# 7 The Infinite Forecast

The concentration of computing resources at a few institutions probably affected no field more than it affected climatology. In the 1960s and the 1970s, this data-driven, regionally oriented, descriptive field would be transformed into a theory-driven, globally oriented discipline increasingly focused on forecasting the future. The change would be wrought not by traditional climatologists, but by scientists based in theoretical meteorology and computer programming, working at a handful of institutions endowed with what were then enormous computing resources. Unlike traditional climatologists, who searched for regularities in data from the past, this new generation of scientists sought to simulate the climate, building models from the same techniques used in numerical weather prediction. From there, they moved gradually toward simulating the entire Earth system, replicating the world in a machine.

If you can simulate the climate, you can do experiments. God-like, you can move the continents, make the sun flare up or dim, add or subtract greenhouse gases, or fill the stratosphere with dust. You can cook the Earth, or freeze it, and nobody will even complain. Then you can watch and see what happens.

For a scientist, experiments are all-important. You use them to find out what really matters in a complicated system. In a laboratory experiment, you create a simplified situation, blocking out most of the real world's complexity while retaining a few variables you can manipulate. Then you compare the outcome with an unmodified "control" that leaves those variables at their ordinary values.

In the geophysical sciences, though, the controlled-experiment strategy generally doesn't work. The system you are dealing with is just too large and too complex. You can isolate some things, such as the radiative properties of gases, in a laboratory, but to understand how those things affect the climate you need to know how they interact with everything else.

There is no "control Earth" that you can hold constant while twisting the dials on a different, experimental Earth, changing carbon dioxide or aerosols or solar input to find out how they interact, or which one affects the climate most, or how much difference a change in one variable might make.

Sometimes you get a "natural experiment," such as a major volcanic eruption that measurably cools the whole planet for a year or two. Similarly, the oceanographer Roger Revelle famously called human carbon dioxide emissions a "large scale geophysical experiment."[1,2] Yet these aren't really experiments, precisely because there is no control Earth. You don't know with certainty what *would have happened* without the eruption, or the $CO_2$ increase. You can assume that without the change things would have remained much the same, which seems like a pretty good assumption until you realize that climate varies naturally over a rather wide range. So unless the effect is very large and sudden—for example, a massive volcanic eruption or a gigantic meteor impact—you can't know for sure that you are seeing a signal and not just more noise.

Simulation modeling opened up a way out of this quandary. Only through simulation can you systematically and repeatedly test variations in the "forcings" (the variables that control the climate system). Even more important, only through modeling can you create a control—a simulated Earth with pre-industrial levels of greenhouse gases, or without the chlorofluorocarbons that erode the ozone layer, or without aerosols from fossil fuel and agricultural waste combustion—against which to analyze what is happening on the real Earth. As we saw in chapter 6, John von Neumann and others understood the significance of this power "to replace certain experimental procedures" almost immediately, although the full extent of it would take some time to dawn on anyone.[3]

A convergence of technical capabilities and theoretical understanding made climate simulation possible. By the late 1930s, theoretical meteorology had set its sights firmly on the planetary scale as the most fundamental level of explanation. Rossby and others had established a theory of large-scale circulation based on very long waves, confirming and detailing the three-cell circulatory structure described by Ferrel almost a century earlier. (See figure 2.6.) Rossby's 1941 summary of "the scientific basis of modern meteorology" already focused on the planetary circulation as the ultimate cause of weather patterns.[4] World War II military aviators, flying frequently at high altitudes, accumulated substantial experience of the polar jet stream at 50–60° latitude, near the northern boundary of the mid-latitude

Ferrel cell.[5] Rossby's long waves explained the jet stream's meanders, which in turn helped explain the movements of weather systems closer to the ground.

Therefore, models of *global* atmospheric motion occupied the pinnacle of Charney's hierarchy of models. Today such models are known as GCMs, an acronym standing interchangeably for "general circulation model" and "global circulation model."[6] GCMs represented the last step in von Neumann's meteorological research program, which would culminate in what he called the "infinite forecast."[7] By this phrase, von Neumann did not intend deterministic prediction of weather over long or "infinite" periods. Instead, he had in mind the statistically "ordinary circulation pattern" that would emerge when "atmospheric conditions . . . have become, due to the lapse of very long time intervals, causally and statistically independent of whatever initial conditions may have existed." This phrase sounds remarkably like the mathematical concept of chaos, by which minute variations in initial conditions rapidly generate extreme divergences in outcomes: a butterfly flaps its wings over Brazil and causes a tornado in Texas. In fact, the theoretical meteorologist Edward Lorenz first discovered what we now call chaos theory while working with atmospheric models in the early 1960s.[8] But in the mid 1950s, these results, and the idea of chaos itself, remained unknown. In 1955, von Neumann's "infinite forecast" expressed the widespread belief that global atmospheric flows might display predictable symmetry, stability, and/or periodicity. Research aimed at finding such predictable features remained active throughout the 1950s.[9]

But how could modelers verify an "infinite forecast"? In other words, what did meteorologists actually know *from data* about the general circulation in the mid 1950s? An image of the state of the art may be found in the work of MIT's General Circulation Project, which began in 1948 and continued for some 20 years under the leadership of Victor Starr, supported principally by the Air Force and the Atomic Energy Commission. (UCLA conducted similar, independent work under the same auspices.) The General Circulation Project collected every available data source that might reveal more details of the circulation's structure. Articles describing these data almost invariably opened with extensive caveats regarding the small quantity and poor quality of upper-air measurements then available. Nonetheless, a crude data-based picture began to emerge. One study, by Starr and Robert White (of the Travelers Insurance Corporation), included all available upper-air observations for 1950 from 75 stations along five latitude bands, each with 10–19 stations. This “involved altogether a total of 176,000 individual wind readings, 57,000 humidity readings, and 77,000 temperature readings.”[10] In the mid 1950s, such a quantity of observations seemed gigantic. Yet these data remained insufficient for all but the crudest possible picture of global flows. After ten years of intensive effort, Starr would write: “. . . whether we like it or not, meteorologists have been struggling with problems of the most primitive kind concerning the motions of the atmosphere. . . . The questions at issue have not been such as relate to some fine points concerning a general scheme that is accepted as sound. Rather [they concern] whether some crucial portion of the system operates forward or in reverse.”

Starr was talking about the basic mechanism of the large-scale circulatory cells. (See figure 2.7.) Did those cells produce a positive energy release, converting potential energy into kinetic energy (as in Ferrel’s scheme), or a negative one, converting kinetic energy into potential energy (as General Circulation Project studies of the mid 1950s seemed to show)? Starr wrote that even this fundamental question could not yet be answered because general circulation theory remained inadequate.

> The limiting factor always has been, and will continue to be, the completeness and accuracy of the de facto pictures of the general circulation. . . . What counts are not mere tabulations of data; it is their intelligent organization according to physical laws so as to lead to physical depiction of relevant processes and schemes of motion. . . . Due no doubt to the complexity of the system considered, correct processes have thus far found their incorporation into theoretical models, almost without exception, only *after* their empirical discovery.[11]

Further details of this issue need not concern us here. What is of interest to us is Starr’s conviction that the absence of sufficient data, especially in the vertical dimension, still rendered theories of the general circulation fundamentally speculative, even on very basic issues. Starr’s *cri de coeur* for “intelligent organization” of data leading to “physical depiction of relevant processes and schemes of motion” would be answered through general circulation modeling.

The first experiments with GCMs came only months after the operational launch of numerical weather prediction. In these models, the limits of predictability, numerical methods, and computer power would be tested together. As Nebeker has shown, GCMs would reunify meteorology’s three main strands—forecasting, dynamical-theoretical meteorology, and empirical-statistical climatology—within a single research program.[12] They would transform climatology from a statistical science oriented toward the particularity of regional climates into a theoretical science more focused on the global scale. Ultimately, they would also guide vast changes in the global data infrastructure, and they would transform the sources and the very meaning of the word 'data'.

In this chapter, I discuss the basic principles of climate simulation, focusing on general circulation models. I then tell the story of the first generation of GCMs and the modeling groups that created them, ending with a genealogy that links them to subsequent groups and models. Finally, I discuss early studies of carbon dioxide doubling (a paradigmatic experiment that later became a benchmark for climate-change studies) and the role of data friction in delaying the empirical evaluation of climate simulations.

## How Climate Models Work

Charney's model hierarchy sketched a path from simple to complex: from two-dimensional, regional forecast models to three-dimensional hemispheric and global circulation models. As climate modeling matured, another model hierarchy emerged, this one aimed not at forecasting but at characterizing how the atmosphere and the oceans process solar energy. This section departs from the historical approach for purposes of exposition, briefly describing how climate models work before returning to the history of GCMs.

Earth is bathed in a constant flood of solar energy. The laws of physics dictate that over time the planet must remain, on average, in thermal equilibrium. In other words, it must ultimately re-radiate all the energy it receives from the sun back into space. The atmosphere's blanket of gases—primarily nitrogen, oxygen, and water vapor—absorbs much of the incoming radiation as heat. The oceans absorb solar energy directly; they also transfer heat to and from the atmosphere. With their great mass, the oceans retain much more energy than the air, functioning as a gigantic heat sink and moderating changes of temperature in the atmosphere. If Earth had no atmosphere or oceans, its average surface temperature would be about –19°C. Instead, the heat retained in the atmosphere and oceans maintains it at the current global average of about 15°C.

At the equator, Earth receives more heat than it can re-radiate to space; at the poles, it re-radiates more heat than it receives. Thus the climate system, as a thermodynamic engine, serves to transport heat from the equator toward the poles. The most fundamental climatological questions regard exactly how much heat is retained (the global average temperature), where the energy resides (in the oceans, atmosphere, land surfaces, etc.), how it is distributed, and how it circulates around the globe in the course of moving poleward.

Fundamentally, then, Earth's temperature is a matter of what climatologists call "energy balance." Modeling the climate therefore begins with the "energy budget": the relationship between incoming solar radiation and outgoing Earth radiation. Energy balance models (EBMs) use measured or calculated values for such factors as solar radiation, albedo (reflectance), and atmospheric absorption and radiation to compute a single global radiative temperature. The simplest, "zero-dimensional" EBMs treat Earth as if it were a point mass. These models involve just a few equations and can be solved by hand, with no need for computers. Energy balance can also be calculated one-dimensionally, by latitude bands or "zones," to study how the relationship changes between the equator and the poles, or two-dimensionally, including both zonal and longitudinal or "meridional" energy flows. Svante Arrhenius's calculations of carbon dioxide's effect on Earth's temperature constituted one of the earliest one-dimensional (zonal) EBMs.[13]

A second type of climate model, the radiative-convective (RC) model, focuses on vertical transfers of energy in the atmosphere through radiative and convective processes. Such models typically simulate the atmosphere's temperature profile in either one dimension (vertical) or two (vertical and zonal). When Callendar revived the carbon dioxide theory of climate change in 1938, he used a one-dimensional radiative model that divided the atmosphere into twelve vertical layers.[14]

A third type is the two-dimensional statistical-dynamical model, employed primarily to study the circulatory cells. In these models the dimensions are vertical and meridional. Schneider and Dickinson, who first described the hierarchy of climate models, identified sub-classes of EBMs and RC models, as well as several kinds of dynamical models less computationally demanding than GCMs.[15]

In contrast with the way NWP models developed, work on computerized climate models did not follow a straightforward path up the hierarchy from simple to complex. Instead, climate modeling *began* with GCMs, the most complex models of all. In the course of this work, new radiative-convective models were developed—sometimes by the same people, such as Syukuro Manabe, who also pioneered general circulation modeling at the Geophysical Fluid Dynamics Laboratory (see below).[16] Major work on new EBMs—the simplest models—followed later, in the late 1960s.[17] Work on RC models and EBMs helped GCM builders conjure up code for vertical transfers of heat, and also provided "reality checks" on GCM results.[18] Climate scientists continue to use these simpler models for many purposes, but this book will not discuss them further.[19]

General circulation models (GCMs) are three-dimensional simulations, integrated over time. The earliest such models used simplified equations, but virtually all modern GCMs are based on the atmospheric primitive equations developed by Vilhelm Bjerknes, Lewis Fry Richardson, and others, which were in turn based on the Navier-Stokes fluid dynamics equations. GCMs simulate not only the planetary heat exchange described by EBMs and RC models, but also the planetary circulation or movement of the atmosphere: patterns of flow, such as the jet streams and Hadley cells, resulting from the interaction of planetary rotation, insolation, gravitation, heat exchange, humidity, orography (surface features such as mountain ranges), sea surface temperature and friction, and many other factors. The oceans also circulate, with dynamics of their own. Transfers of energy between the oceans and the atmosphere play an enormous role in both weather and climate. For this reason, today's atmospheric GCMs (AGCMs) are typically linked to ocean GCMs in "coupled atmosphere-ocean models" (AOGCMs).

All GCMs consist of two major elements. The "dynamical core" simulates large-scale movement using the primitive equations of fluid motion. The underlying mathematics of dynamical cores are relatively well understood. However, like any equations, they may be expressed in different forms for different purposes. Further, solving the equations on a computer requires representing them numerically, and there are numerous ways to do this, each with characteristic computational benefits and drawbacks. For example, the rectangular latitude-longitude grid is only one way to represent the Earth's surface, and it is not the best one for modeling a sphere, because the convergence of longitude lines near the poles inconveniently shortens the model time step. To avoid this, modelers have experimented with many kinds of grids, including triangular, hexagonal, icosahedral, and Gaussian ones.

The second element, the "model physics," includes all the other major processes that occur in the atmosphere. Many of these processes involve transfers of heat. Others involve transfers of moisture—for example, from lakes, rivers, and oceans to the atmosphere and vice versa. In the real atmosphere these processes generally occur at scales much smaller than the model grids—all the way down to the molecular level, at which heat is absorbed and re-radiated by gases; modelers call these "sub-grid scale" processes. Model physics also includes friction between land or ocean surfaces and the air, transfers of heat between the ocean and the atmosphere, cloud formation, and many other processes. Modelers represent sub-grid-scale physics indirectly by means of parameters (mathematical functions and constants that capture the large-scale effects of smaller-scale processes without modeling them directly). Parameterizing physical processes accurately is the most difficult aspect of climate modeling and is a source of considerable scientific and political controversy.

As climate modeling evolved and spread, modelers worked to improve their simulations along three major fronts at once. First, they developed better numerical schemes for integrating model equations, reducing the amount of error incurred by approximating the solutions. Second, to resolve smaller-scale phenomena, they decreased the distance between model gridpoints. Finally, they added more physical processes to the models. Major additions to climate model physics included radiative transfer, cloud formation, ocean circulation, albedo, sulfate emissions, and particulate aerosols. In the 1980s, modelers sought to expand climate studies by adding other elements of the overall climate system, such as sea ice, vegetation, snow, and agriculture, to create "Earth system models" (ESMs). By the mid 1990s, some models included the entire carbon cycle, including uptake by plants, absorption by the oceans, and release through fossil fuel combustion and the decay of plant matter. Figure 7.1 illustrates additions to climate model physics from the mid 1970s to about 2005, based on the climate models used in the four assessment reports of the Intergovernmental Panel on Climate Change. (These include virtually all of the world's GCMs.) In chapter 13, we will explore model physics and the controversies surrounding parameterization in much more detail.

At this writing, in 2009, typical climate AGCM grid resolutions at the surface are 1–5° latitude by 4–8° longitude, translating roughly as rectangles with sides between 100 and 500 km in length. Layers of varying depth represent the vertical dimension to a height of around 20 km, with more layers at lower altitudes, where the atmosphere is denser; modern GCMs typically have 30–50 layers. Early GCMs used a Cartesian grid structure (figure 7.2), computing vertical and horizontal mass and energy transfers between grid boxes at each time step (typically 10–15 minutes). Later GCMs used spectral transform techniques to carry out some computations in "wave space" (see below). Whereas converting early models into computer programs required only a few thousand lines of FORTRAN, today's most sophisticated models contain more than a million lines of program code.

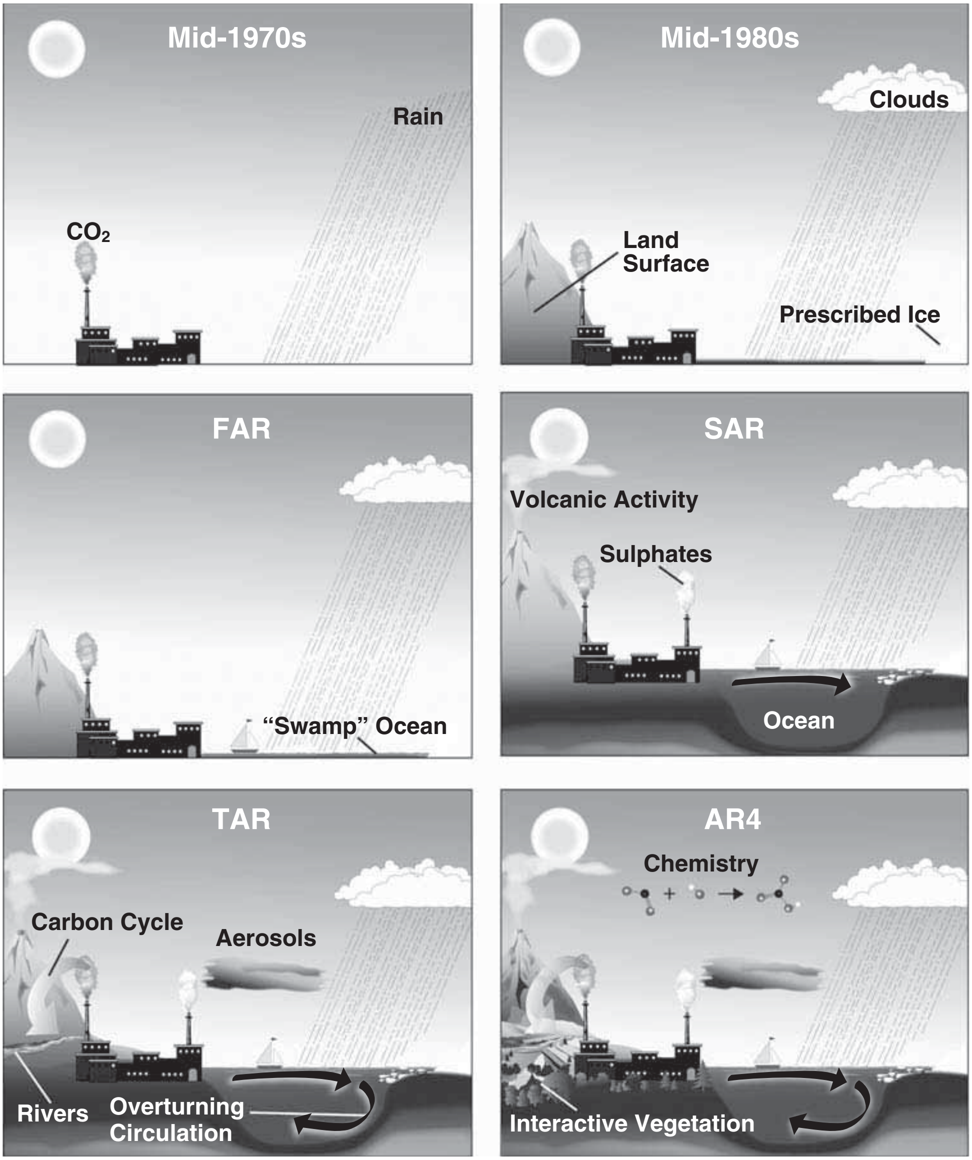


**Figure 7.1**
Processes incorporated in generations of GCMs beginning in the mid 1970s. Acronyms refer to the four assessment reports (AR) of the Intergovernmental Panel on Climate Change, released in 1990 (FAR), 1995 (SAR), 2001 (TAR), and 2007 (AR4). *Source*: *Climate Change 2007: The Physical Science Basis* (Cambridge University Press, 2007). Image courtesy of IPCC.

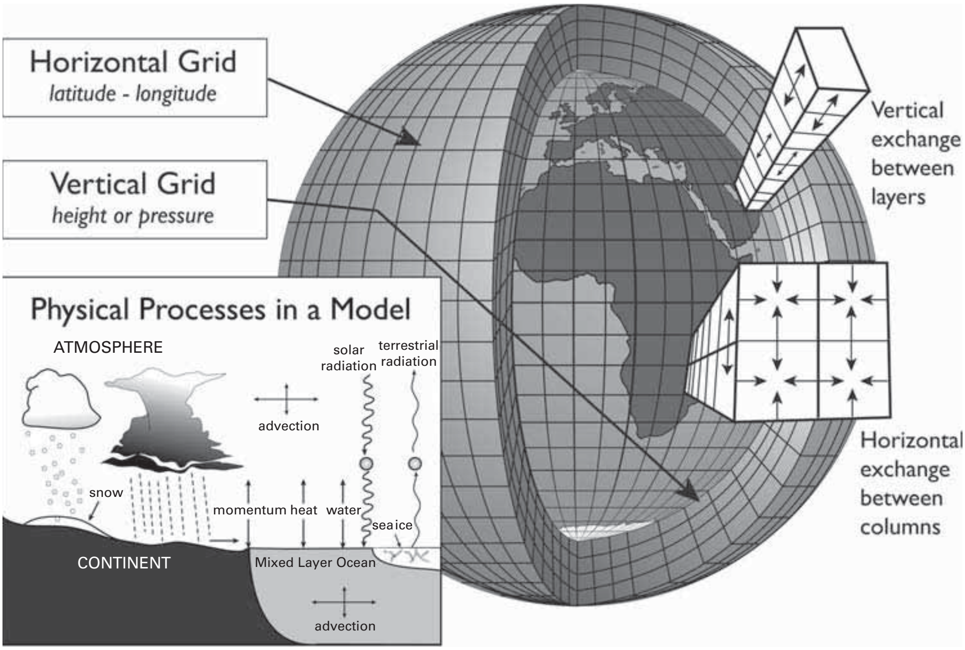


**Figure 7.2**
A schematic representation of the Cartesian grids used in finite-difference GCMs. Graphic by Courtney Ritz and Trevor Burnham.

GCMs can be used both to forecast the weather and to simulate the climate. With a forecast GCM, you want to know exactly what will happen tomorrow, or next week, so you initialize the model with observations. (This means that you set the values for each variable in every grid box using the best available data.) Then you run the model for a week or so at the highest possible resolution. Because of the chaotic nature of weather, however, forecast GCMs lose almost all their predictive skill after two to three weeks. Climate GCMs are used quite differently. You want to see the model's climate—its average behavior over long periods, not the specific weather it generates on any particular day. So you need to run the model for years, decades, or even longer. That can add up to a lot of very expensive supercomputer time. To reduce the amount of computer time each run required, early climate modelers often initialized GCMs with climatological averages—observational data. Today, however, models typically are *not* initialized with data. Instead, they are simply allowed to "spin up" from a resting state, with the various forces driving the climate—solar radiation, gravity, evaporation, the Coriolis effect, and so on—generating the model's circulation. The spin-up phase, which takes years to decades of simulated time, ends when the model comes into a relatively steady state known as "equilibrium." At equilibrium the model has developed its own "climate," with Hadley, Ferrel, and polar cells, circulatory patterns such as jet streams, seasonal changes, a vertical temperature profile, and other characteristic features.

Only when the model comes to equilibrium does the actual climate simulation begin. After that, you run the model for many simulated years (20, 100, perhaps even 1000) and measure its averages, just as you would average real weather data to characterize the real climate. For example, at each gridpoint you might take the maximum and minimum temperature for each day in a simulated January, add them and divide by 2, then add the averages for 50 simulated Januarys and divide by 50 to get the model's average temperature in January (and so on). To evaluate the simulation, you would compare its averages with real climatological data. If your model is a good one, it should more or less reproduce, for example, the seasons and the global distribution of temperature and rainfall.

No climate model, past or present, can precisely reproduce every detail of the real climate. Furthermore, since models represent so many processes and variables, it is commonplace for a GCM to reproduce one variable (e.g. temperature) quite well even as it does poorly on another variable (e.g. winds or rainfall). Because the models are complex, diagnosing the reasons for these performance differences can be extremely difficult. The goal is to get as close as is possible to a realistic climate, using a minimum of ad hoc adjustments, in order to understand why the system behaves as it does. Ultimately you want to know how changes in "forcings"—the variables that alter system behavior, such as solar output, greenhouse gases, and particulate aerosols—affect the global climate. We will return to these matters below, but for the moment we will once again follow the historical thread, beginning with the earliest effort to carry out an "infinite forecast."

The next five sections of this chapter describe pioneering efforts in climate modeling. Readers versed in meteorology and/or computer modeling should have no trouble following the discussion, but others' eyes may glaze over. If you are among the latter, I invite you to skip ahead to the section titled "The General Circulation of Circulation Models."

## The Prototype: Norman Phillips's Model

The first person to attempt a computerized general circulation model was Norman Phillips. During World War II, as an Army Air Force officer, Phillips had studied meteorology. He went on to graduate training at Chicago under George Platzman (a member of the ENIAC experiment team) and Carl-Gustav Rossby. Phillips joined the IAS Meteorology Project in 1951 and worked with Rossby's group in Stockholm during 1953 and 1954. While in Stockholm, he participated in the world's first operational numerical forecasts. Thus Phillips found himself at the very center of early NWP research. By 1954 he had already worked with his generation's foremost dynamic meteorologists, and they had encouraged him in his ambition. By mid 1955, Phillips had completed a two-layer, hemispheric, quasi-geostrophic computer model.[20]

As we saw in chapter 6, results from the initial ENIAC tests of numerical weather prediction had elated the experimenters, who hadn't expected their highly simplified model to work so well. Having worked closely with the group, Phillips shared their euphoria. The historian John Lewis notes that Phillips also paid close attention to another line of research on circulation: "dishpan" model experiments.[21] These analog models consisted of a rotating tank filled with viscous fluid. When heated at the rim and cooled in the center, the tank produced flow patterns resembling those observed in the atmosphere. Watching these flows, Phillips felt "almost forced to the conclusion that at least the gross features of the general circulation of the atmosphere can be predicted without having to specify the heating and cooling in great detail."[22]

Phillips's published study began with a discussion of the chief features of the general circulation then known from observation. These included the following:

- the vertical temperature profile of the atmosphere and the existence of the stratosphere
- the decrease of temperature between the equator and the poles, with the largest effect occurring in middle latitudes
- average wind direction and speed at different latitudes and altitudes, including such features as the trade winds and jet streams
- cyclones (low pressure systems), anticyclones (high pressure systems), and the associated fronts, major features of the circulation above the tropical latitudes
- the absence of an "organized" meridional (equator-to-pole) circulation outside the trade wind regions.[23]

Much of this knowledge had been acquired in the previous 15 years, as upper-air data networks emerged.

For theorists, the above-mentioned features and their interactions demanded explanation. For example, cyclones and anticyclones are large-scale eddies, much like those that form near rocks in a river as water flows over and around them. Globally, the circulation transports solar heat from the equator to the poles. If there is no organized meridional (longitudinal) circulation, such eddies must be involved in this heat transport process—but how? And how did they interact with the average zonal (latitudinal) winds?[24]

Phillips applied nascent NWP techniques, testing whether the geostrophic approximation could reproduce these features of the general circulation. He described his approach as a "numerical experiment" whose "ideal form would . . . be to start with an atmosphere at rest . . . and simply make a numerical forecast for a long time." He hoped that "ultimately some sort of quasi-steady state would be reached, in which the input of energy would be balanced by frictional losses, and the typical flow patterns would have some resemblance to those in the actual atmosphere."

Phillips carried out his first "numerical experiment" on the IAS computer at Princeton, a machine with just 1 kilobyte of main memory and 2 kilobytes of magnetic drum storage. To navigate between these memory constraints and his mathematical model, he chose a 17×16 finite-difference grid, with gridpoints spaced 625 km apart in the *y* coordinate (latitude) and 375 km apart along the *x* coordinate (longitude). This rendered a model surface that was 10,000 km by 6000 km. The *y* axis represented roughly the actual distance from equator to pole, while the *x* axis approximated the size of a single large eddy and was thus much smaller than Earth's circumference at the equator (about 40,000 km). To simulate the circulatory flow, eddies moving off the eastern edge of the model re-entered it on the west, making the model's topology effectively cylindrical. Two pressure levels represented the vertical dimension. The model used a one-day time step during a "spin-up" of 130 simulated days. After that, the time step was reduced to around 2 hours and the model was run for 31 simulated days.[25]

Phillips used numerous simplifying techniques to make his model tractable. For example, the model contained no moisture or clouds. It failed to replicate many characteristics of the observed circulation, but it did reproduce some fundamental features, including the easterly-westerly-easterly zonal distribution of surface winds, a jet stream, and a net transport of heat from equator to pole. It is now generally regarded as the first working numerical general circulation model.

Almost in passing, Phillips made note of what would become a crucial issue for all future GCMs. "The experiment," he wrote, "*contains empirical elements* in that the representation of certain physical effects is based on meteorological experience with the actual atmosphere, *rather than being predicted from fundamental laws of physics*." For example, rather than attempt to simulate evaporation and condensation directly, Phillips simply fixed his model's stability factor at 80 percent of its measured value in the atmosphere. Phillips hoped that "a more complete theory of the atmospheric motions [would] eventually explain these quantities also." This tension between "empirical elements" and prediction from physical theory has persisted throughout the subsequent history of atmospheric modeling. Even as modelers eliminated some empirical elements in favor of theory-based calculation, they introduced others as models became more complex.

Phillips's model provoked enormous excitement. In the short term, it sparked action by John von Neumann, who immediately called a conference at Princeton on "Application of Numerical Integration Techniques to the Problem of the General Circulation" and composed a research proposal on "Dynamics of the General Circulation." As John Lewis points out, by framing the project as a contribution to forecasting von Neumann positioned it strategically to gain further funding from the Weather Bureau, the Air Force, and the Navy.[26] In the long term, Phillips's model inspired an entire generation of dynamical meteorologists and climate scientists, not only in the United States but also in the United Kingdom and Japan. In 1956, his paper received the first Napier Shaw Prize of the UK's Royal Meteorological Society. Akio Arakawa, later a leader in general circulation modeling, has noted more than once that his "excitement about the new developments" in studies of the general circulation "reached its climax when Phillips's paper appeared in 1956." In order to "share this excitement with other Japanese meteorologists" Arakawa, then working at the Japan Meteorological Agency, published a monograph in Japanese describing Phillips's work and its relevance to circulation theories.[27]

With Phillips's experiment as proof of concept, a new generation of theoretical meteorologists began to envision models based directly on the primitive equations. Phillips marked out the path: start with simplifying assumptions, such as barotropy and quasi-geostrophy, then eliminate them, one by one, until nothing remained but the primary physics. Putting this program into practice would require not only a lot more computer power, but also further refinement of numerical methods for solving differential equations. Perfecting primitive-equation GCMs became something of a “holy grail” for both forecasting and climatology. In the following sections, I describe the first four efforts to meet this challenge. All four were based in the United States, but Japanese émigré scientists played major roles in three of them.

### The Geophysical Fluid Dynamics Laboratory

Responding positively to von Neumann’s proposal, the US Weather Bureau created a General Circulation Research Section under the direction of Joseph Smagorinsky in 1955. Smagorinsky saw his charge as completing the final step of the von Neumann–Charney computer modeling program: a three-dimensional, global, primitive-equation general circulation model of the atmosphere.[28] The General Circulation Research Section initially found laboratory space in Suitland, Maryland, near the Weather Bureau’s JNWP unit. Subsequently this lab endured several changes of name and location, moving first to Washington, D.C. as the General Circulation Research Laboratory. Renamed the Geophysical Fluid Dynamics Laboratory in 1963, the lab decamped to Princeton University in 1968, where it remains. (For consistency, I will refer to all these incarnations by the lab’s current acronym, GFDL.)

In 1955–56, as lab operations commenced, Smagorinsky collaborated with von Neumann, Charney, and Phillips to develop a two-level baroclinic model based on a subset of the primitive equations. Like Phillips’s, this model reduced complexity by using “walls” to mark off a section of the planetary sphere. This time the walls were latitudinal instead of longitudinal, so that the model could simulate zonal circulation across about 65° of latitude, roughly two thirds of one hemisphere.[29]

Like virtually all GCMs, GFDL’s early models were developed by collaborative teams consisting chiefly of dynamical meteorologists and computer programmers, many of whom, including Leith Holloway and Richard Wetherald of GFDL, had begun their careers as meteorologists. Often wrongly seen as purely mechanical work, in the late 1950s and early 1960s scientific computer programming was an arcane and difficult art. Scientists expressed GCMs as sets of variables, parameters, and systems of equations, many of them nonlinear. Solving those equations with a computer program required choosing from among multiple possible ways to translate the differential equations into finite-difference equations. These then had to be translated into computer code, which required another series of choices, almost all of which would influence both the efficiency and the accuracy of computer processing.

Writing code for GCMs required great skill and ingenuity not only with programming itself, but also with the complex mathematics of the theoretical models and with numerical and computational methods. Therefore, GCM laboratory teams often consulted, and sometimes included, mathematicians specializing in such techniques as numerical analysis and nonlinear computational stability. (For example, GFDL employed Douglas Lilly.) At first these partners in model development received recognition only as assistants, but within a few years GFDL and some other laboratories acknowledged the scientific importance of their technical contributions by listing the main programmers as co-authors.

In 1959, Smagorinsky invited Syukuro Manabe of the Tokyo NWP Group to join the General Circulation Research Laboratory. Impressed by Manabe's early publications, Smagorinsky assigned Manabe to GCM development. Smagorinsky provided Manabe with a programming staff, allowing him to focus on the mathematics of the models without writing code.[30] Initially, they worked on re-coding Smagorinsky's two-level baroclinic model for the experimental IBM STRETCH supercomputer, then still under development. When the STRETCH finally arrived in 1962, GFDL shared the machine with the Weather Bureau's numerical weather prediction unit. In an interview with me, programmer Richard Wetherald described this arrangement as "disastrous" for GFDL, which had second priority on the breakdown-prone machine. By 1965, Smagorinsky, Manabe, Holloway, Wetherald, and other collaborators had completed a nine-level, hemispheric GCM using the full set of primitive equations.[31] They began by re-coding relevant parts of the old two-level model in FORTRAN to avoid the difficult STRAP assembly language used by the IBM STRETCH.

From the beginning, GFDL took a long-range view of the circulation modeling effort. Lab members expected a slow path to realistic simulations, and they remained acutely aware of the pitfall of getting the right results for the wrong reasons. Their research strategy used GCMs to diagnose what remained poorly understood or poorly modeled, and simpler models to refine both theoretical approaches and modeling techniques, in an iterative process:

> We first constructed with considerable care, and in fact programmed, the most general of a hierarchy of models in order to uncover in some detail the body of physics needed, to determine where the obvious weaknesses were, and to give us some idea of the computational limitations we could expect. The perspective thus gained was invaluable. We then laid out a program of simplified models which can be constructed as a sub-set of the most general one. The main requirements were (1) that each model represent a physically realizable state, (2) that they could be

constructed computationally . . . , and (3) that they collectively would provide a step-by-step study of the behavior of new processes and their influence on the interactive system. Hence, many of the intermediate models in themselves may lack detailed similitude to the atmosphere but provide the insight necessary for careful and systematic scientific inquiry.[32]

This strict attention to correcting physical theory and numerical methods before seeking verisimilitude became a hallmark of the GFDL modeling approach.[33] The full primitive-equation GCM ("the most general" model) served as a conceptual framework, driving work on simpler models which led to refinements of the GCM.

Exchanges of energy between the oceans and the atmosphere are fundamental to general circulation physics. Sea water, far denser than the atmosphere, retains much more heat. Ocean currents such as the Gulf Stream absorb, release, and circulate this heat around the planet, strongly affecting global atmospheric temperatures and flows. Smagorinsky foresaw, very early, the need to couple ocean circulation models to atmospheric GCMs. In 1961 he brought the ocean modeler Kirk Bryan to the GFDL to begin this work.[34] At first, GFDL used a highly simplified one-layer ocean model, widely known as the "Manabe swamp ocean." Ultimately, however, better climate simulations would require coupling atmospheric GCMs to ocean GCMs. In 1969, Manabe and Bryan published the first results from a coupled atmosphere-ocean general circulation model (AOGCM).[35] However, this model used a highly idealized continent-ocean configuration that did not much resemble the real Earth. The first results from an AOGCM with more realistic continent-ocean configurations did not appear until 1975.[36]

By the mid 1960s, Smagorinsky had taken a leading role in planning the gigantic Global Atmospheric Research Program (GARP), a project which would continue into the 1980s. GARP occupied an increasing share of Smagorinsky's time, and Manabe emerged as the de facto leader of GFDL's GCM effort. Manabe's work style was always highly collaborative. Manabe's group was among the first to perform carbon dioxide doubling experiments with GCMs,[37] to couple atmospheric GCMs with ocean models,[38] and to perform very long runs of GCMs under carbon dioxide doubling.[39] Box 7.1 sketches the major GFDL model series through the mid 1990s.

## The UCLA Department of Meteorology

Jacob Bjerknes founded the UCLA Department of Meteorology in 1940. He soon established a General Circulation Project as a central focus of the department's research. Yale Mintz, a Bjerknes graduate student who

**Box 7.1**
The GFDL GCM Series

The following list, derived from interviews with various GFDL staff members in the late 1990s, describes the major GFDL models in the informal terms used at the laboratory.

**MARKFORT**

MARKFORT was GFDL's first "production" model. The prototype for the MARKFORT series was the original nine-level Smagorinsky-Manabe hemispheric model described in the text.[a] Used well into the 1960s, a two-level version of the model was initially run on the IBM STRETCH.

**Zodiac**

The Zodiac finite-difference model series was the second major GFDL GCM and its first fully global one. Used throughout the 1970s, its most important innovation was a spherical coordinate system developed by Yoshio Kurihara.[b]

**Sector**

Not a separate GCM but a subset of the GFDL global model series. To conserve computer time (especially for coupled atmosphere-ocean modeling), integrations were performed on a longitudinal "sector" of the globe (e.g. 60° or 120°) with a symmetry assumption for conversion to global results. The early Sector models employed highly idealized land-ocean distributions.[c]

**Skyhigh**

Work on Skyhigh, a GCM with high vertical resolution covering the troposphere, the stratosphere, and the mesosphere, began in 1975.[d]

**GFDL Spectral Model**

In the mid 1970s, GFDL imported a copy of the spectral GCM code developed by William Bourke at the Australian Numerical Meteorological Research Centre.[e] Bourke and Barrie Hunt had originally worked out the spectral modeling techniques while visiting GFDL in the early 1970s.

**Box 7.1**
(continued)

**Supersource**

In the late 1970s, Leith Holloway began to re-code the GFDL spectral model to add modularity and user-specifiable options. The resulting model, Supersource, remained in use at GFDL through the 1990s. Supersource physics descend from Manabe et al.'s Zodiac grid model series. Users can specify code components and options. Supersource has often been used as the atmospheric component in coupled atmosphere-ocean GCM studies.[f]

a. J. Smagorinsky et al., "Numerical Results from a Nine-Level General Circulation Model of the Atmosphere," *Monthly Weather Review* 93, 1965: 727–68.
b. Yoshio Kurihara, "Numerical Integration of the Primitive Equations on a Spherical Grid," *Monthly Weather Review* 93, no. 7, 1965: 399–415.
c. See e.g. S. Manabe and K. Bryan, "Climate Calculations with a Combined Ocean-Atmosphere Model," *Journal of the Atmospheric Sciences* 26, no. 4, 1969: 786–89.
d. J. D. Mahlman et al., "Simulated Response of the Atmospheric Circulation to a Large Ozone Reduction," in *Proceedings of the WMO Symposium on the Geophysical Aspects and Consequences of Changes in the Composition of the Stratosphere*, Toronto, 1978.
e. W. Bourke, "A Multi-Level Spectral Model. I. Formulation and Hemispheric Integrations," *Monthly Weather Review* 102 (1974): 687–701; T. Gordon and B. Stern, "Spectral Modeling at GFDL," in *Report of the International Symposium on Spectral Methods in Numerical Weather Prediction*, 1974; C. T. Gordon, "Verification of the GFDL Spectral Model," in *Weather Forecasting and Weather Forecasts*, ed. D. L. Williamson et al., Advanced Study Program, National Center for Atmospheric Research, 1976, volume 2.
f. S. Manabe and R. J. Stouffer, "Two Stable Equilibria of a Coupled Ocean-Atmosphere Model," *Journal of Climate* 1, 1988: 841–65; S. Manabe et al., "Response of a Coupled Ocean-Atmosphere Model to Increasing Atmospheric Carbon Dioxide," *Ambio* 23, no. 1, 1994: 44–49.

received his PhD in 1949, stayed at UCLA as Bjerknes's associate project director. Among other things, the General Circulation Project carried out extensive data analysis for a climatological atlas. An obituary later recalled Mintz's "heroic efforts . . . in the earlier phase of this project during which he orchestrated an army of student helpers and amateur programmers to feed a prodigious amount of data through paper tape to SWAC, the earliest computer on campus."[40]

In the late 1950s, Mintz began to design numerical GCMs.[41] As Smagorinsky had done, Mintz recruited a Tokyo University meteorologist, Akio Arakawa, to help him build general circulation models. Arakawa, known for his wizardry with numerical methods, was particularly interested in building robust schemes for parameterizing cumulus convection, a major but poorly understood process of vertical heat transport in the atmosphere. Beginning in 1961, Mintz and Arakawa constructed a series of increasingly sophisticated GCMs. Arakawa persuaded Mintz to pay more attention to designing model dynamics that could sustain long-term integration.[42] The first UCLA GCM, completed in 1963, was a two-level global primitive-equation model with 7° latitude by 9° longitude horizontal resolution. It included realistic land-sea distributions and surface topography. Mintz never learned to program computers; Arakawa did all the model coding. With this project completed, Arakawa returned to Japan, but Mintz persuaded him to return to UCLA permanently in 1965.

Of all the world's general circulation modeling groups, the UCLA laboratory probably had the greatest influence on others, especially in the 1960s and the 1970s. This influence resulted not only from continuing innovation, particularly in cumulus parameterization, but also from the UCLA group's exceptional openness to collaboration and sharing. Whereas GFDL was a pure-research institution, UCLA operated in the mode of an academic graduate program, with a mission that included training and knowledge diffusion. Also more typical of the academic tradition, until the 1980s the UCLA group focused primarily on model development, leaving "production" uses of the models (e.g. experimental studies) to other institutions.

Because the UCLA group emphasized advancing the state of the art rather than perfecting the models in detail, its models developed somewhat more rapidly than those of more experiment-focused GCM groups. In addition, the more open nature of the institution encouraged migration of the model to other laboratories. UCLA Department of Meteorology graduates carried the model with them to numerous other institutions, and visitors from around the world spent time at the group's laboratories. This pattern is vividly apparent in the history of the UCLA model series, described by Arakawa in a festschrift celebrating his work.[43] Box 7.2, based on Arakawa's account, my interviews with him, and model documentation, summarizes the models' characteristics and their migration to other laboratories.

## The Livermore Atmospheric Model (LAM)

In 1960, Cecil E. "Chuck" Leith began work on a GCM at the Lawrence Livermore National Laboratory in Livermore, California. Trained as a physicist, Leith became interested in atmospheric dynamics through his discussions with Joseph Knox, a meteorologist at Livermore. As Leith recalled it in a 1997 interview, Knox was there because of the lab's interest in nuclear

**Box 7.2**
The UCLA GCM Series

(N.B.: The numbering in this box follows Arakawa, "A Personal History.")

**UCLA I** The initial model, completed in 1963.

**UCLA II** When Arakawa returned from Japan in 1965, he and Mintz abandoned the UCLA prototype and began work on the first "production" GCM (UCLA II). It increased model resolution to 4° latitude by 5° longitude (although it still had only two vertical levels), and it introduced a new horizontal grid structure. In the latter half of the 1960s, IBM's Large Scale Scientific Computation Department in San Jose provided important computational assistance and wrote a manual describing the model.[a] Around 1970, Lawrence Gates, a UCLA graduate, carried the model with him to the RAND Corporation, where he deployed it in studies sponsored by the Advanced Research Projects Agency of the US Department of Defense. The RAND version of the model eventually migrated to Oregon State University.[b] A three-level version of UCLA II, developed around 1968, soon traveled to three NASA laboratories. In 1972, the Goddard Institute for Space Studies (GISS) adopted the model. Later in the 1970s, it migrated to the Goddard Laboratory for Atmospheric Sciences and the Goddard Laboratory for Atmospheres.

**UCLA III** Extended vertical resolution to six or twelve levels and incorporated the Arakawa/Lamb "C" finite-difference horizontal grid, used in all subsequent UCLA models. Two versions of this model, with slightly different sets of prognostic variables, were built in the mid 1970s. One version was exported to the US Naval Environment Prediction Research Facility and the Fleet Numerical Oceanographic Center, both in Monterey, California, where it evolved into an operational forecasting system called NOGAPS.[c]

**Box 7.2**
(continued)

It also traveled to the Meteorological Research Institute in Tsukuba, Japan, where it continues to be used in a wide variety of forecasting and climate studies.

**UCLA IV** Begun in the late 1970s, UCLA IV employed a new vertical coordinate system which used the top of the planetary boundary layer as a coordinate surface and extended vertical resolution to 15 layers. This model was adopted by the Navy research centers mentioned above, as well as by the Goddard Laboratory for Atmospheres. Versions also made their way to Lawrence Livermore National Laboratory and the Central Weather Bureau of the Republic of China. In 1988, David Randall, a former student of Arakawa's, introduced the model at Colorado State University.

**UCLA V** An improved version of UCLA III with up to 29 vertical levels. Begun around 1990, UCLA V included new schemes for radiation, cloud prediction, cumulus convection, and other parameters.

a. W. E. Langlois and H. C. W. Kwok, "Description of the Mintz-Arakawa Numerical General Circulation Model," in *Numerical Simulation of Weather and Climate* (IBM-UCLA technical report, 1969); "Numerical Simulation of Weather and Climate Part II: Computational Aspects," n.d.

b. D. Randall, "Colorado State University General Circulation Model: Introduction," kiwi.atmos.colostate.edu.

c. T. F. Hogan and T. E. Rosmond, "The Description of the Navy Operational Global Atmospheric Prediction System's Spectral Forecast Model," *Monthly Weather Review* 119, no. 8, 1991: 1786–815.

fallout. When Leith expressed interest in numerical simulations of the atmosphere, Knox invited him to go to MIT to visit Charney and Norman Phillips. They made the trip together in the spring of 1960.[44]

With Charney's encouragement and the blessing of the Livermore Laboratory's director, Edward Teller, who had long been interested in weather modification, Leith spent the summer of 1960 at the Swedish Institute of Meteorology, studying the literature on global circulation and learning about numerical simulation methods. By the end of the summer he had coded a five-level GCM for Livermore's newest computer, the Livermore Automatic Research Calculator (LARC), due to be delivered in the fall of 1960. Leith wrote the code in Stockholm, basing it on the manual for the new machine. His initial model, like Smagorinsky's first effort, covered only the northern hemisphere, with a "slippery wall" at

60°N. It had five vertical levels, a 5°×5° horizontal grid, and a five-minute time step. At John von Neumann's suggestion, Leith introduced an artificially high viscosity to damp the effects of small-scale atmospheric waves. (This caused serious problems and helped to stimulate Leith's career-long interest in turbulence.) By the end of 1960, Leith's five-level simulation was running on the LARC. The model came to be known as the LAM (for Leith Atmospheric Model or Livermore Atmospheric Model).

The fate of Leith's work contrasts starkly with that of the GFDL and UCLA modeling efforts, illustrating significant institutional contrasts of Cold War–era American science. Livermore and GFDL were both government laboratories, but whereas GFDL served a pure research function in a civilian environment, most of Livermore's work was on secret military projects related to the design of atomic weapons. Although unclassified work such as the LAM *could* have been published in the open literature, Livermore's culture of secrecy did not reward such publication. Leith's other work (like most Livermore research) appeared only in classified reports circulated internally. As a result, Leith's first nonclassified publication did not appear until 1965, a long delay in a fast-evolving field.[45] Around that time, Leith abandoned work on the model. As a result, the LAM's mathematics and computer code did not have much direct effect on GCM development.

However, by 1963 Leith had already presented his model in numerous talks. These talks made a deep impression on their audiences because Leith often screened an animated film of LAM results. In that era, with the field of computer graphics in its earliest infancy, most output took the form of printouts. Leith collaborated with a Hollywood company called Pacific Title to turn these printouts into a film, using color tints to highlight particular features.

The film showed a hemispheric projection, with the North Pole in the center of the frame. Sixty days' worth of simulation results appeared. One second's worth of film equaled one simulated model day. In the first few minutes, atmospheric features appeared one by one; in the final segment, all the features appeared superimposed. Diurnal tides—the 12-hourly rise and fall of the atmosphere under the influence of solar heating and gravity—were among the features that showed up quite clearly. "I remember I drove places to give talks about what I was doing," Leith recalled, "and people would be watching the film with interest. I remember once somebody came up to me afterwards and said, 'I'm from Israel, and I noticed the remarkably realistic way in which you've got these things tracking across Israel.' And of course I don't know what's going on in Israel, I had never paid any attention to it, but he had spotted the fact that . . . it was doing the right sort of things as far as he was concerned."[46] In interviews with me, several pioneering climate modelers who had seen Leith's talks in the 1960s mentioned the elation they experienced on watching his movie. For the first time they could actually witness the dynamic activity of their models, rather than having to imagine it.

Leith became increasingly interested in statistical modeling of turbulence, one of the many points of commonality between atmospheric science and nuclear weapons design. Although Leith ceased work on his own GCM, he became involved with the nascent GCM group at the National Center for Atmospheric Research. In the summers of 1965 and 1966, as the NCAR team awaited delivery of a new CDC 3600 computer, Leith offered use of Livermore's computer to Warren Washington of NCAR, who described Leith to me as "a kind of father figure" for his own modeling work. Leith began to visit NCAR frequently, contributing especially in the area of mathematical methods.[47] In 1968, Leith left Livermore permanently to join NCAR, where he played instrumental roles in several climate modeling projects, both as an administrator and as a turbulence specialist.

### The National Center for Atmospheric Research

The US National Center for Atmospheric Research, established in 1960, initiated its own GCM effort in 1964 under Akira Kasahara and Warren Washington. Kasahara—like Syukuro Manabe, a veteran of the Tokyo University meteorology department under Shigekata Syono—had arrived in the United States in 1954 to join the Department of Oceanography and Meteorology at Texas A&M. He moved to NCAR in 1963 following a year at the Courant Institute of Mathematical Sciences, where numerical analysis for nonlinear equations, with particular attention to shock waves, was a specialty. Washington, still writing his PhD thesis on objective analysis techniques in numerical weather prediction, arrived soon afterward. NCAR's founding director, Walter Orr Roberts, informed them that he wanted to mount a global circulation modeling effort. Roberts told Washington: "I really want you to work about half the time on helping us get started on modeling. The other half, work on what you think is important."[48]

Kasahara and Washington began by studying the advantages and drawbacks of the three existing GCM efforts (GFDL, UCLA, and LAM), which both already knew well. They also reconsidered Lewis Richardson's 1922 effort, looking at it "more carefully, because we thought that Richardson's model didn't have all the problems [of] the sigma-type models."[49] They made an early decision to "go global," and they adopted a *z*-coordinate system, in which the vertical coordinate is height rather than a pressure-related quantity. This allowed their model to function more realistically with orography (mountain ranges).

The Kasahara-Washington modeling group focused a great deal of attention on numerical schemes for finite-difference approximations. In addition, much work was done on problems of computational error arising from truncation. Two major GCM series were eventually constructed; these are summarized in boxes 7.3 and 7.4.

**Box 7.3**
The Kasahara-Washington GCM Series

**NCAR 1** A two-layer global model with a 5° horizontal resolution.[a]
**NCAR 2** Completed around 1970, this version added considerable flexibility. The basic model had a 5° horizontal resolution and six vertical layers, but it could also be run at resolutions as fine as 0.625° horizontal over a limited domain, with up to 24 vertical layers.[b]
**NCAR 3** Around 1972, NCAR began work on a third-generation GCM incorporating improved finite-difference schemes. This model also allowed multiple resolutions, including a user-specifiable vertical increment. Although under evaluation as early as 1975, this model did not see "production" use until the end of the decade.[c]

a. A. Kasahara and W. M. Washington, "NCAR Global General Circulation Model of the Atmosphere," *Monthly Weather Review* 95, no. 7, 1967: 389–402.
b. J. E. Oliger et al., *Description of NCAR Global Circulation Model*, National Center for Atmospheric Research, 1970; A. Kasahara and W. M. Washington, "General Circulation Experiments with a Six-Layer NCAR Model, Including Orography, Cloudiness and Surface Temperature Calculations," *Journal of the Atmospheric Sciences* 28, no. 5, 1971: 657–701; A. Kasahara et al., "Simulation Experiments with a 12-Layer Stratospheric Global Circulation Model. I. Dynamical Effect of the Earth's Orography and Thermal Influence of Continentality," *Journal of Atmospheric Sciences* 30, no. 7, 1973: 1229–51.
c. W. M. Washington et al., "Preliminary Atmospheric Simulation with the Third-Generation NCAR General Circulation Model: January and July," in *Report of the JOC Conference on Climate Models: Performance, Intercomparison, and Sensitivity Studies*, ed. W. Lawrence, WMO/ICSU Joint Organizing Committee and Global Atmospheric Research Programme, 1979.

**Box 7.4**
The NCAR Community Climate Model Series

**CCM-0A** The initial version of the Community Climate Model was based on the spectral model of the Australian Numerical Meteorological Research Centre.[a] A member of the ANMRC team, Kamal Puri, brought the model to NCAR during an extended visit. Later it was extensively revised.
**CCM-0B** A second version of the Community Climate Model was developed in 1981. This version combined medium-range and long-range global forecasting (from three days to two weeks) and climate simulation in a single set of model codes. A modular design permitted flexible choices of resolution and other features. 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.[b] Energy balance and flux prescriptions similar to GFDL models were used. The vertical and temporal finite-difference schemes were derived from the Australian spectral model that was also the basis for CCM-0A.[c]
**CCM-1, 2, and 3** Evolved from CCM-0B, coming into use in 1987. The primary differences were changed parameterizations, new horizontal and vertical diffusion schemes, and changes to moisture adjustment and condensation schemes. CCM versions 2 and 3 were developed in the early 1990s.
**CCSM** In 1994, NCAR initiated work on a Community Climate System Model (CCSM), coupling atmosphere, ocean, land surface, and sea ice models. Greater efforts were made to involve NCAR's extended community of users in model development.

a. W. Bourke, "A Multi-Level Spectral Model. I. Formulation and Hemispheric Integrations," *Monthly Weather Review* 102 (1974): 687–701; Bourke et al., "Global Modeling of Atmospheric Flow by Spectral Methods," in *General Circulation Models of the Atmosphere*, ed. J. Chang (Academic Press, 1977); B. J. McAvaney et al., "A Global Spectral Model for Simulation of the General Circulation," *Journal of Atmospheric Sciences* 35, no. 9 (1978): 1557–83.
b. V. Ramanathan et al., "The Response of a Spectral General Circulation Model to Refinements in Radiative Processes," *Journal of Atmospheric Sciences* 40, 1983: 605–30.
c. D. L. Williamson, ed., *Report of the Second Workshop on the Community Climate Model* (NCAR, 1988).

Along with most other major GCM groups, after 1975 NCAR gradually abandoned its finite-difference models in favor of spectral models. Spectral models ameliorate one of the most difficult problems in Earth system modeling: representing wave motion on a sphere. All early weather and climate models used rectangular latitude-longitude grids. However, these grids encountered difficulties similar to the well-known distortions of Mercator and other world map projections, especially at higher latitudes, where the distance between longitude lines shrinks—eventually to zero at the poles. Many solutions were devised, including stereographic projections and spherical, hexagonal, and icosahedral grids, but none proved ideal.[50] Spectral transform methods offered a useful alternative to grid-point schemes.

The technical details of spectral mathematics lie beyond the scope of this book, but their essence may be expressed briefly as follows. Atmospheric motion can be conceived as numerous waves of varying frequency and amplitude; the superimposition of these waves upon one another produces highly complex patterns. To visualize this, imagine dropping a stone into a completely still pond, then dropping several other stones of various sizes into the same pond at other points. The first stone produces a single set of simple, concentric waves, but as other stones fall the interacting waves rapidly create a complex surface with much more complicated patterns.

Horizontal atmospheric motion can be described as a set of interacting waves, like ripples crossing each other on the surface of a pond. These can be analyzed in "wave space." Mathematical techniques—Fourier transforms, reverse transforms, and others—convert model variables back and forth between physical space (the familiar Cartesian grid) and wave space, a mathematical construct that is difficult to visualize (figure 7.3). Spectral techniques can also handle the vertical dimension (interaction between horizontal model layers), but usually modelers retain physical grids for this part of the analysis.

The idea of using spectral methods to analyze planetary atmospheric waves was explored as early as 1954.[51] Their mathematical advantages rapidly became obvious. As noted above, all grid-point schemes inevitably face problems related to Earth's spherical shape. Since they do not compute wave interaction in physical space, spectral methods avoid these difficulties. Other mathematical properties of this technique, including the simplification of certain nonlinear partial differential equations and the reduction of nonlinear computational instability, also offer substantial advantages over finite-difference schemes. By the latter half of the 1950s experiments with two-dimensional spectral models had begun, but three-

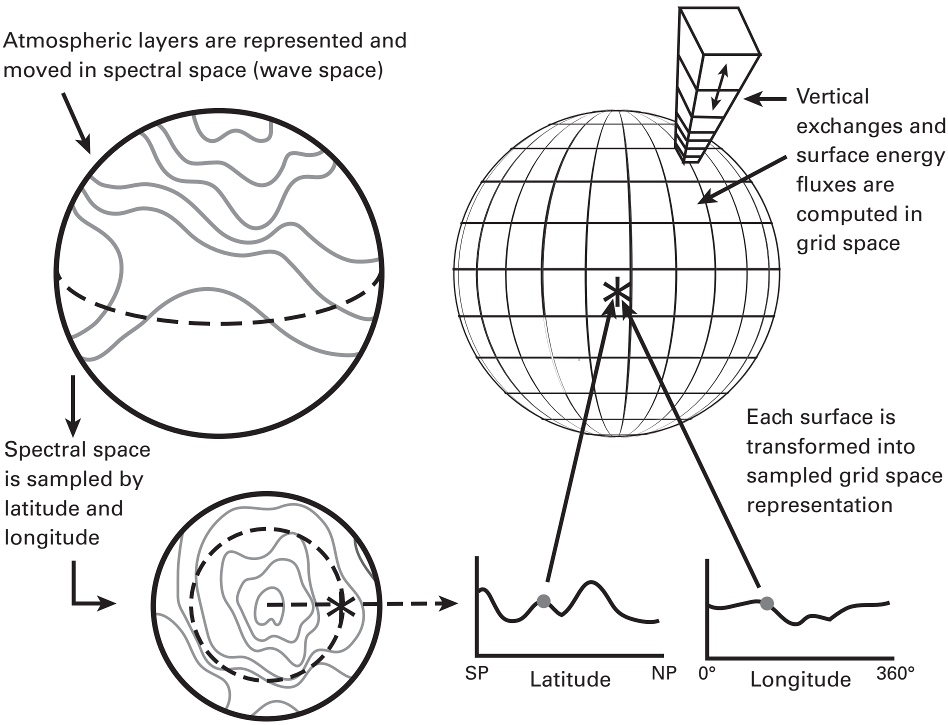


**Figure 7.3**
Spectral models handle horizontal motion in mathematical "wave space" and vertical motions in physical grid space. Gridpoint values are computed by sampling the wave space.
Graphic by Courtney Ritz and Trevor Burnham.

dimensional models posed greater difficulties.[52] Initially the method required far more calculation than finite-difference techniques, so it was not favored for use in GCMs. However, by 1973 spectral methods had become more efficient than finite-difference schemes, since computers had gotten faster and algorithms had been improved.[53] In the early 1970s both NWP and GCM developers began to adopt these techniques.

One spectral model, NCAR's Community Climate Model (CCM) series, has been especially important because a relatively large number of researchers were able to use it. As its name implies, NCAR intended the CCM to serve not only modelers working at NCAR but also its large constituency at universities affiliated with its parent organization, the University Corporation for Atmospheric Research. The CCM's construction was highly collaborative and international. The first two model versions, CCM-0A and CCM-0B, were based on, respectively, a spectral model constructed at the Australian Numerical Meteorological Research Center model and an early version of the European Centre for Medium-Range Weather Forecasts model. Several other groups adopted versions of the CCM in the late 1980s; NCAR's strong focus on documentation and modularity made this relatively easy. In an early manifestation of what might today be called "open source" development, NCAR made user manuals and code documentation available for all elements of the models beginning with CCM-0B.

## The General Circulation of Circulation Models

Modelers, dynamical cores, model physics, numerical methods, and computer code soon began to circulate around the world, like ripples moving outward from the three pioneering climate modeling groups (the Geophysical Fluid Dynamics Laboratory, the US National Center for Atmospheric Research, and UCLA's Department of Meteorology). By the early 1970s, a large number of institutions had established new programs in general circulation modeling. Computer power had grown to the point that major weather forecast centers began moving to hemispheric, and later global, GCMs for operational use. Figure 7.4 illustrates the genealogy of atmospheric GCMs from Phillips's prototype up to the early 1990s.

Figure 7.4 is merely a sketch, of course. It tells only part of the story, it includes only three weather forecast GCMs (NMC, ECMWF, and UKMO), and it does not capture any details of relationships among models. In some cases, one lab imported another's computer code with only minor changes; in others, one lab adopted another's *mathematical* model but programmed it for a different computer. Often labs imported only one part of an existing model (for example, a dynamical core, a grid scheme, or a cloud parameterization) and built the rest themselves. An exhaustive account of modeling groups, model variations, and the relationships among them after the 1960s would require a volume of its own. Here I will simply highlight certain interesting features of the circulation of circulation models (so to speak), as they traveled from lab to lab around the world.

The Australian GCM story, and especially Australia's contribution to spectral modeling, is perhaps the most dramatic case in point. Several labs had briefly considered spectral transform techniques in the 1950s, but computer capacity and numerical methods limitations rendered them impractical until the late 1960s, when André Robert began developing spectral models at the Canadian Meteorological Centre (CMC). In 1970–71,

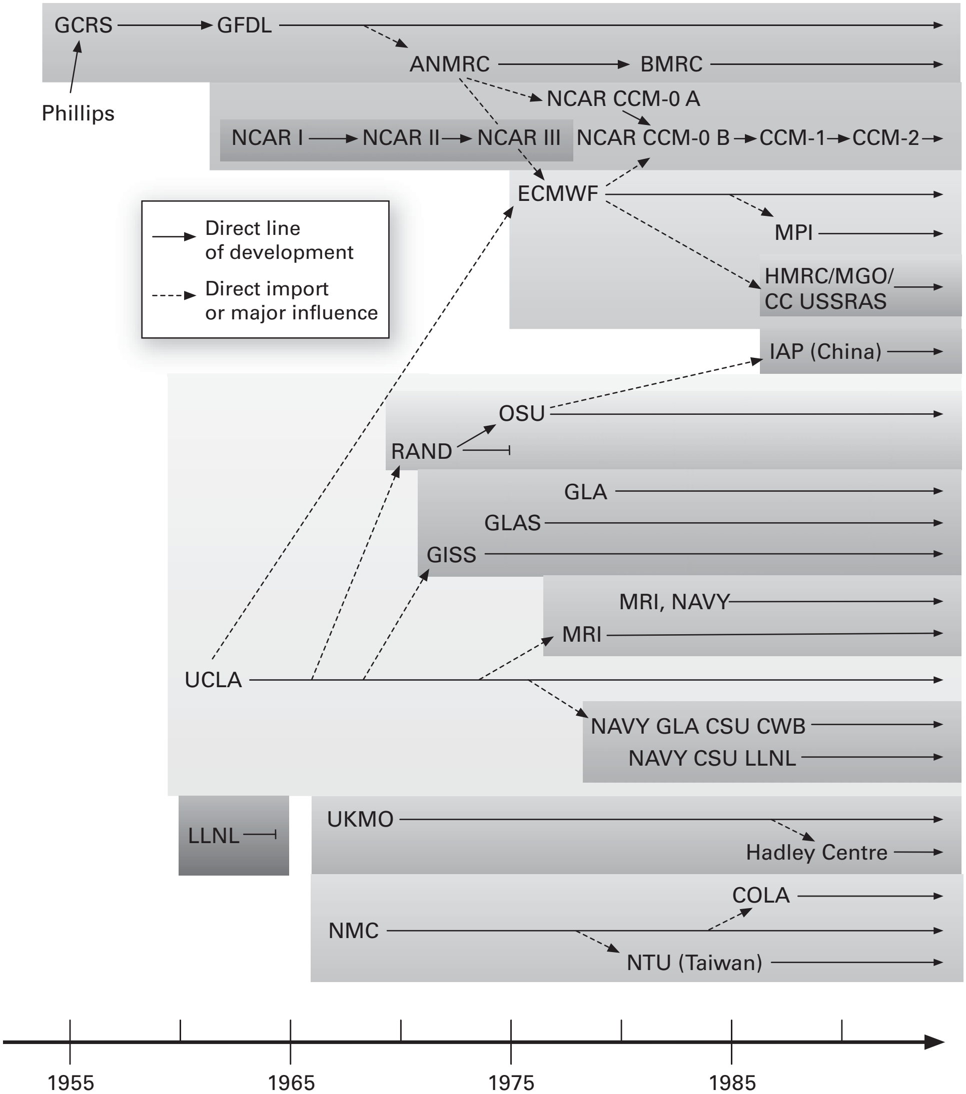


**Figure 7.4**
The AGCM family tree. Revised and expanded from P. N. Edwards, "A Brief History of Atmospheric General Circulation Modeling," in *General Circulation Development, Past Present and Future*, ed. D. A. Randall (Academic Press, 2000).
Graphic by Trevor Burnham.

seeking to deepen its expertise in weather modeling, Australia's new Commonwealth Meteorology Research Centre (CMRC) seconded its modeler William Bourke to McGill University and the CMC. At the CMC, Bourke learned Robert's spectral techniques.[54] Bourke recalled the ninth Stanstead Seminar, held in Montreal in 1971,[55] as a watershed for spectral modeling techniques.[56]

A couple of years earlier, in 1969, another Australian researcher, Doug Gauntlett, had visited GFDL and the US National Meteorological Center. Gauntlett had returned to Australia with code for the GFDL N30 nine-level hemispheric GCM (a finite-difference model). The CMRC adapted this to the southern hemisphere in hopes of using it for NWP, but it took four times as long to make a prediction as the existing baroclinic model, so it was never used operationally.[57] When Bourke returned to Australia in 1971, he joined with Gauntlett and others to build the CMRC's seven-level spectral GCM, which replaced its gridpoint model for operational forecasting in 1976.[58] Bourke, Bryant McAvaney, Kamal Puri, and Robert Thurling also developed the first global spectral GCM.[59] McAvaney recalled that this work was mostly completed in 1974–1975, but that "it took a while to publish."[60] Later, Puri carried code for the Australian spectral model to NCAR, where it became the principal basis of CCM0-A.

McAvaney's six-month visit to the Soviet Union in 1977 also contributed to spectral modeling. Though the Soviet modelers lacked the computer capacity to implement their models operationally, on the level of theory and mathematical methods "they were as good, definitely as good as anybody," McAvaney recalled when I interviewed him in 2001. "Certainly their numerical techniques were up there with anything . . . in the US or anything that we'd done. . . . They were using a spectral approach for diagnostic work, and had done a lot of spectral decomposition of atmospheric fields and particularly interaction between atmospheric fields."[61]

A similar story surrounds GCM development at the European Centre for Medium-Range Weather Forecasts. Conceived in the latter half of the 1960s, the ECMWF opened its doors at Shinfield Park, England, in 1974, with Aksel Wiin-Nielsen as director. Wiin-Nielsen, a Dane, had joined Rossby's International Meteorological Institute in Stockholm in 1955. He moved to the JNWP Unit in the United States in 1959 and, soon afterward, worked at the US National Center for Atmospheric Research during its earliest years. His career thus embodied the international movement of people and ideas typical of meteorology during this period.

From the outset, the ECMWF's goal was to forecast weather for up to 10 days: the "medium range." This would require a global GCM. The US

National Meteorological Center had introduced a hemispheric forecast GCM several years earlier, but after periods beyond a few days this and other hemispheric models developed problems related to the artificial handling of computations at their equatorial "edge." Using a global model would avoid such problems. Rather than build the ECMWF's global forecast GCM from scratch, Wiin-Nielsen contacted Smagorinsky at GFDL and Arakawa and Mintz at UCLA, requesting copies of their models. Both institutions agreed to share their code, with no conditions attached other than appropriate credit—impressive generosity, considering that each model had taken more than a decade to develop.

Acquiring the code called for in-person visits. In 1975, Robert Sadourny, a French modeler who had studied with Arakawa and Mintz in the 1960s, spent four weeks at UCLA. Meanwhile, Tony Hollingsworth made his way to GFDL. Both returned to ECMWF bearing model code and documentation, as well as personal knowledge gained during the visits. ECMWF comparison tested the two models before settling on the GFDL scheme. Soon, however, the Centre replaced the GFDL model physics with a new physics package of its own, retaining only the dynamical core. Later this too was replaced with a spectral core developed internally.[62]

This circuitous exchange of concepts, mathematical techniques, and computer code became entirely typical of computational meteorology and climatology after the mid 1960s. Rather than start from scratch, virtually all the new modeling groups began with some version of another group's model. Veterans and graduate students from the three original GCM groups left to form new groups of their own, taking computer code with them. Others coded new models, most often modified versions of the physical equations and parameterizations used in existing models. The availability of a widely shared, well-standardized scientific computer language (FORTRAN, short for FORmula TRANslation) facilitated these exchanges substantially, as did the scientific-internationalist culture of meteorology.

Yet, as I have mentioned, the number of modeling groups remained small. The count can be expanded or contracted under various criteria, but a reasonable upper limit might be the 33 groups that submitted GCM output to the Atmospheric Model Intercomparison Project (AMIP), an ongoing effort to compare climate models systematically.[63] A smaller figure comes from the Coupled Model Intercomparison Project (CMIP), an AMIP follow-on, which evaluated 18 coupled atmosphere-ocean GCMs.[64]

Notably, all the CMIP simulations came from modeling groups based in Europe, Japan, Australia, and the United States, the historical leaders in climate modeling. The AMIP models (simpler and less computer-intensive than coupled AOGCMs) also included entries from Russia, Canada, Taiwan, China, and Korea. But the elite world of global climate simulation still includes no members from South or Central America, Africa, the Middle East, or southern Asia. The barriers to entry in climate modeling remain high. They include not only the cost and complexity of supercomputers, but also the human infrastructure required to support advanced research of this nature. In the political arena, this fact contributes to a widespread perception that the issue of climate change "belongs" to the developed countries, not only because they are the initial (and still principal) sources of fossil fuel emissions but also because they are the "owners" of knowledge about the problem.

## Climate Modeling and Computational Friction

The mathematical complexity of general circulation modeling was one reason it did not spread further or faster. But a more important reason was access to supercomputers. These expensive, highly advanced machines used new techniques such as parallel processing (multiple instructions handled at the same time), reduced instruction sets, and vector processing (multiple data items handled at the same time). Today's personal computers employ such methods routinely, but in the 1960s and the 1970s those techniques were seen as highly specialized, uniquely suited to scientific computing and not to much else. For programmers, working with these machines required specialized knowledge and training. Their operating systems were minimal; sometimes a new-model supercomputer was delivered to eager customers with no operating system at all. Typically, manufacturers sold at most a few dozen copies of any given model. Little or no commercial software was available for this minuscule customer base. While supercomputer manufacturers such as Control Data Corporation and Cray provided high levels of support, the highly specialized scientific programming of GCMs remained the province of a tiny elite.

As modelers sought to increase model resolution and include more physical processes directly in the models, their models required more and more computer power. Every group building GCMs either owned or had access to the largest, fastest supercomputers available. Greater computer power allowed longer runs, higher resolution, and larger numbers of runs.

Because modelers' appetite for computer power constantly outstripped the available capacity, climate laboratories endured a nearly continuous cycle of re-purchasing, re-learning, and re-coding as successive generations of supercomputers arrived, typically every 3–5 years. The machines required a substantial, highly trained staff of operators, programmers, and technical support personnel. They also needed air-conditioned rooms and consumed prodigious quantities of electric power. (The Cray 1-A processor, for example, sucked down 115 kilowatts, and its cooling and disk storage systems devoured a similar amount.)

With a handful of exceptions, such operations lay beyond the means of academic institutions, which might otherwise have been expected to develop their own modeling programs.[65] Instead, until the 1990s most climate modeling activity was confined to national laboratories, weather services, and a few other large, well-financed institutions. As a result, the number of GCMs remained small. In the mid 1990s—four decades after Phillips's pioneering prototype—just 33 groups worldwide submitted GCMs for the first Atmospheric Model Intercomparison Project.[66]

Tables 7.1 and 7.2 illustrate the rapid growth of computer power at major modeling centers. As table 7.1 shows, the capabilities of GFDL's best computers increased by a factor of 3000 between 1956 and 1974. Table 7.2 catalogs the vast performance improvements of ECMWF's IBM POWER5+ computer (installed in 2006) over its Cray 1-A (installed in 1978), including a 90,000-fold increase in sustained computational performance. Virtually all climate laboratories could produce similar charts.

**Table 7.1**

Computers in use at GFDL, 1956–1982. Data from Geophysical Fluid Dynamics Laboratory, *Activities—FY 80, Plans—FY 81: With a Review of Twenty-Five Years of Research 1955–1980* (Geophysical Fluid Dynamics Laboratory, 1980).

| | Time period | Relative performance |
|---|---|---|
| IBM 701 | 1956–1957 | 1 |
| IBM 704 | 1958–1960 | 3 |
| IBM 7090 | 1961–1962 | 20 |
| IBM 7030 "STRETCH" | 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 |

**Table 7.2**
ECMWF's latest supercomputer vs. its first one.

| Specification | Cray-1A | IBM POWERS5+ system | Approximate ratio |
|---|---|---|---|
| Year installed | 1978 | 2006 | |
| Architecture | Vector processor | Dual cluster of scalar CPUs | |
| Number of CPUs | 1 | ~5000 | 5000:1 |
| Clock speed | 80 megahertz | 1.9 gigahertz | 24:1 |
| Peak performance of each CPU | 160 megaflops | 7.6 gigaflops | 48:1 |
| Peak performance of whole system | 160 megaflops | ~34 teraflops | 200,000:1 |
| Sustained performance | ~50 megaflops | ~4.5 teraflops | 90,000:1 |
| Memory | 8 megabytes | ~9 terabytes | 1,000,000:1 |
| Disk space | 2.5 gigabytes | ~100 terabytes | 40,000:1 |

*Source*: European Centre for Medium-Range Weather Forecasts, "ECMWF Supercomputer History," 2006, www.ecmwf.int. Flops are "floating-point operations per second," a measure of calculating speed.

No fields other than nuclear weapons research and high-energy physics have ever demanded so much calculating capacity. As a result, like the nuclear weapons labs, the world's major climate and weather modeling centers have consistently maintained state-of-the-art supercomputer facilities, and have significantly influenced the development path of the supercomputer industry. For example, in 1977 NCAR purchased the first production supercomputer from Cray Research, a Cray 1-A with serial number 3.[67] (A test model, serial number 1, had been delivered to the nuclear weapons laboratory at Los Alamos the previous year.) Toward the end of the 1970s, NCAR insisted for the first time that its computer suppliers deliver operating systems, compilers, and other basic software for the machines. Previously this had been the responsibility of customers rather than manufacturers. As a result, users—including scientists themselves as well as laboratory computing staff—wrote their own software, sometimes even operating systems. Manufacturers considered themselves responsible only for technical assistance with software development, while customers generally preferred to retain control of their highly specialized, lab-specific software.[68] According to Elzen and MacKenzie, NCAR's break with this traditional social contract helped force Cray Research to supply system software. A former Cray vice president, Margaret Loftus, recalled: "Before, we had difficulty selling software to the sophisticated scientific labs. Now, we have difficulty selling a Cray without software."[69] Packaged weather modeling software for workstations and personal computers has appeared in recent years,[70] but in meteorology the craft tradition persists even today, especially in the relatively small field of climate modeling.

The prestige attached to having built the fastest computer in the world, combined with the small customer base, sometimes injected a heavy dose of nationalism into the competition among supercomputer manufacturers. Between 1994 and 1996, NCAR held a competition for the contract to replace its aging Crays with new supercomputers. For the first time in history, the winning bidder was a non-US firm: the Japanese firm NEC, whose SX-4 registered the highest performance of any computer NCAR had ever evaluated.[71] NCAR planned to lease four SX-4s at a price near $35 million, but US-based Cray Computing challenged NEC's bid before the US Department of Commerce. Cray accused NEC of illegally "dumping" its machines below their cost. The Commerce Department ruled in favor of Cray, imposing a 454 percent tariff on NEC, a move which effectively prevented NCAR from acquiring the SX-4s. Many observers viewed the Commerce Department's decision as motivated by nationalism, under behind-the-scenes pressure from Congress (Edwards interviews). NEC retaliated by suing the Commerce Department in the US Court of International Trade, alleging that the agency had "revealed itself as a partisan ally of NEC's competitor [Cray] for the UCAR contract."[72] The suit went to the Supreme Court, which in 1999 upheld the Commerce Department ruling without comment. NCAR mourned the decision: "We are denied access to the most powerful vector computing systems in the world."[73] Eventually it adopted an IBM machine, which it clearly viewed as a stopgap.

Because computers are so fundamental to modeling work, climate laboratories typically display a certain fetishism regarding their machines. In the late 1990s I spent time at more than a dozen weather and climate modeling centers, including NCAR, GFDL, ECMWF, the UK's Hadley Centre for Climate Prediction and Research, and the Australian Bureau of Meteorology Research Centre (BMRC). Almost invariably, and usually within an hour of my arrival, my hosts would offer a tour of the computer facility. Often such a facility occupies an entire floor, housing at least one supercomputer and numerous large disk drives, robotic tape libraries, and other peripherals. Some labs, such as NCAR and the BMRC, feature prominent viewing windows through which visitors can admire the machines, quietly humming in their spotless rooms. Likewise, the websites and publications of climate laboratories virtually always highlight their computer capacity.[74]

After flaunting the beautiful machines, climate modelers typically proceed to explain the difficult balancing act they must perform. In their accounts, a kind of Heisenberg principle of modeling results from computational friction. Modelers can increase model resolution by sacrificing complexity, or they can increase model complexity by decreasing resolution—but they cannot do both at once. Other tradeoffs can balance these limits differently; for example, modelers can "nest" a higher-resolution limited-area model within a lower-resolution global model. All solutions depend on the availability of central processing unit (CPU) time, data storage (for the very large model outputs), CPU speed, and other technical aspects of the machines and the software. This discourse of insufficient computer power is a basic trope of climatology, widely reported in journalistic treatments of the climate-change issue.

Yet computational friction appears in many other less public but more interesting and subtle forms. As one of many possible examples, consider the problem of round-off error in GCMs. In order to handle a vast range of numerical values, from the extremely small to the very large, scientific mathematics conventionally represents numbers in two parts: a mantissa and an exponent. The mantissa expresses the value, while an exponent of 10 (positive or negative) gives the scale. Thus 256859.6235 becomes $2.568596235 \times 10^5$, and 0.000164757852 is rendered as $1.64757852 \times 10^{-4}$. Computer arithmetic employs a similar strategy. A computer's word length is fixed at the hardware level, as the basic unit of addressable memory.[75] Floating-point notation divides each word into two parts, one for the mantissa and one for the exponent. Software techniques can increase the functional word length to almost any desired (finite) number of digits, but since they must work around the hardware constraint, these techniques impose a prohibitive computational cost on calculation-intensive operations such as GCMs. In modern supercomputers, word length is typically 64 or 128 bits, corresponding roughly to a precision limit of 16 or 32 decimal digits respectively.

Floating-point arithmetic handles irrational numbers such as $\pi$, and other numbers with mantissas longer than the available word length, by rounding them off at the last available digit. This limit on precision produces no noticeable effects for most purposes. But in simulations that require extremely long series of calculations, the tiny errors that occur with each rounding can accumulate to a problematic degree. Furthermore, although standards issued by the Institute of Electrical and Electronics Engineers govern most computers' floating-point arithmetic, nonstandard conventions also exist. And as with most standards, *implementations* of IEEE standards vary slightly among manufacturers, so that different machines produce slightly different results. Scholars have argued that such differences can never be entirely eliminated, because designers base computer arithmetic on human arithmetic, whose conventions remain subject to debate and potentially to change.[76] Intel demonstrated one aspect of this problem to mass consumers in 1995 when it released its Pentium chip with a faulty floating-point unit that resulted in substantial division errors under a few rare circumstances. The floating-point algorithm used in the chip had been subjected to mathematical proof, but a (human) mistake in the proof led to errors in the chip design. The mistake led to a recall that cost Intel about $475 million.[77]

GCMs' enormously long series of interdependent calculations make them sensitive to round-off error. In 1973, NCAR considered adopting new supercomputers that would operate most efficiently at a lower precision than its existing CDC 6600 and 7600 machines (24-bit or 21-bit mantissas vs. the CDC's 48-bit mantissa). David Williamson and Warren Washington tested the effects of this lower precision on a GCM and found that predictability errors in the model itself—essentially, the effects of nonlinear chaotic behavior—exceeded round-off error so greatly that the lower precision of the new machines would not appreciably affect NCAR model results.[78] Errors in observational data also exceeded round-off error. Therefore, Williamson and Washington argued, the round-off error problem could be ignored for the time being. However, as model quality improved and model codes began to spread from one group to another, this and other issues of computational error emerged once again.

Between the 1960s and the 1990s, supercomputer architecture underwent two major changes. Cray computers, first released in 1975, embodied the first major innovation: vector processing, which permits the same operation to be performed simultaneously on many data elements. A second innovation followed in the late 1980s: massively parallel computers, with dozens to hundreds of processing units permitting multiple instruction streams to proceed simultaneously. Both changes presented difficult challenges—especially parallel processing, which required programmers to reconfigure instruction streams to take advantage of many processors. Supercomputing thus remained a highly specialized niche, requiring knowledge and technical skill entirely different from those well known (and well understood) in business and consumer computing. In these difficult conditions, climate modelers—or rather the programmers who worked on climate modeling teams—had to "port" old GCM code to the new machines or else reprogram them from scratch, working from the mathematical model rather than the existing computer code.

Meanwhile, GCMs grew ever more complex. Resolution increased, and the typical length of GCM runs rose from a few months to 20–100 years or more. In the mid 1990s, as they prepared to convert to massively parallel architectures, James Rosinski and David Williamson of NCAR investigated the effects of round-off error, code branches, and other computer-related problems on GCMs, including the porting of old GCMs to new computers. They ran NCAR's CCM2 twice on the same computer, the two runs identical except for a tiny difference in the specified initial temperature. Comparing the results, they saw "small, rounding-sized differences between model solutions grow rapidly, much faster than expected from the predictability error growth associated with nonlinear fluid flow." They isolated this particular problem to effects of computer round-off error on an algorithm associated with cloud parameterization, and speculated that similar errors would affect other parameterizations. Round-off error also produced differences between the same model run on the same computer from identical initial conditions but using two different versions of a FORTRAN compiler and a code library of intrinsic functions (figure 7.5, two Cray lines). Finally, Rosinski and Williamson demonstrated differences between two runs of the same GCM with the same initial data on two different computers (figure 7.5, thick solid line).

Thus hardware and low-level software differences each created idiosyncratic errors that accumulated to a small but significant degree. Since each climate laboratory develops much of its own low-level software (such as the "new" and "old" libraries of intrinsic function codes indicated in figure 7.5), their individual computers have calculating "styles" or "personalities" (my terms) that show up as small differences in outcomes over long model runs. The effect is that the "same" model, when ported to a different computer, will behave somewhat differently for reasons related to how the machine implements computational processes, rather than to the model's mathematics. Rosinski and Williamson suggested that although these computational differences cannot be eliminated, ported models can be statistically validated against original model results to ensure that computer "personalities" do not substantially alter model behavior.

## 2×$CO_2$: A Paradigmatic Modeling Experiment

As GCMs added vertical levels, going from two in Phillips's prototype to nine levels or more by the mid 1960s, modelers had to work out how to

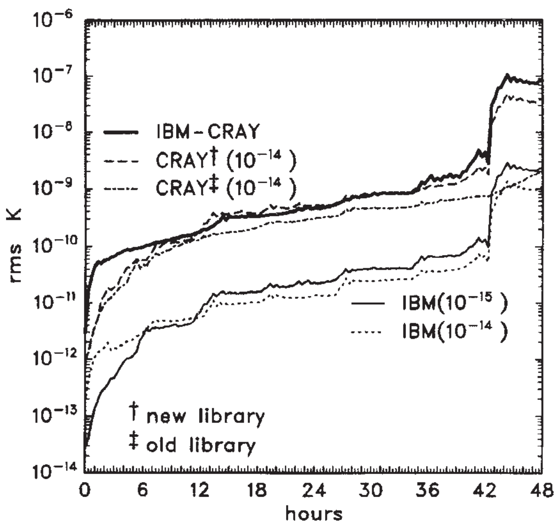


**Figure 7.5**
An illustration of differences between IBM and Cray runs of NCAR CCM2, differences between control and perturbed versions of CCM2 Cray and IBM runs, and differences between Cray runs using two versions (new and old) of an intrinsic code library. Original legend: "Global RMS [root mean square] temperature differences between IBM and Cray versions of CCM2 and various perturbation pairs on the IBM and Cray. The notation ($10^{-x}$) denotes an initial perturbation taken from a rectangular distribution bounded by $\pm 1.0 \times 10^{-x}$."
*Source*: J. M. Rosinski and D. L. Williamson, "The Accumulation of Rounding Errors and Port Validation for Global Atmospheric Models," *SIAM Journal on Scientific Computing* 18, no. 2 (1997), 560.

simulate transfers of energy, mass, and moisture from one level to another. Among other things, without such transfers GCMs would not reproduce large-scale vertical circulatory features, such as the giant Hadley, Ferrel, and polar cells (see figure 2.7). These features, which span tens of degrees of latitude and encircle the entire planet, could not simply be entered into the models. Instead, they would have to emerge from grid-scale processes. Research on vertical structures and processes became critical to the scientific agenda of modelers during this period.

Modelers focused much of their attention on *radiative transfer*.[79] Atmospheric gases absorb and re-radiate solar energy, heating and cooling the atmosphere. These energy transfers drive the entire climate system. The atmosphere consists mostly of nitrogen (78 percent), oxygen (21 percent), and argon (1 percent). However, none of these gases absorbs much radiation in the infrared portion of the spectrum responsible for heating. Instead, the principal "radiatively active" gases are water vapor, ozone, and carbon dioxide. These and other radiatively active trace gases create the greenhouse effect, which maintains Earth's average temperature at around 15°C.

Recall from chapter 4 that, just before World War II, G. S. Callendar had revived the carbon dioxide theory of climate change, first proposed by Tyndall, Arrhenius, and others in the nineteenth century. Climatologists initially received Callendar's results quite skeptically, but Callendar doggedly continued to promote the idea despite its chilly reception.[80] By the 1950s, numerous scientists—many trained in fields other than meteorology—began to reconsider the carbon dioxide theory.

Among others, the physicist Gilbert Plass, inspired by World War II and early Cold War military research on radiation (he had worked on the Manhattan Project), revisited the work of Arrhenius and Callendar. In 1956, Plass published a series of articles reviewing the $CO_2$ theory of climate change.[81] Unlike his predecessors, Plass had access to a computer (the MIDAC at the University of Michigan) and thus was able to calculate $CO_2$'s radiative transfer effects without resorting to the "many approximations . . . used . . . in earlier attempts to solve this complex problem." Plass calculated radiation fluxes at 1-km intervals from the surface to an altitude of 75 km. He performed these calculations for the existing concentration of $CO_2$, then repeated them for half and for double the existing $CO_2$ concentration. His result: "The surface temperature must rise 3.6°C if the $CO_2$ concentration is doubled."[82] Plass warned of significant and enduring global warming by the twentieth century's end. In 1957, Hans Suess and Roger Revelle published their famous paper on the carbon cycle, indicating that not all the carbon dioxide from combustion of fossil fuels could be absorbed by the oceans, so that the gas's concentration in the atmosphere would continue to rise.[83] I discuss this work further in chapter 8.

As they began to construct their nine-level GCM a few years later, Manabe and his colleagues at the GFDL also examined the effects of doubling or halving $CO_2$ concentrations (using the one-dimensional model, not the GCM). Smagorinsky had assigned Manabe to create radiative transfer code for the model. Manabe recalled it this way when I interviewed him:

> My original motivation for studying the greenhouse effect had very little to do with concern over environmental problems. But greenhouse gases . . . are the second

most important factor for climate next to the sun. Greenhouse gases on this planet change Earth's surface temperature by as much as 30°C. So in order to test the radiative computation algorithm, how effective it is to simulate the thermal structure of the atmosphere, you have to put this greenhouse gas in. . . . Here my job requirement to try to develop a radiation algorithm came in very handy. . . . So I was an opportunist. I took this opportunity to do this problem.

But then a funny thing happened. Fritz Möller, who was working with me, . . . found out that the methods of Callendar and Plass . . . start failing when . . . the temperature warms up in the atmosphere. When the temperature warms up, you get more water vapor in the atmosphere. And that means more downward flux of radiation. So when Möller started putting in what we call water vapor feedback, [previous] methods started failing miserably. . . . Sometimes when you doubled $CO_2$ you got a cooling of 10 degrees, depending upon temperature, but at another temperature you doubled $CO_2$ and you got a 15 degree warming. All kinds of crazy results, mainly because including Arrhenius, *all the pioneers who worked on greenhouse warming thought about only the radiation balance at Earth's surface*.[84]

In other words, any given parcel of air not only receives radiant energy from incoming sunlight, but also re-radiates energy in all directions. This re-radiated energy is, in turn, absorbed, reflected, or re-radiated by other parcels of air. Therefore, to handle radiation in a nine-level model, Manabe needed his radiation code to work out these radiative transfers *within* the atmosphere, i.e., between model levels.

Furthermore, it was necessary to model the problem Möller had discovered: how changes in $CO_2$ would affect the concentration of water vapor (a problem known as "water vapor feedback"). Möller's 1963 calculation showed that cloud and water vapor feedbacks associated with $CO_2$ doubling could have huge effects, producing "almost arbitrary temperature changes" of up to 9.6°C, for which no existing model could account. He also argued that scientists had focused on $CO_2$ because they could measure its global concentration adequately with relative ease, whereas the extreme variability of clouds and water vapor made those phenomena almost impervious to empirical study at the global scale.[85] A warmer atmosphere at the surface causes greater evaporation, but more water vapor in the atmosphere can translate into more clouds, which may either cool or warm the atmosphere depending on their structure, altitude, and color. Finally, water vapor is implicated in moist convection, another process of vertical heat transfer. Working out the relationships among all these factors would take decades; some remain controversial today.

Throughout the 1960s, Manabe, collaborating with Möller, Smagorinsky, Robert Strickler, Richard Wetherald, Doug Lilly, and Leith Holloway, slowly worked out a new, one-dimensional radiative-convective model. His group then used that model to create radiation code for the three-dimensional, nine-level GFDL GCM.[86] At first, they simply wanted to understand the model's sensitivity to changes in and relationships among key variables involved in vertical radiation transfer, including $CO_2$, water vapor, ozone, and cloudiness. In the first Manabe one-dimensional model, doubling the concentration of carbon dioxide produced an increase of 2.3°C in global average temperature. Revisions to the model later reduced the increase to 1.9°C.[87] In 1975, Manabe and Wetherald became the first investigators to test the climate's sensitivity to carbon dioxide doubling in a GCM. Their results indicated a rise of about 2.9°C at the surface, notably larger than the simple radiative-convective model's predictions.[88]

Table 7.3 lists the most significant papers on carbon dioxide's temperature effects from Arrhenius's seminal work through Manabe and Wetherald's pioneering GCM calculation. Nearly all these papers used carbon dioxide doubling as a benchmark. (Many also calculated the effects of halving the concentration.) In view of the complexity of the problem, these results all fell within a strikingly restricted range. Leaving aside Arrhenius's early result (based on very approximate measures of $CO_2$'s radiative properties) and Möller's 1963 calculation of 9.6°C (by his own admission a model that produced "almost arbitrary temperature changes"), these calculations vary from a low of 0.8°C to a high of 4°C, approximately a factor of 4. Stephen Schneider, reviewing these and other results and comparing his own model with that of Manabe and Wetherald, argued for a likely climate sensitivity of 1.5–3°C.[89] Furthermore, *all the reported values are positive*. In other words, every single result pointed to warming from carbon dioxide doubling; the question was not whether, but how much. This striking consistency would help to place global warming theory on the political agenda, the subject of chapter 14. Thus climate sensitivity to carbon dioxide doubling had already become a paradigmatic modeling experiment by the 1950s. So it was not only natural, but necessary, to try the same experiment with GCMs. The "$2\times CO_2$" simulation became a standard modeling exercise.

As Kuhn pointed out long ago, paradigmatic experiments—those that settle an issue and create a widely accepted framework for solving further problems—can unify a scientific field.[90] In this case, however, simulations of $CO_2$ doubling had a paradoxical dual effect. First, because virtually all simulations gave results within a fairly narrow range of positive values, they unified the field in something like the way Kuhn suggested, creating a set of puzzles to be solved within the dominant framework of simulation modeling and establishing a set of techniques for solving those puzzles.

**Table 7.3**
Selected estimates of the effects of carbon dioxide doubling on global average temperature, 1896–1975.

| Investigator(s) | Year | Climate sensitivity to $CO_2$ doubling | Remarks |
|---|---|---|---|
| Arrhenius | 1896 | 5–6°C | 2-D (zonal and vertical) radiative transfer model; hand calculation |
| Hurlburt | 1931 | 4°C | Unnoticed until 1960s owing to general rejection of $CO_2$ theory; Callendar unaware of Hurlburt's work until about 1942 |
| Callendar | 1938 | 1.5°C | 1-D radiative transfer model; $CO_2$ doubling not mentioned in text, but appears in graph; no convection |
| Callendar | 1949 | 2.1°C | Revised version of his 1938 calculations; $CO_2$ doubling explicitly mentioned |
| Plass | 1956 | 3.8°C | 1-D radiative transfer model; no convection or water vapor feedback |
| Möller | 1963 | 1.5–9.6°C | 1-D surface energy balance model; combined $H_2O$ and $CO_2$ absorption reduces overall warming, but water vapor feedback produces "almost arbitrary temperature changes" |
| Conservation Foundation | 1963 | 3.8°C | Consensus statement by Plass, Keeling, and others |
| Manabe and Wetherald | 1967 | 2.4°C | 1-D radiative-convective model; humidity and cloudiness levels strongly influence $CO_2$ effects |
| Manabe | 1970 | 1.9°C | Revised version of Manabe and Wetherald 1967 1-D radiative-convective model; sensitivity is for "average" cloudiness |
| Rasool and Schneider | 1971 | 0.8°C | 1-D radiation balance model with fixed relative humidity and cloudiness |
| Manabe and Wetherald | 1975 | 2.9°C | First use of a GCM to simulate effects of $CO_2$ doubling |

Yet, in contrast with the classic Kuhnian cases, they did not settle the issue. Instead, the range of results remained large enough to generate ongoing controversy for several decades. The "benchmark" aspect of this experiment became more salient as climate change became a policy issue. (See chapter 14.)

At the end of chapter 4, we saw that Callendar's 1938 revival of the carbon dioxide theory foundered on the objections of C. E. P. Brooks, David Brunt, and other climatologists. They argued that Callendar could not connect the apparent warming trend with carbon dioxide levels, because the warming might be caused by circulatory effects that no one yet understood. Though Callendar did not live to see it (he died in 1964), GCMs would permit climatologists to analyze the connection of $CO_2$ and circulation in detail. In a real sense, climate modelers have been working on that problem ever since.

## Data Friction, GCMs, and Climate Change

How do you distinguish a good simulation from a bad one? Of course your simulation should look like the reality it's simulating. But before you can tell whether it is doing that, you need a reliable picture of that reality. You need a data image. The more detailed your simulation gets, the more precise your data image must become if you are going to evaluate your model's quality. In the case of the planetary circulation, that picture of reality proved exceedingly hard to come by.

The long-term data record available at the dawn of the GCM era remained severely fragmented. No single data set covered both the oceans and the land surface. The standard "global" climate data—the Réseau Mondial and the *World Weather Records*—tracked only about 400 surface stations on land. Before 1938, upper-air data—critical to studies of the general circulation—remained extremely sparse. Collecting and publishing climate data still took years, even decades. Large libraries of digitized data had been collected in a few places, but the storage medium (punch cards) was too bulky, heavy, and fragile to be widely or readily shared. Large data voids remained, especially in the southern hemisphere and the extreme polar regions.

An example illustrates the extent of the problem. In 1965, Smagorinsky, Manabe, and their colleagues wanted to evaluate their hemispheric GCM. They could find no single data source containing sufficient information about the entire hemisphere at every altitude represented in the model. Instead, they had to combine observational data from numerous sources

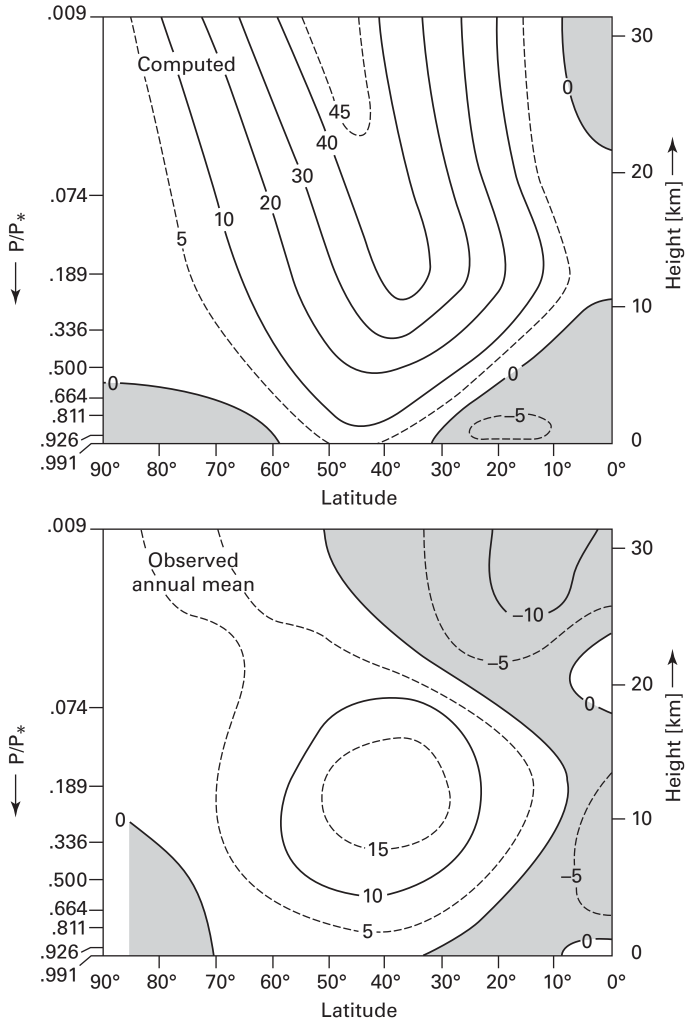


**Figure 7.6**

Zonal mean winds in the northern hemisphere as computed in the GFDL nine-level GCM (top) and as observed (bottom). The diagram represents a cross-section of the atmosphere taken from the equator to the north pole. The observed mean combines tropospheric winds for 1950 with stratospheric winds for 1957–58.

*Source*: J. Smagorinsky et al., “Numerical Results from a Nine-Level General Circulation Model of the Atmosphere,” *Monthly Weather Review* 93 (1965), 736.

in dubious ways. For instance, the best wind data for the troposphere came from H. S. Buch's analysis for the year 1950, which was based on 81 northern hemisphere wind stations. But these data did include the stratosphere, so Smagorinsky et al. had to combine them with data for a different year: Abraham Oort's data for the International Geophysical Year (1957–58), from 240 northern hemisphere radiosonde stations at three pressure levels. No traditional climatologist would have accepted combining data from two different years in this way; circulatory patterns varied too much. But all other data on the circulation above the surface exhibited similar limits, so the modelers had no real choice. To top it off, the nine-level GCM contained well over 10,000 gridpoints, a resolution that far exceeded those of all existing observational data sets.[91]

Fortunately, in 1965 no one expected much accuracy. Modelers just wanted to know whether they were in the ballpark. They would be happy if their crude GCMs reproduced even the most basic features of the circulation, such as the trade winds and the vertical temperature distribution. Comparing GCM outputs they expected to be inaccurate with data they knew to be imprecise worked well enough for the time being. But this strategy could not work in the long run. In time, modelers would need better data, especially in the vertical dimension. How else could they tell whether their models were improving?

Furthermore, by 1970 modelers were already becoming embroiled in emerging political controversies over anthropogenic climate change, provoked in part by their own research on carbon dioxide and aerosol effects. This made the demand for accurate global climate data much more urgent. It also changed the nature of the research problems modelers had to solve. As we have just seen, most theoretical models projected a 2–4°C temperature increase from $CO_2$ doubling. But $CO_2$ had not doubled; in fact, as of 1970 it had risen only about 13 percent above pre-industrial levels. Climate scientists therefore faced new questions that could only be answered by comparing simulations with observational data. For example, could they already detect a warming "signal" against the natural "noise"—as Callendar already believed in 1938? GCM simulations might serve as the "control" against which to detect that signal. If they did find a signal, could they prove that greenhouse gases were the cause? Again, simulations would be needed as controls. Could they project how climate would change as $CO_2$ continued to increase? $CO_2$ was not going to double overnight; instead, it would rise slowly. How would this "transient" increase affect the climate's response? In addition, how would particulate aerosols, chlorofluorocarbons, methane, and other anthropogenic pollutants affect the climatic future? What about water vapor? Perhaps the increased evaporation caused by a warmer climate would ultimately paint the planet white with clouds, paradoxically reflecting so much heat back into space that temperatures would plummet, leading to an ice age. Or perhaps the cooling effect of particulate aerosols would cancel out carbon dioxide warming, stabilizing temperatures. How would temperature changes affect ocean circulation? Et cetera, et cetera, in a list that mushroomed along with the new field.

Answering all these questions would require much more, and more precise, climate data. To make their projections credible, modelers would have to show not only that they could simulate the present climate but also that they could reproduce its past. To do that, they would need to know much more about the history of the global atmosphere than anyone had yet attempted to discover. How much information could be wrung from the spotty, mostly two-dimensional historical record? Could new observing systems provide a sufficiently detailed picture of the vertical dimension? How long would it take to accumulate a truly global, three-dimensional climate record? In the following chapters, I trace the evolution of weather and climate data networks since World War II—the sources of the information meteorologists required in order to address these complex questions.

## Chapter 7

1. R. Revelle and H. E. Suess, “Carbon Dioxide Exchange Between the Atmosphere and Ocean and the Question of an Increase of Atmospheric $CO_2$ During the Past Decades,” *Tellus* 9, no. 1 (1957): 18–27.

2. Others, including Callendar, had already used the “experiment” metaphor, but Revelle’s statement became the best known.

3. John von Neumann, quoted in Nebeker, *Calculating the Weather*, 136; see also Galison, “Computer Simulations and the Trading Zone.”

4. Rossby, “The Scientific Basis of Modern Meteorology.”

5. A weaker, subtropical jet stream also appears at around 30° latitude, the boundary between the Ferrel cell and the tropical Hadley cell. The jet streams occur in both hemispheres.

6. Sometimes the abbreviation is also said to stand for "global climate model," but this applies only to long-term integrations.

7. "Proposal for a Project on the Dynamics of the General Circulation," 1955, reproduced in Smagorinsky, "Early Recollections," 31–33.

8. J. Gleick, *Chaos: Making a New Science* (Viking, 1987); E. N. Lorenz, "Deterministic Nonperiodic Flow," *Journal of the Atmospheric Sciences* 20, no. 2 (1963): 130–48; Lorenz, *The Essence of Chaos* (University of Washington Press, 1993).

9. Lorenz, "Deterministic Nonperiodic Flow"; Lorenz, "A Study of the General Circulation and a Possible Theory Suggested By It," in *Scientific Proceedings of the International Association of Meteorology* (Rome, 1954).

10. Lorenz, "Study of the General Circulation," 603–04.

11. V. P. Starr, "What Constitutes Our New Outlook on the General Circulation?," *Journal of the Meteorological Society of Japan* 36, no. 5 (1958), 168–169, sentences re-ordered and emphasis added.

12. Nebeker, *Calculating the Weather*. See also chapter 4.

13. S. Arrhenius, "On the Influence of Carbonic Acid"; Uppenbrink, "Arrhenius and Global Warming."

14. Callendar, "The Artificial Production of Carbon Dioxide."

15. S. H. Schneider and R. E. Dickinson, "Climate Modeling," *Reviews of Geophysics and Space Physics* 12, no. 3 (1974), 456–60. For a more complex version of the model hierarchy, see K. McGuffie and A. Henderson-Sellers, *A Climate Modeling Primer* (Wiley, 2005).

16. S. Manabe and F. Möller, "On the Radiative Equilibrium and Heat Balance of the Atmosphere," *Monthly Weather Review* 89 (1961): 503–32; S. Manabe and R. F. Strickler, "Thermal Equilibrium of the Atmosphere with a Convective Adjustment," *Journal of the Atmospheric Sciences* 21 (1964): 361–85; S. Manabe and R. Wetherald, "Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity," *Journal of the Atmospheric Sciences* 24 (1967): 241–59.

17. McGuffie and Henderson-Sellers, *A Climate Modeling Primer*, chapter 2.

18. M. Ghil and A. W. Robertson, "Solving Problems with GCMs: General Circulation Models and Their Role in the Climate Modeling Hierarchy," in *General Circulation Model Development: Past, Present, and Future*, ed. D. A. Randall (Academic Press, 2000), 285–326; J. T. Houghton et al., *An Introduction to Simple Climate Models Used in the IPCC Second Assessment Report: IPCC Technical Report* (Intergovernmental Panel on Climate Change, 1997).

19. For a longer discussion, see S. R. Weart, *The Discovery of Global Warming: A Hypertext History of How Scientists Came to (Partly) Understand What People Are Doing to Cause Climate Change* (American Institute of Physics, 2008), www.aip.org.

20. N. A. Phillips, "The General Circulation of the Atmosphere: A Numerical Experiment," *Quarterly Journal of the Royal Meteorological Society* 82, no. 352 (1956): 123–64.

21. J. M. Lewis, "Clarifying the Dynamics of the General Circulation: Phillips's 1956 Experiment," *Bulletin of the American Meteorological Society* 79, no. 1 (1998): 39–60.

22. Phillips, "The General Circulation of the Atmosphere," 123.

23. Ibid., 124, partially paraphrased.

24. These and other questions Phillips raised lead into technical terrain that is beyond the scope of this book, so I will discuss only a few of them, with the goal of imparting the flavor of this work rather than its details. For an excellent semi-technical discussion and assessment, see Lewis, "Clarifying the Dynamics of the General Circulation."

25. Lewis ("Clarifying the Dynamics," 48) notes that, according to Aksel Wiin-Nielsen, Phillips would have had to run his model for a simulated 14 years in order for it to reach equilibrium. Only much later would computer power be sufficient to allow simulations lasting so long.

26. Lewis, "Clarifying the Dynamics," 54.

27. A. Arakawa, "A Personal Perspective on the Early Years of General Circulation Modeling At UCLA," in *General Circulation Model Development*, ed. D. A. Randall (Academic Press, 2000), 10.

28. Smagorinsky, "Early Recollections."

29. J. Smagorinsky, "On the Numerical Integration of the Primitive Equations of Motion for Baroclinic Flow in a Closed Region," *Monthly Weather Review* 86, no. 12 (1958): 457–66.

30. P. N. Edwards, interviews with Syukuro Manabe (American Institute of Physics, 1998) and Richard Wetherald (1995, 1998, unpublished).

31. J. Smagorinsky et al., "Numerical Results from a Nine-Level General Circulation Model of the Atmosphere," *Monthly Weather Review* 93 (1965): 727–68. Manabe and Wetherald, "Thermal Equilibrium of the Atmosphere."

32. Smagorinsky et al., "Numerical Results from a Nine-Level General Circulation Model," 728.

33. S. Shackley, "Epistemic Lifestyles in Climate Change Modeling," in *Changing the Atmosphere: Expert Knowledge and Environmental Governance*, ed. C. A. Miller and P. N. Edwards (MIT Press, 2001); Edwards, interviews.

34. Smagorinsky, "Early Recollections."

35. S. Manabe and K. Bryan, "Climate Calculations with a Combined Ocean-Atmosphere Model," *Journal of the Atmospheric Sciences* 26, no. 4 (1969): 786–89.

36. S. Manabe et al., "A Global Ocean-Atmosphere Climate Model: Part I. The Atmospheric Circulation," *Journal of Physical Oceanography* 5, no. 1 (1975): 3–29.

37. S. Manabe, "The Dependence of Atmospheric Temperature on the Concentration of Carbon Dioxide," in *Global Effects of Environmental Pollution*, ed. S. F. Singer (Reidel, 1970); S. Manabe, "Estimates of Future Change of Climate Due to the Increase of Carbon Dioxide," in *Man's Impact on the Climate*, ed. W. H. Mathews et al. (MIT Press, 1971).

38. Manabe and Bryan, "Climate Calculations with a Combined Ocean-Atmosphere Model."

39. S. Manabe and R. J. Stouffer, "Multiple-Century Response of a Coupled Ocean-Atmosphere Model to an Increase of Atmospheric Carbon Dioxide," *Journal of Climate* 7 (1994): 5–23.

40. "In Memoriam—Yale Mintz, Atmospheric Sciences: Los Angeles," University of California, 1993, www.calisphere.universityofcalifornia.edu.

41. Y. Mintz, "Design of Some Numerical General Circulation Experiments," *Bulletin of the Research Council of Israel* 76 (1958): 67–114.

42. D. R. Johnson and A. Arakawa, "On the Scientific Contributions and Insight of Professor Yale Mintz," *Journal of Climate* 9, no. 12 (1996): 3211–24.

43. A. Arakawa, oral history interview with P. N. Edwards (American Institute of Physics, 1997); Arakawa, "A Personal Perspective on the Early Years of General Circulation Modeling At UCLA," in *General Circulation Model Development: Past, Present, and Future*, ed. D. A. Randall (Academic Press, 2000).

44. C. E. Leith, oral history interview with P. N. Edwards (American Institute of Physics, 1997).

45. C. E. Leith, "Numerical Simulation of the Earth's Atmosphere," in *Methods in Computational Physics*, ed. B. Alder et al. (Academic Press, 1965), 1–28; Leith, oral history interview.

46. Leith, oral history interview.

47. W. M. Washington, oral history interview with P. N. Edwards (American Institute of Physics, 1998.

48. Ibid.

49. This phrase refers to the sigma coordinate system, in which the vertical coordinate is pressure normalized by its value at the surface (as opposed to its value relative to sea level). This system simplifies the model equations compared to using sea-level

pressure or height as the vertical coordinate, making it easier to introduce land surface topography into the models.

50. Kurihara, “Numerical Integration of the Primitive Equations on a Spherical Grid”; R. Sadourny et al., “Integration of the Nondivergent Barotopic Vorticity Equation with an Icosahedral-Hexagonal Grid for the Sphere,” *Monthly Weather Review* 96, no. 6 (1968): 351–56.

51. I. Silberman, “Planetary Waves in the Atmosphere,” *Journal of the Atmospheric Sciences* 11, no. 1 (1954): 27–34; G. W. Platzman, “The Spectral Form of the Vorticity Equation,” *Journal of Meteorology* 17, December (1960): 635–44.

52. Manabe, oral history interview.

53. A. J. Robert, “The Integration of a Spectral Model of the Atmosphere By the Implicit Method,” in *Proceedings of the WMO IUGG Symposium on Numerical Weather Prediction in Tokyo, Japan, November 26–December 4, 1968* (Meteorological Society of Japan, 1969), VII-9–VII-24; S. A. Orszag, “Transform Method for the Calculation of Vector-Coupled Sums: Application to the Spectral Form of the Vorticity Equation,” *Journal of the Atmospheric Sciences* 27 (1970): 890–95; Orszag, “Fourier Series on Spheres,” *Monthly Weather Review* 102, no. 1 (1974): 56–75; E. Eliasen et al., *On a Numerical Method for Integration of the Hydrodynamical Equations with a Spectral Representation of the Horizontal Fields*, Report No. 2, Institut for Teoretisk Meteorologi, Köbenhavns Universitet, 1970; W. Bourke et al., “Global Modeling of Atmospheric Flow By Spectral Methods,” in *General Circulation Models of the Atmosphere*, ed. J. Chang (Academic Press, 1977); Bourke, “A Multi-Level Spectral Model. I.”

54. E. Eliasen et al., *On a Numerical Method for Integration of the Hydrodynamical Equations with a Spectral Representation of the Horizontal Fields*, Report No. 2, Institut for Teoretisk Meteorologi, Köbenhavns Universitet, Denmark (1970); Orszag, “Transform Method.”

55. P. E. Merilees, ed., *Proceedings of the Ninth Stanstead Seminar* (Department of Meteorology, McGill University, 1972).

56. W. Bourke, “History of NWP in Australia—1970 to the Present,” in *The Past, Present and Future of Numerical Modeling: The 16th BMRC Modeling Workshop* (Melbourne, 2004), 4, note 1.

57. D. J. Gauntlett and D. R. Hincksman, “A Six-Level Primitive Equation Model Suitable for Extended Operational Prediction in the Southern Hemisphere,” *Journal of Applied Meteorology* 10, no. 4 (1971): 613–25.

58. Bourke, “History of NWP in Australia.”

59. Bourke et al., “Global Modeling of Atmospheric Flow”; McAvaney et al., “A Global Spectral Model.”

60. B. McAvaney, interview with P. N. Edwards, 2001.

61. Ibid.

62. A. Woods, *Medium-Range Weather Prediction: The European Approach* (Springer, 2006), chapter 7.

63. World Climate Research Programme Working Group on Numerical Experimentation, “Atmospheric Model Intercomparison Project” (Lawrence Livermore National Laboratories, Program for Climate Model Diagnosis and Intercomparison: 1999), www-pcmdi.llnl.gov.

64. C. Covey et al., “An Overview of Results from the Coupled Model Intercomparison Project,” *Global and Planetary Change* 37, no. 1–2 (2003): 103–33.

65. To make supercomputer power available to academic institutions, the National Science Foundation funded five supercomputer centers in the 1980s. The agency required each center to provide computer time and networking support, free of charge, for any institution that wished to use its facilities. Without this support virtually no academic laboratories could have afforded the most advanced computers. The NSFNET, created for accessing the supercomputer centers, went on to become the backbone of the Internet in the United States. See J. Abbate, *Inventing the Internet* (MIT Press, 1999).

66. W. L. Gates, *AMIP: The Atmospheric Model Intercomparison Project*, Report 7, Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory, 1997.

67. NCAR Supercomputer Services Group, “Supercomputer Services Group—History” (University Corporation for Atmospheric Research, 2004), www.cisl.ucar.edu.

68. In the 1950s and the early 1960s, most computing facilities developed their own software in house. By the mid 1970s, however, computer users in most fields could assume that computer manufacturers and third-party software developers would provide operating systems and packaged software for many basic operations. Supercomputing was an exception to this rule.

69. B. Elzen and D. MacKenzie, “The Social Limits of Speed: The Development and Use of Supercomputers,” *IEEE Annals of the History of Computing* 16, no. 1 (1994), 50–51.

70. See e.g. Digital Atmosphere by Weather Graphics Technologies (www.weathergraphics.com), or nCast and eCast by Atmospheric and Environmental Research, Inc. (www.aer.com). In general such desktop or workstation models use data generated by analysis models at major forecast centers such as ECMWF.

71. B. Henson, “What Next for SCD? Buzbee’s Thoughts,” 1997, www.ucar.edu.

72. US Federal Circuit Court of Appeals, *98–1020, NEC Corporation and HNSX Supercomputers, Inc. vs. United States and Dept. of Commerce, 98-1020* (1998).

73. R. A. Anthes, "President's Report for October 1999 UCAR Board of Trustees, Member Representatives and University Relations Committee Meetings" (University Corporation for Atmospheric Research, 1999), www.ucar.edu.

74. See e.g. NCAR Scientific Computing Division Digital Information Group, "History of Supercomputing at the National Center for Atmospheric Research" (University Corporation for Atmospheric Research, 2002), www.cisl.ucar.edu.

75. A computer "word" is made up of a number of "bytes." Historically, one byte represented one character (a number, letter, punctuation mark, etc.). Bytes have ranged in length from five to twelve bits, depending on the size of the character set to be represented. Typical personal computers today use a word length of 32 or 64 bits, corresponding respectively to four or eight eight-bit bytes.

76. D. MacKenzie, "Negotiating Arithmetic, Constructing Proof: The Sociology of Mathematics and Information Technology," *Social Studies of Science* 23, no. 1 (1993): 37–65. See also Collins, *Artificial Experts*.

77. D. Price, "Pentium FDIV Flaw: Lessons Learned," *IEEE Micro* 15, no. 2 (1995): 86–88.

78. D. L. Williamson and W. M. Washington, "On the Importance of Precision for Short-Range Forecasting and Climate Simulation," *Journal of Applied Meteorology* 12, no. 8 (1973): 1254–58.

79. The other major focus of modeling efforts was cumulus convection, the process responsible for the well-defined, puffy clouds such as thunderheads. In a tacit division of labor, Manabe's group at GFDL focused on radiative transfer, while Arakawa's group at UCLA specialized in understanding and parameterizing cumulus convection. See A. Arakawa and W. H. Schubert, "Interaction of a Cumulus Cloud Ensemble with the Large-Scale Environment, Part I," *Journal of the Atmospheric Sciences* 31 (1974): 674–701; S. J. Lord and A. Arakawa, "Interaction of a Cumulus Cloud Ensemble with the Large-Scale Environment. Part II," *Journal of the Atmospheric Sciences* 37 (1980): 2677–92; Arakawa, "A Personal History"; Arakawa, "The Cumulus Parameterization Problem: Past, Present, and Future," *Journal of Climate* 17, no. 13 (2004): 2493–525. I will not discuss this further, except to note that the problem of cumulus convection remains a major area of climate modeling research.

80. Callendar, "Can Carbon Dioxide Influence Climate?"; Callendar, "On the Amount of Carbon Dioxide in the Atmosphere"; Callendar, "Temperature Fluctuations and Trends Over the Earth." For a full account, see Fleming, *The Callendar Effect*.

81. G. N. Plass, "Effect of Carbon Dioxide Variations on Climate," *American Journal of Physics* 24 (1956): 376; Plass, "The Carbon Dioxide Theory of Climate Change," *Tellus* 8, no. 2 (1956): 140–54; Plass, "The Influence of the 15μ Carbon-Dioxide Band

on the Atmospheric Infrared Cooling Rate," *Quarterly Journal of the Royal Meteorological Society* 82, no. 353 (1956): 310–24.

82. Plass, "Effect of Carbon Dioxide Variations on Climate," 141–42.

83. Revelle and Suess, "Carbon Dioxide Exchange."

84. Manabe, oral history interview, edited for readability and emphasis added.

85. F. Möller, "On the Influence of Changes in the $CO_2$ Concentration in Air on the Radiation Balance of the Earth's Surface and on the Climate," *Journal of Geophysical Research* 68 (1963): 3877–86.

86. Manabe and Möller, "On the Radiative Equilibrium and Heat Balance of the Atmosphere"; Manabe and Strickler, "Thermal Equilibrium of the Atmosphere"; S. Manabe et al., "Simulated Climatology of General Circulation with a Hydrologic Cycle," *Monthly Weather Review* 93, no. December (1965): 769–98; Manabe and R. Wetherald, "Thermal Equilibrium of the Atmosphere."

87. Manabe, "Estimates of Future Change."

88. S. Manabe and R. T. Wetherald, "The Effects of Doubling the $CO_2$ Concentration on the Climate of a General Circulation Model," *Journal of Atmospheric Sciences* 32, no. 1 (1975): 3–15.

89. S. H. Schneider, "On the Carbon Dioxide–Climate Confusion," *Journal of the Atmospheric Sciences* 32, no. 11 (1975): 2060–66.

90. Kuhn, *The Structure of Scientific Revolutions*.

91. Smagorinsky et al., "Numerical Results from a Nine-Level General Circulation Model."