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Chapter 2

# A Brief History of Atmospheric General Circulation Modeling

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## I. INTRODUCTION

This article presents preliminary results of an attempt to trace the history of atmospheric general circulation modeling, focusing on the period through 1985. *Important caveats*: This is *not* intended as a definitive account. Rather, it is an exploratory study that will be revised and corrected over the next 2 years, as I prepare a book-length history of climate modeling (Edwards, in press). More information about this project is provided at the end of the essay. This chapter certainly contains mistakes and incomplete coverage, for which I apologize in advance. I encourage anyone who finds significant omissions or errors to let me know about them, so that the final version of this history can be accurate and complete.

Finally, I should stress that what follows is written from the perspective of a historian of science, rather than that of a scientist.

## II. BEFORE 1955: NUMERICAL WEATHER PREDICTION AND THE PREHISTORY OF GCMs

In the early 20th century, the Norwegian Vilhelm Bjerknes argued that atmospheric physics had advanced sufficiently to allow weather to be forecast using calculations. He developed a set of seven equations whose solution would, in principle, predict large-scale atmospheric motions.

Bjerknes proposed a "graphical calculus," based on weather maps, for solving the equations. Although his methods continued to be used and developed until the 1950s, both the lack of faster calculating methods and the dearth of accurate observational data limited their success as forecasting techniques (Nebeker, 1995).

### A. Richardson's "Forecast Factory"

In 1922, Lewis Fry Richardson developed the first numerical weather prediction (NWP) system. His calculating techniques—division of space into grid cells, finite difference solutions of differential equations—were the same ones employed by the first generations of general circulation model (GCM) builders. Richardson's method, based on simplified versions of Bjerknes's "primitive equations" of motion and state (and adding an eighth variable, for atmospheric dust) reduced the calculations required to a level where manual solution could be contemplated. Still, this task remained so large that Richardson did not imagine it as a weather forecast technique. His own attempt to calculate weather for a single 8-hr period took 6 weeks and ended in failure.

His model's enormous calculation requirements led Richardson to propose a fanciful solution he called the "forecast factory." The "factory"—really more like a vast orchestral performance—would have filled a vast stadium with 64,000 people. Each one, armed with a mechanical calculator, would perform part of the calculation. A leader in the center, using colored signal lights and telegraph communication, would coordinate the forecast.

Yet even with this fanciful apparatus, Richardson thought he would probably be able to calculate weather only about as fast as it actually happens. Only in the 1940s, when digital computers made possible automatic calculation on an unprecedented scale, did Richardson's technique become practical (Richardson, 1922).

## B. Computers, Weather, and War in the 1940s

The Princeton mathematician John von Neumann was among the earliest computer pioneers. Engaged in computer simulations of nuclear weapons explosions, he immediately saw parallels to weather prediction. (Both are nonlinear problems of fluid dynamics.) In 1946, soon after the ENIAC became operational, von Neumann began to advocate the application of computers to weather prediction (Aspray, 1990). As a committed opponent of Communism and a key member of the WWII-era national security establishment, von Neumann hoped that weather modeling might lead to weather control, which might be used as a weapon of war. Soviet harvests, for example, might be ruined by a U.S.-induced drought (Kwa, 1994, in press).

Under grants from the U.S. Weather Bureau, the Navy, and the Air Force, he assembled a group of theoretical meteorologists at Princeton's Institute for Advanced Study (IAS). If regional weather prediction proved feasible, von Neumann planned to move on to the extremely ambitious problem of simulating the entire atmosphere. This, in turn, would allow the modeling of climate. Jule Charney, an energetic and visionary meteorologist who had worked with Carl-Gustaf Rossby at the University of Chicago and with Arnt Eliassen at the University of Oslo, was invited to head the new Meteorology Group.

The Meteorology Project ran its first computerized weather forecast on the ENIAC in 1950. The group's model, like Richardson's, divided the atmosphere into a set of grid cells and employed finite-difference methods to solve differential equations numerically. The 1950 forecasts, covering North America, used a two-dimensional grid with 270 points about 700 km apart. The time step was 3 hr. Results, while far from perfect, were good enough to justify further work (Charney *et al.*, 1950; Platzman, 1979).

## C. The Swedish Institute of Meteorology

The Royal Swedish Air Force Weather Service in Stockholm was first in the world to begin routine real-time numerical weather forecasting (i.e., with broadcast of forecasts in advance of weather). The Institute of Meteorology at the University of Stockholm, associated with the eminent meteorologist Carl-Gustaf Rossby, developed the model. Forecasts for the North Atlantic region were made three times a week on the Swedish BESK computer using a barotropic model, starting in December 1954 (Bergthorsson *et al.*, 1955; Institute of Meteorology, 1954).

### D. The Joint Numerical Weather Prediction Unit

About 1952, Von Neumann, Charney, and others convinced the U.S. Weather Bureau and several research and forecasting agencies of the Air Force and Navy to establish a Joint Numerical Weather Prediction (JNWP) Unit. The JNWP Unit opened in Suitland, Maryland, in 1954, under the directorship of George Cressman. It began routine real-time weather forecasting in May 1955 (Nebeker, 1995). Yet it was more than a decade before numerical methods began to outstrip in accuracy the "subjective method" employed by human forecasters.

Initially, the computer models used for NWP employed simplifying assumptions. Only in the 1960s did models based on the Bjerknes/Richardson primitive equations replace barotropic and baroclinic models.

## III. 1955–1965: ESTABLISHMENT OF GENERAL CIRCULATION MODELING

In the mid-1950s, the weather models used by forecasters were still regional or continental (versus hemispherical or global) in scale. Calculations for numerical weather prediction were limited to what could be accomplished in a couple of hours on then-primitive digital computers. In addition, the time constraints of analog-to-digital data conversion and long-distance communication imposed limitations on the scale of operational weather forecasting.

Yet for theoretical meteorologists—unconcerned with real-time forecasting—general circulation modeling became a kind of holy grail.

By mid-1955 Normal Phillips had completed a two-layer, hemispheric, quasi-geostrophic computer model of the general circulation (Phillips, 1956). Despite its primitive nature, Phillips's model is now often regarded as the first working GCM.

As computer power grew, the need for simplifying assumptions (such as barotropy and quasi-geostrophy) diminished. Many individuals throughout the world, including Phillips, began experiments with primitive equation models in the late 1950s (Hinkelmann, 1959). Between the late 1950s and the early 1960s, four separate groups began—more or less independently—to build many-leveled, three-dimensional GCMs based on the primitive equations of Bjerknes and Richardson. Details of these efforts are given in the four following sections.

## IV. THE GEOPHYSICAL FLUID DYNAMICS LABORATORY

The first laboratory to develop a continuing program in general circulation modeling opened in 1955. In that year, at von Neumann's instigation, the U.S. Weather Bureau created a General Circulation Research Section under the direction of Joseph Smagorinsky. Smagorinsky felt that his charge was to continue with the final step of the von Neumann/Charney computer modeling program: a three-dimensional, global, primitive equation GCM of the atmospheric (Smagorinsky, 1983). The General Circulation Research Section was initially located in Suitland, Maryland, near the Weather Bureau's JNWP unit. The lab's name was changed in 1959 to the General Circulation Research Laboratory (GCRL), and it moved to Washington, D.C.

In 1955–1956, Smagorinsky collaborated with von Neumann, Charney, and Phillips to develop a two-level, zonal hemispheric model using a subset of the primitive equations (Smagorinsky, 1958). Beginning in 1959, he proceeded to develop a nine-level primitive equation GCM, still hemispheric (Smagorinsky, 1963). Smagorinsky was among the first to recognize the need to couple ocean models to atmospheric GCMs; he brought the ocean modeler Kirk Bryan to the GCRL in 1961 to begin this research (Smagorinsky, 1983).

The General Circulation Research Laboratory was renamed the Geophysical Fluid Dynamics Laboratory (GFDL) in 1963. In 1968, GFDL moved to Princeton University, where it remains.

### A. Manabe and the GFDL General Circulation Modeling Program

In 1959, Smagorinsky invited Syukuro Manabe of the Tokyo NWP Group to join the General Circulation Research Laboratory. (Smagorinsky had been impressed by Manabe's publications in the *Journal of the*

*Meteorological Society of Japan*.) He assigned Manabe to the GCM coding and development.

By 1963, Smagorinsky, Manabe, and their collaborators had completed a nine-level, hemispheric primitive equation GCM (Manabe, 1967; Manabe *et al.*, 1965; Smagorinsky *et al.*, 1965). Manabe was given a large programming staff. He was thus able to focus on the mathematical structure of the models, without becoming overly involved in coding.

In the mid-1960s, as Smagorinsky became increasingly involved in planning for the Global Atmospheric Research Program (GARP), Manabe became the *de facto* leader of GFDL's GCM effort, although Smagorinsky remained peripherally involved. Until his retirement in 1998, Manabe led one of the most vigorous and longest lasting GCM development programs in the world.

Manabe's work style has been highly collaborative. With his colleagues Strickler, Wetherald, Holloway, Stouffer, and Bryan, as well as others, Manabe was among the first to perform carbon dioxide doubling experiments with GCMs (Manabe, 1970, 1971), to couple atmospheric GCMs with ocean models (Manabe and Bryan, 1969), and to perform very long runs of GCMs under carbon dioxide doubling (Manabe and Stouffer, 1994). Another characteristic of Manabe's work style is a focus on basic issues rather than on fine-tuning of model parameterizations. He retired in 1998, but remains active.

## B. The GFDL Atmospheric GCMs

Note that the names given in the following section are informal terms used by GFDL members, who do not always agree on their interpretation.

### 1. MARKFORT

The MARKFORT series began with Smagorinsky's nine-level, 3-D hemispheric model. It was used well into the 1960s. Initially, the model was run on the IBM STRETCH. A number of GFDL's most influential publications resulted from the MARKFORT model.

### 2. Zodiac

The Zodiac finite-difference model series was the second major GFDL GCM. The chief innovation was the use of a new spherical coordinate system developed by Yoshio Kurihara (Kurihara, 1965). This model remained in use throughout the 1970s.

### 3. Sector

The Sector series was not an independent GCM, but a subset of the GFDL global models. To conserve computer time (especially for coupled ocean–atmospheric modeling), integrations were performed on a 60-deg longitudinal "slice" of the globe, with a symmetry assumption for conversion to global results. In the early sector models, highly idealized land–ocean distributions were employed (Manabe *et al.* 1975).

### 4. SKYHI

Work on SKYHI, a high-vertical-resolution GCM covering the troposphere, stratosphere, and mesosphere, began in 1975 (Mahlman *et al.*, 1978).

### 5. GFDL Spectral Model

In the mid-1970s, GFDL imported a copy of the spectral GCM code developed by W. Bourke at the Australian Numerical Meteorological Research Centre (Bourke, 1974; Gordon, 1976; Gordon and Stern, 1974). Interestingly, Bourke and Barrie Hunt had originally worked out the spectral modeling techniques while visiting GFDL in the early 1970s.

### 6. Supersource

Beginning in the late 1970s, Leith Holloway began to recode the GFDL spectral model to add modularity and user-specifiable options. The result was Supersource, the modular, spectral atmospheric GCM that remains in use at GFDL today. "Holloway fit the physics from Manabe's grid model (Zodiac and relatives) into the spectral model. Holloway then unified all the versions of this new spectral model into one Supersource" (Ron Stouffer, personal communication, 1997).

Users can specify code components and options. Among these options is a mixed-layer ocean model, but Supersource itself does not contain an ocean GCM. Supersource code has frequently been used as the atmospheric component in coupled OAGCM studies (Manabe and Stouffer, 1988, 1994). It will be replaced by a new model in 2000.

## V. THE UCLA DEPARTMENT OF METEOROLOGY

Jacob Bjerknes, who founded the UCLA Department of Meteorology in 1940, had a strong interest in the problem of the atmospheric general circulation. This tradition continued with Yale Mintz, a graduate student of Bjerknes's who received his Ph.D. in 1949. He continued to work at UCLA, becoming associate project director with Bjerknes. In the late 1950s, Mintz began to design numerical general circulation experiments (Mintz, 1958).

## A. Mintz and Arakawa

Like Smagorinsky, Mintz recruited a Japanese meteorologist, Akio Arakawa, to help him build GCMs. Arakawa, known for his mathematical wizardry, was particularly interested in building robust schemes for the parameterization of cumulus convection. Mintz and Arakawa constructed a series of increasingly sophisticated GCMs beginning in 1961. "Ironically, Arakawa's first role after joining the project was to persuade him to slow the development, giving first priority to designing model dynamics suitable for long-term integrations" (Johnson and Arakawa, 1996). The first-generation UCLA GCM was completed in 1963. Arakawa then went back to Japan, but Mintz persuaded him to return to UCLA permanently in 1965.

In the latter half of the 1960s, IBM's Large Scale Scientific Computation Department in San Jose, California, provided important computational assistance and wrote a manual describing the model (Langlois and Kwok, 1969).

## B. Widespread Influence

Of all the GCM groups in the world, the UCLA laboratory probably had the greatest influence on others, especially in the 1960s and 1970s. This was due not only to continuing innovation (particularly in cumulus parameterization), but also to the openness of the UCLA group to collaboration and sharing. Whereas GFDL, and to a lesser extent the National Center for Atmospheric Research (NCAR), were pure-research institutions, UCLA operated in the mode of an academic graduate program. The Department of Meteorology's graduates carried the UCLA model with them to other institutions, while visitors from around the world spent time at the group's laboratories (Arakawa, 1997, personal communication to Paul N. Edwards).

## C. The UCLA Models

The key characteristics of the UCLA model series and its spinoffs are neatly pictured in a chart made by Arakawa (see Fig. 7 in Chapter 1). Until the 1980s, UCLA typically focused on model development, leaving "production" of the models (i.e., use in experimental studies) to other institutions. Generation numbers given here are my own.

### 1. UCLA I (Prototype)

The first Mintz–Arakawa model was a two-level global, primitive equation GCM at a 7° latitude × 9° longitude horizontal resolution. It included realistic land–sea distributions and surface topography. Mintz never learned to program computers; Arakawa carried out all the model coding. This prototype model was abandoned about 1965.

### 2. UCLA II

When Arakawa returned to UCLA from Japan in 1965, he and Mintz began work on the first-generation "production" UCLA GCM. It increased model resolution to 4° latitude × 5° longitude, although it still had only two vertical levels, and introduced a new horizontal grid structure—the Arakawa–Lamb B Grid (Arakawa and Lamb, 1977). This was an extremely influential GCM. About 1970, Lawrence Gates, a UCLA graduate, carried the model with him to the RAND Corporation, where he used it in a series of studies sponsored by the Advanced Research Projects Agency of the U.S. Department of Defense. The RAND version of the model was eventually carried to Oregon State University (Gates, 1975).

### 3. UCLA II (3-level)

The second-generation UCLA model essentially extended the vertical resolution of the second-generation model to three levels. This model was carried to three NASA laboratories. In 1972, a nine-level version was begun at the Goddard Institute for Space Studies (GISS) in New York, whose current model is a direct descendant. Later in the 1970s it traveled to the Goddard Laboratory for Atmospheric Sciences and the Goddard Laboratory for Atmospheres (A. Del Genio, 1998, personal communication).

### 4. UCLA III

This 6- and 12-level model used the Arakawa–Lamb C Grid, a finite-difference horizontal grid. All subsequent UCLA models have also employed this scheme. In the mid-1970s, versions of this model, with slightly different sets of prognostic variables, were built. One version was exported to the U.S. Naval Environment Prediction Research Facility and the Fleet Numerical Oceanographic Center, both in Monterey, California. This model evolved into the operational NOGAPS forecasting system (Hogan and Rosmond, 1991). It was also given to the Meteorological Research Institute in Tsukuba, Japan, where it continues to be used in a wide variety of forecasting and climate studies.

### 5. UCLA IV

Work on the fourth-generation UCLA model began in the late 1970s. The chief innovation of this model generation was a new vertical coordinate system, which used the top of the planetary boundary layer as a coordinate surface. A version of this model remains in use at UCLA into the present, although a fifth-generation model was built in 1990.

UCLA IV was also adopted by the Navy research centers mentioned earlier. In addition, it was taken to the Goddard Laboratory for Atmospheres in the early 1980s. Code for this model was extensively rewritten (Randall, 2000, personal communication). In 1988, the model was brought to Colorado State University by David Randall, another former student of Arakawa.

Versions of this model made their way to Lawrence Livermore National Laboratory and also to the Central Weather Bureau of the Republic of China.

## VI. THE LIVERMORE ATMOSPHERIC MODEL

In 1960, Cecil E. "Chuck" Leith began work on a GCM at Lawrence Livermore National Laboratories (LLNL). Trained as a physicist, Leith became interested in atmospheric dynamics and received the blessing of LLNL director Edward Teller for a project on the general circulation. Teller's approval stemmed from his long-term interest in weather modification.

After receiving encouragement from Jule Charney, Leith spent a summer in Stockholm at the Swedish Institute of Meteorology. There he coded a five-level GCM for LLNL's newest computer, the Livermore Automatic Research Calculator (LARC), due to be delivered in the fall of 1960. Leith wrote the code based solely on the manual for the new machine.

Although aware of the Smagorinsky–Manabe and Mintz–Arakawa efforts, Leith worked primarily on his own. He had a working five-level model by 1961. However, he did not publish his work until 1965 (Leith, 1965). Nevertheless, by about 1963 Leith had made a film showing his model's results in animated form and had given numerous talks about the model.

Leith ceased work on his model—known as LAM (Leith atmospheric model or Livermore atmospheric model)—in the mid-1960s, as he became increasingly interested in statistical modeling of turbulence. In 1968, he went to NCAR, where he was instrumental in a number of climate modeling projects.

The initial LAM model was based on the Bjerknes–Richardson primitive equations. It had five vertical levels and used a 5° × 5° horizontal grid. It covered only the Northern Hemisphere, with a "slippery wall" at 60°N. To damp the effects of small-scale atmospheric waves, Leith introduced an artificially high viscosity, which caused serious problems and helped to stimulate Leith's career-long interest in turbulence.

## VII. THE NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

The National Center for Atmospheric Research, established in 1960, began a GCM effort in 1964 under Akira Kasahara and Warren Washington. Two different model series were eventually constructed, designated here as NCAR 1–3 and CCM 0–1.

### A. The Kasahara–Washington Models (NCAR 1–3)

The first-generation NCAR GCM was developed starting in 1964, with first publication in 1967. It was a simple two-layer global model with a 5° horizontal resolution.

The second-generation model, completed around 1970, added a great deal of flexibility. The basic model had a 5° horizontal, six-layer resolution, but it could also be run at resolutions as fine as 0.625° horizontal over a limited domain, with up to 24 vertical layers.

NCAR 3, finished about 1973, also allowed multiple resolutions, including a user-specifiable vertical increment. The most significant changes, however, involved improved finite-difference schemes.

The Kasahara–Washington group focused a great deal of attention on numerical schemes for finite-difference approximations. In addition, a great deal of work was done on problems of computational error arising from round-off (Kasahara and Washington, 1967).

## B. The Community Climate Model

In the latter part of the 1970s, NCAR gradually abandoned the Kasahara–Washington model. In its place, NCAR developed a community climate model (CCM), intended to serve not only modelers working at NCAR, but the large constituency of affiliated universities associated with NCAR's parent organization, the University Corporation for Atmospheric Research. The CCM was initially based on the Australian Numerical Meteorological Research Centre model and an early version of the European Centre for Medium Range Weather Forecasts (ECMWF) model. It also incorporated elements of the GFDL models.

The NCAR CCM series of models was especially important because of the relatively large community of researchers who were able to use it. Versions of the model were adopted by a number of other groups in the late 1980s. This was made possible by NCAR's strong focus on documentation and modularity. User manuals and code documentation were made available for all elements of the models starting with CCM-0B.

### 1. CCM-0A

The initial version of the community climate model was based on the spectral model of the Australian Numerical Meteorological Research Centre (Bourke *et al.*, 1977). One member of the ANMRC team (K. Puri) brought the model to NCAR during an extended visit. Later, it was extensively revised.

### 2. CCM-0B: A Combined Forecast and Climate Simulation Model

A second version of the community climate model was developed in 1981. This model's guiding purpose was "NCAR's decision to utilize the same basic code for global forecast studies (both medium- and long-range) and for climate simulation. Economy and increased efficiency could then be achieved by documenting and maintaining only one set of codes. Changes from one application to the other could be relatively straightforward in a model with modular design. The use of one basic model for both forecasting and climate studies has potential scientific value since a major part of long-range (one- to two-week) forecast errors is due to the drift toward a model climate which differs from that of the atmosphere. Thus, improvements in the climate aspects of the model should lead to improvements in forecasts" (Williamson *et al.*, 1987).

CCM-0B was designed to include the best elements of other existing models. Initial code for CCM-0B came from an early version of the ECMWF model. Physical parameterizations, including the radiation and cloud routines of Ramanathan, and numerical approximations were added from CCM-0A (Ramanathan *et al.*, 1983). Energy balance and flux prescriptions from the early GFDL models were incorporated, while vertical and temporal finite differences matched from the Australian spectral model that was the basis for CCM-0A (Williamson *et al.*, 1987).

### 3. CCM-1

CCM-1 evolved from CCM-0B in the mid-1980s. The primary differences were changed parameterizations, new horizontal and vertical diffusion schemes, and changes to moisture adjustment and condensation schemes.

## VIII. 1965–1975: SPREAD OF GCMs

By 1965, then, three groups in the United States had established ongoing efforts in general circulation modeling:

- Geophysical Fluid Dynamics Laboratory
- UCLA Department of Meteorology
- National Center for Atmospheric Research

In addition, a small group at the UK Meteorological Office had begun work on a GCM, under Andrew Gilchrist, but published very little until the 1970s. At this point, GCMs and modeling techniques began to spread by a variety of means. Commonly, new modeling groups began with some version of another group's model. Some new groups were started by post-docs or graduate students from one of the three original GCM groups. Others built new models from scratch.

The GCM family tree, shown in the Appendix at the end of this chapter, offers a visual map of these relationships.

### A. Modeling Groups Proliferate

Among the important GCM groups established in 1965–1975 were these:

- RAND Corporation (Santa Monica, California)

- Goddard Institute for Space Studies (New York, New York)
- Australian Numerical Meteorological Research Centre (Melbourne, Australia; later this became the Bureau of Meteorology Research Centre)

Each group initially borrowed an existing model, but subsequently made significant modifications of its own.

## B. Modeling Innovations

Two important innovations of the 1965–1975 decade were coupled atmosphere–ocean models and spectral transform techniques.

### 1. Coupled Atmosphere–Ocean Models

GFDL was among the first groups to attempt coupling of an atmospheric GCM to an ocean model. Initially, highly simplified ocean models (one-layer "swamp" oceans) were used. These were succeeded by two-level "mixed-layer" ocean models. In 1969, Manabe and Bryan published the first results from a coupled ocean–atmosphere general circulation model (OAGCM). However, this model used a highly idealized continent–ocean configuration. Results from the first coupled OAGCM with more realistic configurations were published in 1975 (Manabe *et al.*, 1975).

### 2. Spectral Transform Techniques

Spectral methods are an alternative to finite-difference schemes, the method used by all of the first-generation primitive equation GCMs. They express the horizontal variation of dynamic model fields in terms of orthogonal spherical harmonics. The technique simplifies the solution of many of the nonlinear partial differential equations used in general circulation modeling. Its utility had been explored as early as 1954 (Platzman, 1960; Silberman, 1954).

Heavy calculational demands made spectral methods unsuitable for use in early GCMs. Faster computers, and improvements in algorithms for spectral methods that reduced their calculational intensity, led to their adoption in GCMs around 1970 (Bourke, 1974; Eliasen *et al.*, 1970; Orszag, 1970; Robert, 1969).

## C. Research on Carbon Dioxide and Climate

The important role of carbon dioxide, water vapor, and other "greenhouse" gases in the atmosphere's heat retention capacity had been recognized in the 19th century by the Swedish scientist Svante Arrhenius, who had also speculated—with remarkable prescience—on the possibility of anthropogenic climate change from the combustion of fossil fuels (Arrhenius, 1896).

Little further work on the greenhouse effect was done until the late 1940s, when radioactivity in the atmosphere stimulated interest in "tracer" studies of various atmospheric constituent gases (Callendar, 1949; Suess, 1953). This gradually led to a revival of interest in the possibility of anthropogenic influences on climate (Plass, 1956). During the International Geophysical Year (1957–1958), Revelle and Suess (1957) proposed monitoring the carbon dioxide content of the atmosphere. This led to the establishment of Keeling's station at Mauna Loa in the same year, which soon established the regular annual increases in the carbon dioxide concentration (Keeling, 1960).

During 1965–1975, studies of the effect of changing carbon dioxide concentrations on the Earth's radiative equilibrium began in earnest, as data from Mauna Loa continued to show steady $CO_2$ increases. The first studies used simpler one- and two-dimensional models, rather than GCMs (Manabe and Wetherald, 1967). Responses to $CO_2$ doubling became the standard form of this experiment. The first use of a GCM to study the effects of carbon dioxide doubling came in 1975 (Manabe and Wetherald, 1975).

## D. Early Climate Politics and GCMs

During this period, anthropogenic effects on climate were usually considered under the rubric of weather modification, which had been among the stimuli for early efforts in weather modeling. Literature on the subject frequently uses the phrase "inadvertent climate modification" when discussing anthropogenic climate change, to make the parallel (National Research Council, 1966; Study of Man's Impact on Climate, 1971).

### 1. SCEP and SMIC

With the rise of the environmental movement in the early 1970s came early interest in world-scale environmental problems. Two important studies, both prepared as input to the 1972 United Nations Conference on the Human Environment, noted the possibility of "inadvertent climate modification." The Study of Critical Environmental Problems (SCEP) focused on pollution-induced "changes in climate, ocean ecology, or in large terrestrial ecosystems." It cited GCMs as "indispensable" in the study of possible anthropogenic climate change.

The Study of Man's Impact on Climate (SMIC) also endorsed GCMs. (Its section on this subject was drafted by Manabe.) Both SCEP and SMIC recommended a major initiative in global data collection, new international measurement standards for environmental data, and the integration of existing programs to form a global monitoring network. These reports are widely cited as the origin of public policy interest in anthropogenic climate change (Study of Critical Environmental Problems, 1970; Study of Man's Impact on Climate, 1971).

### 2. Other Issues

In the early 1970s, several other large-scale atmospheric issues rose to public awareness. Notable among these were stratospheric ozone depletion, acid rain, and upper atmosphere pollution problems raised by the controversial supersonic transport.

## IX. 1975–1985: GCMs MATURE

In this decade, more modeling groups were established. Research programs consisted primarily of improving existing modeling techniques through higher resolution, better parameterizations, and coupling ocean and atmospheric GCMs. Increasingly, modelers began to perform GCM-based experiments. Longer models runs, made possible by faster computers, were an important part of experimental strategies. Increasing political attention to the climate change issue, especially in the United States, raised the visibility of GCMs both inside and outside climate science.

## A. Computer Power

The rapid growth of computer power during this period is illustrated by the following in Table I. Most groups building GCMs either owned or had access to large, fast supercomputers. Greater computer power allowed longer runs, smaller grids, and larger numbers of runs.

## B. Spread of Modeling Capacity

New GCM modeling groups established during this period include these:

- Max Planck Institut (Hamburg, Germany)
- NASA Goddard Laboratory for Atmospheric Sciences
- NASA Goddard Laboratory for Atmospheres
- Colorado State University
- Oregon State University
- National Meteorological Center
- Lawrence Livermore National Laboratory
- European Centre for Medium-Range Weather Forecasts (Reading, UK)

By the end of this period, European modeling groups—especially the ECMWF—had begun to mount a significant challenge to U.S. dominance in general circulation modeling.

## C. Modeling Innovations and Experiments

The decade from 1975 to 1985 was marked by steady improvement in existing techniques, rather than major innovation. Increasingly sophisticated and computationally efficient schemes were developed for these areas of interest:

- Spectral transforms
- Hydrological cycles

**Table I**
**Computers in Use at GFDL, 1956–1982**

| Computer | Time period | Relative power |
|---|---|---|
| IBM 701 | 1956–1957 | 1 |
| IBM 704 | 1958–1960 | 3 |
| IBM 7090 | 1961–1962 | 20 |
| IBM 7030 | 1963–1965 | 40 |
| CDC 6600 | 1965–1967 | 200 |
| UNIVAC 1108 | 1967–1973 | 80 |
| IBM 360/91 | 1969–1973 | 400 |
| IBM 360/195 | 1974–1975 | 800 |
| Texas Instruments X4ASC | 1974–1982 | 3000 |

From Geophysical Fluid Dynamics Laboratory (1981).

- Coupled OAGCMs
- Radiative transfer, including atmospheric chemistry
- Moist convection
- Continental surfaces
- Boundary layer turbulence

Carbon dioxide doubling experiments became commonplace.

### D. Climate Politics

During 1975–1989, the possibility of global warming became a policy issue within scientific agencies both in the United States and internationally. Studies were conducted by the National Academy of Sciences, the Council on Environmental Quality, the U.S. Department of Energy, the World Meteorological Organization, and others. Congressional hearings called for action, and funding for climate research grew steadily. In 1985, at Villach, Austria, an influential climate science conference recommended policy studies of climate change mitigation techniques, including international treaties.

In the early 1980s, the effects of smoke and dust from a superpower nuclear exchange were tested with climate models, leading to the issue of "nuclear winter" (Covey *et al.*, 1984; Sagan, 1983; Thompson and Schneider, 1986). Action on the ozone depletion issue—sparked by observations of an Antarctic ozone "hole"—produced the Montreal Protocol on the Ozone Layer in 1985. Transboundary pollution problems, notably acid rain, were also high on the political agenda. All of these raised public awareness of global atmospheric problems, but the issue of climate change did not achieve the status of mass politics until about 1988 (Schneider, 1989).

## X. CONCLUSION

By the 1980s, computer models of atmosphere and ocean general circulation had become the primary tool in studies of climate. This marked a major historical transformation from a previous era, in which virtually the only tool for climate studies was the statistical record.

Perhaps the most important aspect of this shift was the ability to perform model-based "experiments" to project possible causes of climatic change. This led to the remarkable visibility of GCMs in political debates over anthropogenic climate change, which continues into the present with the work of the Intergovernmental Panel on Climate Change and the Conferences of Parties to the Framework Convention on Climate Change, signed at Rio de Janeiro in 1992.

Another major product of the shift to numerical models was the development of vast global data networks, from many different instrument modalities. These were built to supply the information necessary to predict weather, but the data record is now very nearly sufficient in length and global coverage to allow accurate studies of climate as well. Without the availability of computer models, these data networks would probably not have been constructed, since they could not have been processed or understood in any other way. The pioneering GCM builders have now retired, turning over their monumental project to a large and growing generation of successors. This volume of essays dedicated to Akio Arakawa is a fitting tribute to one of the major scientific achievements of the 20th century.

## APPENDIX

### The GCM Family Tree

A "family tree" that describes important relations among the major modeling groups is shown in Fig. 1. While the GCM Family Tree captures only the most direct relationships among GCM groups, it can serve a useful heuristic purpose in tracing the main lines of institutional affiliation.

#### Participating in GCM History

The GCM Family Tree is part of an evolving WWW-based project in "participatory history." We hope to collect archival materials—including documents, informal memoirs, and any other information related to the history of GCMs—and make them available on-line to historians, scientists, and anyone interested in this fascinating story.

The group building the site—funded by the Alfred P. Sloan Foundation and sponsored by the American Institute of Physics and the American Geophysical Union—is posting materials that (like this article) are *still in draft form*. The Web address is www.aip.org/history/gcm. Anyone interested in participating in the project can be added to a notification list by contacting the author at pne@umich.edu.

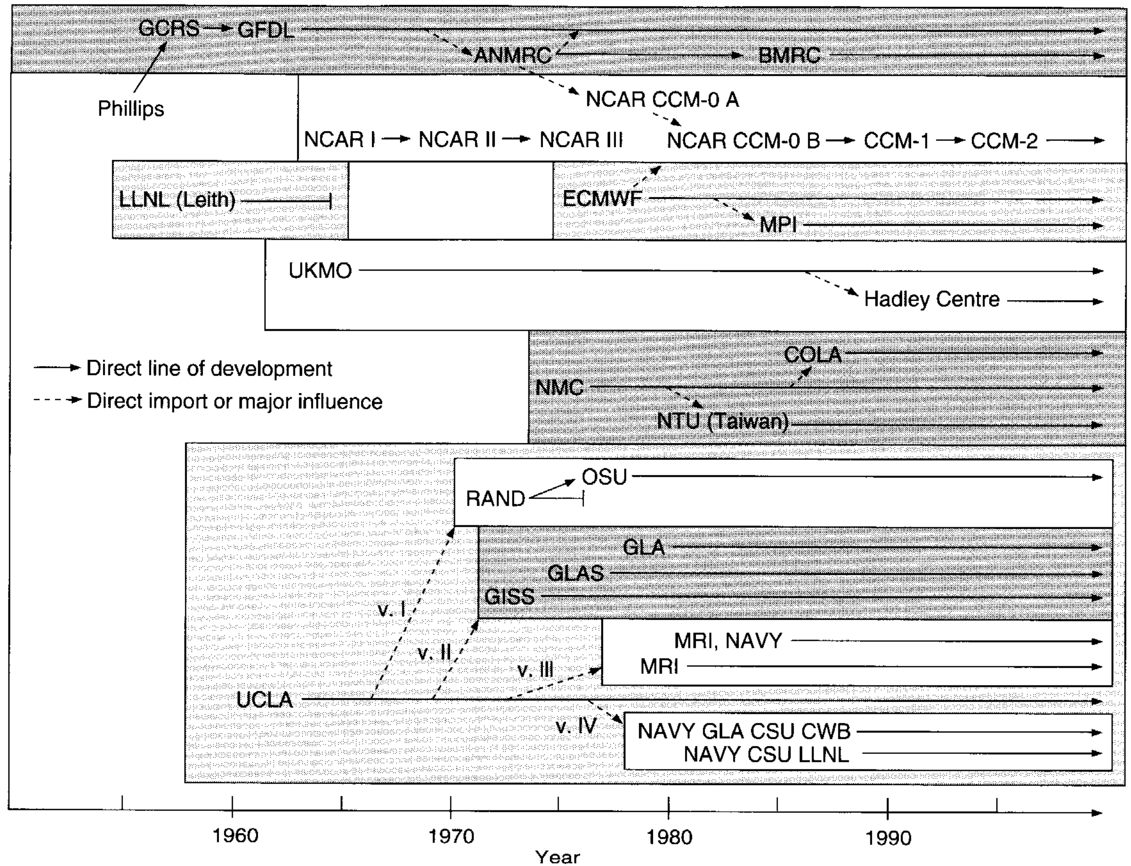


**Figure 1** The GCM Family Tree.

**Why Contribute to the Archive?**

The purpose of the project is to see if the interactive capability of the World Wide Web can be used not only to present information, but also to collect it. We are especially interested in information that might not otherwise be preserved or that researchers would not easily be able to find.

We would like to gather information that would not be part of any official record while it is still relatively fresh in participants' memories. We seek physical material related to the development of GCMs, such as model documentation, memoirs, and correspondence. We are also interested in learning about existing collections of material related to this history.

All contributions will become part of a public archive on the history of atmospheric GCMs. For the life of the Web site, e-mail contributions will be posted there. Eventually, they will be preserved in an electronic archive, along with the physical material donated to us.

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