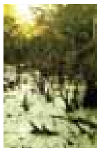
CHAPTER 6

Future Model Development

Climate models are evolving toward greater comprehensiveness, incorporating such aspects of the chemical and biological environment as active vegetation on land and oceanic biogeochemistry that affect and are affected by the physical climate. Climate models are simultaneously evolving toward finer spatial resolution.

Improvements in climate simulations as resolution increases can be both incremental and fundamental. Incremental improvements are expected in treatment of the atmosphere due to better simulation of atmospheric fronts, interactions among extratropical storms and sharp topographic features, and, especially, tropical storms. In the ocean, finer resolution incrementally improves the simulation of narrow boundary currents and the circulation in relatively small basins, such as the Labrador Sea, that play key roles in oceanic circulation.

More fundamental changes also happen in both the atmosphere and the ocean as resolution improves. In the ocean a key transition occurs at grid scales of tens of kilometers, at which point mesoscale eddies (see Chapter 2) begin to be explicitly resolved. In the atmosphere, a fundamental transition takes place when the grid scale drops to a few kilometers, where direct simulation of dominant deep convective circulations begins to be feasible and the model's dependence on uncertain subgrid-scale parameterization of deep moist convection diminishes.



In the following, we discuss these more fundamental oceanic and atmospheric transitions and then describe some examples of increased comprehensiveness in climate modeling (see also Chapter 2 for glacial modeling, another important future development).

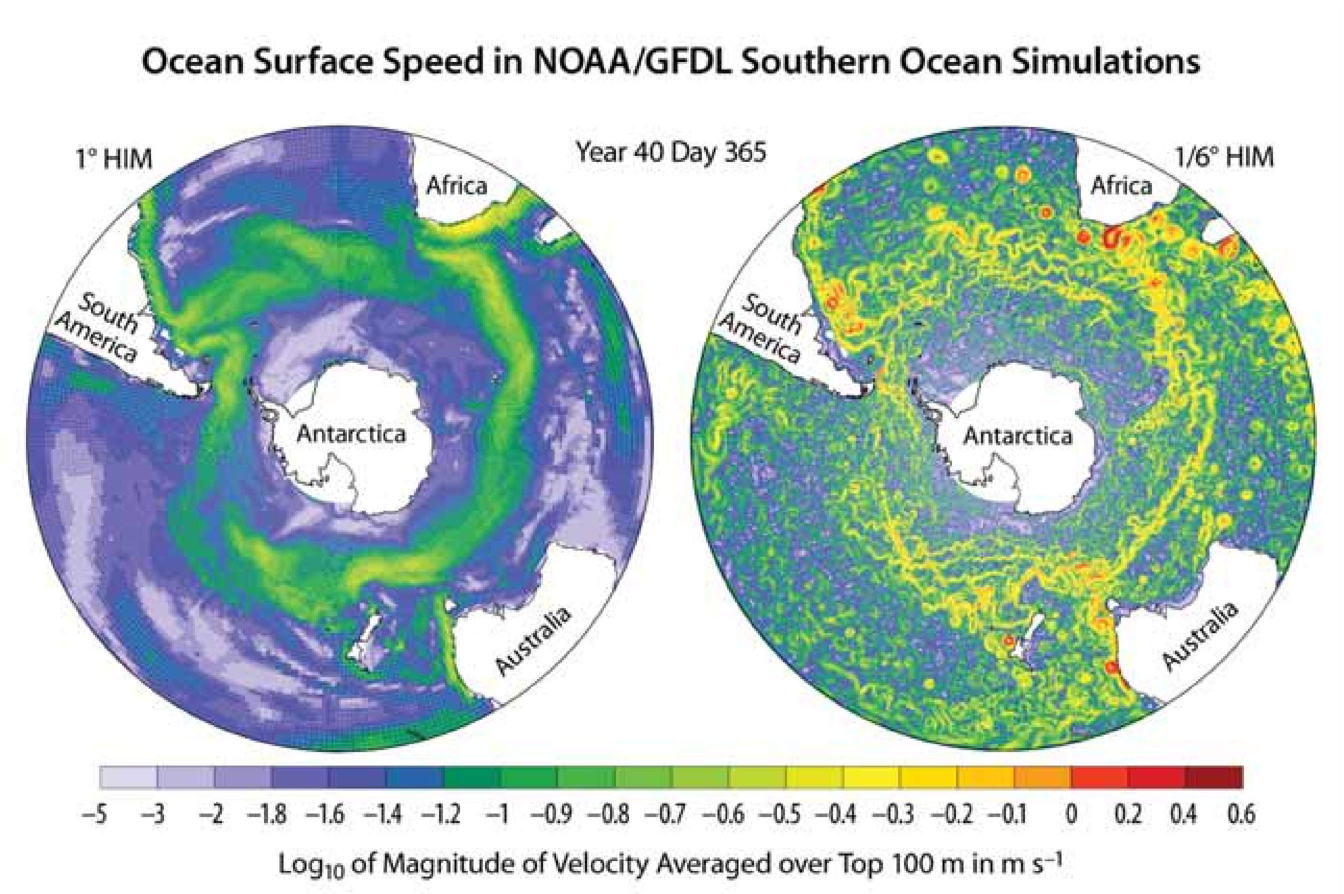
The climate modeling enterprise is evolving along additional paths (apart from evolution of the models themselves) that are not discussed here. One path is the creation of large ensembles of model simulations by varying uncertain physical parameters so as to better estimate the associated uncertainties [quantifying uncertainty in model predictions (called QUMP); Murphy et al. 2004; climateprediction.net]. Others include the movement toward initializing climate models with estimates of observed climatic states, particularly the observed oceanic state, so as to optimize the realism of decadal forecasts, which marks an evolution toward the merging of seasonal-interannual and decadal forecasting (Troccoli and Palmer 2007).

6.1 HIGH-RESOLUTION MODELS

6.1.1 Mesoscale Eddy-Resolving Ocean Models

The distinction between laminar and turbulent flow in the ocean is fundamental. Simulations of the more realistic turbulent regime promise to substantially raise the level of realism in oceanic climate simulations. For example, Fig. 6.1 shows two simulations of the Southern Ocean by an ocean model developed at the Geophysical Fluid Dynamics Laboratory (GFDL) (Hallberg and Gnanadesikan 2006). The field shown is an instantaneous snapshot of the surface current speed. Resolution of the model on the left is about 1° latitude. The result is a relatively laminar (nonturbulent) flow with a gently meandering circumpolar current. The figure on the right is obtained by reducing the grid size to 1/6 of a degree. A much more turbulent flow is simulated by the model with abundant vortex generation. This model is beginning to resolve the spectrum of mesoscale eddies that populate the Southern Ocean and many other oceanic regions. As discussed in Chapter 2, the effects on ocean circulation of mesoscale eddy-induced mixing are parameterized in current ocean models, which can be thought of as essentially laminar.

While progress has been made in recent years, explicit simulation of these eddies undoubtedly is more reliable than mixing parameterizations. In the Southern Ocean, eddies are thought to control the circumpolar current's response to wind changes (Hallberg and Gnanadesikam 2006) and the way carbon dioxide is taken up by the Southern Ocean.



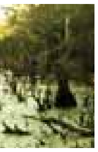


Figure 6.1. Surface-Current Speed in Two Simulations of the Southern Ocean in Low- and High-Resolution Ocean Models.

[From Fig. 6 in R. Hallberg and A. Gnanadesikam 2006: The role of eddies in determining the structure and response of the wind-driven Southern Hemisphere overturning: Results from the modeling eddies in the Southern Ocean (MESO) project. *J. Physical Oceanography*, **36**, 2232–2252. Reproduced by permission of the American Meteorological Society (AMS).]

Global mesoscale eddy-resolving ocean models are beginning to be examined in various modeling centers in the United States and around the world, even though exploiting such models will require substantial increases in computational resources. Challenges that may arise when these models are integrated for long time periods include maintaining realistically small amounts of mixing across constant-density surfaces in the more turbulent flows to avoid distortion of much slower thermohaline circulations.

As noted in Chapter 5, models provide estimates of the climate system's centennial-scale variability that underlies attribution studies of climatic trends. Seeing if eddy-resolving OGCMs increase the variability level on long time scales in climate models will be of great interest.

6.1.2 Cloud-Resolved Atmospheric Models

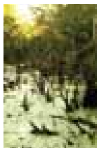
As atmospheric models attain higher resolution and more detailed representation of physical processes, short-range weather prediction and longer-range climate prediction become more synergistic (Phillips et al. 2004). This is particularly evident in "cloud-resolving models" (CRMs) with spatial resolutions of less than a few kilometers. CRMs can explicitly simulate atmospheric systems that exist on scales much smaller than the grid resolution of conventional atmospheric general circulation models (AGCMs) (Randall et al. 2003; Khairoutdinov, Randall, and DeMott 2005). These systems include mesoscale organizations in squall lines, deep updrafts and downdrafts, and cirrus anvils. CRMs also allow calculation of cloud properties and amounts based on more realistic small-scale structure in the flow field. The desired result is not only better simulations of regional climates, especially in the tropics, but also more reliable estimates of cloud feedbacks and climate sensitivity.

CRMs are variations of models designed for mesoscale storm and cumulus convection simulations. At CRM grid scales, hydrostatic balance is no longer universally valid. CRMs are therefore formulated with nonhydrostatic equations in which vertical accelerations are calculated explicitly (Tripoli 1992). Like AGCMs, CRMs must employ empirical parameterizations to calculate the impact of subgrid scale processes, but CRMs explicitly represent a larger portion of the size spectrum of meteorological systems, so the parameterizations' impact on large-scale circulation and climate may be less severe. Most important, cumulus parameterizations for deep tropical convection are not needed in CRMs. CRMs can accommodate more realistic microphysical processes, including those by which aerosols nucleate cloud drops, allowing more convincing treatment of aerosol and cloud interactions involved in indirect aerosol radiative forcing.

However, shallow nonprecipitating convection (which produces fair-weather cumulus clouds) is dominated by flows on scales less than 1 km and will probably still require subgrid-scale parameterization in foreseeable global CRMs. Cloud feedbacks in regions of shallow convection are an important source of disparity in climate sensitivity in CMIP3 models (Bony et al. 2006). Furthermore, most cloud microphysical processes take place on CRM subgrid scales and so must be parameterized. Thus, uncertainty in cloud feedbacks will not disappear when global CRMs begin to play a role in climate assessments, but modelers hope that uncertainty will be reduced substantially.

Global models with CRM resolution have been attempted to date only at the Japanese Earth Simulator, but, with continued increase in computer power, global CRMs are expected to become centrally important in climate (as well as weather) research. Nevertheless, as noted above, major uncertainties in cloud microphysics will remain, especially in the prediction of ice-particle concentrations, fall speed of cloud particles, hydrometeorological spectra evolution, and entrainment rates into convective plumes (Cotton 2003). At CRM resolutions, more sophisticated algorithms of radiative-transfer calculation than those in current GCMs may be required because the plane parallel assumption for convergence of radiant energy may not be valid. Validation of CRMs probably will continue to take place in regional models and short-range forecasts, followed by their incorporation into global models.

Several observational programs such as the DOE Atmospheric Radiation Measurement

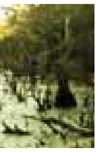


(ARM) Program have collected data essential to evaluate CRMs (M.H. Zhang et al. 2001; Tao et al. 2004). Results from such programs will facilitate improvement of CRM subgrid-scale physics. Extensive parameter-sensitivity tests with global models will still be needed to reduce uncertainties in microphysics and the treatment of shallow convection for climate sensitivity and regional climate-change simulation.

6.2 BIOGEOCHEMISTRY AND CLIMATE MODELS

6.2.1 Carbon Cycle

The physical climate system and biogeochemical processes are tightly coupled. Changes in climate affect the exchange of atmospheric CO_2 between land surface and ocean, and changes in CO_2 fluxes affect Earth's radiative forcing and thus the physical climate system. Some recently developed atmosphere-ocean general circulation models (AOGCMs) include the carbon cycle and have confirmed the potential for strong feedback between it and global climate (Cox et al. 2000; Friedlingstein et al. 2001; Govindasamy et al. 2005). The next generation of AOGCMs may include the carbon cycle as well as interactive atmospheric aerosols and chemistry. Models that include the carbon cycle are able to predict time-evolving atmospheric CO_2 concentrations using, as input, anthropogenic emissions rather than assumed concentrations.



Simulation of the global carbon cycle must account for the processes shown in Fig. 6.2. As the figure shows, the present-day global carbon cycle is not in equilibrium because of fossil-fuel burning and other anthropogenic carbon emissions. These carbon sources must, of course, be included in models of climate change. Such a calculation is not easy because human-induced changes to the carbon cycle are small compared to large natural fluxes, as shown in the figure. In addition, although the globally and annually averaged carbon reservoirs and fluxes shown in the figure are consistent with estimates from a variety of sources, substantial uncertainties are attached 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.

Feedbacks between the physical climate system and the carbon cycle are represented plausibly but with substantial differences in various 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, thus boosting the model's simulated atmospheric CO_2. Friedlingstein et al. (2001) obtained 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 of the physical climate system.

A recent study examined carbon-cycle feedbacks in 11 coupled AOGCM carbon-cycle models using the same forcing (Friedlingstein et al. 2006). The models unanimously agreed that global warming will reduce the fraction of anthropogenic carbon absorbed by the biosphere—a positive feedback—but the magnitude of this feedback varied widely among models (Fig. 6.3). When models included an interactive carbon cycle, predictions of the additional global warming due to carbon-cycle feedback ranged between 0.1 and 1.5°C. Eight models attributed most of the feedback to the land biosphere, while three attributed it to the ocean.

These results demonstrate the large sensitivity of climate model output to assumptions about carbon-cycle processes. Future carbon-cycle models, coupled to physical climate models and constrained by new global remote-sensing datasets and in situ measurements, may allow more definitive projection of CO_2 concentrations in the atmosphere for given emission scenarios. CCSP SAP 2.2 contains more information on the carbon cycle and climate change (CCSP 2007).

6.2.2 Other Biogeochemical Issues

Methane (CH4) is a potent greenhouse gas whose atmospheric concentration is controlled by its emission rate and the atmosphere's oxidative capacity (especially hydroxyl radical concentration). Methane concentrations are now much higher than in preindustrial times but have

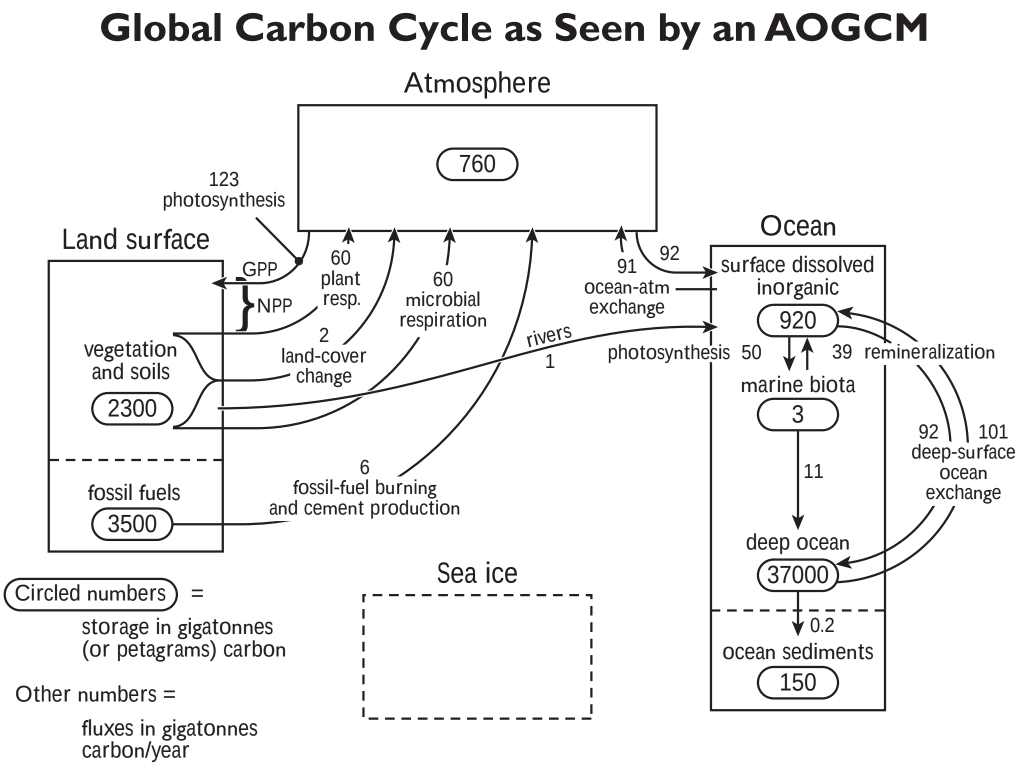


Figure 6.2. Global Carbon Cycle from the Point of View of Existing Physical Climate System Models (Coupled AOGCMs).

The four boxes represent atmosphere, land surface, ocean, and sea ice—major components of AOGCMs. Earth system models will evolve from AOGCMs by incorporating relevant biogeochemical cycles into the four-box framework (with sea ice not acting as a carbon reservoir). Numbers shown are average values for the 1990s. Small (≤1 PgC/year) fluxes such as those involving methane are not shown, except for burial of 0.2 PgC/year in ocean-bottom sediments, assuming a 50-50 split between plant and microbial respiration.

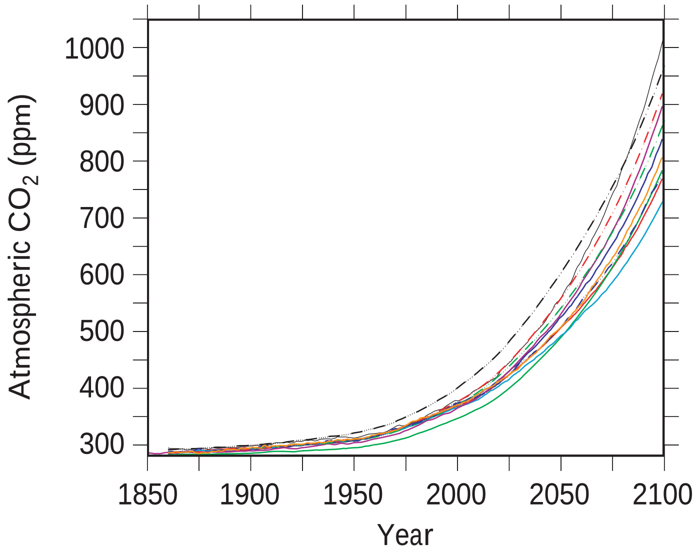
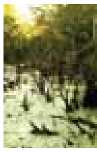


Figure 6.3. Time Series of Atmospheric CO_2 from 11 Different AOGCM Carbon-Cycle Models.

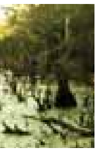
[From Fig. 1(a) of P. Friedlingstein et al. 2006: Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison. *J. Climate*, **19**, 3337–3353. Reproduced by permission of the American Meteorological Society (AMS).]



not increased in the past decade, for reasons that continue to be debated. Whether or not this trend carries into the future has substantial implications for radiative forcing. To resolve this question, AOGCMs would need to include atmospheric chemistry models incorporating a number of different trace gases and reaction rates.

Another emerging issue is the interactive evolution of climate with the storage of water and carbon by plants. To address this process, dynamic vegetation models (in which plant growth is calculated rather than specified a priori) are under development at modeling centers in the United States and elsewhere. This inclusion of a wider range of processes poses challenges [e.g., it amplifies errors in rainfall prediction (Bonan and Levis 2006)]. In addition, ecosystems fertilized with CO_2 are limited by the availability of nutrients such as nitrogen and phosphorous that are important to the carbon cycle (Field, Jackson, and Mooney 1995; Schimel 1998; Nadelhoffer et al. 1999; Shaw et al. 2002; Hungate et al. 2003). Future climate-carbon models probably will need to include these nutrients. 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, Ellsworth, and Smith 2004). Incorporation of other known limiting factors such as acclimation of soil microbiology to higher temperatures (Kirschbaum 2000; Tjoelker, Oleksyn, and Reich 2001) will be important in developing comprehensive Earth system models. Aerosol modeling also will be a central element in future models (this subject will be covered by CCSP SAP 2.3, whose estimated publication date is June 2008).

Often, climate-carbon simulations include natural ecosystems but do not include the effects of human land-cover and land-management changes (e.g., deforestation and reforestation). Land-cover change often is accounted for simply by prescribing estimates for the historical period (e.g., Houghton 2003) and for future scenarios from the IPCC Special Report on Emissions Scenarios (IPCC 2000). These estimates do not include practices such as crop irrigation and fertilization. Many models with “dynamic vegetation” do not actually simulate crops; they only allow natural vegetation to grow. Deforestation, land cultivation, and related human activities probably will be included in at least some future AOGCMs, enabling more complete assessment of total anthropogenic effects on the global climate and environment (Ramankutty et al. 2002; Root and Schneider 1993).



6.2.3 Ocean Biogeochemistry

Climate change impacts on the marine environment—including changes in the ocean’s biota and carbon content due to modified ocean temperature, salinity, and circulation patterns—must be accounted for, along with terrestrial biogeochemistry, in a complete Earth system model. Implementation of ocean biogeochemistry processes into AOGCMs is under way to improve simulation of the ocean carbon cycle under various scenarios [e.g., “CCSM Biogeochemistry Working Group Meeting Report,” March 2006 (www.ccsm.ucar.edu/working_groups/Biogeo/reports/060328_BGCWGrpt.pdf); GFDL’s Earth system model (gfdl.noaa.gov/~jpd/ esmdt.html); Doney et al. 2004]. One issue receiving particular attention in recent years is that ocean productivity may be increased through iron fertilization via dust particles, potentially reducing atmospheric CO_2 (Martin 1991). This effect is being assessed by both observational programs (e.g., Bishop, Davis, and Sherman 2002) and climate-carbon models (Jickells et al. 2005).

An important challenge to these efforts is the complexity of ocean ecosystems. Adding to this complexity are organisms that fix nitrogen and denitrify, calcify, or silicify; accounting for each adds parameterizations and variables to the system (Hood et al. 2006). Biological models need to be sufficiently complex to capture the observed variability on various time scales, since this variability provides essential tests for the models. As in many aspects of climate modeling, however, complexity that outgrows the ability to constrain models with available data should be avoided (Hood et al. 2006).

Modeling groups have undertaken systematic comparison of different models in the Ocean Carbon Cycle Model Intercomparison Project (OCMIP) under the auspices of the International Geosphere-Biosphere Programme. OCMIP’s most recent phase involved 13 groups—including several from the United States—implementing a common biological model in their different OGCMs (Najjar et al. 2007). 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 system’s acid- and base-buffering capacity). Model intercomparison revealed significant differences in simulated biogeochemical fluxes and reservoirs. A biogeochemistry model’s realism was found to be tied closely to the dynamics of the simulation’s ocean circulation. Just as for land vegetation modeling, a serious challenge to climate models is presented by the quality of the physical climate simulation required for realistic biogeochemical modeling.