## Chapter 9

# The Evolution of Complexity In General Circulation Models

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## Introduction

We all value simplicity. Einstein famously remarked that a theory should be as simple as possible, but not simpler. On the other hand, the myriad phenomena of the global atmosphere are undeniably complex. The majestic Hadley and Walker cells, monsoons and planetary waves, midlatitude baroclinic waves and tropical typhoons, squall lines and thunderstorms, and the turbulent eddies of the boundary layer perpetually interact across a huge range of space and time scales, and across the full range of the Earth's weather regimes, without spectral gaps, and without the slightest regard for our human preference for simplicity.

Atmospheric general circulation models (AGCMs) are intended to simulate the many emergent phenomena of the global circulation by starting from fundamental physical principles that apply on small scales. AGCMs are among humanity's most elaborate creations. The trend has been towards ever more complex AGCMs, because the amazing intricacy of the real atmosphere motivates continuing refinement, because the relentless growth of computing power makes possible increasingly comprehensive simulations, and because society's appetite for more detailed and quantitatively accurate predictions can never be satisfied (WCRP, 2009).

In the context of AGCMs, it is useful to distinguish three types of complexity:

- The *conceptual complexity* of AGCMs is a measure of the intellectual effort needed to understand their formulations. It has been increasing rapidly (Claussen et al., 2002), driven by the deepening subtlety of the underlying ideas, the growing level of physical detail, the increasing sophistication of the mathematical methods, and the sheer size of the computer codes that embody the models.
- *Coupling complexity* arises because AGCMs are including ever more coupled processes, and are linked to an increasingly wide variety of similarly elaborate models representing other components of the Earth system.
- Finally, the spatial and temporal resolutions of the models are being dramatically refined, giving rise to *numerical complexity*, which can be measured by the sheer number of numbers needed to represent the state of a simulation.

Complexity creates challenges. Conceptual complexity raises the ante in terms of the talent and training needed by modelers, while slowing the publication process that is key to the reward system for scientific professionals. Coupling complexity makes the results of a model vulnerable to the deficiencies of its weakest component, regardless of the merits of its stronger components. This also slows the publication process, because the strengths of a model component may be hidden by the weaknesses of other components. Numerical complexity makes simulations expensive and time consuming, even on the fastest available computers, and it renders the model output difficult to store, transport, analyze, visualize and interpret.

Increasing the number of lines of code in a model does not necessarily increase our confidence in the model's predictions[1], and the results produced by longer codes are often harder to interpret. Complex models sometimes have impressive predictive power, but only simple

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[1] Here I am roughly quoting Bjorn Stevens of the Max Planck Institute for Meteorology.

models have true explanatory power. For example, suppose that a complex AGCM is used to forecast a severe winter storm on the east coast of North America, and that the prediction turns out to be accurate. Does the numerical forecast explain why the storm developed? Most scientists would say No. We look for explanations in the form of simple but physically based interpretations, often in the form of idealized models, which distill the essence of complex observations or simulations while omitting or glossing over the details (e.g., Held, 2005). *Useful explanations are simple, more or less by definition.*

This chapter discusses the complexity of AGCMs as it has evolved up to now, analyzes the trade-offs among the different types of complexity, and projects future developments, especially in light of the continuing rapid increase in computer power and the society's dramatically increasing reliance on model-generated predictions of weather and climate.

## In the beginning

It is useful to compare today's models with their esteemed ancestors. The early predecessors of today's models are discussed in the Chapters by Peter Lynch, and by Washington and Kasahara, elsewhere in this volume. The first true AGCMs, created during the early 1960s, are discussed in the Chapter by Washington and Kasahara. They were actually similar in many ways to today's models. It is perhaps slightly embarrassing that some of today's AGCMs still contain a few snippets of code that, like highly conserved genes, have survived unchanged from that primordial era. The ancestral models were:

- *The GFDL[2] model, created by Joseph Smagorinsky, Syukuru Manabe and colleagues (Smagorinsky et al.,1965; Manabe et al., 1965).* The early GFDL AGCM had the first cumulus parameterization, namely Manabe's moist convective adjustment, which contains important elements of the truth and is still used today in a few models. The simple "bucket" model for the land surface was also introduced. The early GFDL AGCM was also distinguished by its relatively high vertical resolution: nine glorious layers, in an age of two-layer models. Today, GFDL is still very active in the AGCM arena.
- *The UCLA[3] model, also called the Mintz-Arakawa model, created by Akio Arakawa in collaboration with Yale Mintz (Mintz, 1965).* This two-layer model was the first to overcome the nonlinear numerical instability discovered by Norman Phillips (1956, 1959), though the use of energy-conserving numerical methods (Arakawa, 1966). It was also the first AGCM to predict the distribution of radiatively active clouds. Drastically updated versions of the UCLA model are still in use today.
- *The Livermore model (Leith, 1965), created by Cecil Leith of the Livermore Radiation Laboratory[4].* This five-layer model had a short lifetime, because its creator moved on to the

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[2] Geophysical Fluid Dynamics Laboratory

[3] University of California at Los Angeles

[4] Now called the Lawrence Livermore National Laboratory.

National Center for Atmospheric Research (NCAR) which had its own AGCM development effort, as discussed below.

- *The NCAR[5] model, created by Akira Kasahara, Warren Washington, and colleagues (Kasahara and Washington, 1967; Washington, 2007).* This began as another two-layer model. The first version did not predict the distribution of water vapor, but assumed saturation everywhere, so that latent heat was released wherever and whenever the air moved upward. The Chapter by Washington and Kasahara discusses this model in some detail.

The four ancestral models listed above shared several common elements. All were developed in the United States, although the developers of three of them (GFDL, UCLA, and NCAR) included scientists who had immigrated to the U.S. from Japan (Fig. 1). All were developed primarily for the sake of their scientific or academic utility, rather than for any immediate practical applications, although of course the potential for such applications was apparent to the model-builders.

All four models used finite differences to represent the three-dimensional structure of the atmosphere. All used horizontal grids based on spherical coordinates. Leith's model included a particularly strong horizontal smoothing that suppressed realistic variability (Charney et al., 1966). The sigma coordinate proposed by Norman Phillips (1957) was used in the GFDL and UCLA models. Leith used a pressure coordinate, with a predicted surface pressure, despite the complexities associated with pressure surfaces whose intersections with the Earth's surface move as the model runs. A unique feature of the early NCAR model is that, to this day, it is the only AGCM that has ever used height as its vertical coordinate. The impending era of nonhydrostatic AGCMs, discussed later, may see the return of the height coordinate.

All four models included suites of physical parameterizations to represent solar and terrestrial radiation, the effects of latent heat release, and the surface fluxes of sensible heat, moisture, and momentum. The specifics of the parameterizations differed drastically among the models, but in general they were much simpler than the parameterizations in today's AGCMs. The early GFDL model included moist convective adjustment, which is still occasionally used today, and also the simple "bucket model" representation of the land-surface. The bucket model was quickly adopted by other modeling groups; e.g., it was used in the UCLA model. The UCLA AGCM used the earliest "mass flux" representation of cumulus convection (Arakawa, 1969).

Further discussion of the early days of AGCMs can be found in the Chapter by Washington and Kasahara, elsewhere in this volume, and in the papers by Smagorinsky (1983), Lewis (1998), Arakawa (2000), Edwards (2000), and the books by Washington (2007) and Edwards (2010). Additional information is available on the following web sites:

http://www.aip.org/history/sloan/gcm/

http://www.aip.org/history/climate/GCM.htm#L000

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[5] U. S. National Center for Atmospheric Research

**Figure 1: The creators of the world’s first four AGCMs. Top: Syukuru Manabe and Joseph Smagorinsky of GFDL. Middle: Yale Mintz and Akio Arakawa of UCLA. Bottom left: Cecil Leith of the Lawrence Radiation Laboratory. Bottom right: Akira Kasahara and Warren Washington of NCAR.**

I obtained these photos from a variety of sources. The pictures of Manabe (probably) and Smagorinsky (almost certainly) belong to GFDL. The photo of Mintz and Arakawa was provided by Prof. Michio Yanai of UCLA. The photo of Leith was found on the web; I don’t know who owns it. The photo of Kasahara and Washington was found on the web site of either NCAR or UCAR.

## Numerics

The components of an AGCM that solve the equations of fluid motion, including the thermodynamic energy equation and various constituent-advection equations, are conventionally referred to as the “dynamical core” of the model. Modeling enthusiasts can be overheard comparing the designs of their “dycores.”

As mentioned above, the dynamical cores of all of the early AGCMs used finite difference methods in both the horizontal and vertical. The early UCLA model used what is now called the “finite-volume” approach, in which conservation principles for mass, momentum, and energy are emphasized (see the retrospective by Arakawa, 2000). Some of the early finite-difference models worked pretty well; others did not. A problem with finite-difference methods based on spherical coordinates is that the meridians converge at both poles. This “pole problem” necessitates the use of very short time steps unless a filter of some kind is used to remove short zonal wavelengths at high latitudes (e.g., Arakawa and Lamb, 1977).

Spectral methods eliminate the pole problem. The basic idea is to represent the horizontal structure of the global atmosphere using truncated spherical harmonic expansions (Silberman, 1954; Platzman, 1960). By including a sufficient number of spherical harmonics, the resolution can be made as high as desired. A problem with this approach is that the quadratically nonlinear processes of a model, notably advection, are represented by sums in which the numbers of terms increase quadratically with the number of spherical harmonics kept, making high-resolution models impractical. A further difficulty is that it would be virtually impossible to formulate the physical parameterizations of a model in wave-number space.

These obstacles were overcome by Orszag, and independently by Eliasen et al., both in 1970. They proposed the “transform method,” in which a grid is used to evaluate the products appearing in the nonlinear terms, while the spectral method continues to be used to evaluate the horizontal derivatives appearing in these terms. The physical parameterizations, many of which are also highly nonlinear, are also evaluated on the grid. Transforms are used to go back and forth between wave-number space and the grid, as needed.

The spectral method was further developed and advocated by Bourke (1974), Baer (1972), and others. One of its strengths is that it can easily be adapted to semi-implicit time differencing for the linear terms of the dynamical core. The spectral method became popular after it was adopted by GFDL (Manabe and Hahn, 1981) and the European Centre for Medium Range Weather Forecasts (ECMWF; Jarraud and Simmons, 1983).

The implementation of the spectral transform method has become fairly standard, with just a few variations, and in many respects it works well. In contrast, there are infinitely many ways to construct a finite-difference scheme, almost all of them bad. From this point of view, the spectral approach is simpler than the finite-difference approach. The widespread adoption of spectral methods during the 1980s can therefore be viewed as a step towards simplification of the dynamical cores of AGCMs -- a retreat from complexity. Note, however, that the finite-difference dynamical cores that worked well in 1980 were in many cases retained (and further refined) by their modeling groups (e.g., the United Kingdom Meteorological Office, and UCLA).

A serious drawback of the spectral transform method is that, when applied to advection, it has a strong tendency to produce spurious negative concentrations of atmospheric constituents such as water vapor (e.g., Williamson and Rasch, 1994). Spectral advection also requires the use of relatively short time steps, because of the pole problem mentioned earlier. Both of these issues have been addressed through the introduction of the “semi-Lagrangian” advection method (Ritchie et al., 1995), as a replacement for spectral-transform advection. Semi-Lagrangian advection is intrinsically stable and sign-preserving, and allows long time steps. It is a grid-point method, and its widespread adoption starting in the 1990s can be viewed as a partial retreat from the spectral method.

In fact, much of the recent work on AGCM dynamical cores has been based on finite-difference methods. This is motivated in part by the recent development of very high-resolution AGCMs, with horizontal grid spacings of just a few kilometers (e.g., Miura et al., 2007). Especially for these very high-resolution models, there has been a move towards finite-difference methods based on spherical grids that are not derived from spherical coordinates. These include “cubed sphere” grids (e.g., Adcroft et al., 2004; Nair et al., 2005) and icosahedral or “geodesic” grids (Sadourny et al., 1968; Williamson, 1968; Heikes and Randall, 1995; Ringler et al., 2000). Cubed sphere grids are being used at GFDL, MIT[6] (Adcroft et al., 2004), and GISS[7]. Geodesic grids are being used at Colorado State University, Deutsche Wetterdienst (Majewski et al., 2002), the Frontier Research Center for Global Change (e.g., Tomita et al., 2001, 2004, 2005; Miura et al., 2005; Satoh et al., 2005), NOAA’s ESRL [8] (http://fim.noaa.gov/), and the Max Planck Institute for Meteorology (Bonaventura, 2004). A geodesic grid is also being evaluated for

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[6] The Massachusetts Institute of Technology

[7] The Goddard Institute for Space Studies of the National Aeronautics and Space Administration and Columbia University

[8] The Earth System Research Laboratory of the National Oceanic and Atmospheric Administration

possible use in a global nonhydrostatic model under development at NCAR (Skamarock et al., 2008). Fig. 2 shows an example of a geodesic grid.

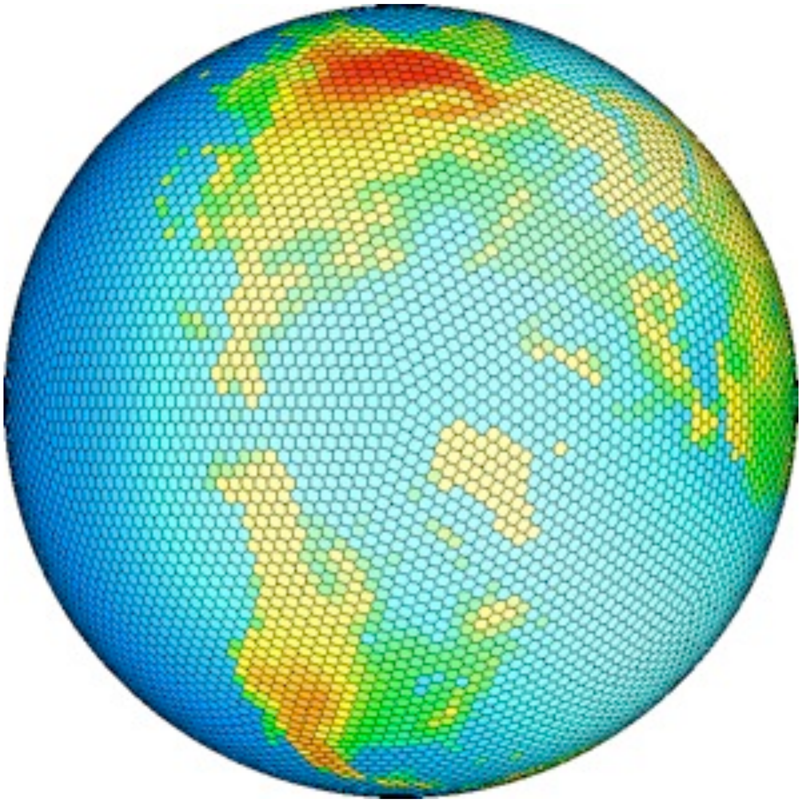

**Figure 2: The distribution of surface elevation, plotted on a geodesic grid with about 10,000 cells. The figure has been made in such a way that the individual grid cells are visible.**

This figure was created by David Randall's research group at Colorado State University.

Further discussion is given in the Chapter by Warren Washington and Akira Kasakara, elsewhere in this volume.

## Parameterizations

The fundamental principles of fluid dynamics, radiative transfer, etc., are simple to state, but not so simple to use. They apply locally, at a point. Limited computer resources make it necessary to formulate AGCMs in terms of averages over finite volumes. Because the governing equations are nonlinear, this averaging introduces new unknowns, which are essentially statistics characterizing relevant aspects of the unresolved processes. The fundamental principles cannot be directly applied to determine such statistics, except by revising the model to use much higher (and unaffordable) spatial resolution. *The need to predict statistics over (large) finite volumes is a fundamental source of conceptual complexity.*

The earliest AGCMs included parameterizations of important processes that were not at all well understood. They had to be parameterized anyway, simply because they were too fundamental to neglect. Forty years layer, we still struggle with many of the same parameterization challenges (Randall et al., 2003).

Perhaps the most difficult of these problems is that of cumulus parameterization, which is designed to represent the collective effects of an “ensemble” of cumulus clouds on the larger-scale circulation of the atmosphere (Fig. 3). Arakawa (2004) recently published an in-depth review of the status of cumulus parameterization. As mentioned earlier, the simple moist convective adjustment scheme of Manabe et al. (1965) captures some of the essential physics of cumulus convection. It eliminates conditional instability, releases latent heat, and produces precipitation. It also transports water and energy upward, although only through a simple layer-by-layer mixing, rather than through realistic penetrative cumulus towers.

**Figure 3: A field of cumulus congestus clouds. Models use parameterizations to include the effects of such clouds on the large-scale circulation of the atmosphere.**

Document Title: Cumulus congestus (DI00157), Photo by Jim Coakley
Description: When a developing cumulus gains the appearance of a head of cauliflower, it is known as a cumulus congestus. Several of these clouds may grow into each other, forming a line of towering clouds. Precipitation may fall from these in the form of showers. Some may mature into towering cumulus (taller, thinner and not-so-rounded clusters), visible in the foreground, or cumulonimbus, or thunderstorm, clouds seen in the distance with the characteristic anvil of ice crystals.
Creditline: copyright University Corporation for Atmospheric Research, Photo by Jim Coakley
Keywords: DI00157,clouds,cumulonimbus,cumulus congestus,thunderstorm,storm cloud,anvil,cloud,s-torm clouds,Jim Coakley

Less than a decade later, Arakawa and Schubert (1974) published what is probably still the most conceptually complex cumulus parameterization ever devised. They included a spectrum of penetrative cumulus cloud “types” or sizes, each represented by a simple “entraining plume” cloud model. Their closure required solution of a system of equations for which the matrix of coefficients is computed through a very complicated procedure. Nevertheless, Arakawa and Schubert (1974) neglected many important processes, such as convective downdrafts and mesoscale organization (Randall et al., 2003). Some of these missing ingredients have been added by later researchers. Simplified versions of the Arakawa-Schubert parameterization have also been proposed (e.g., Moorthi and Suarez, 1992; Pan and Randall, 1998).

The area-averaged non-radiative “apparent heat source” and “apparent moisture sink” defined by Yanai et al. (1973) are given by

$$Q_1 - \overline{Q_R} = L\overline{C} - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho\overline{w's'}) - \frac{1}{\rho}\nabla_H \cdot (\rho\overline{\mathbf{v}'_H s'}),$$

$$Q_2 = -L\overline{C} - \frac{1}{\rho}\frac{\partial}{\partial z}(L\rho\overline{w'q'_v}) - \frac{1}{\rho}\nabla_H \cdot (L\rho\overline{\mathbf{v}'_H q'_v}).$$

The notation is standard. *The overbars are very important*; an overbar represents an area average, which we interpret as a horizontal average over a grid cell. The expressions given above for $Q_1$ and $Q_2$ are valid regardless of how large or small the grid cells are; the grid spacing can be 100 km, or 100 m. The leading terms on the right-hand sides represent the effects of condensation, the next terms represent vertical divergences of the convective “eddy fluxes”of dry static energy and water vapor, respectively; and the last terms represent the horizontal divergences of the convective eddy fluxes, which are normally (and justifiably) neglected in large-scale models.

As pointed out by Jung and Arakawa (2004), the roles and relative magnitudes of the various terms of $Q_1$ and $Q_2$ systematically change as the grid spacing becomes finer:

- The vertical transport terms become less important. Later horizontal averaging does not alter this.

- The horizontal transport terms become more important locally. Horizontal averaging over a sufficiently large area renders them negligible, however.

- The phase-change terms become more important, and ultimately become dominant at high resolution.

Models intended for use with a coarse grid spacing, which includes all existing climate models, must use a parameterization that can represent the area-averaged effects of vertical eddy flux divergences due to cumulus clouds. “Mass-flux” parameterizations (e. g., Arakawa and Schubert, 1974) are designed with this in mind. In contrast, models with much higher resolution appropriately focus on phase changes (as represented by microphysical processes), and place much less emphasis on the parameterization of eddy fluxes, which on fine grids are due only to turbulence.

A model that includes parameterizations of both deep convection and grid-scale saturation contains the elements of both low-resolution and high-resolution physics, as discussed above. If the grid spacing of such a model is incrementally refined from, say, 200 km to 2 km, the results may show that the deep convection parameterization is active with coarse resolution but "goes to sleep" and is supplanted by the grid-scale saturation parameterization with high resolution (Molinari and Dudek, 1992). This is *qualitatively* the right answer, but we lack any theory of how this transition should occur, especially for intermediate grid spacings on the order of 20 km. The intermediate case is, not surprisingly, the hardest.

The parameterizations used in high-resolution models can be simpler than those of low-resolution models because, as discussed above, the need to predict statistics over (large) finite volumes is one of the main sources of conceptual complexity. The equations that are actually used in a fine-mesh model can and should be closer to the fundamental principles of our science than those of a coarse-mesh model. High-resolution models are conceptually simpler than low-resolution models, but of course their numerical complexity is greater.

Model components are usually formulated separately and coupled at the end. "Modularity" has been advocated as a goal of model design. In this view, an AGCM is a software system; it should be possible to test alternative parameterizations and/or numerical schemes by *simply* plugging them into a suitably designed modeling chassis, using a standardized programming framework. Simplicity is in fact one of the main goals motivating this approach, and that in itself is certainly laudable.

The trouble with modular models is that nature is not modular. In the real atmosphere, the various physical processes interact on a wide range of space and time scales, and also nonlinearly across a wide range of scales, so that their effects are thoroughly entangled. It is impossible to formulate the processes independently and snap them together at the end.

As an example, cumulus clouds grow out of the boundary layer, and modify the boundary layer through the effects of convective downdrafts. Stratiform clouds are formed by cumulus detrainment. The stratiform clouds contain convective turbulence, which is driven in part by radiative cooling near the cloud tops. The microphysical processes in the cloud are influenced, on small scales, by both turbulence and the radiation. Meanwhile, all of these processes interact with the large-scale circulation, and the land-surface or ocean at the lower boundary. The various processes and their interactions are represented through numerical schemes, and the equations must be solved simultaneously. These various connections imply that the model's dynamical core and the various parameterized processes -- boundary layer, cumulus clouds, stratiform clouds, turbulence in clouds, radiation, and microphysics -- must be formulated in a coordinated, coherent, and coupled way. Such an architectural unity can only be achieved by increasing the conceptual and coupling complexities of the model.

## From academia to enterprise: A loss of innocence

The early AGCMs were used only for scientific research. There was relatively little funding, but on the other hand the practical demands on the time and resources of modeling groups were modest. As the predictive power of the models increased and became well established, practical applications were quickly identified and undertaken. Now that AGCMs are being extensively used in the service of society, the idyllic era of purely academic modeling has ended. A portion of the today's AGCM work has become quasi-industrial in character. This change has brought a major increase in funding for modeling centers, but it has also burdened modelers with new responsibilities, and with deadlines and metrics that measure success in practical terms. Global modeling has become, in part, an enterprise. Our field has experienced a loss of innocence.

Operational global numerical weather prediction (NWP) began in the late 1970s, when increasing computer power finally made it practical (Woods, 2006). Today, humanity relies on weather forecasts based on simulations with AGCMs, although of course most of the people in our society have no idea how the forecasts are generated. Operational global NWP is a very expensive business, especially considering the hugely expensive global observing system, which includes many orbiting sensors. The operational centers that do global NWP have the benefit of substantial public resources that support infrastructure, personnel, and computing, although they could certainly use more, and in some cases much more.

The need for better weather forecasts has been steadily driving the AGCMs that are used for NWP towards higher resolution; see the Chapter by Senior et al., elsewhere in this volume. For example, over the past twenty years, the horizontal resolution of the ECMWF AGCM has increased from T106 (~190 km grid spacing) to T799 (~25 km grid spacing). In the near future, it will increase further to T1279 (~16 km grid spacing). The number of layers has increased from O(20) to O(100). The physical parameterizations of the models have also improved, and this has led to major improvements in forecast skill (Woods, 2006).

Climate change assessments in service to society are a newer development, and operational national climate services, analogous to weather services, are now being discussed. As discussed in the Chapter of this book by Richard Somerville, the Intergovernmental Panel on Climate Change (IPCC) began delivering its assessments during the 1990s. As the most mature components of coupled global climate models, AGCMs have played a crucial role in all of this.

The first coupled ocean-atmosphere GCM was created by Manabe and Bryan (1969), but coupled ocean-atmosphere modeling reached a degree of maturity only during the 1990s; see the Chapter by Kirk Bryan, elsewhere in this volume. Land-surface modeling underwent a qualitative improvement during the 1980s, under the influence of Robert Dickinson and Piers Sellers; see the Chapter by Dickinson elsewhere in this volume. Today there is continuing pressure to couple with additional submodels; for example, the climate models used in the IPCC Fourth Assessment did not include submodels of the continental ice sheets, which are obviously very important for sea level changes, among other things. As a second example, many of the AGCMs used for climate research have only recently incorporated parameterizations of the effects of aerosols on radiation and/or cloud microphysics. Work is underway to include more processes, and more interactions among processes, than ever before.

At operational NWP centers, models are used in complicated suites of runs on fixed schedules, with data assimilation, optimized ensembles, and obsessively tracked skill scores. Similarly, in the climate modeling arena, years of work are needed to prepare and thoroughly test improved model designs in support of the quasi-periodic IPCC assessments. To perform and analyze the required simulations by their due dates requires enormous amounts of computer time, a lot of people time, and attentive management. This is noble and important work, but it is demanding, and the climate modeling community is small.

We obviously need bleeding-edge models that incorporate the latest ideas from the physical and computational sciences that form the foundation of global modeling. On the other hand, the models used for NWP and IPCC assessments must adhere to somewhat conservative designs; it would not be appropriate to undertake such applications with bleeding-edge models that are still being tested. There is a danger that modeling innovation will be inhibited by a combination of staggering external demands, a small modeling work force (Jakob, 2010), and inadequate resources.

One way to avoid stifling innovation, while still meeting operational requirements, is to create two-track modeling centers. Track 1 supports operational weather and/or climate services using well-tested models. Track 2 innovates aggressively. Over time, successful new ideas migrate from Track 2 to Track 1.

## Peta-flops and giga-grids

Increases in resolution and, to a lesser degree, increases in conceptual complexity explain why the most elaborate of today's global NWP models are about $10^4$ times as costly, in computational terms, as the AGCMs of the 1960s. Climate models are different. The AGCMs used for climate simulation today have horizontal and vertical resolutions only marginally finer than those of the 1960s. The parameterizations used in climate models have become more complex, but not drastically so. The bottom line is that today's AGCMs for climate simulation are, at most, only a few hundred times more expensive than their counterparts of the 1960s.

Weather prediction models maximize numerical complexity and conceptual complexity, with (so far) only moderate coupling complexity. Climate prediction makes use of models with a lot of coupling complexity and conceptual complexity, but less numerical complexity. It seems likely that climate models will continue to have more coupling complexity than NWP models.

While these modeling changes have been evolving, *computer power has increased by about a factor of a million* or more -- from megaflops to teraflops and beyond, following Moore's Law, with roughly a 100-fold increase in FLOP-rate per decade.

**Fig. 4:** NCAR takes delivery of the first production model of the CRAY-1 supercomputer, in 1977. This machine provided a dramatic increase in computer power at NCAR.

Document Title: CRAY Computer (DI01246)
Description: NCAR accepts the first production model of the CRAY-1 supercomputer. The five-ton machine is lowered through the ceiling of a newly built underground computing center. Subsequent machines from Cray Research dominate NCAR computing into the 1990s.
Creditline: copyright University Corporation for Atmospheric Research
Keywords: History,DI01246,first CRAY,CRAY,computer,computers,1977,CRAY I

It has always been a challenge to adapt AGCMs to evolving computer architectures. The earliest models executed on serial machines that had, at most, just a few megabytes of main memory. During the 1970s and 80s, vector machines such as the Cray-1 (see Fig. 4) imposed a new style of programming, while available memory increased rapidly. The 1990s saw a transition to increasingly parallel, cache-based architectures. At the same time, the speed of individual processors continued to increase, although this rate of increase has slowed recently. An inexpensive laptop computer today is faster, has more memory and disk space, consumes much less power, is more reliable, and is considerably easier to use than the venerable, multi-million-dollar Cray-1 of the 1970s.

The annual cycle is a fundamental unit of climate. The first numerical simulations of full annual cycles with AGCMs were performed during the 1960s (e. g., Mintz, 1965), but such long runs became commonplace only after about 1980. Prior to that, limited computer power dictated that what was then called a "climate simulation" was typically nothing more than a perpetual January run of an AGCM coupled to a simple land-surface model and a prescribed ocean.

Simulations of decades, centuries, and millennia are recent achievements. The goal of understanding Milankovitch cycles leads us to contemplate future simulations of hundreds of thousands or even millions of years. To perform such long simulations with fixed (i.e., similar to current) resolution on million-processor machines, we have to decrease the number of grid cells per processor, which probably will not be feasible due to communication bottlenecks, or else we have to increase the processor speed, which appears to be ruled out by power-consumption issues. Therefore, *the ongoing evolution of supercomputers towards greater and greater parallelism, with fixed processor speeds, favors simulations with a fixed number of time steps and higher-resolution models, rather than longer simulations with models of fixed resolution.* With this strategy, as we add grid cells, we also add processors, so that (ideally) the amount of computation per processor per time step remains constant. In this way, massive parallelism strongly favors increased numerical complexity. Unfortunately, however, the size of the time step must decrease linearly as the resolution increases, so that the actual simulation length decreases for a fixed number of time steps.

It used to be true that as computers got faster, the additional speed could be used to refine the grid or to make longer runs on the same grid. No more. Technology trends now encourage us to dramatically refine our grids, but are not compatible with dramatically longer runs on our existing grids. This situation will persist until a major, currently unforeseeable technology change occurs.

How did we use the million-fold increase in computer power that has been achieved since the 1960s? The answers are different for NWP and climate applications. For NWP, we have argued above that increases in resolution and other changes have increased computing requirements by about a factor of $10^4$. The additional factor of 100 needed to go from $10^4$ to a million can be accounted for in terms of shorter execution times (enabling operational use on a fixed schedule) and the introduction of forecast ensembles. For the AGCMs used for climate, on the other hand, we have argued that current models are only a few hundred times slower than their predecessors. The additional factor of several thousand needed to go from a few hundred to a million is accounted for by much longer simulations -- centuries instead of months -- and by an increase in the number of simulations performed.

Over the next few decades, computers are expected to speed up by another factor of a million. Here is a question for the young scientists reading this chapter: What are you going to do with that next million?

Within the past ten years, computer power has crossed a threshold, such that brief simulations can now be performed with global atmospheric models that have resolution sufficiently fine to resolve important processes that have previously been parameterized, including deep moist convection and vertically propagating waves produced by flow over mountains. To take this qualitative leap, we must, at first, drastically decrease simulation lengths, from centuries to days or weeks, as we increase the number of floating point operations per simulated day by a factor of $10^5$ to $10^6$. Running the new very-high-resolution global models requires $O(10^5)$ processors, whereas up to now most models have used only O(100) processors. This huge jump in parallelism is challenging beyond any of the previous challenges mentioned above. It will undoubtedly take a few years to learn how to do this well.

Because they have grid spacings comparable to the native scales of large clouds, global cloud-resolving models (GCRMs) do not need and in fact cannot use the parameterizations of deep cumulus convection needed by conventional AGCMs. GCRMs also have no need for parameterizations of cloud overlap, or gravity-wave drag, because these can be explicitly simulated. GCRMs do still rely on parameterizations of cloud microphysics, turbulence, and radiation, but all three of these parameterization problems become much more tractable with the high resolution of a GCRM. In fact, a strength of GCRMs is that they are ideal vehicles for the implementation of more advanced parameterizations of microphysics, turbulence, and radiation.

A GCRM can simulate interactions across a very wide range of spatial scales, including large individual clouds, tropical cyclones, midlatitude baroclinic waves, larger planetary waves and monsoons, and elements of the zonally averaged circulation such as the Hadley Cells. As is well known, the atmospheric circulation does not contain any convenient spectral gaps in which the energy density is low. All scales contain energy, and interact through a wide variety of processes, many of them involving cloud systems in important ways.

The high-resolution statistics simulated by GCRMs can be compared directly with high-resolution observations. This greatly simplifies the diagnosis of model deficiencies.

From a computational point of view, GCRMs are intrinsically more amenable to modularization than today's AGCMs, simply because the various physical processes represented by the parameterizations are less inter-dependent on the cloud scale. This means that the conceptual complexity of GCRMs is less than that of lower-resolution AGCMs, although of course the numerical complexity of GCRMs is much greater.

A decrease of the horizontal grid spacing by another factor of ten, relative to today's models, together with the introduction of non-hydrostatic dynamics and major changes in parameterizations, will yield global NWP models with grid cells just a few km across, at the coarse end of the "cloud-resolving" range. Taking into account the decrease in time step needed to permit simulation of the birth and death of individual large clouds, we can estimate that these cloud-resolving NWP models of the not-too-distant future will be about 1000 times as expensive as today's high-resolution global NWP models. Such GCRMs will become marginally practical for operational global NWP within the coming decade, which means that now is the time to begin their development.

A GCRM has already been developed at the Frontier Research Center for Global Change (FRCGC), in Japan. The model has been tested on the Earth Simulator, with very provocative results (Tomita et al., 2005; Miura et al., 2005). The FRCGC's GCRM is called NICAM, which stands for "Nonhydrostatic Icosahedral Atmospheric Model." It is constructed on a "geodesic" grid based on the icosahedron. At the highest tested resolution, NICAM has cells 3.5 km across. The recent tests of NICAM represent a milestone in global modeling. They are analogous to the heroic early experiments in numerical weather prediction that were performed by Charney, Fjortoft, von Neumann, and colleagues over 50 years ago, using the ENIAC computer (Charney et al., 1950; Platzman, 1979). The model of Charney et al. was highly simplified compared to today's AGCMs, and the ENIAC was painfully slow compared to the computers we have now. What Charney et al. really wanted to do is what we can do now, but it was far beyond their reach. That didn't stop them. They did what they could in the time when they lived. All of the subsequent achievements of atmospheric modelers have been built on the foundation that they created.

Similarly, the FRCGC scientists would like to have a computer much faster than the Earth Simulator, and a model that is more advanced than the current version of NICAM. The GCRMs of the future will no doubt have many improvements, including even higher resolution, better numerics, and more advanced parameterizations of cloud microphysics, turbulence, and radiation. Using future exa-flop computers, such improved GCRMs will eventually be run for simulated centuries, far beyond what is possible today. Although these future models and future computers are out of reach for now, the FRCGC scientists have done what they can with the modeling and computer know-how of the early 21st century. They have created a new foundation on which a large body of work will be built.

With a 4 km grid spacing and 128 layers, a GCRM contains approximately 3 billion grid cells. It uses a time step of about 10 simulated seconds. Simulation of one day requires about $10^{17}$ floating point operations. A snapshot of the model's prognostic (i. e., time-stepped) fields occupies about 1 TB. The data volume written for archival per simulated day can easily reach 100 TB, depending of course on the frequency of output and the number of fields saved. In these ways, emerging petascale computational resources are enabling and will enable global atmospheric models that are *qualitatively* more advanced than the models of the past. *This is a transformative rather than incremental change,* because GCRMs directly simulate important processes that were previously parameterized.

Computational challenges of GCRMs include:

- Efficient execution on a very large number of processors, in order to achieve acceptably fast run times;
- Parallel I/O (especially O);
- Management and distribution of the voluminous archived model output; and
- Visualization of the results.

It is remarkable that three of these four challenges relate to working with the model output. For some applications of GCRMs, the fine-scale details of the flow will be of secondary interest, so that a spatially and temporally sub-sampled or filtered depiction of the simulation is all that is needed. This can drastically reduce the output volume. For other applications, e.g., analysis of a rapidly intensifying tropical cyclone, full spatial resolution and high time resolution are needed to depict the growth of individual convective cells. Typically such detailed output will only be needed in selected portions of the global domain, but the locations will not necessarily be known in advance. Intelligent algorithms are needed to provide the capability to dynamically adapt the high-resolution output to specific geographical regions of interest.

Conventional climate models generally write four types of output files:

- A small (a few kB per simulated day) "day file" that suffices to reveal pathological behavior, allowing the model user to monitor the vital signs of the simulation.
- Restart files, which can be used to restart the model at intervals during a long run. For the atmospheric component of a conventional climate model, individual restart files are typically O(100 MB) or smaller. They might be written once per simulated day, or once per simulated month, but in either case the output volumes are small.
- Diagnostic or "history" files, which provide detailed information on the progress of the simulation. Examples of fields included here would be three-dimensional distributions of atmospheric heating due to solar radiation, or the two-dimensional surface precipitation rate produced by the cumulus parameterization; a recommended list can be found at

  http://www-pcmdi.llnl.gov/projects/amip/OUTPUT/WGNEDIAGS/.
- The total number of diagnostic fields is of course under the control of the modeler, but the data volume of a single record will approach 1 TB for one 3D field at 1-km resolution with 100 vertical levels. In many cases, these files would be written once per simulated month, but depending on the nature of the study they might be written as often as once per simulated day. In the extreme, they will be written up to hourly or perhaps 3 hourly depending on the capacity of the IO and storage systems in use and the expected use of the data.
- "Point-by-point" files, which contain selected fields with high time resolution (e.g., every 30 simulated minutes) at O(100) selected grid points. This type of output has been in use since the 1970s, if not before, but it is occasionally reinvented by new generations of modelers.

Up to now, global atmospheric models have relied almost entirely on serial output. With a GCRM, highly parallel output is obviously essential, because using a single "pipe" to send all of the model output to disk creates an unacceptable bottleneck.

A low-resolution but global depiction of the atmospheric circulation can be created by subsampling or filtering "on the fly," inside the model. This dataset can be analyzed using conventional methods. At the same time, a high-resolution but local analysis is needed to identify important centers of action, such as tropical cyclones or major snowstorms. One possible approach is to automatically identify where and when such events occur, and to automatically create "chunks" of model output, of manageable size, that can be used to analyze the events at high resolution. To do this, it will be necessary to create rule-based "agents" that live inside the model and monitor the simulated weather as the model runs. The agents will use pre-specified criteria to flag events of interest for the postprocessing program mentioned above. The criteria will be user-selectable and user-programmable during the set-up of a simulation.

Depending on the user-selectable specifics of the GCRM output, following the strategy discussed above, simulation of one annual cycle will produce several petabytes of model output. Strategies are needed to catalog, browse, subsample, and transport the output rapidly and efficiently.

Data will be staged from disk to archival media as available on-line storage is currently limited to the 10s of TB range at most supercomputing centers. While it is obviously desirable to avoid transporting huge volumes of data around the country or the world, via network or otherwise, some long-distance data transportation will be necessary. Physically mailing disk drives is an option, but even this is currently impractical for petabytes of data. For these reasons, major portions of GCRM data analysis and visualization work will have to be carried out at the same center where the simulation is performed. Only subsamples of the GCRM output can be transported between geographically separated research centers.

With a 1 km global grid, the range of scales involved (in one dimension) is roughly 40,000 km to 1 km. Displays, printers, eyes, and brains cannot handle that all at once. A zooming capability is therefore needed. Sampled or filtered data can be used to depict the larger scales over the entire globe. Full-resolution data is needed to study local weather systems, but it is needed only in selected limited regions. We need a software system that can, on demand, automatically supply visualizations of appropriately sampled model output, in appropriately sized regions, and with appropriate resolutions. “Google Earth” comes to mind as an application that works in much this way. Obviously Google Earth itself is just a visualization tool, but we need an analogous tool that can be used for both more elaborate visualization and physically meaningful analysis of model output.

## Conclusions

I am writing this Chapter in early 2009. It is a tumultuous time for global atmospheric modeling. Climate change has become a major societal issue. There are calls for large increases in funding for climate research, but the world economy is staggering into a deep recession. The conceptual complexity of our models has reached the point that no single human being can possibly comprehend one of them in its entirety. The number of coupled processes is rapidly growing; the carbon cycle and terrestrial ice sheets are particularly active areas of current research. New technology is enabling dramatic increases in model resolution, and thus driving major changes in model design, but with many serious practical challenges.

Looking ahead, we can dimly see an era in which exaflop computers will permit global cloud-resolving atmospheric models, coupled to ocean, land surface, and ice-sheet models of comparable resolution. Such models will be used to produce highly detailed simulations of the earth system on time scales relevant to both weather and climate prediction. Their conceptual complexity may be less than that of today’s models, but their numerical complexity will begin to rival the that of the beautiful physical system that they represent.

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