A University Perspective on Global Climate Modeling

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ABSTRACT

Global atmospheric models are proliferating, in part because of the widespread availability of powerful computers. There are about two dozen global modeling groups at work in the United States today. These groups are put into four categories, considering both laboratories and universities and development and applications. Community models are a special subgroup and in principle are both developed and applied by the community. Most U.S. global modeling groups are focusing on applications rather than on development. This is especially true in the university community, although over the years university groups have made important contributions in the model-development arena. A key role of university groups is to train new model developers at a rate matched to the community's demand for such scientists. A simple but functional conceptual organization of the U.S. global modeling community is suggested.

1. Introduction

Global atmospheric modeling began in the 1960s (Smagorinsky 1963; Leith 1964;[1] Mintz 1968; Kasahara and Washington 1967). University groups have been involved in general circulation model (GCM) development and applications since the dawn of global modeling[2] and have made major contributions to the state of the art.

In the middle 1970s, when I was doing my Ph.D. thesis work at the University of California, Los Angeles (UCLA), the UCLA GCM was running on an IBM 360 Model 91. In those days, the 360/91 was one of the fastest machines in the world. The GCM had seven levels, with a horizontal grid spacing of 5° longitude by 4° latitude, and on the 360/91 it took about 1.5 CPU h to crunch through one simulated day. The model required more than the few megabytes of memory that were available in the computer, so special-purpose code "paged" the model's working data in and out of disk. You could tell which part of the model was executing by listening to the sounds that the disk drives were making. It was wonderful.

GCMs were pretty exotic beasts in those days and much less familiar to meteorologists than they are today. The community climate model did not yet exist. GCMs were not yet being used for operational numerical weather prediction, although this was being actively contemplated. Climate models were not yet on the front pages of the newspapers, which meant not only that relatively little funding was available, but also that the purity of the science had not yet been defiled by the oily slime of fossil fuel politics. There were fewer than 10 global atmospheric modeling groups in the world in the middle 1970s, considering all types of institutions together. All of these groups were doing a significant amount of model-development research because there were no long-established models that could be borrowed from other centers. The UCLA group, under the direction of Profs. A. Arakawa and Y. Mintz, was virtually unique in that it was developing and running a GCM in a university environment (e.g., Mintz 1968).

[1] See also Leith, C. E., 1965: Numerical simulation of the Earth's atmosphere. *Methods Compute. Phys.*, **4**, 1–28.
[2] Picture the opening scene of *2001: A Space Odyessy.*

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Times have changed. The recent Atmospheric Model Intercomparison Project (AMIP; see Gates 1992) has drawn the participation of several dozen atmospheric general circulation models from all over the world. Roughly two dozen of these are from various U.S. institutions, including both laboratories and universities. In short, there have been tremendous and very rapid changes in the U.S. global modeling community; we have been on a frantic and disorienting roller coaster ride. Where in the world has the roller coaster carried us, and where do we go from here? This essay addresses these questions from a university perspective; other views are out there, but here is mine.

2. Are GCMs "big science"?

We are all aware that GCMs are run in large laboratories like the National Center for Atmospheric Research (NCAR) and the Geophysical Fluid Dynamics Laboratory. This gives the impression that GCMs are "big science," at least by atmospheric science standards, but the reality is different.

As everyone knows, computers have been increasing in speed, and most of all in speed per unit cost, at an amazing rate. This trend is having a dramatic effect on our ability to model the atmosphere, especially in the arena of global atmospheric modeling. It is now possible to do useful work with a low- to medium-resolution GCM on a workstation that costs $20,000 or less. While this is a lot of money by the standards of day-to-day life, it is tiny compared to the cost of a supercomputer, and it is well within the means of most university-based research groups. Very soon it will be possible to run a GCM on a laptop computer.[3,4]

In terms of numbers of personnel, GCM groups need not be very large and in reality are not very large, even in the major laboratories. Although a laboratory housing a comprehensive GCM development effort may employ hundreds of people, the number of Ph.D.-level FTEs (scientists) who are actively involved in developing a GCM is not likely to be more than 10 and is often closer to 5. Of course, all GCM development groups benefit enormously through collaborations with researchers at other institutions. Two or three talented in-house M.S.-level support scientists are needed to support a model-development effort and a modest model-applications effort besides. If a GCM is made available for community use, as at NCAR, then a substantial number of additional staff will be needed to provide "user services." If the model is in operational use, as at the National Centers for Environmental Prediction, then additional manpower is needed to ensure reliable real-time performance, to develop operational "products" for the end users, and to deal with the model's customer base.

The number of people involved in GCM applications (as opposed to development) obviously depends on the number of applications being undertaken at one time, but in a research environment the total number of persons per application is typically on the order of one to three. Here we use the term "applications" in a broad sense, to include everything from paleoclimate simulations, to diagnoses of specific circulation phenomena such as blocking or monsoons, to comparisons of model results with observations.

3. Categories of global modeling efforts

Broadly speaking, global modeling groups can be divided into two types:

- groups that specialize in *applications* (as defined above) of a model developed elsewhere; and
- groups that pursue a comprehensive program of model *development,* spanning most or all of the many elements of a model; model development groups typically also undertake applications of their models.

Each of these modeling group types exists in both laboratories and universities. It is thus useful to distinguish a total of four categories of modeling groups.

LD: Laboratory groups that do comprehensive development. By my count, there are five U.S. groups in this category. The major LD centers have operational or quasi-operational roles with large communities of "users." As a result, LD centers are forced to be somewhat conservative and they

[3] Due to FAA regulations, it will be necessary to shut the model down for 10 min after take-off and 10 min before landing.

[4] At about the same time, GCMs will begin running on workstations in high schools, and possibly elementary schools. They may even be running in the offices of congressmen. In fact, high school and junior high school students have already been running a GCM remotely on supercomputers at the Lawrence Livermore National Laboratory for several years now (M. McCracken 1996, personal communication).

tend to be bureaucratic. The LD groups do applications as well as development.

LA: Laboratory groups that specialize in applications. There are four U.S. groups in this category. The LA centers are mission oriented: they exist to support the research objectives of their agency patrons.

UD: University groups that do comprehensive model development. There are three U. S. groups here. The UD centers, which do not support user communities, have maximum freedom of action. The UD groups do applications as well as development.

UA: University groups that specialize in applications. There are 10 U.S. groups in this category. The UA groups tend to be discipline specific; for example, some focus on paleoclimate.

Note that this is a classification scheme for modeling groups, not for models. Because I have a strong instinct for self-preservation, I am not going to list out the various modeling groups that I have placed into each of the four categories listed above. The numbers of groups within each category are based on my own judgements and perceptions, and there is undoubtedly some room for disagreement on a case-by-case basis. Nevertheless, the main conclusions to be drawn from this categorization, listed below, are not likely to be widely disputed.

- There are, altogether, about two dozen global modeling groups in the United States.
- Considering laboratories only, there are about as many groups doing applications as development.
- The university community has many more groups doing applications than groups doing development.
- Even considering the universities and laboratories together, there are many more applications groups than development groups.

There is a special class of global models, called "community models." The concept of community models emerged during the 1980s. A community climate model can "belong" to the climate research community in two different ways: there can be community-based development and there can be community-based applications. There have been remarkably few instances, however, in which a university-developed parameterization or numerical method has been transplanted by a university researcher into a laboratory model and then adopted for "operational use" by the laboratory. The few exceptions tend to be cases in which the university researcher has a close contact inside the laboratory itself. In principle, however, true community development of a community model is quite feasible.

It is sometimes suggested that it is possible to make a plug-compatible global model so that an "outside" scientist can "easily make changes." With a few exceptions (e.g., radiation codes), however, this is a fantasy, and I am surprised that such claims are not greeted with more skepticism. Kalnay et al. (1989) make some good, common sense suggestions for programming styles that do in fact make it somewhat easier to exchange codes between models, but major difficulties remain. There are any number of concrete examples of real parameterizations that have been developed for one specific model and that, for very good physical and/or numerical reasons, can be transferred to another model only through a major surgical procedure, somewhat analogous to an organ transplant but more painful. One reason for such difficulties is that the different components of a model have to be designed to work together. For example, a land-surface vegetation parameterization or a sea ice parameterization or a snow-cover parameterization inevitably makes close connections with the boundary layer turbulence parameterization to which it is coupled. Adaptations can indeed be made for purposes of porting, but only through a substantial amount of work. Similarly, a stratiform cloud parameterization has to work with a turbulence parameterization, and a cumulus parameterization has to work with a stratiform cloud parameterization, and all of these have to work together with the model's discretization scheme. It is easy to talk about plugging together modules, but the reality is that a global model must have a certain *architectural unity* or it will fail.

For the past decade and more, NCAR has supported a community climate model (CCM) that is made available (now via anonymous FTP) to anyone anywhere. The CCM, which has evolved through several versions,[5] has been and is being used in a wide variety of applications by the climate research community, but its development has been carried out almost exclusively through an in-house effort at NCAR, and in the classification scheme discussed above NCAR has been counted in the LD category. Groups that use the CCM for applications have been counted in the LA

[5] Version 3 was released in May 1996.

or UA categories. Other community models have appeared and subsequently faded away; at present, the CCM is the only community climate model that is being actively supported by a U.S. institution.

4. The role of universities

What is the proper role of a university-based GCM group in the 1990s? Should it compete with the premier national laboratories in performing comprehensive and meticulously documented climate change simulations with possible policy implications (hint: No), such as those used by the Intergovernmental Panel on Climate Change (Houghton et al. 1990)? Should it support a large community of model users around the nation and the world? Should it provide operational numerical weather forecasts? Although some of these activities might be marginally possible in or on the periphery of a university environment, they are arguably inconsistent with the essentially educational mission of a university.

The first and most important thing that a university-based GCM group can do and should do is to educate new global modelers. The most critical factor limiting the rate of generation of new ideas is the number of people at work thinking them up. University-based GCM groups can increase the overall rate of generation of new ideas simply by adding to the population of thinkers. Consider the current population of graduate students clawing their way up through the ranks. Some of them will have an opportunity to work with a GCM. A subset of these will be successful in their research and at the same time develop a fascination with the model. They will be rewarded with the privilege of working 70 hours a week for the rest of their lives. It is not optimal for a student to learn climate modeling simply by running a community model developed by people the student has never met, working at facilities far away. Aspiring young model developers can learn best through close apprenticeships with scientists who are themselves actively contributing to model development. For this reason alone, enough model development work must occur in universities so as to supply newly trained young model developers fast enough to meet the needs of the climate research community.

The second thing that a university-based GCM group can do is to explore and test new ideas, through either development of new parameterizations and new numerical techniques or through innovative applications. Model development projects are very much in the spirit of academic research, and there is a strong history of such work. Of course, national laboratories can, should and do generate and explore new ideas too; universities have no monopoly on these creative activities. In a laboratory-based modeling center that is set up to support either a large user community or the mission of a particular agency, however, changes to the model must be approved through a bureaucratic and typically rather conservative process. A university group can "just do it." This freedom of action is a tremendous advantage when, as with model development, the name of the game is taking chances and trying new things.

5. A modest proposal

Wide-spread perceptions exist that 1) there are dozens of global models being developed in the United States today and 2) each global modeling group employs dozens of scientists and needs a supercomputer. The preceding discussion is intended to make it clear that both of these perceptions are wrong. Global modeling groups are generally modest in size and can make use of inexpensive workstations; the majority of global modeling groups are making applications of existing models but are not doing much in the way of model development.

Science is not about knowing things, it is about learning things. There are now and always will be differences of opinion about the best ways to formulate models. Such differences are both good and useful because they show where the climate research community has an opportunity to learn something. It is widely accepted that there are strong differences of opinion within the global modeling community about the best basic dynamical framework for global models—spectral, finite difference, and so on. At the same time, however, there are also strong differences of opinion about cumulus convection, about land-surface processes, about boundary layer turbulence, about stratiform clouds, about radiative transfer, about sea ice dynamics and thermodynamics, about the resolution needed in ocean models, and in short about nearly everything. This is good because these differences of opinion are signs of vitality in the field, and they drive the competition of ideas that leads to progress.

Model development efforts are by definition focused on what we do not understand very well, and so the key to successful model development is the generation of (good) new ideas, which can and usually do come from unanticipated directions, out of the blue. The only way to speed the generation of new ideas is to bring more and diverse (and hopefully better) minds to bear on the issues. Centralization is exactly the wrong approach.

With relatively minor adjustments, the U.S. global modeling community could be organized in a way that is both simple and functional. The four categories of modeling groups defined in this essay help to expose that order, as shown in Fig. 1. The diagram shows a single community model, which is both used and developed by the community. Development occurs at multiple LD and UD centers and also through close interactions with the operational numerical weather prediction center, which is an LD center of special importance. Each of these development centers pursues its own vision of the best model, and through a competition of ideas the most successful developments from each are incorporated into the community model. The community model is the primary vehicle that provides input to policy makers. The UA and LA centers all make use of the community model, thus maximizing the amount of feedback on its performance. Over a period of some years, it might be possible to bring about a convergence between the operational numerical weather prediction model and the (or a) community model. Certainly the rigors and reality checks of operational forecasting represent a particularly potent form of feedback to a model-development effort.

The status quo, which seems to have developed spontaneously and without strategic planning, is actually not very different from what is shown in Fig. 1. This organizational structure is "American" in style, in that it is pluralistic, distributed, and competitive. Such a distributed effort can make scientific progress much more quickly and efficiently than a centralized, bureaucratic system.

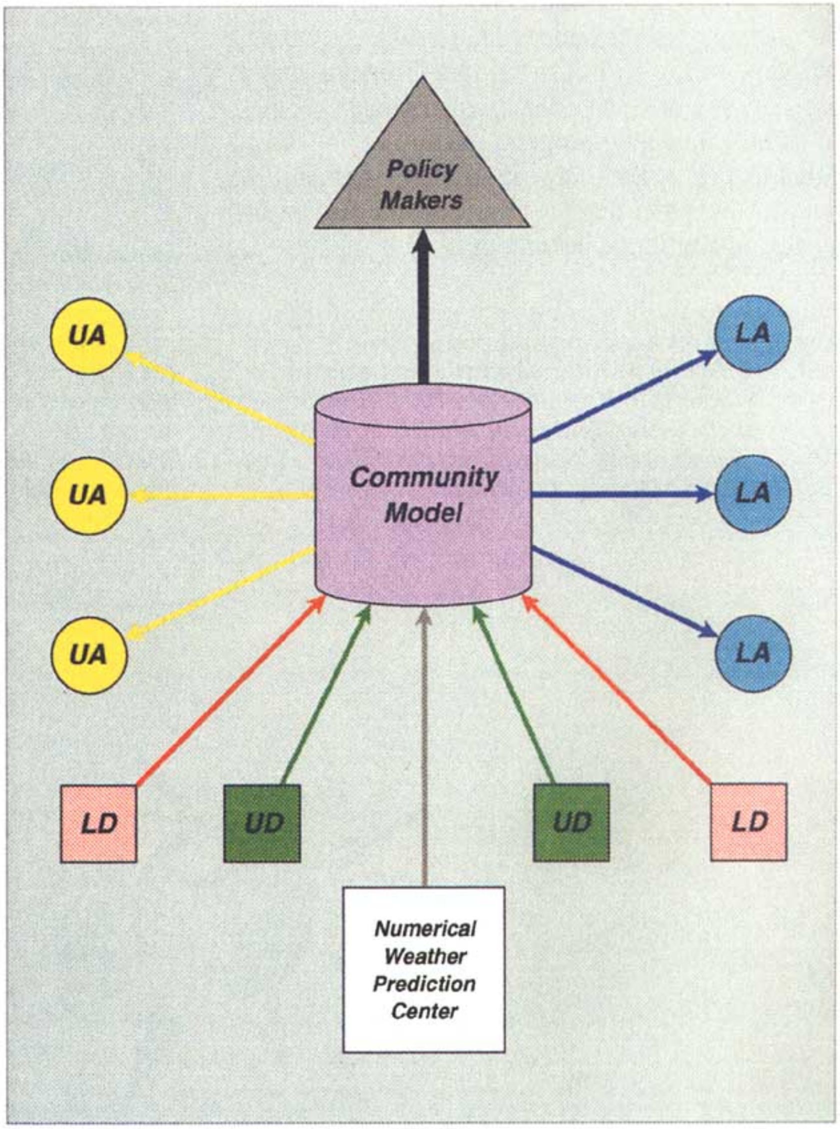

FIG. 1. Diagram illustrating a proposed conceptual structure for the U.S. global modeling effort. The community model is developed based on inputs from a distributed development community, including the numerical weather prediction center, national laboratories, and universities. The community model is used in applications at both laboratories and universities. In addition, results from the community model are made available to policy makers.

6. Summary and concluding remarks

The rapid increase in computing performance per unit cost and increased societal concerns with climate change have led to an explosion in global climate modeling research. University-based global climate modeling groups have played an important role from the beginning. At present, there are more groups in both universities and laboratories who are making applications of models (including diagnosis and evaluation of model results, as well as various kinds of numerical experiments) than there are groups doing broad-based model development. This marks a major change from the early days of global climate modeling, when virtually all modeling groups were doing a lot of model development. The key roles of university-based groups are training new scientists and contributing to the development of new ideas, taking advantage of the particularly great freedoms that a university environment offers. A distributed U.S. global climate modeling program, along the lines suggested in Fig. 1, can draw upon a national pool of talent and expertise that far surpasses what can be assembled in any single institution.

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