

# Degrees of Change

A Newsletter from the Global Change Integrated Assessment Program

Department of Engineering & Public Policy, Carnegie Mellon, Pittsburgh, PA 15213 Vol. 1(5) July, 1996

## Pursuing Climate Modelling's Grail

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There is a small but persistent debate on the utility of general circulation climate models (GCMs) relative to simpler climate models. Yet for all their shortcomings (and because of their complexity), GCMs provide the only plausible model platform for producing regionally specific climate simulations. This fact is widely recognized, and is important given that impacts researchers and policy makers prefer climate change information at regional scales rather than global scales. Regional detail allows researchers to assess potential climate impacts on particular ecosystems and economic sectors, thereby providing a basis for formulating policy responses. Less clear at present is how rapidly GCMs are progressing towards the provision of reliable regional climate simulations, and how climate research should be directed to attain this goal. This essay is an initial exploration of these questions.

The task of modelling the earth's climate leads almost inexorably to the contemporary GCM. The reasons for this are apparent from an examination of the role of water in the climate system, which is perhaps the major issue in climate change research. In its gaseous form, water vapor is the most important greenhouse gas. In its liquid form in clouds, water's reflectivity and absorption are major components in the earth's radiation balance. The role of clouds and water vapor in the climate system are generally acknowledged as being among the principal determinants and uncertainties of climate change. Transports of water vapor and changes of phase between its gaseous and liquid forms are critical in redistributing energy in the vertical and horizontal through the atmosphere. Redistribution of heat and water influences regional climate directly and by altering temperature dependent feedbacks, and influences global climate by modifying the amount of energy radiated to space.

To produce detailed simulations of earth's climate that account for the major flows of energy and their conversion from one form to

another, it is necessary to account for the processes that partition water between its various phases and distribute it through the atmosphere. This task requires simulation of radiation, convection, and transport processes in three dimensions in an internally consistent manner. GCMs are the only climate models that provide the appropriate three dimensional framework in which to attempt to account for these processes and provide regionally specific detail that follows from their simulation.

In recent years, a loosely defined, but coherent vision of the future path of GCMs has emerged in the technical climate literature discussing the utility of the models for providing information about greenhouse climate change. This vision describes an expectation of incremental progress leading up to the provision of useful regional climate simulations the "Grail" of climate modelling for impacts research and policy. The vision contains the following implicit and explicit assumptions:

**Internal Consistency** GCMs are useful because they can generate three-dimensional fields of hydroclimatological variables. Further, these fields are internally consistent, giving the GCM an advantage over other methods for generating insight into climate change.

**Large Scale Simulation Adequate** The large scale circulation fields simulated by GCMs are sufficiently well simulated that these fields provide useful input to methodologies for producing regional scale information from the large scale.

**Steady Improvement** GCMs are improving steadily as their resolution increases, and as they incorporate representations of more of the processes known to be important in determining climate.

**Imminent Regional Skill** Within a modest period of time, GCMs will have advanced to the point that they are capable of producing reliable simulations of regional climate.

Below we discuss these assumptions and check progress toward climate modelling's Grail.

### INTERNAL CONSISTENCY

Since GCMs provide physically based representations of atmospheric and oceanic processes, their simulations of physical quantities such as precipitation and temperature can be internally consistent. That is, the model can keep track of how changes in one quantity effect changes in other quantities, propagating interactions through the model. For instance, the temperatures calculated by the model during precipitation episodes will be influenced by the thermodynamic effects of the precipitation process on *in situ* environmental temperatures. Further, the model system as a whole usually conserves energy, mass, and momentum, ensuring that physical laws are not violated in simulating changes in model quantities. So far so good. However, if one looks deeper at the way precipitation is simulated in the models, one finds that the world of internal consistency in the model is different from the real world equivalent.

In the real atmosphere, precipitation occurs in fairly discrete events, with relatively high intensity in convective cloud systems, and with relatively low intensity in stratiform cloud systems. Convective and stratiform precipitation events are less discrete in climate models, and they tend to be simulated with much weaker intensities than their real world counterparts. The models tend to precipitate relatively continuously with weak intensity in order to deliver the same amount of precipitation on the surface of the earth as the real system. This suggests that a different set of physical processes is generating precipitation in the model. Thus while the model may well be internally consistent in propagating interactions and conserving energy, mass, and momentum, it is doing so according to a different set of physical processes.

The above result is not surprising given that precipitation is not explicitly resolved in climate models, and must be parameterized. It seems more appropriate to look at the simulation of the storm systems in which much of the precipitation is embedded, since synoptic scale storm systems are explicitly resolved in climate models. In a study of the simulation of synoptic storm systems over the North Pacific North America region, Risbey and Stone (1996) found that the climate models

they examined simulated very different synoptic configurations for storm events than the real world. The behavior of the jet streams and associated low pressure systems in the models during storm events in northern California bore little qualitative resemblance to the jet stream responses known to produce storms in that region. Thus again, while the models may be internally consistent in accounting for flows of heat, mass, and momentum through the earth system in simulating climate responses, those flows are generated through a set of large scale dynamic processes that do not necessarily bear even a qualitative resemblance to their real world counterparts. While deficiencies of this kind would vitiate attempts to simulate regional climate, the shortcomings giving rise to these deficiencies have not been systematically identified, and it is therefore not yet clear how difficult it will be to overcome them. Internal consistency is a *necessary*, but not a *sufficient* condition to ensure the qualitative realism of climate model simulations. Claims of internal consistency are more meaningful when coupled with a consideration of the realism of the representations of the physical and dynamical processes in the model.

### LARGE SCALE SIMULATION ADEQUATE

The adequacy of the simulation of large scale fields in GCMs for use as input for producing regional information is generally not explicitly questioned. The above study of the synoptic climatology of several GCMs in the North Pacific North America region suggests that more scrutiny of the large scale fields is required. The stationary waves, jet streams, and storm tracks in the GCMs show major differences from the observations, both in the mean and in their interannual variations. In addition, although the stationary wave and jet stream patterns associated with individual storms exhibit robust differences from mean fields in the observations, these differences are not captured in the models. Consequently, the larger scale fields necessary for driving nested models and impacts models for the basin, or for western North America in general, are problematic in these models. These results are probably generalizable to other models and regions, since they pertain to generic large scale features of the mid-latitude planetary circulation and appear to stem from deficiencies that are likely common among models. In any event, it does suggest that the adequacy of large scale GCM simulations should not be taken for granted.

### STEADY IMPROVEMENT

Climate models undergo constant modifications by the research teams that run them. Parameterizations for physical processes not hitherto included in the model are developed from time to time as it becomes clear that those processes are potentially important for climate. Existing parameterizations are also refined as more information comes to light on the physics of the parameterized process, or on shortcomings of the original parameterization. Further, as computers become more powerful, the resolution of the models is slowly increased. For instance, the horizontal resolution of typical climate models has roughly doubled over the last decade or so. It is tempting to equate these modifications with an overall improvement of climate models, and this is the general impression that is given in the literature. However, these modifications do not necessarily entail improvement. Furthermore, it is difficult to measure the improvement of something as complex as a climate model, where more apparent realism may be obtained for some variables or processes at the expense of a loss of apparent realism for others. While there do exist objective measures of some aspects of the simulation of a model, these are inherently partial, and the overall assessment of improvement is inherently subjective. The subjective nature of the assessment does not necessarily detract from its force, but it makes the practice of quality control in model assessment all the more difficult.

An increase of resolution *per se* may not necessarily improve the performance of a climate model. Model parameterizations are tuned within the context of a particular resolution, and so the parameterizations may not be as effective when the resolution alone is changed. Reworking or retuning the parameterizations at higher resolution can overcome this problem, but again there are no guarantees that the simulation will improve uniformly. For example, the National Center for Atmospheric Research developed a new Community Climate Model (CCM2) to supersede the older CCM1, incorporating new parameterizations and a doubling in resolution. While this resulted in clear improvements in a number of aspects of the simulation, there were still some features of the large scale flow field in the model that were better represented in CCM1 than CCM2.

### IMMINENT REGIONAL SKILL

The culmination of steady improvements of GCMs is sometimes taken to be the capability to generate useful regional climate simulations. For instance, IPCC (1990) stated that “a major advance in the ability to predict the regional differences in climate change is expected to take place in the late 1990s, with the implementation of higher resolution models of the atmosphere.” The IPCC time-line for narrowing the uncertainties for “predictions of regional differences in climate including water resources” ends in the year 2005 as “a result of higher resolution models and a better understanding of the water cycle.”

The fact that a model is ‘improved’ does not mean that it is necessarily better at simulating regional climate. First we need to establish prerequisites for gaining confidence in a model’s ability to generate useful regional simulations. In addition, the definition of what is good enough in a regional climate simulation depends on the purposes for which the climate output is used (Risbey, 1994). Lacking a theory of climate as such, it is difficult to know what the prerequisite features of a model simulation are that provide a sound basis for regional simulations. To date there has been little, if any, systematic effort in this direction. It seems safe to conclude that there is not a sufficiently well articulated view of what climate models would need to simulate well, and what the major impediments to doing that are. If this is true, then it is not clear whether there is any rational basis for concluding that GCMs are approaching a point where useful regional simulations will be possible.

### SUMMARY

In summary, GCMs may provide internally consistent representations of model climate processes, but do not necessarily provide realistic representations of the physical and dynamical processes that govern flows of mass, energy, and momentum in the real system. Detailed studies of the changes in large scale flow fields in GCMs for a variety of precipitation regimes show that the changes in the model fields do not correspond well with the changes in large scale fields in the real atmosphere. This casts doubt on the tacit assumption that GCM simulations of the large scale fields are already adequate for climate change studies. The notion that GCMs are improving steadily due to increases in resolution and development of parameterizations is difficult to prove or disprove. This is partly due to the multifaceted nature of model out-

puts, where some features of a simulation may improve while others degrade when a change is made. To be sure, model development is not a synonym for model improvement. The idea that model improvement is leading inexorably to a state where GCMs can provide useful regional simulations is not grounded on a reasoned consideration of the hurdles that need to be overcome in reaching this goal.

In light of these results, it is difficult to know when GCMs will have progressed to the point that they can provide useful regional climate simulations. One possible way forward is to try to bridge the gaps between the 'wish-lists' of the different impacts groups and the capabilities of the climate mod-

els rather than naively projecting the model capabilities forward to a point where there is no gap. This may require compromises from both climate modelers in terms of the information that can be supplied to impacts groups, and from the impacts community in terms of the level of detail and type of features desired. Further, isolated 'wish lists' have not proven to be of much use, and may only contribute to the wanton projection of GCM capabilities. Wish lists need to be accompanied by analyses of what kinds of climate processes (and at what scales) are important in governing changes in the variables in the lists. These processes can then be explicitly scrutinized in the climate models to provide some calibration of the match between what is desired and what can reasonably be produced. If it turns out that the GCM of the future can provide reliable information for regional climate simulations, then the above process should help produce a convergence on that outcome by directing attention to salient climate processes.

Despite the limitations of GCMs (Stone and Risbey, 1990), they provide the only plausible framework for potentially attaining the useful regional prediction Grail. We may never know for sure whether that Grail is attainable or not, but there is potential to approach it in more systematized ways than presently seems to be the case. In addition, it would be prudent to define a range of alternative goals for policy-oriented climate research.

#### FURTHER READING

Cohen, S. 1990: Bringing the global warming issue closer to home: the challenge of regional impact studies. *Bulletin Amer. Met. Soc.* 71 (4), 520--526.

Gates, W. 1985: The use of general circulation models in the analysis of the ecosystem impacts of climatic change. *Climatic Change* 7, 267--284.  
 IPCC 1990: *Climate Change. The IPCC Scientific Assessment.* J. T. Houghton, G. J. Jenkins, and J. J. Ephraums (Eds.), Cambridge Univ. Press, Cambridge, England, 365pp.  
 Kerr, R. 1994: Climate Modeling's fudge factor comes under fire. *Science* 265, 1528.  
 Risbey, J., 1994: *On the Use of Climate Models to Assess the Impacts of Regional Climate Change on Water Resources.* Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, Mass., 213pp.  
 Risbey, J., and P. Stone, 1996: A Case Study of the Adequacy of GCM Simulations for Input to Regional Climate Change Assessments. *J. Climate* 9 (7), 1441--1467.  
 Shackley, S., P. Young, S. Parkinson, and B. Wynne 1996: Uncertainty, complexity and concepts of good science in climate change modelling: Are GCMs the best tools? Submitted to *Climatic Change*.  
 Stone, P., and J. Risbey 1990: On the limitations of general circulation climate models. *Geophysical Research Letters* 17 (12), 2173-2176.

#### GLOSSARY OF TERMS

**convective cloud:** Convection refers to the vertical motion of air masses due to buoyant or mechanical forces. A convective cloud forms when an air parcel saturates while undergoing convective motion.

**GCM:** A GCM solves discrete representations of the equations of motion of a fluid (atmosphere and ocean) on a three-dimensional grid (latitude, longitude, height) on a sphere. The equations express conservation laws for energy, momentum, and mass, along with an equation of state. As much as possible, GCMs model climate processes from first principles - i.e. by trying to explicitly include the physics underlying climate processes at the relevant scales of action. Some compromise is inevitable (parameterization) since some important climate processes (e.g. convection) are not resolved by GCM grids.

**large scale:** The scales associated with synoptic weather systems and the processes that drive them (e.g. jet streams) spanning temporal scales from a week to a month and spatial scales from thousands to tens of thousands of kilometers.

**parameterize:** From parametric representation. To develop a representation of a process in terms of a selected set of characteristic parameters rather than from first principles.

**stratiform cloud:** Clouds forming in layers due to the forced lifting of stable air over a

large horizontal scale. Often associated with the lifting of warm air masses in a low pressure system.

**synoptic scale:** The scale associated with high and low pressure systems in the atmosphere, typically spanning a week in time and thousands of kilometers in space.

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Our work at the Center for Integrated Study of the Human Dimensions of Global Change is made possible through grants from: The National Science Foundation, the Department of Energy, the Electric Power Research Institute, the National Oceanic and Atmospheric Administration, STATOIL, and Carnegie Mellon University.

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