Climate Damages in the MIT IGSM

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Integrated assessment models (IAMs) have proven useful for analysis of climate change because they represent the entire inhabited earth system, albeit typically with simplified model components that are reduced form or more highly aggregated than for example, high resolution coupled atmosphere-ocean-land general circulation models. The MIT Integrated Global System Model has been developed to retain the flexibility to assemble earth system models of variable resolution and complexity, however, even at its simplest it remains considerably more complex than most other IAMs. In its simplest formulation it retains a full coupled general circulation model of the ocean and atmosphere. Solved recursively, it solution time for a 100-year integration on a single node of computer cluster is on the order of 24-36 hours, compared with seconds or minutes for other IAMs. In that form it is not numerical feasible to solve the whole system as a fully dynamic optimizing model to find an optimal cost-benefit solution as with the DICE, PAGE, or FUND models. Indeed, inclusion of climate damages is still a work in progress in the MIT IGSM. The slow progress relative to other efforts stems from a commitment to represent explicitly the physical impacts of climate and environmental change on activities (e.g. crop yields, water availability, coastal, inundation, ecosystem processes and functioning, health outcomes, etc.) and represent market response to these outcomes and value that response consistent with projections of resource prices as they are projected to change in the future with economic growth and under different policies to mitigate greenhouse gas emissions. This is in contrast to most of the optimizing models where climate damages are estimated as a reduced form relationship in dollars of economic loss as a function of mean global temperature change as a sufficient indicator of many dimensions of climate change, and where the damage function is itself completely independent and separable from the economy as it affects energy use and greenhouse gas emissions. In the "horses for courses" metaphor, the MIT IGSM is not a horse designed (bred) to run well if the course is to estimate a net present value social cost of carbon. The IGSM is best seen as complementary to such efforts, and probably the focus on uncertainty in future climate outcomes is one of the areas where it can make the most contribution to the social cost of carbon discussion.

Computationally efficient versions of the IGSM have been assembled for simulating large ensembles to study uncertainty (***Sokolov et al.,* 2009***; Webster et al.,* **2009**). Less complete but more highly-resolved model components can be combined where research demands them, such as in the study of the climate effect of aerosols (***Wang,* 2009***; Wang et al.,* **2009*a,b***), changes in atmospheric composition and human health (***Selin et al.,* 2009a**) or agricultural impacts and land use change (**Reilly, et al. 2007; Felzer et al., 2005; *Melillo et al.,* 2009**). The IGSM framework encompasses the following components:

- global economic activity resolved for large countries and regions that projects changes in human activities as they effect the earth system including emissions of pollutants and radiatively active substances and changes in land use and land cover;

- earth system modules linked to the macroeconomy that address effects of climate and environmental change on human activity, adaptation, and their consequences for the macroeconomy (this includes modules that represent water use and land use at disaggregated spatial scales, energy and coastal infrastructure again at disaggregate spatial scales, and demography, urbanization, urban air chemistry, and epidemiological relationships that relate environmental change to human health);
- the natural and managed land system including vegetation, hydrology, and biogeochemistry as affected by human activity, environmental change and feedbacks on climate and atmospheric composition;
- the circulation and biogeochemistry of the ocean including its interactions with the atmosphere, and representations of physical and biological oceanic responses to climate change; and
- the circulation and chemistry of the atmosphere including its role in radiative forcing, and interactions with the land and ocean that determine climate change.

The suite of models that have been employed in this framework and their capabilities are briefly described below.

3.1 Human Drivers and Analysis of Impacts

Human activities as they contribute to environmental change or are affected by it are represented in multi-region, multi-sector models of the economy that solves for the prices and quantities of interacting domestic and international markets for energy and non-energy goods as well as for equilibrium in factor markets. The MIT Emissions Predictions and Policy Analysis (EPPA) model (***Paltsev et al.,*** **2005**) covers the world economy. It is built on the GTAP dataset (maintained at Purdue University) of the world economic activity augmented by data on the emissions of greenhouse gases, aerosols and other relevant species, and details of selected economic sectors. The GTAP database allows flexibility to represent the world economy with greater country or sector detail (the data set has 112 countries/regions and 57 economic sectors) that we aggregate further for numerical efficiency. The model projects economic variables (GDP, energy use, sectoral output, consumption, *etc*.) and emissions of greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) and other air pollutants (CO, VOC, NO_x, SO_2, NH_3, black carbon, and organic carbon) from combustion of carbon-based fuels, industrial processes, waste handling, and agricultural activities.

The model has been augmented with supplemental physical accounts to link it with the earth system components of the IGSM framework. To explore land use and environmental consequences, the EPPA model (***Gurgel, et al.,*** **2007**; ***Antoine, et al***.,**2008**) is coupled with the Terrestrial Ecosystem Model (***Melillo et al.,*** **2009**). The linkage allows us to examine the ability of terrestrial ecosystems to supply biofuels to meet growing demand for low-emissions energy sources along with the growing demand for food, and to assess direct and indirect emissions from an expanded cellulosic bioenergy program. The approach generates worldwide land-use scenarios at a spatial resolution of 0.5º latitude by 0.5º longitude that varies with climate change. To analyze the economic impacts of air pollution, the EPPA model is extended to include pollution-generated health costs, which reduce the resources available to the rest of the economy (***Nam et al.,*** **2009*; Selin et al.,*** **2009a**). The model captures the amount of labor and leisure lost and additional medical services required due to acute and chronic exposure to pollutants. The GTAP database allows considerable flexibility to represent the world economy with greater country or sector detail (the underlying data has 112 countries/regions and 57 economic sectors). To assess distributional and regional impacts of carbon policy in the US, we use a model that is based on a state-level database and resolves large U.S. states and multi-state regions and households of several income classes. The U.S. Regional Energy Policy (USREP) model (***Rausch et al.,*** **2009; 2010**) is nearly identical in structure to the EPPA model, except that it models states and multi-state regions in the US instead of countries and multi-country regions. The main difference from the EPPA model is the foreign sector that is represented as export supply and import demand functions rather than a full representation of foreign economies. This sacrifice of global coverage allows explicit modeling of distributional details of climate legislation and linking the USREP model to very detailed electricity dispatch models. Efforts, under separate funding, to integrate the USREP database into the GTAP base to provide a complete representation of trade are underway. Physical impacts of environmental change have been included in the model as a feedback by identifying factors (land productivity as it affects crops, livestock and forests) or sectors affected by climate or by introducing additional household production sectors (household health services that uses leisure and medical services). Thus, the approach is to work with underlying input-output and Social Accounting Matrix (SAM) that is the basis for the economic model (***Matus, et al.,*** **2008**). This provides a framework for potentially linking other impacts such as coastal (***Franck et al.,*** **2010a,b, 2010;** ***Sugiyama, et al.*****, 2008**), agriculture (Reilly et al., 2007), health (***Selin, et al*****., 2009;** ***Nam et al*****., 2010**), or water (***Strzepek et al.,*** **2010**) impacts.

3.2 Hydrology and Water Management

Research on components representing water management are aimed at linking hydrological changes projected by the atmospheric component of the IGSM to impacts of those changes on water availability and use for irrigation, energy, industry and households, and in-stream ecological services. These demands are driven by macroeconomic changes and changes in water supply and will in turn affect the economy as represented in the EPPA and the USREP models. Techniques have been developed to take IGSM 2-D GCM outputs and use results from the IPCC AR-4 3-D GCMs to provide IGSM-generated 3-D climates to the hydrology component of the IGSM-Land Surface Model (NCAR Community Land Model, CLM) to project runoff. Tests have been conducted for the US, where adequate data are available, to determine the spatial resolution needed to provide reliable estimates of runoff using CLM. A Water Resources System (WRS) model has been adapted from and further developed in collaboration with the International Food Policy Research Institute (IFPRI) to represent river reaches and natural and management components that affect stream-flow. The major natural components are wetlands, unmanaged lakes, groundwater aquifers and flood plains. The major managed components are reservoirs and managed lakes, and water diversions for irrigation, cooling in thermal power plants, and industrial and household needs. Constraints on use to preserve in-stream ecological water requirements can be imposed.

A series of models were adapted and developed to represent water use. These include a crop growth model (CLICROP) developed to be able to run at 2° latitude-longitude grid resolution while retaining the accuracy of a 0.5° resolution, thereby improving numerical efficiency of the modeling system (***Strzepek***

et al.,* 2010a**). A model of Municipal and Industrial water demand driven by per capita GDP was developed jointly with the University of Edinbourgh (*Hughes et al.,* 2010; ***Strzepek et al.,* 2010a**). To investigate changes in thermal electric cooling water demands, a geospatial methodology based on energy generation and geo-hydroclimatic variables has been developed (Strzepek et al.,* 2010b**). An assessment of environmental flow requirements to assure aquatic ecosystem viability has been undertaken and an approach for using the IGSM was selected (***Strzepek & Boehlert,* 2010; *Strzepek et al.,* 2010a**). These developments provide the foundation for completing linkages of the WRS with other IGSM components.

3.3 Atmospheric Dynamics and Physics

Research utilizing the IGSM framework has typically included a 2-D atmospheric (zonally-averaged statistical dynamical) component based on the Goddard Institute for Space Studies (GISS) GCM. The IGSM version 2.2 couples this atmosphere with a 2D ocean model (latitude, longitude) with treatment of heat and carbon flows into the deep ocean ***(Sokolov et al, 2005).*** The IGSM version 2.3 (where 2.3 indicates the 2-D atmosphere/full 3-D ocean GCM configuration) (***Sokolov et al.,* 2005**; ***Dutkiewicz et al.,* 2005**) is a fully-coupled Earth system model that allows simulation of critical feedbacks among its various components, including the atmosphere, ocean, land, urban processes and human activities. A limitation of the IGSM2.3 is the above 2-D (zonally averaged) atmosphere model that does not permit direct regional climate studies. For investigations requiring 3-D atmospheric capabilities, the National Center for Atmospheric Research (NCAR) Community Atmosphere Model version 3 (CAM3) (***Collins et al.,*** 2006) has been used with offline coupling.

The IGSM2.3 provides an efficient tool for generating probabilistic distributions of sea surface temperature (SST) and sea ice cover (SIC) changes for the 21st century under varying emissions scenarios, climate sensitivities, aerosol forcing and ocean heat uptake rates. Even though the atmospheric component of the IGSM2.3 is zonally-averaged, it provides heat and fresh-water fluxes separately over the open ocean and over sea ice, as well as their derivatives with respect to surface temperature. This resolution allows the total heat and fresh-water fluxes for the IGSM2.3 oceanic component to vary by longitude as a function of SST so that, for example, warmer ocean locations undergo greater evaporation and receive less downward heat flux.

In offline coupling between the IGSM2.3 and CAM3, the 3-D atmosphere is driven by the IGSM2.3 SST anomalies with a climatological annual cycle taken from an observed dataset (*Hurrell et al.*, 2008), instead of the full IGSM2.3 SSTs, to provide a better SST annual cycle, and more realistic regional feedbacks between the ocean and atmospheric components. This approach yields a consistent regional distribution and climate change over the 20th century as compared to observational datasets, and can then be used for simulations of the 21st century.

3.4 Urban and Global Atmospheric Chemistry and Aerosols

The model of atmospheric chemistry includes an analysis of all the major climate-relevant reactive gases and aerosols at urban scales coupled to a model of the chemistry of species exported from urban/regional areas (plus the emissions from non-urban areas) at global scale. For calculation of the atmospheric composition in non-urban areas, the atmospheric dynamics and physics model is linked to a detailed 2-D zonal-mean model of atmospheric chemistry. The atmospheric chemical reactions are thus simulated in two separate modules: one for the sub-grid-scale urban chemistry and one for the 2-D model grid. In addition, offline studies also utilize the 3-D capabilities of the CAM3 as noted above, as well as the global Model of Atmospheric Transport and Chemistry (MATCH; *Rasch et al.,* 1997), and the GEOS-Chem global transport model (http://geos-chem.org/).

Global Atmospheric Chemistry: Modeling of atmospheric composition at global scale is by the above 2-D zonal-mean model with the continuity equations for trace constituents solved in mass conservative or flux form (**Wang *et al*.**, **1998**). The model includes 33 chemical species including black carbon aerosol, and organic carbon aerosol, and considers convergences due to transport, convection, atmospheric chemical reactions, and local production/loss due to surface emission/deposition. The scavenging of carbonaceous and sulfate aerosol species by precipitation is included using a method based on a detailed 3-D climate-aerosol-chemistry model (***Wang***, **2004**) that has been developed in collaboration with NCAR. The interactive aerosol-climate model is used offline to model distributions of key chemical species, such as those utilized in the development of the urban air chemistry model.

Urban Air Chemistry: A reduced-form urban chemical model that can be nested within coarser-scale models has been developed and implemented to better represent the sub-gridscale urban chemical processes that influence air chemistry and climate (***Cohen & Prinn***, **2009**). This is critical both for accurate representation of future climate trends and for our increasing focus on impacts, especially to human health and down-wind ecosystems. The MIT Urban Chemical Metamodel (UrbanM) is an update of our ***Mayer et al.* (2000)** model, and applies a third-order polynomial fit to the CAMx regional air quality model (*ENVIRON*, 2008) for 41 trace gases and aerosols for a 100 km x 100 km urban area. While a component of the IGSM, the urban modular UrbanM is also designed to facilitate inclusion in a number of other global atmospheric models. It has recently been embedded in the MIT interactive climate-aerosol simulation based on CAM3 in order to assess its influence on the concentration and distribution of aerosols in Asia (***Cohen et al.*, 2009**). Work is underway to further test the sensitivity of the probabilistic uncertainty results with the IGSM2.2/2.3 to this improved representation of urban chemistry. The UrbanM is presently being benchmarked in a case study of the Northeast U.S., and embedded in a global 3-D chemistry-climate model including a detailed chemical mechanism (NCAR CAM-Chem).

Chemistry-Climate-Aerosol Component: A 3-D interactive aerosol-climate model has been developed at MIT in collaboration with NCAR based on the finite volume version of the Community Climate System Model (CCSM3; *Collins et al.,* 2006). Focused on analysis of aerosols, this companion sub-model is not yet integrated into the IGSM but serves as a step toward overcoming the limitations for analysis of regional issues using the IGSM 2-D atmosphere configuration. The modeled aerosols include three types of sulfate, two external mixtures of black carbon (BC), one type of organic carbon, and one mixed state (comprised primarily of sulfate and other compounds coated on BC); each aerosol type has a prognostic size distribution (***Kim et al***., **2008**). The model incorporates such processes as aerosol nucleation, diffusive growth, coagulation, nucleation and impaction scavenging, dry deposition, and wet removal. It has been used to investigate the global aerosol solar absorption rates (***Wang et al.*, 2009a**) and the impact of absorbing aerosols on the Indian summer monsoon (***Wang et al.,*** **2009b**). The UrbanM has recently been introduced into this model to study the roles of urban processing in global aerosol microphysics and chemistry and to compute the abundance and radiative forcing of anthropogenic aerosols (***Cohen et al.,*** **2010**). This effort also serves as the first step toward introducing the full UrbanM into the 3-D aerosol-chemistry-climate framework.

3.5 Ocean Component

The IGSM framework retains the capability to represent ocean physics and biogeochemistry in several different ways depending on the question to be addressed. It can utilize either the 2-D (latitude-longitude) mixed-layer anomaly-diffusing ocean model or the fully 3-D ocean general circulation model (GCM). The IGSM with the 2-D ocean is more computationally efficient and more flexible for studies of uncertainty in climate response. In applications that need to account for atmosphere-ocean circulation interactions, or for more detailed studies involving ocean biogeochemistry, the diffusive ocean model is replaced by the fully 3D ocean GCM component.

2-D Ocean Model: The IGSM2.2 has a mixed-layer anomaly-diffusing ocean model with a horizontal resolution of 4º in latitude and 5º in longitude. Mixed-layer depth is prescribed based on observations as a function of time and location. Vertical diffusion of anomalies into the deep ocean utilizes a diffusion coefficient that varies zonally as well as meridionally. The model includes specified vertically-integrated horizontal heat transport by the deep oceans, and allows zonal as well as meridional transport. A thermodynamic ice module has two layers and computes the percentage of area covered by ice and ice thickness, and a diffusive ocean carbon module is included (***Sokolov et al, 2005; Holian et al***., **2001; *Follows et al*. 2006**).

3-D Ocean General Circulation Model: The IGSM2.3 ocean component is based on a state-of-the-art 3D MIT ocean GCM (*Marshall et al.*, 1997). Embedded in the ocean model is a thermodynamic sea-ice module (***Dutkiewicz et al.,*** **2005**). The 3D ocean component is currently configured in either a coarse resolution (4° by 4° horizontal, 15 layers in the vertical) or higher resolution (2° by 2.5°, 23 layers; or alternate configuration with higher resolution in the topics) depending on the focus of study and the computational resources available. The efficiency of ocean heat uptake can be varied (e.g., ***Dalan et al.*** **2005**) and the coupling of heat, moisture, and momentum can be modified for process studies (e.g., ***Klima 2008***). In addition, a biogeochemical component with explicit representation of the cycling of carbon, phosphorus and alkalinity can be incorporated. Export of organic and particulate inorganic carbon from surface waters is parameterized and biological productivity is modelled as a function of available nutrients and light (***Dutkiewicz et al***., **2005)**. Air-sea exchange of CO_2 allows feedback between the ocean and atmosphere components. An additional module with explicit representation of the marine ecosystem (***Follows et al***., **2007**) has been introduced in an "offline" (i.e. without full feedbacks to the full IGSM) configuration (see further discussion in Section 4.2.3).

3.6 Land and Vegetation Processes

The Global Land System (GLS, ***Schlosser et al***., **2007**) of the IGSM links biogeophysical, ecological, and biogeochemical components: (1) the NCAR Community Land Model (CLM), which calculates the global, terrestrial water and energy balances; (2) the Terrestrial Ecosystems Model (TEM) of the Marine Biological Laboratory, which simulates carbon (CO_2) fluxes and the storage of carbon and nitrogen in vegetation and soils including net primary production and carbon sequestration or loss; and (3) the Natural Emissions Model (NEM), which simulates fluxes of CH_4 and N_2O, and is now embedded within TEM. A recent augmentation to the GLS enables a more explicit treatment of agricultural processes and a treatment of the managed water systems (***Strzepek et al*., 2010a**). The linkage between econometrically based decisions regarding land use (from EPPA) and plant productivity from TEM has been enhanced (***Cai et al*., 2010**). And the treatment of migration of plant species to include meteorological constraints (i.e. winds) to seed dispersal has been enhanced (***Lee et al***., **2009, 2010a,b**). The representation of natural and vegetation processes also includes a diagnosis of the expansion of lakes and changes of methane emissions from thermokarst lake expansion/degradation (***Gao et al*., 2010**; ***Schlosser et al*., 2010**). In addition, continuing updates to CLM and TEM are also incorporated into the GLS framework. In all these applications, the GLS is operating under a range of spatial resolutions (from zonal to gridded as low as 0.5º), and is configured in its structural detail to accommodate various levels of process-oriented research both in a coupled framework within the IGSM as well as in standalone studies (i.e. with prescribed atmospheric forcing).

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