Chapter VI – Future Model Development

Cloud-resolved models

Cloud resolving models (CRMs) have spatial resolutions of less than a few kilometers. CRMs can therefore explicitly calculate many atmospheric systems that are on sub-grid scales of AGCMs (Randall *et al*. 2005). These include the mesoscale organizations in squall lines, updrafts and downdrafts, and cirrus anvils. The CRMs also allow calculation of cloud properties and cloud amount with more realistic dynamical conditions, and thus their impact on radiative transfer. Because of improved resolution, CRMs can also better simulate the spatial distribution of precipitation and convective enhancement of the surface fluxes, which are important to describe the interaction of the atmosphere with the land and ocean surfaces.

CRMs are variations of models designed for mesoscale storm and cumulus convection simulations. At CRM scales, hydrostatic balance is no longer universally valid. CRMs are therefore formulated with non-hydrostatic equations in which vertical accelerations are calculated. Tripoli (1992) contains a good review of the various model formulations used to simulate non-hydrostatic meteorological dynamics.

Similar to AGCMs, CRMs also contain empirical relationships to calculate the impact of sub-grid scale processes. These relationships however have different roles from those in AGCMs. First, because CRMs capture a larger portion of the size spectrum of the meteorological systems, the impact of the empiricism is less important in CRMs. For example, cumulus parameterizations for deep tropical convection are no longer needed in CRMs. Second, since CRMs better resolve atmospheric dynamics, cloud processes can be formulated based on more realistic physical conditions.

CRMs can therefore accommodate more sophisticated microphysical and precipitation processes than AGCMs. One-moment bulk microphysical schemes (mass concentration only) with two-class liquid (cloud water and rain) and three-class ice (cloud ice, snow and graupel/hail) are commonly used in CRMs. This level of sophistication is rare in AGCMs and, in any case, unlikely to be useful given the absence of the needed detail in the small scale flow field. Some CRMs have started to use explicit bin-microphysical schemes. These schemes solve the stochastic kinetic equations for the size distribution functions of water droplets (both cloud droplets and raindrops) and different ice particle habitats (i.e., columnar, plate-like, dendrites, snowflakes, graupel and frozen drops). Because of better size information, these schemes can more realistically calculate the nucleation or activation processes of clouds, along with more accurate calculation of conversion processes among different cloud habitats (Tao 2007).

Subgrid scale processes in CRMs are calculated by using turbulence models. The majority of CRMs use either simple first-order closure to diagnostically compute the turbulent diffusion strength, or the one-and-a-half order closure to prognostically calculate the turbulent kinetic energy which is then used to determine turbulent diffusion coefficients. Prognostic methods typically take into account the thermodynamic stability, deformation, shear stability, diffusion, dissipation, moist processes and transport of sub-grid energy (Klemp and Wilhelmson 1978). Other CRMs use higher order turbulence closures (Krueger 1988).

Radiative transfer in the atmosphere and surface fluxes of heat and moisture in CRMs are computed using algorithms similar those in AGCMs. Because of better spatial resolution atmospheric fields such as clouds and precipitation, CRMs calculate these parameters more accurately than AGCMs.

High resolution of CRMs, however, is at the expense of model domain size and integration length. Current computing infrastructure, with the exception of the Japanese Earth Simulator, only allows CRMs to simulate the atmosphere of less than a few thousand kilometers. Most previous CRM studies were carried out only for two-dimensional slices of the atmosphere, an assumption that somewhat compromises the fidelity of three-dimensional convective cloud simulations. Few CRM simulations are carried out for longer than a year. CRMs with explicit bin-microphysics or high order turbulence closures have been integrated only for a few days.

Research with CRM falls into two categories. In the first one, CRMs are used to investigate the time evolution of cloud systems by specifying realistic initial conditions. This type of study enables deterministic understanding of convection initiation, cold pools, surface fluxes and their direct comparison with aircraft and other high resolution observation. The simulations are however only valid for a few hours. In the second category, CRMs are used to study the properties of cloud ensembles by specifying external forcing fields. This approach allows statistical description of multiple cloud types with different life cycles (Tao 2007).

Although CRMs are advantageous over ACGMs in describing moist processes, they also face unique challenges when utilized in forecasting mode. CRM results are often very sensitive to the specification of initial conditions and external forcing conditions. They are also sensitive to the physical algorithms in themit. There are still large uncertainties in the CRM cloud microphysics, including prediction of ice particle concentrations, falling speed calculation of cloud habitats, initial broadening of cloud droplet spectra in warm clouds, details of hydrometeor spectra evolution, quantitative simulations of entrainment rates (Cotton 2003). The high sensitivity of model results makes it difficult to rigorously validate CRMs.

Several field programs, such as the DOE ARM program, have enabled collection of observational data that are essential to evaluate CRMs (Zhang *et al*. 2001; Tao *et al*. 2004). Results from these programs will facilitate the improvement of model physics. On the other hand, a global model approaching CRM resolution has been developed and has been integrated on the Earth Simulator with spatial resolution of 7 kilometers (Miura *et al*. 2005). There is another paradigm for multiscale problems that will be likely attempted in the next decade. This is the nesting of coupled regional models of the atmosphere and the ocean within global coupled GCMs. Progress on these fronts will guide where climate models should go in the future.

Biogeochemistry

The Carbon Cycle *Libes* [1992] defined biogeochemistry as "the science that studies the biological, chemical, and geological aspects of environmental processes". At present, three-dimensional climate models are usually limited to the physical climate system: atmosphere, land, ocean, and sea ice. However, the physical climate system and biogeochemical processes are tightly coupled. For example, changes in climate affect the exchange of atmospheric CO_2 with the land surface and ocean, and changes in CO_2 fluxes affect Earth's radiative forcing and thus the physical climate system. Some recently developed AOGCMs have included the carbon cycle and confirmed the potential for strong feedback between it and global climate (Cox *et al*., 2001; Friedlingstein *et al*., 2001; Govindasamy *et al*., 2005). The next generation of AOGCMs is expected to include the carbon cycle and possibly interactive atmospheric aerosols and chemistry. Such models would predict time-evolving atmospheric concentrations of CO_2, etc., using anthropogenic emissions rather than assumed concentrations as input.

Models that include the global carbon cycle must account for the processes shown in **Figure VI.1**. Boxes represent the carbon reservoirs and arrows show the direction and magnitude of the fluxes. The present-day atmosphere holds about 750 Petagrams of carbon atoms in the form of CO_2. ("Petagrams of carbon" is abbreviated PgC; note that 1 Petagram $=10^{15}$ grams $= 10^9$ metric tons.) A roughly equal amount of carbon is contained in land vegetation and about twice as much in soils. The ocean is by far the largest reservoir of carbon with about 40,000 PgC. The largest flows of carbon in the system are photosynthetic uptake of ~120 PgC / year by terrestrial ecosystems (gross primary productivity or GPP), plant respiration which releases ~60 PgC / year back to the atmosphere (hence the remainder—net primary production or NPP—is ~60 PgC / year), and heterotrophic (soil) respiration which releases ~60 PgC / year. In the upper ocean, photosynthesis by marine organisms incorporates carbon at the rate of ~50 PgC / year, about 4/5 of which is reconverted to CO_2 and related inorganic carbon molecules by respiration. The remaining ~10 PgC / yr of organic matter sinks into deep ocean, a process sometimes called the "biological pump." This organic matter is oxidized and eventually returns to the surface ocean via a combination of both convective / turbulent mixing and the "solubility pump" (the latter so named because it involves sinking of cold water, with high levels of dissolved inorganic carbon, near the poles).

The present-day global carbon cycle is not in equilibrium because of fossil fuel burning and other anthropogenic carbon emissions. These must of course be included in models of climate change, but such a calculation is not easy because human-induced changes to the carbon cycle are small compared to the large natural fluxes discussed above. Fossil fuels are estimated to contain about 4,000 PgC. During the 1990's, fossil fuel emissions averaged ~6 PgC / year and carbon release from land cover change (e.g. deforestation) averaged ~2 PgC / year, providing a net anthropogenic source of ~8 PgC / year to the atmosphere. Terrestrial and ocean ecosystems together absorbed about half of this flux, i.e. ~4 PgC / year, with the net uptake of carbon by the terrestrial biosphere and the net flux of CO_2 into the ocean each estimated as ~2 PgC / year. The rest (~ 4 PgC/ year) accumulated in the atmosphere, appearing as an increasing concentration of atmospheric CO_2.

The globally averaged carbon reservoirs and fluxes shown in **Figure VI .1** are consistent with estimates from a variety of sources, but substantial uncertainties attach to the numbers (e.g. often a factor > 2 uncertainty for fluxes; see Prentice *et al*. 2001). Additional uncertainty applies to regional, seasonal and interannual variations in the carbon cycle. Evaluation of climate-carbon cycle models is therefore problematic: for many aspects of a simulation it is not clear what the "right answer" is.

Recent three-dimensional climate-carbon modeling studies

The feedbacks between the physical climate system and the carbon cycle are represented plausibly, but with substantial differences, in different AOGCM / carbon-cycle models. Cox *et al*. (2000) obtained a very large positive feedback, with global warming reducing the fraction of anthropogenic carbon absorbed by the biosphere and thus boosting the model's simulated atmospheric CO_2; Friedlingstein *et al*. (2001) obtained a much weaker feedback. Thompson *et al*. (2004) demonstrated that making different assumptions about the land biosphere within a single model gave markedly different feedback values. Using the same model, Govindasamy *et al*. (2005) noted a positive correlation between the magnitude of carbon cycle feedback and the sensitivity (q.v.) of the physical climate system.

A recent study examined carbon cycle feedbacks in eleven coupled AOGCM / carbon-cycle models using the same forcing (Friedlingstein *et al*., 2006). There was unanimous agreement among the models that global warming will reduce the fraction of anthropogenic carbon absorbed by the biosphere, but the magnitude of this feedback varied widely among the models (Fig VI .2), leading to additional global warming (when the models included an interactive carbon cycle) ranging between 0.1 to 1.5 °C. Eight models attributed most of the feedback to the land biosphere, while three attributed it to the ocean.

These results demonstrate extreme sensitivity of climate model output to assumptions about carbon-cycle processes. To reduce the consequent uncertainties in model predictions of the future, it will be necessary to thoroughly compare model output with real-world observations for present day conditions. Studies that span a broad range of ecosystems and climate regimes, including both and global remote sensing by satellites and local in situ measurements, are beginning to be integrated with diagnosis and improvements of the models. For example, the CCSM Biogeochemistry Working Group has recently begun intercomparison of three different biogeochemistry sub-models within the CCSM (climate.ornl.gov/bgcmip).

Other biogeochemical cycles Methane (CH_4) is a potent greenhouse gas and part of the carbon cycle. Also, CO_2-fertilized ecosystems are limited by the availability of nutrients such as nitrogen and phosphorous, so changes in their availability are important to the carbon cycle through changes in plant nutrient availability (Field *et al*. 1995; Schimel 1998; Nadelhoffer *et al*. 1999; Shaw *et al*. 2002; Hungate *et al*. 2003). Future climate-carbon models will probably represent these variables. The few models that do so now show less plant growth in response to increasing atmospheric CO_2 (Cramer *et al*. 2001, Oren *et al*. 2001, Nowak *et al*. 2004). Incorporation of other known limiting factors such as acclimation of soil microbiology to the higher temperatures (Kirschbaum, 2000; Tjoelker, *et al*., 2001), and other elemental cycles such as the sulfur cycle (which affects aerosol and cloud properties), will also be important in developing comprehensive Earth system models.

Land Cover and land management practice changes

Generally, climate-carbon models do not include the effects land cover and land management changes on natural ecosystems. Land cover change is often accounted for simply by prescribing estimates for the historical period (e.g., Houghton, 2003) and the IPCC SRES scenarios for the future. These estimates do not include practices such as crop irrigation and fertilization. Many models with “dynamic vegetation” do not actually simulate crops; they allow only natural vegetation to grow. Deforestation, land cultivation and related human activities will probably be included in at least some future AOGCMs, enabling assessment of total anthropogenic effects on the global climate and environment (Ramankutty *et al*. 2002, Root and Schneider 1993).

Ocean Biogeochemistry

With respect to the ocean, we are concerned with how global warming impacts the marine environment including changes in the carbon content of the ocean and feedbacks to the atmosphere. Also of importance are the effects of modified ocean temperature, salinity and circulation patterns on the ocean's biota. Implementation of ocean biogeochemistry processes into AOGCMs is still in the development stage (e.g. CCSM Biogeochemistry Working Group Meeting Report, Mar. 2006, and GFDL Earth System Model, *http://gfdl.noaa.gov/~jpd/esmdt.html*) but is expected to proceed rapidly (*Doney et al.* 2004) to improve simulation of the ocean carbon cycle under various scenarios.

One challenge to this effort is the complexity of the ocean's ecosystems. Complexity is added with each organism that fixes nitrogen, denitrifies, calcifies, or silicifies because each adds additional parameterizations and variables to the system (*Hood et al*. 2006). There needs to be sufficient complexity in the biological models to capture the variability of the system as observed. In addition, models should include processes that are important over time periods substantially greater than a year (*Rothstein et al.* 2006) in addition to much shorter periods. However, Earth system models cannot be so complex that their computational cost precludes their actual use, and adding complexity to the biogeochemistry models may lead to a decrease in their predictive ability because the inability to constrain the model with the available data (*Hood et al*. 2006). Thus, as with other component models such as those simulating clouds and convection, the development of ocean (and land) BGC models for incorporation into physical climate models involves a trade-off between realism and tractability.

The current strategy of climate modeling groups to address ocean carbon and biogeochemistry includes systematic comparison of different models in the Ocean Carbon-Cycle Model Intercomparison Project (OCMIP) under auspices of the International Geosphere-Biosphere Programme (IGBP). The most recent phase of OCMIP involved 13 groups—including several from the USA—implementing a common biological model in their different GCMs (*Najjar et al.* 2006). The common biological model includes five prognostic variables: inorganic phosphate (PO_4^{2-}), dissolved organic phosphorus (DOP), dissolved oxygen (O_2), dissolved inorganic carbon (CO_2 + HCO_3^- + CO_3^{2-}) and total alkalinity (the acid / base buffering capacity of the system). Intercomparison of the models revealed significant differences in simulated biogeochemical fluxes and reservoirs. A biogeochemistry model's realism of any particular simulation is closely tied to the dynamics of the simulation's circulation model. The US climate modeling groups are building upon this community effort to incorporate biogeochemistry into the ocean component of the models.

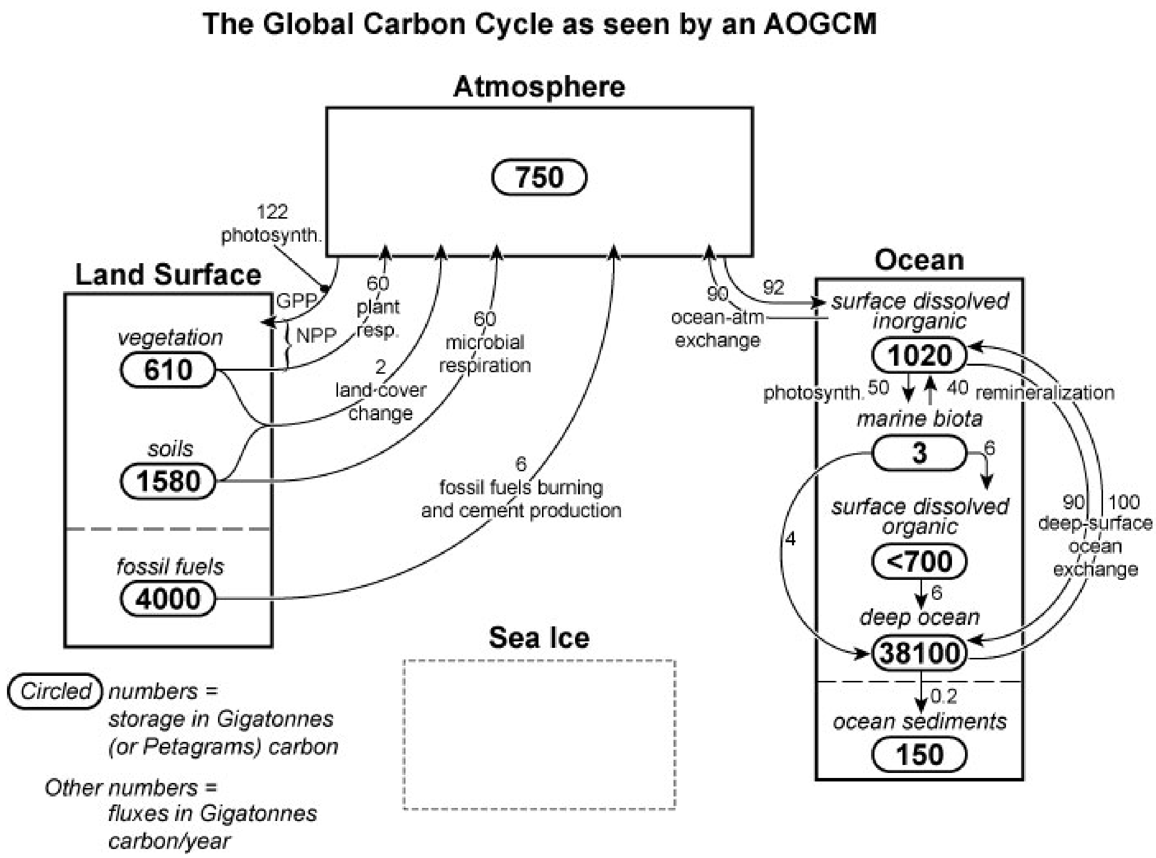

Figure VI 1: *The global carbon cycle from the point of view of existing physical climate system models (coupled AOGCMs). The four boxes represent atmosphere, land-surface, ocean and sea-ice—the major components of AOGCMS. Earth System Models will evolve from AOGCMS by incorporating the relevant biogeochemical cycles into the four-box framework (with the sea-ice component not being a reservoir of carbon). Numbers shown are average values for the 1990s. Small (≤1 PgC / year) fluxes such as carbon runoff from land to ocean and methane fluxes are not shown, except for burial of ~0.2 PgC / year in ocean bottom sediments. Burial in ocean sediments removes carbon from the AOGCM four-box domain;*

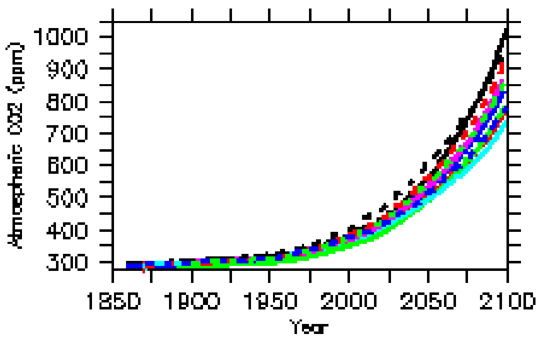

Figure VI .2: *Time series of atmospheric CO_2 temperature from eleven different AOGCM / carbon cycle models (from Friedlingstein et al. 2006, Figure 1(a))*