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Challenges in Earth System Modelling: Approaches and Applications

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CHAPTER SEVENTEEN

CHALLENGES IN EARTH SYSTEM MODELLING:
APPROACHES AND APPLICATIONS

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Contents

17.1. Introduction 297
17.2. Key Challenges (1) 298
  17.2.1 Atmosphere modelling 299
  17.2.2 Land modelling 299
  17.2.3 Ocean modelling 301
17.3. Key Challenges (2) 302
  17.3.1 Overall discussion 302
  17.3.2 Biogeochemical modelling needs 302
  17.3.3 Methodologies for employing output from Earth system models 302
17.4. Conclusions 305
References 305

17.1. INTRODUCTION

Earth system modelling has taken on increasing importance over the past several years. These models are being used to address an increasing number of environmental and global change problems of societal concern (e.g. Adams et al., 1998; Easterling et al., 2000; Foley et al., 2003). Perhaps most commonly known is the application to possible greenhouse-gas induced warming (Hoffman et al., 2005). Other compelling problems include the climatic effects of land use changes, aerosols (including sulphate emissions, and smoke from biomass burning; Erickson et al.,

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1995; Oglesby et al., 1999), changing trace gas fluxes, interactions and feedbacks with the global carbon cycle and the impacts of changing nutrient fluxes to Earth's ecosystems. While originally based on general circulation models of the atmospheric component of climate, over the years the models have expanded to include oceanic circulation, land and sea ice, the full biosphere, atmospheric and oceanic chemistry, and biogeochemical cycles (such as carbon, sulphur, oxygen and iron).

These models attempt to simulate the full complexity of natural systems, which includes the rendering of many interconnected physical processes that range across orders of magnitude in temporal and spatial scale (Washington and Parkinson, 2005; McGuffie and Henderson-Sellers, 2005). This poses a massive challenge in how to incorporate all the relevant processes, in developing a computer code that has appropriate numerical capabilities, and in obtaining computational resources sufficient to make the many required model runs at the necessary resolution in time and space. Satisfactory solutions for all of these remain to be found. But these are hardly all the challenges. These models produce voluminous output, which if nothing else tax data storage and processing systems. But since the models also try to capture the full complexity of natural systems, interpreting the many feedbacks and interplays is essentially as difficult as understanding them in the real Earth system using real observations. Indeed, among other tasks, these models are used to fill in massive gaps in our observational network, as well as understanding of the key physics involved. The above are primarily scientific and numerical engineering issues. Perhaps the most important problem, however, is how to use the model results to understand and help to solve real issues; that is, how to apply the results in a manner that will help stakeholders address their problems. This can be posed as how to employ the model results, both direct, quantitative output, and the qualitative understandings obtained from them, into Decision Support Systems (DSS) (Oglesby, 2004; Evans et al., 2004). It is also becoming increasingly important to explicitly include significant feedbacks that involve the human dimension and activities, though what these links would be and how to implement them is at a very rudimentary stage.

The preliminary drafting of this chapter and the subsequent workshop brought together model developers, experienced users of Earth system models, along with interested potential users, and persons interested in the application or implication of model results, including integration of these models within DSS frameworks. The goal was to move beyond mere presentation of individual projects and results, and have a truly interactive dialogue between all of these interested parties.

17.2. **Key Challenges (1)**

Model development, including making and refining simulation of key physical processes and numerical developments needed to run the models on current and planned future computer systems. Listed below by model component are some key areas that need to be addressed.
17.2.1 Atmosphere modelling

(i) Convection is one of the hardest atmospheric phenomena to model (Boville et al., 2006; Roads et al., 2005). This is both because of the very small spatial scale over which it occurs and because of limited physical knowledge on how and when it occurs. Yet convection is a key way by which vertical motions, and associated mass and energy fluxes, occur in the atmosphere. This need exists for almost all regions, but is especially important for the tropics, since it is a region where convection dominates weather phenomena and exerts a strong influence on the heat and energy budget of the entire Earth. Fully-coupled climate models generally simulate a fairly constant double Inter-Tropical Convergence Zone (ITCZ), but such a double-occurrence is only rarely seen in observations. See Figure 17.1 and note the very strong double band of precipitation over the low latitude Pacific Ocean in the model simulation (top), compared to observations (middle). This is very apparent in the model minus observations difference (lower plot in Figure 17.1). This very serious deficiency is almost certainly related to basic shortcomings in the simulation of convective processes.

(ii) Clouds and radiation, along with convection, are the most poorly simulated phenomena in the atmosphere. We are not even sure if clouds have a negative or positive feedback overall on atmospheric temperatures. While clear-sky radiation is fairly well-known, cloudy sky radiation is much less so. Clouds also share with convection the problem of spatial scale. To fully solve the problem may ultimately require explicit cloud-resolving models, which in turn require spatial resolutions of 5 km or less; this is much smaller than any current Global Climate Model (GCM) resolution, and at the frontier of what even limited area (e.g. Evans et al., 2005) regional climate models can accomplish.

(iii) The boundary layer is the region of the atmosphere probably the most poorly simulated overall, and yet it is the key by which fluxes are transferred from the free atmosphere to land and water surfaces and vice-versa (Hu et al. 2000, 2005). In large part, model deficiencies are due to our poor physical understanding of key boundary layer physical processes; this is most severe over land, but is also problematic over oceans. This lack of understanding in turn is almost certainly because of a lack of suitable observations. These observations are extremely difficult and costly to make, especially at the very fine time and space scales required, but are likely essential before sufficient progress can be made in improving climate models in this regard.

(iv) The ability to conduct specific tracer transport in atmospheric models is a critical component of simulations that use inverse techniques to assess surface source-sink relationships. As the number of tracers reach several hundred and interact with both gas phase and particulate species the challenges of atmospheric chemistry and biogeochemistry increase.

17.2.2 Land modelling

(i) Inclusion of dynamic vegetation schemes. Progress is being made in this direction but more is needed, both to understand how vegetation will change as climate
Figure 17.1  Precipitation rate (in units of mm/day) for the model run, observations (Legates, 1987) and the difference plot.
changes, and because these changes in vegetation can in turn have feedbacks that affect climate.

(ii) Energy and moisture fluxes with higher resolution and greater physical precision. These fluxes are the key way in which the land surface interacts with the atmosphere; they have very small spatial scales, are in many instances poorly measured, and usually simulated with simplistic routines most appropriate for smooth surfaces (Evans et al., 2005). In many aspects, this need overlaps with the required improvements in boundary layer understanding and simulation described above.

(iii) Mixed vegetation types in a single grid box. Given the fairly coarse resolution of even present-day global models (the latest IPCC model runs are at a resolution of approximately 140 km by 140 km in latitude and longitude), how best to describe the small-scale structure in vegetation and other land surface types contained within a single model grid. At the most basic level, it is still unclear whether the best approach is to lump vegetation types into one uniform ‘average type’ and perform calculations based on this (homogeneous approach) or to perform the calculations separately for each vegetation type, and then average the results (heterogeneous approach).

(iv) Vertical structure of the vegetation. This will allow a better simulation of vertical transport of fluxes, and is related to both items (ii) and (iii). Better simulation of forest canopies is a particular need. This is also important for biogeochemical flux modelling.

17.2.3 Ocean modelling

(i) Eddy resolving ocean models. The spatial scales of ocean eddies are much smaller than those of atmospheric eddies, making it much more difficult to properly resolve and simulate these motions. Yet such eddies are a major source of mass, energy and constituent transport in the oceans.

(ii) Explicit treatment of ocean convection. Convection in the ocean is very different from, and even more poorly understood and modelled than that in the atmosphere. Furthermore, because the ocean is largely barotropic, convection is restricted to just a few key geographic regions. Yet this convection is responsible for most of the deep water in the ocean. Hence changes in the nature of this convection are likely to have dramatic consequences on climate (Stephens et al., 2005).

(iii) Oceanic ecosystem model with the carbon cycle and several other biogeochemical tracers. The ocean is an often overlooked portion of climate when ecosystems are considered. Yet it is a key part of the carbon cycle, and other tracers such as dimethyl sulphide are increasingly known to be important yet poorly understood and modelled. Many other trace gases impact atmospheric chemistry and climate variability.

(iv) Sea ice is a critical component of the Earth system; for example, at present there is considerable concern about the sharp reduction, and possible disappearance, of perennial sea ice in the Arctic. Earth system models have consistently shown that sea ice is one of the most sensitive components of the overall system, yet it remains poorly understood, much less modelled. Furthermore, the Arctic and the Antarctic have very different sea ice regimes (the Arctic is convergent; the Antarctic
divergent) – models may be tuned to replicate one or the other for at least present-day conditions, but have considerable difficulty in simulating both properly.

17.3. **Key Challenges (2)**

*Application of Earth system models to relevant scientific questions of global change including feedbacks in the integrated biogeochemical-physical climate system.*

17.3.1 **Overall discussion**

Several new climate, carbon and biogeochemical modelling results that require multi-teraflop computational resources were discussed within the context of climate science and high performance computing. Fully coupled Earth system models, in both the biogeochemical and physical sense, that specifically track carbon dioxide and dimethyl sulphide exchange between the ocean, land and atmosphere systems need to be better defined. As an example of the utility of next generation Earth system models, a series of specific biogeochemical processes and feedbacks in the climate system need to be examined. As computational platforms evolve to the level whereby a detailed portrayal of atmospheric chemistry and biogeochemistry is possible, this will allow a greater state of realism in climate and Earth system simulation.

17.3.2 **Biogeochemical modelling needs**

(i) Inclusion of a fully interactive carbon cycle with the physical climate system. This will allow the complex feedbacks between the carbon cycle and climate to be investigated. An example of this type of feedback involves atmospheric precipitation, soil moisture trends and the exchange of atmospheric carbon dioxide with the terrestrial biosphere.

(ii) Full biogeochemistry in land and ocean models. This approach will allow feedbacks and interactions between the myriad of chemical cycles in the terrestrial and oceanic systems to be evaluated. An example is atmospheric deposition of iron. Changes in the atmospheric transport of dust particles from continental regions to the ocean due to climate changes in soil moisture will impact the ability of the ocean to uptake carbon dioxide.

(iii) Terrestrial biosphere response to nutrient tracer deposition. This will allow the impact of the deposition of nutrients, such as nitrogen, iron and phosphorus, to be examined in the fully-coupled biogeochemical physical climate system.

17.3.3 **Methodologies for employing output from Earth system models**

17.3.3.1 **Energy modelling**

Consistent with the theme of fully-coupled, comprehensive Earth system model creation, highly detailed numerical models of energy usage, resource allocation and quantitative estimates that feedback with climate are required. As an example, an
energy use and resource allocation model is driven with GCM-simulated climate variables from 2000–2025 so as to predict the financial impacts and feedbacks of global warming (Hadley et al., 2006). In this study, the output from the global climate simulations are used to computed heating and cooling days for the time period 2000–2025. The heating and cooling days evolve over time as the climate essentially warms and this impact is assessed by the use of a detailed economic/energy model. The relative energy usage between natural gas, coal and hydro in a changing climate is evaluated as a function of climate change and resource availability. Figure 17.2 shows the change in usage of various fuels as a function of time over the next 25 years. As the US warms due to increased atmospheric carbon dioxide levels, there is an increased need for cooling (air conditioning) and a decreased need for heating.

Since cooling, for the most part, requires electricity the burning of coal is a feedback whereby the flux of carbon dioxide into the atmosphere increases due to global warming. Energy is not the only need; we also must evaluate many Earth system model predictions within the context of guiding policy and decision making.

### 17.3.3.2 Central America climate change and implications

Another example is a modelling project in Central America whereby future climate as a function of greenhouse gas increases and land use change is simulated. This allows the climate to be predicted and assessments made with regard to precipitation and temperature on agriculture. In this case, simulations using IPCC scenarios made with a GCM were used to drive a regional climate model (RCM, see Evans et al., 2005). The RCM was necessary because the fairly coarse horizon-
Figure 17.3 (a) Temperature differences (in °C) and (b) precipitation differences (in cm/month) 2050–2005 for a business as usual simulation from the MM5 RCM as driven by the global CCSM3 GCM.
tal resolution (approximately 150 km in latitude and longitude) of the GCM does not satisfactorily resolve the complex, mountainous topography of Central America. The 12 km horizontal resolution of the RCM, though still not perfect, does a much better job (Hernandez et al., 2006). Figure 17.3 shows simulated surface temperature and precipitation differences between 2005 and 2050 under a “business as usual” IPCC scenario (http://www.ipcc.ch/). A warming is seen almost everywhere; this is largest (up to 5°C) where the land mass is largest (e.g. south Mexico, Guatemala and Honduras) and smaller (generally 1°C or less) where the land mass is smaller (e.g. Costa Rica and Panama). Precipitation generally decreases along the Caribbean coast, due to a reduction of the trade winds in this very moist region, but shows small increases elsewhere. The overall conclusion is that Central America becomes warmer and more humid, with less precipitation in currently wet regions, and more where sufficient precipitation is more problematical. These results have profound implications for agriculture and tourism, the two major industries, and are being used in conjunction with a decision support system to make explicit predictions as to future behaviour (http://servir.nsstc.nasa.gov/).

17.4. CONCLUSIONS

The creation of fully-coupled Earth system models includes not only the physical and chemical Earth system but a variety of human dimension-related simulations such as an explicit treatment of policy decisions. A key challenge is to successfully incorporate human feedbacks into the models so that they can be integrated into decision support systems (see Chapter 3). Prediction of energy usage and demand as a function of future climate change is a new and evolving aspect of global climate modelling and has a series of complicated and sensitive feedbacks embedded in the science. This type of model simulation requires High Performance Computing and is a significant challenge to computer science, climate science and economic and policy simulation science. A further challenge in Earth system modelling, and the one concentrated upon in this chapter has been the limited understanding of many of the key physical and biogeochemical processes, which is in turn partly a result of a lack of suitable observations due to the high costs and difficulties involved. Further progress in refining the simulation of the key physical processes is therefore subject to the capabilities of producing observations at the finer temporal and spatial scales required.

REFERENCES


