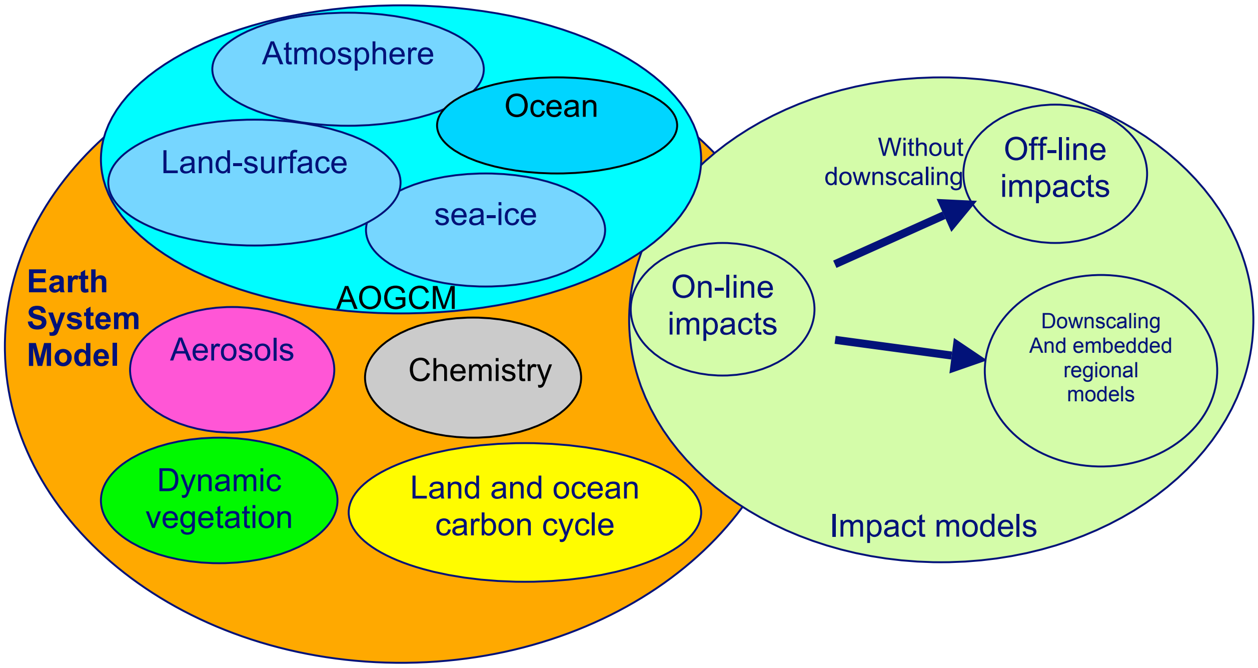


**Fig. 1**: Schematic diagram of an AOGCM (upper left), and Earth System Model (encompassed by orange oval), and various types of impact models (right).

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 generationESMs will take, with particular application for the 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 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 will provide fuel for discussion at the 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 what new components are ready now or will be ready in the next six months for inclusion in AOGCMs to be used in the IPCC AR5
2) Establish communication through WCRP, IGBP and TGNES to coordinate activities in preparation for climate change simulations that will be performed with this next generation of models for the IPCC AR5
3) Propose an experimental design for 21st 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 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, followed by a proposed experimental design that integrates impacts and scenarios (represented in IPCC WG2 and WG3, respectively) and physical climate science (WG1) for the next Assessment Report. We summarize with a suite of recommendations for the joint WGCM, AIMES and IPCC communities.

## 2. New components for inclusion in AOGCMs to make ESM-type models

### *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 O3 that is frequently used in today's ESMs is the use of prescribed oxidant distributions (OH and O3 for example in the oxidation of SO2 to sulfates). Alternatively, extreme simplifications to the photochemistry can be employed (the chemistry of peroxides in the oxidation of SO2 to SO4 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=> O3, CH4, 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 in the next climate assessment.

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 IPCC 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 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 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 IPCC AR5.

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

In summary, for AR5, 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 AR5, 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, 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 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 amount 30% (Hadley Center) to 100% (NCAR). For tropospheric chemistry the overhead ranges from a 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 IPCC 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 AR5, most models 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 AR5 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 ESMs for AR5***

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 models (e.g. NPZD: nutrient, phytoplankton, zooplankton, detritus).
- 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 (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 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. bugs or model instabilities).

Not all modeling groups will incorporate all of the DGVM and carbon cycle components in time for AR5. 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 is critical in this respect (see text on "*Experimental Design for AR5 ESM runs"*).

### ***"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 zoo-plankton functional groups.
- River biogeochemistry (especially DOC fluxes from land-to-ocean).
- Micronutrient limits (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 types
- 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 (as low as 3-5% GFDL, as high as 30% 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 *"Experimental Design for AR5 ESM runs").*
- 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 more 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 activities).

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. A Proposed Experimental Design for the AR5

The pathways of model development over the next ten years are not 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 model resolution and hypotheses.

## *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. Stratospheric ozone recovery from chlorine loading will be affecting climate 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 very fine resolution (on the order of 0.5° for latitude and longitude) would allow for a better regional assessment of climate change, although additional downscaling to even finer resolution might be required for some climate change impact studies. Most AOGCMs currently have about 2° resolution (at best). 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 _º to 1° latitude x 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. 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 models on finer resolution 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. 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 anthropogenic 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 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. The past decades will also provide the possibility of validating the model for regional scale predictions. 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, but salinity reconstructions remain a significant problem. 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.

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 would be unchanged, possibly having just the observed 11-year cycle superimposed. 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. It is not anticipated that these choices will play a determining role in the climate simulation results.

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 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 10-15 for the base case in order to discriminate changes in hydrologic extremes.

### d. Initialization and Model Spinup Considerations

While historical simulations for spin-up and model validation are necessary, there are conflicting influences concerning the starting date for these runs. The atmosphere is in better radiative balance starting in 1950 than at later times. 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. 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 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 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°) 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 to be supplied by WG3: (1) a reference (e.g., A2-type), (2) stablization (e.g., B1-type); and possibly (3) mid-range scenario 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. The first two experiments are considered 'core' for all groups to participate in, with a third, optional experiment. WG3 would provide time series of concentrations of GHGs for these experiments.

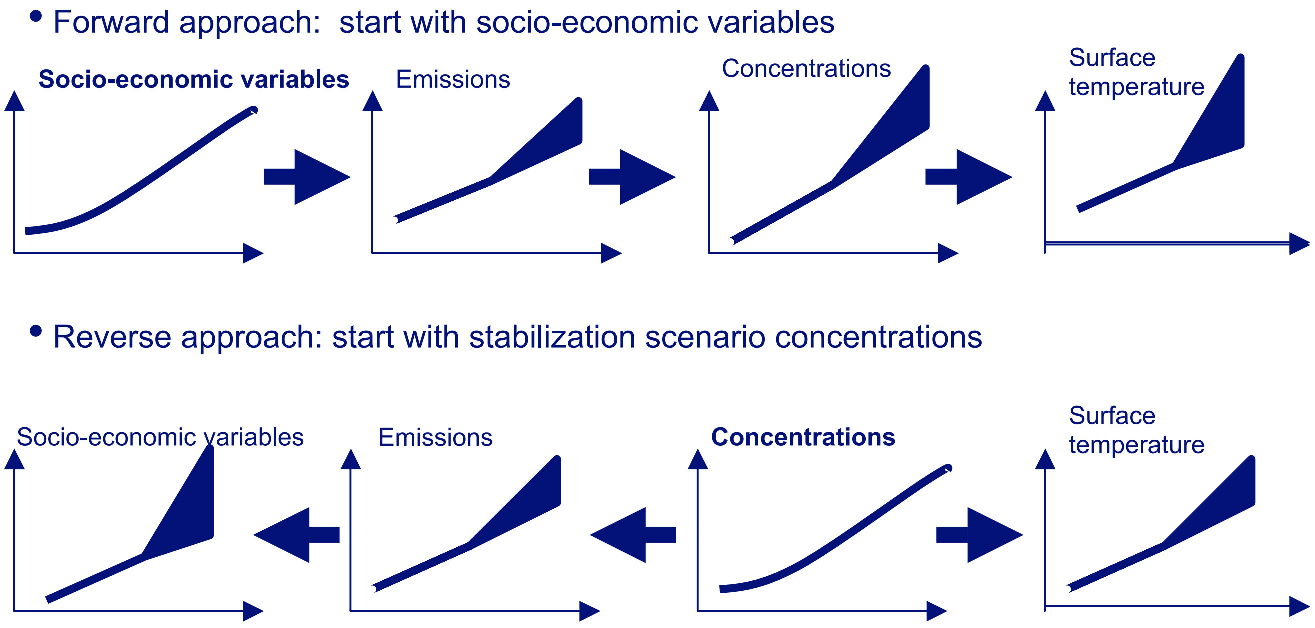


**Fig. 2**: Schematic of traditional forward approach starting with socio-economic variables to derive emissions, concentrations and then temperature and other climate changes from climate models (top), and new proposed methodology where the starting point is concentrations run in climate models, that are used to derive emissions and then socio-economic factors to achieve those emissions.

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. However, by using benchmark concentration scenarios that are then applied to derive emissions and then socio-economic factors to achieve them, 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.

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 AR5. 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, 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 the scenarios proposed are stabilization scenarios. To implement this strategy, two experiments are proposed, each of which uses a given benchmark concentration scenario, and each representing a high and a low radiative forcing. There is also an optional third scenario which ies between the high and the low scenario:

**Experiment 1:** 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 GHG 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. Who/How these are developed needs to be determined.). Each scenario would also include the prescribed changes in the future land use. 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 – See Stouffer et al. 2004). 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 in AR5 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 insist that the long-term mean land-atmosphere and ocean-atmosphere fluxes of $CO_2$ should be within 0.2 GtC/yr of zero net flux[p2])

The climate system only responds to benchmark concentrations, and temperature changes accordingly. As the model runs, the carbon cycle component produces a time-series of $CO_2$ fluxes that are saved. Note: – these $CO_2$ fluxes do not enter the atmosphere to change the climate system response to the specified concentration time series. The computed CO2 fluxes from this experiment (e.g., land/ocean $CO_2$) are returned to WG3 where inverse calculations of these fluxes are used to derive corresponding emissions, and then mitigation policies to achieve those derived emissions. Emissions can be calculated when the CO2 fluxes and the CO2 concentration time series are known.

At various points in the pre-industrial control, historical integrations 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 GHG and aerosol concentrations and land use changes. This is similar to what was needed for the AR4 common integrations.

The future projections start from the end of the historical integrations. The concentrations of GHG (including CO2) and aerosols and the future land use changes are prescribed according to the input scenario (see below for details). Even though the ESM model can predict changes in atmospheric CO2 concentrations, the CO2 concentrations are prescribed. The prescribed atmospheric CO2 concentration is 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 AR5 common set. reason[p3].

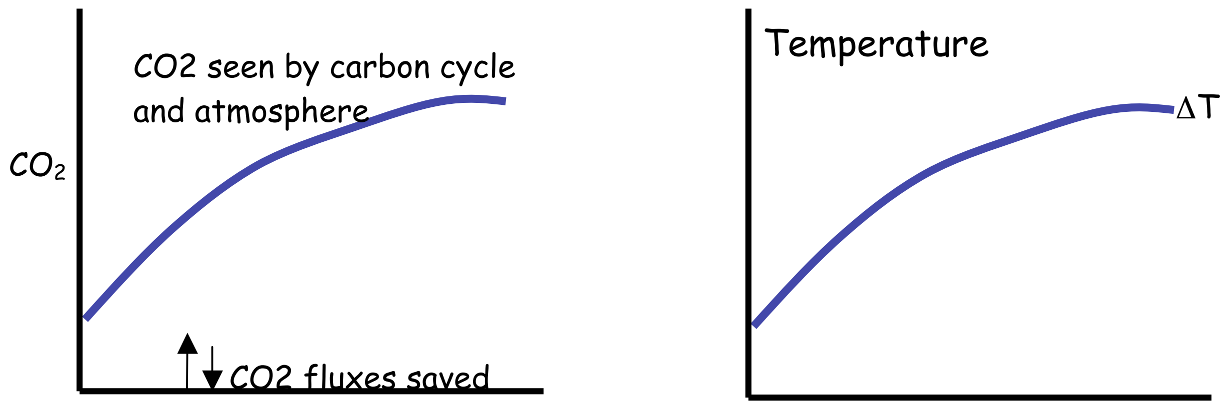
The ESMs that include an interactive carbon cycle will calculate land and ocean $CO_2$ sinks which are consistent with the prescribed $CO_2$ concentration scenario and the climate change predicted by the component AOGCM. These fluxes can be used to calculate the "permissible $CO_2$ emissions" profile consistent with the prescribed $CO_2$ stabilization scenario, 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 profile of emissions consistent with the prescribed rate of carbon dioxide 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. 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 (from one IPCC assessment to the next) will be required to derive achieveable 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 CO2 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 interactive within the models.

**Experiment #1:**

Carbon Cycle sees increasing CO2 Concentrations and $\Delta T$;
Land/Ocean CO2 fluxes saved to derive emissions for WG3

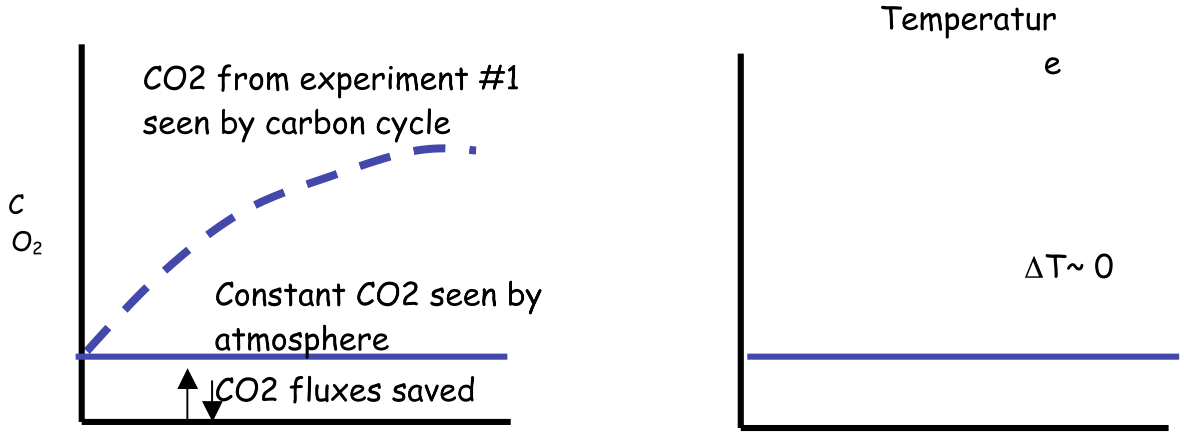


Land/Ocean $CO_2$ fluxes are NOT interactive with atmosphere

**Experiment 2**: A second integration to evaluate the impact of the climate changes on the carbon 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 CO2 concentration throughout the experiment. Therefore, no climate change occurs, and the temperature will remain about the same throughout (except for internal climate variability). However, the CO2 concentrations from Experiment 1 are given to the carbon cycle component, and the resulting CO2 fluxes are saved as they were in Experiment 1, but the carbon cycle only responds to the increasing CO2 since the temperature remains about the same. Consequently, the CO2 fluxes in experiments 1 and 2 can be used to derive emissions, and the difference between the two time series is a measure of the carbon cycle feedback on 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 will be noisy, and WG3 will have to fit, or smooth the time series of emission pathways.

**Experiment #2:**

Carbon Cycle sees $CO_2$ Concentrations from Experiment #1; atmospheric $CO_2$ and T are constant; Land/Ocean $CO_2$ fluxes saved to derive emissions for WG3

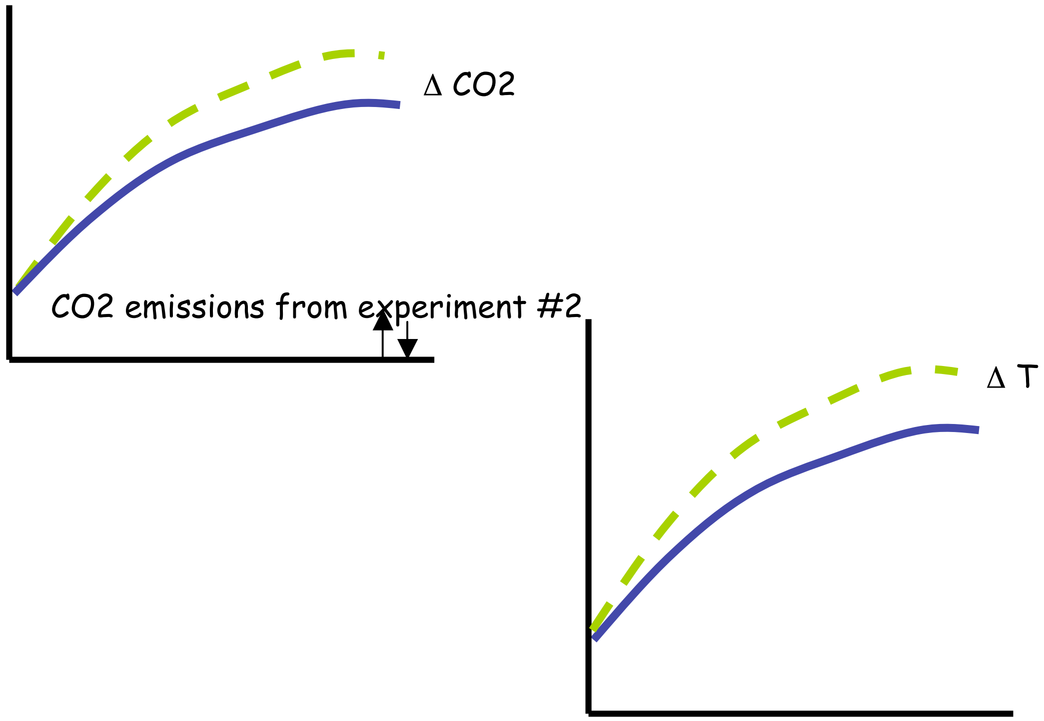


Land/Ocean $CO_2$fluxes are NOT interactive with atmosphere

Two scenarios are required to be integrated by the AR5 models: a high and a low case. As noted above, both are GHG stabilization scenarios. The high case would stabilize near 700 ppm CO2 (or about 950 ppm in terms of equivalent CO2) concentration in the atmosphere corresponding to about 6.5 W/m2 radiative forcing relative to present day. The low case would stabilize near 400 ppm CO2 (or about 500 ppm equivalent CO2) concentration corresponding to about 3 W/m2. In each scenario, there would be a land use scenario consist with the GHG scenarios.

**Experiment 3 (optional):** In order to determine the magnitude of a carbon cycle feedback in terms of temperature from the climate models, the derived emissions from Experiment 2 can be run with a fully interactive carbon cycle in Experiment 1. Since in this experiment CO2 fluxes from the carbon cycle will be allowed to enter the atmosphere to supplement the prescribed CO2 concentrations from a given scenario, CO2 will evolve differently from the original prescribed CO2 scenario (of Experiment 1), and will thus produce a different temperature response in the model. The temperature difference between experiments 1 and 3 defines the magnitude of the carbon cycle feedback.

**Experiment #3 (optional)**: Derived emissions in the absence of climate change from Experiment #2 are used to drive carbon cycle-climate model from Experiment #1



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 AOGCM to diagnose the feedback from Experiments 1 and 2, and Experiment 3 explores whether there are differences in climate change for a given scenario due to the inclusion of the carbon cycle feedback. If a modeling group only has an AOGCM (i.e. not carbon cycle), Experiment 1 could still be run to obtain a climate change outcome, 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.

Advantages of a three-phase 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 yielding four future integrations. Modeling groups that do not have an ESM would have only two future required future integrations.

2. Non-ESMs 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 several years. 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 drastically shortens the time frame required for developing new scenarios and climate projections.

## 3. Overall Recommendations

- The development of Earth System Models (ESMs) requires new common integrations to be developed for the Fifth IPCC Assessment (AR5). Here we view this generation of ESM to include components of the terrestrial and ocean biology to close the carbon cycle. The ESM may include other components such as atmospheric chemistry or sophisticated aerosol components, but they will be optional. The input scenarios should supply information (emissions or concentrations) so that models of varying sophistication can be integrated.

- 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, 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. 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 fore the modeling groups to make new climate change projection simulations 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 for AR5, in particular a list of fields related to the carbon cycle.

## References

Friedlingstein, P., P. Cox , R. Betts, W. von Bloh, V. Brovkin, S. Doney, M. Eby, I. Fung, B. Govindasamy, J. John, C. Jones, F. Joos, M. Kawamiya, W. Knorr, K. Lindsay, H. D. Matthews, T. Raddatz, P. Rayner, C. Reick, E. Roeckner, K.-G. Schnitzler, R. Schnur, K. Strassmann, S. Thompson, A. J.Weaver, and N. Zeng, 2006. Climate –carbon cycle feedback analysis, results from the $C^4$MIP model intercomparison. *J. Climate*, **19**, 3337-3353.

Jones, C.D., Cox, P.M., Huntingford, 2006. Impact of climate-carbon cycle feedbacks on emissions scenarios to achieve stabilisation. In "*Avoiding Dangerous Climate Change*", chapter 34, 323-332. Eds: H.J. Schenhuber, W. Cramer, N. Nakicenovic, T. Wigley, G. Yohe. Pub: Cambridge University Press.

## Participants

Dave Bader, PCMDI, Livermore, CA
Olivier Boucher, Hadley Centre, Exeter, U.K.
Guy Brasseur, NCAR, Boulder, CO
Peter Cox, Exeter University, U.K.
Peter Gent, NCAR, Boulder, CO
Claire Granier, CNRS, Paris, France
Kathy Hibbard, NCAR, Boulder, CO
George Hurtt, Univ. of New Hampshire
Michio Kawamiya, Frontier Research Center for Global Change, Yokohama, Japan
David Kicklighter, Woods Hole, MA
Masahide Kimoto, Univ. of Tokyo, Tokyo, Japan
Jean-Francois Lamarque, NCAR, Boulder, CO
Dave Lawrence, NCAR, Boulder, CO
Norm McFarlane, Univ. of Toronto, Toronto, Canada
Linda Mearns, NCAR, Boulder, CO
Gerald Meehl, NCAR, Boulder, CO
Richard Moss, UN Foundation and Univ. of Maryland, College Park, MD
Naki Nakicenovic, Vienna University of Technology, Laxenburg, Austria
Phil Rasch, NCAR, Boulder, CO
David Rind, NASA Goddard Institute for Space Studies, New York, NY
Steve Smith, PNNL and Univ. of Maryland, College Park, MD
Ron Stouffer, GFDL, Princeton, NJ