



History of climate modeling

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The history of climate modeling begins with conceptual models, followed in the 19th century by mathematical models of energy balance and radiative transfer, as well as simple analog models. Since the 1950s, the principal tools of climate science have been computer simulation models of the global general circulation. From the 1990s to the present, a trend toward increasingly comprehensive coupled models of the entire climate system has dominated the field. Climate model evaluation and intercomparison is changing modeling into a more standardized, modular process, presenting the potential for unifying research and operational aspects of climate science. © 2010 John Wiley & Sons, Ltd. *WIREs Clim Change* 2011 2 128–139 DOI: 10.1002/wcc.95

INTRODUCTION

The global climate system functions to transport heat from the equator toward the poles. Therefore, climatology's principal questions regard how much heat the Earth system retains, where the energy resides (in the oceans, atmosphere, land surfaces, etc.), how it is distributed, and how it circulates around the globe. Due to its immense size and long time scales, the climate system cannot be studied by experimental methods. Therefore, scientists have relied on climate models—theory-based representations that characterize or simulate essential features and mechanisms—to explore how Earth's climate works. This article surveys climate modeling from the ancient world to the present, focusing the bulk of attention on climate simulation by computerized general circulation models (GCMs).

CONCEPTUAL MODELS

Early attempts to understand climate phenomena resulted in conceptual models. Greek astronomer-geographers such as Eratosthenes (3rd century BCE) and Ptolemy (2nd century CE) deduced the Earth's spherical shape and connected climate to the inclination of the sun. Ptolemy based his system of fifteen climatic zones on the lengths of their longest day (the same figure he used to express latitude).

In 1686, seeking to understand the physics of the trade winds, Edmond Halley published one of the first theories to go beyond the Ptolemaic view of climate

as a function of latitude. Halley theorized that solar heating caused air to rise near the equator.¹ This 'rarefied' air caused denser air from higher latitudes to 'rush in', creating the trade winds. Halley's term 'circulation', as well as his notion that the atmosphere must 'preserve the Æquilibrium', remains in use today. Fifty years later, Hadley modified Halley's explanation to take account of the Coriolis effect.² Dove hypothesized a second, high-latitude circulatory cell in the 1830s.³ In the 1850s, Ferrel proposed a third cell to account for prevailing winds at the poles (Figure 1). Meteorologists' picture of the gross atmospheric circulation has changed little since Ferrel's day.

These conceptual models explained the prevailing winds over the globe and captured the fundamental energy-transport function of the climate system. However, meteorologists of the 19th and early 20th centuries could only infer the structure of atmospheric circulation above the surface, as large-scale, systematic data collection for the upper air did not begin until around World War II.

Conceptual models of the carbon cycle also contributed to understanding of climate. By 1861 Tyndall had concluded that geophysical cycles involving heat-trapping gases were responsible for major climatic change. Chamberlin later pursued this further, producing a sweeping explanation of global climatic changes on geological time scales with carbon dioxide as the fundamental driver.^{5,6} Chamberlin argued that periods of high volcanic activity released vast quantities of CO₂, warming the Earth. In slow weathering processes, carbon dioxide in the atmosphere combines with the calcium in igneous rock, forming calcium carbonate. Organic matter would also absorb carbon. During periods of low volcanic activity, more CO₂ would be absorbed than released, causing global temperatures to cool. However, by the early 20th century

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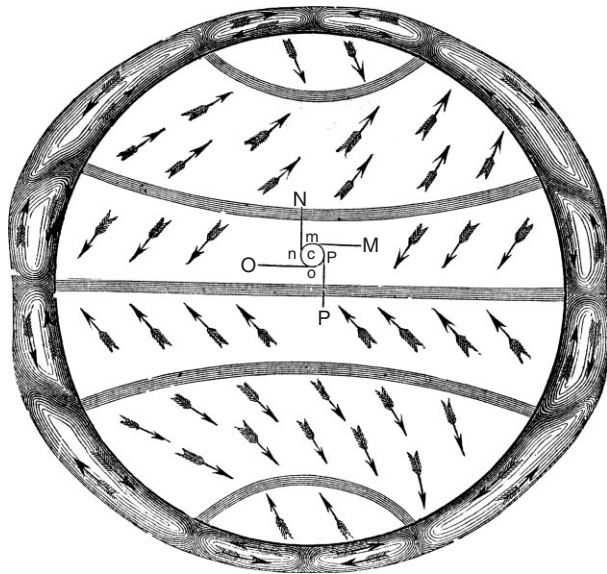


FIGURE 1 | Ferrel's three-cell general circulation diagram.⁴

the carbon dioxide theory was generally rejected after Ångström and others concluded that water vapor's effect on Earth's temperature overwhelmed that of CO₂. Thus (they believed) changes in CO₂ levels could have virtually no effect on global temperature.^{7,8}

ANALOG MODELS

Physical models, such as bowls or globes filled with cloudy, viscous fluids, were constructed at least from the early 20th century.⁹ Turbulent patterns appeared when the bowl or globe was rotated, presenting a striking resemblance to atmospheric motions. Later 'dishpan' models used a rotating tank heated at the rim and cooled in the center, thus simulating equatorial solar heating and polar cooling.^{10–12} Despite their very limited capabilities, these analog models demonstrated fundamental principles of fluid motion on a globe and inspired the first generation of general circulation modelers.¹³ Phillips wrote that the dishpan experiments 'almost forced (one) to the conclusion that at least the gross features of the general circulation ... can be predicted without having to specify the heating and cooling in great detail'.¹⁴

ENERGY BALANCE AND RADIATIVE–CONVECTIVE MODELS

Early mathematical models of climate approached the problem by calculating the balance between incoming solar energy and outgoing heat, attempting to isolate determining factors. Astronomical cycles clearly played a role. In the 19th century, Adhémar and Croll

hypothesized that orbital cycles caused ice ages by reducing insolation (solar energy received), but their theories fell into disfavor.^{15,16} Milanković revived the idea in the 1920s, demonstrating that three major astronomical cycles—the eccentricity of Earth's orbit (a 100,000-year period), Earth's axial tilt (a 41,000-year period), and the precession of Earth's axis (a 26,000-year period)—could explain recurring climatic changes.¹⁷ These cycles interact, producing large variations—up to 20 or 30%—in the amount of insolation at a given latitude. Although the cycles do not much alter *overall* planetary insolation, they can cause large changes in albedo (reflectance). When ice-covered areas of the northern hemisphere receive less insolation, more ice remains from year to year; meanwhile, as snow- and ice-covered areas expand, their white surfaces reflect more heat and amplify the cooling effect. This albedo feedback is now understood to be a major mechanism of climatic change. (Albedo feedback can also amplify heating trends, as retreating ice sheets leave behind darker surfaces which absorb more heat.) These interacting astronomical cycles are presently held to be a principal cause of ice ages, but other factors (including variations in the carbon cycle) also appear to play determining roles.¹⁸

As early as 1807, Fourier hypothesized that by retaining heat, the atmosphere keeps the Earth's surface temperature far higher than it would otherwise be. Histories of global warming invariably reference Fourier's term *serre*, French for 'greenhouse'.¹⁹ Fourier also described the principle of radiative equilibrium, which states that the Earth maintains a balance between the energy it receives from the sun and the energy it re-radiates to space. Numerous 19th-century theorists explored how Earth receives and emits radiation and the consequences for climatic variation over the globe. Hann's *Handbook of Climatology* (1883)—the standard textbook in theoretical climatology for some five decades—reviewed this work in a chapter on 'solar or mathematical climate', i.e., the climate of an abstract globe, due only to differential insolation. In 1895 Arrhenius estimated how much the heat retained by 'carbonic acid' (CO₂) and water vapor contributes to Earth's surface temperature. His now-famous 1896 paper calculated that doubling atmospheric CO₂ would raise the global average temperature by 5–6°C.^{20,21}

These and later 'energy balance' models (EBMs) used measured or calculated values for such factors as solar radiation, albedo (reflectance), and atmospheric absorption and radiation to compute the global radiative temperature. The simplest, zero-dimensional EBMs treat the Earth as if it were a point mass, but energy balance can also be calculated

one-dimensionally, by latitude bands or ‘zones’ (as in Arrhenius’ 1896 model). EBMs can also be two-dimensional, with both zonal and longitudinal or ‘meridional’ energy flows. A second type of mathematical climate model, the radiative–convective model, focuses on vertical transfers of energy in the atmosphere. Such models typically simulate the atmosphere’s temperature profile in either one dimension (vertical) or two (vertical and meridional). When Callendar revived the carbon dioxide theory of climate change in 1938 (following new, more sensitive measurements that disproved Ångström’s argument), he used a one-dimensional radiative model that divided the atmosphere into twelve vertical layers.²² 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.^{23,24}

These three categories of models play key roles in climate science.²⁵ The simplest of them can be worked out by hand. As their complexity increases, however, it becomes increasingly difficult to solve the systems of equations involved without a computer.

GENERAL CIRCULATION MODELS

In the early 20th century Vilhelm Bjerknes showed how to compute large-scale weather dynamics using what are now known as the ‘primitive equations’ of motion and state.^{26,27} These equations include Newton’s laws of motion, the hydrodynamic state

equation, mass conservation, and the thermodynamic energy equation. Bjerknes’s mathematical model described how mass, momentum, energy, and moisture are conserved in interactions among individual parcels of air. However, Bjerknes’ equations did not have closed-form solutions, and numerical techniques capable of approximate solutions did not yet exist.

During World War I, Richardson developed a numerical forecasting method based on Bjerknes’ equations, using a finite-difference grid.^{9,28} Due to an error in the input observations, Richardson’s only test of the method led to a surface pressure prediction 150 times larger than the actual observed change. Further, his methods were not sophisticated enough to keep numerical instabilities from building up as he iterated the calculations. These problems led meteorologists to abandon numerical modeling for the next two decades.²⁹ Better mathematical methods for minimizing numerical instabilities in massively iterative calculations emerged only after the advent of digital computers, becoming a central preoccupation of weather and climate modeling from the 1940s into the present.

Immediately after World War II, weather prediction was among the first major applications of digital computers, heavily supported by both military agencies and civilian weather services.³⁰ Early experiments with computerized numerical weather prediction (NWP) followed Richardson’s lead in employing Cartesian grids (Figure 2) and finite-difference methods, computing vertical and horizontal mass and

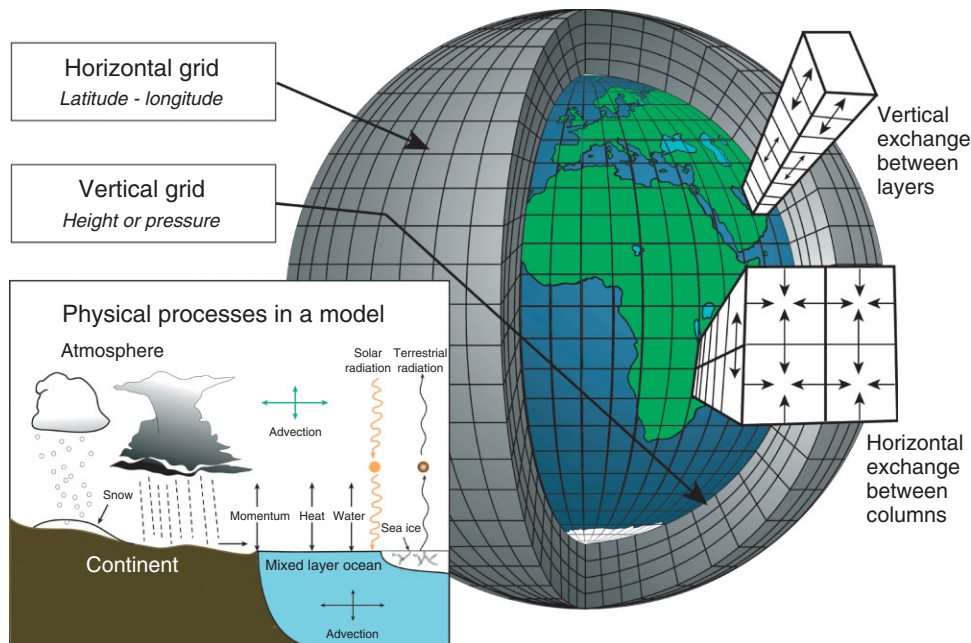


FIGURE 2 | Schematic representation of the Cartesian grid structure used in finite-difference GCMs. Graphic by Courtney Ritz and Trevor Burnham.

energy transfers between grid boxes on a time step (typically 10–15 min). Early NWP models imposed many simplifying assumptions in order to reduce the models' calculational demands, and all of them were regional (rather than global) in scale.

The swift success of NWP led almost immediately to efforts to model the global circulation over longer periods, i.e., to model the atmospheric component of climate. GCMs used the same techniques as early NWP models, but extended them to the hemispheric or global scale and used the full, unsimplified primitive equations to compute atmospheric motion. GCMs may be used to simulate either weather or climate. When used for climate studies, some resolution and complexity are sacrificed in order to permit longer model runs (20–100 years or more). Climate statistics (average winds, temperature, precipitation, etc.) are then calculated for the entire run.

All GCMs consist of a 'dynamical core', which simulates large-scale fluid motion using the primitive equations, and 'model physics', which simulates other climatologically significant physical processes such as radiative transfer, cloud formation, and convection. In the real atmosphere, these processes generally occur on scales much smaller than the model grids, as far down as the molecular level. Model physics also includes friction between land or ocean surfaces and the air, heat transfers between the ocean and the atmosphere, effects of particulate aerosols, and many other processes. Modelers represent sub-grid scale physics indirectly through 'parameters', or 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 the source of considerable scientific and political controversy.^{31–37} Figure 3 shows how climate models added an increasing number of physical processes over time.

All early GCMs used rectangular latitude–longitude grids. These grids encountered problems at higher latitudes, where the distance between longitude lines shrinks, reducing to zero at the poles. Various alternatives were tested, including stereographic projections and spherical, hexagonal, and icosahedral grids, but none proved ideal.^{39,40} To overcome these problems, during the second half of the 1970s the major modeling groups turned to spectral modeling techniques. Spectral models—first explored as early as 1954^{41,42}—ameliorate one of the most difficult issues in atmospheric modeling: how to represent wave motion on a sphere. Atmospheric motion consists of numerous waves of varying frequency, scale,

and amplitude; the superimposition of these waves produces highly complex patterns. These patterns can be analyzed in 'wave space', a mathematical construct that is difficult to visualize. Fourier transforms, reverse transforms, and other techniques convert model variables back and forth between physical space (the familiar Cartesian grid) and wave space (Figure 4). Usually modelers retain physical grids for the vertical component of the analysis. Initially the spectral method required far more calculation than finite-difference techniques, so it was not favored for use in GCMs. However, by around 1973 improved algorithms made spectral methods more efficient than finite-difference schemes.^{43–48}

Phillips' Prototype

The first person to attempt a computerized GCM was Norman Phillips at Princeton's Institute for Advanced Study. Phillips applied nascent NWP techniques, completing a 2-layer, hemispheric, quasi-geostrophic computer model in mid-1955.^{13,14} Navigating between his mathematical model and the memory constraints of the IAS computer—which had just 1 kB of main memory and 2 kB of magnetic drum storage—Phillips chose a 17×16 finite-difference grid to render a simulated surface of 10,000 km \times 6000 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. After a 'spin-up' of 130 simulated days, the model time step was reduced to around 2 h and the model run for 31 simulated days. Phillips' paper describing the model received the first Napier Shaw prize of Britain's Royal Meteorological Society. This dramatic accomplishment led John von Neumann to create a research program on 'Dynamics of the General Circulation', which he called the 'infinite forecast'.

With Phillips' experiment as proof of concept, a new generation of theoretical meteorologists began to design models based directly on the primitive equations. Phillips marked out the path: start with simplifying assumptions, then eliminate them one by one until nothing remained but the primary physics. Putting this program into practice would require not only computer power, but also further refinement of numerical methods for solving differential equations. Perfecting primitive-equation GCMs became a kind of holy grail for both forecasting and climatology. Three major early efforts sought to meet this challenge. They were based in the United States, but Japanese emigré scientists played central roles in all of them.

The world in global climate models

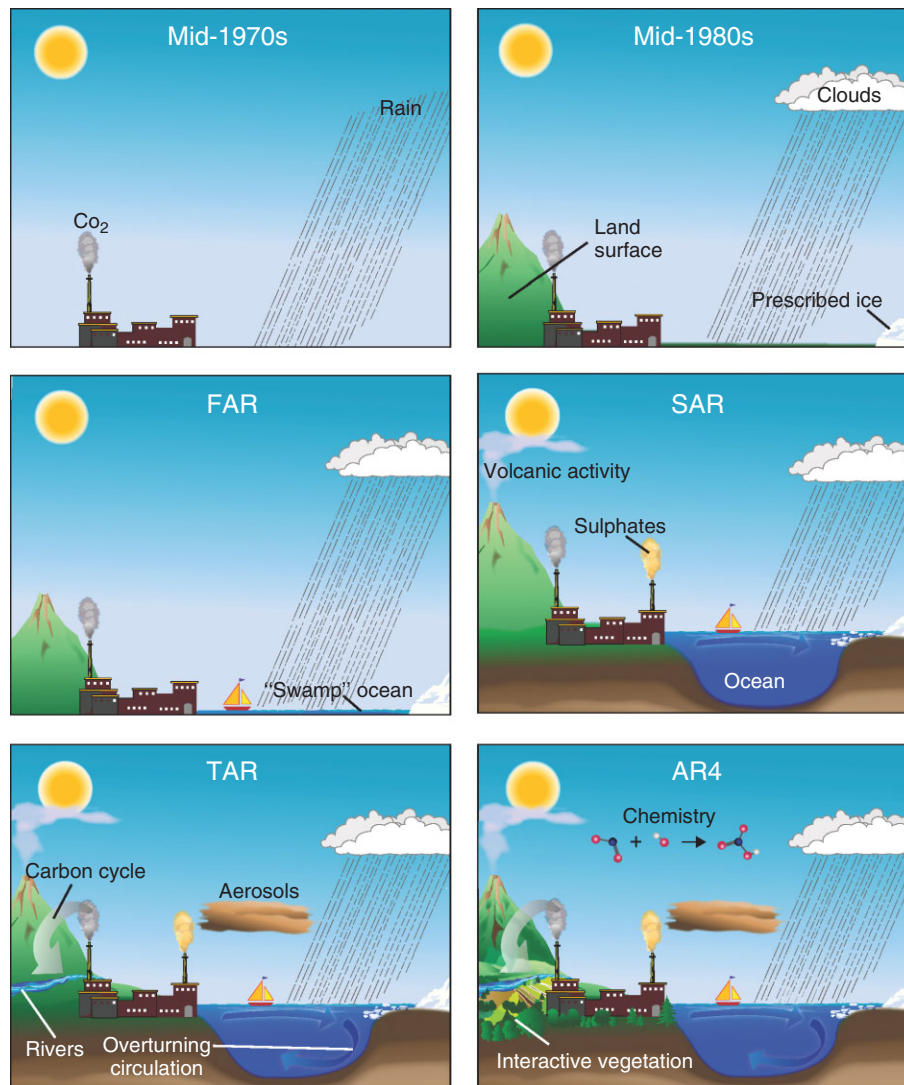


FIGURE 3 | Processes incorporated in generations of GCMs from the mid-1970s. Acronyms refer to the four assessment reports (AR) of the Intergovernmental Panel on Climate Change (IPCC), released in 1990 (FAR), 1995 (SAR), 2001 (TAR), and 2007 (AR4). (Reprinted with permission from Ref 38. Copyright 2007 Cambridge University Press.)

The Geophysical Fluid Dynamics Laboratory

The US Weather Bureau created a General Circulation Research Section under the direction of Joseph Smagorinsky in 1955. In 1955–1956, as lab operations commenced, Smagorinsky collaborated with von Neumann, Phillips, and Jule Charney to develop a 2-level baroclinic model.⁴⁹ In 1959, Smagorinsky invited Syukuro Manabe of the Tokyo NWP Group to join the laboratory and assigned him to GCM development. By 1965, Smagorinsky, Manabe, and their collaborators had completed a 9-level, hemispheric GCM using the full set of primitive equations.^{50,51}

From then on, GFDL treated the primitive-equation GCM as a conceptual framework that also drove work on simpler models, such as the RCMs discussed above, which they then used to improve the GCM's handling of physical processes. Strict attention to developing physical theory and numerical methods before seeking verisimilitude became a hallmark of the GFDL modeling approach³² (Edwards interviews).

Smagorinsky foresaw the need to couple ocean circulation models to atmospheric GCMs to achieve realistic climate simulations. In 1961 he brought ocean modeler Kirk Bryan to GFDL.⁵² The first GFDL coupled model used a highly simplified 1-layer 'swamp' ocean. However, the oceans have their

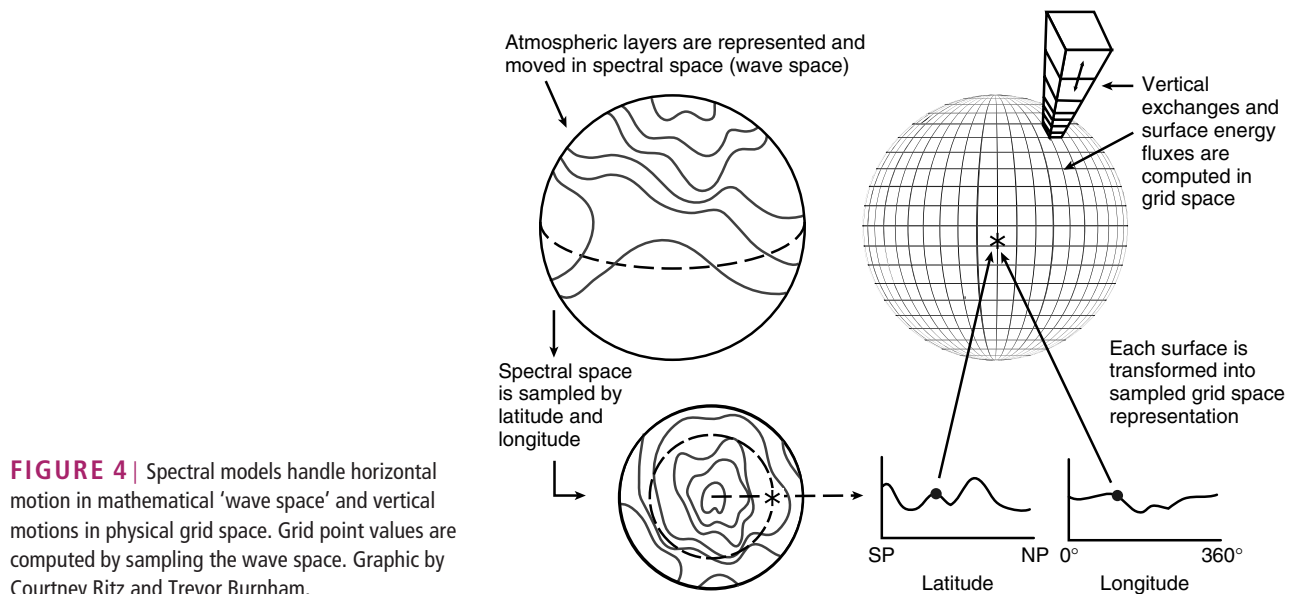


FIGURE 4 | Spectral models handle horizontal motion in mathematical ‘wave space’ and vertical motions in physical grid space. Grid point values are computed by sampling the wave space. Graphic by Courtney Ritz and Trevor Burnham.

own general circulation, which would ultimately have to be included in climate models. In 1969 Manabe and Bryan published the first results from a coupled atmosphere–ocean general circulation model (AOGCM).⁵³ This early coupled model used a highly idealized continent–ocean configuration. Results from the first coupled AOGCM with more realistic configurations did not appear until 1975.⁵⁴

By the mid-1960s, Smagorinsky had taken a leading role in planning the gigantic Global Atmospheric Research Program (GARP), which continued into the 1980s. Manabe emerged as the *de facto* leader of GFDL’s GCM effort until his retirement in 1998. Manabe’s group was among the first to perform carbon-dioxide doubling experiments with GCMs,^{55,56} to couple atmospheric GCMs with ocean models,⁵³ and to perform 1000-year runs of GCMs under carbon-dioxide doubling.⁵⁷

The UCLA Department of Meteorology

In the late 1950s, as part of the General Circulation Project at the UCLA Department of Meteorology, Mintz started to design numerical GCMs.⁵⁸ Like Smagorinsky, Mintz recruited a Tokyo University meteorologist, Akio Arakawa, to help him build the models. The first Mintz-Arakawa GCM, completed in 1963, was a 2-level global primitive-equation model with $7^\circ \times 9^\circ$ horizontal resolution. It included realistic land–sea distributions and surface topography. Between 1963 and the mid-1990s, UCLA produced five major revisions of its GCM.

Of all the world’s general circulation modeling groups, the UCLA laboratory probably had the greatest influence on others, especially in the 1960s and

1970s. This effect 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 and NCAR (discussed below) were pure-research institutions, UCLA operated in the mode of an academic graduate program, with training and knowledge diffusion as part of its mission. Also more typical of the academic tradition, until the 1980s the UCLA group focused primarily on model *development*, leaving ‘production’ uses of the models (such as model experiments) to other institutions. The more open nature of the institution encouraged migration of the model to other laboratories. UCLA graduates carried the model with them to numerous other institutions, while visitors from around the world spent time there. This pattern appears vividly in the history of the UCLA model series (Figure 5).^{59,60}

The US National Center for Atmospheric Research

The US National Center for Atmospheric Research, established in 1960, began its own GCM effort in 1964 under Akira Kasahara and Warren Washington. Kasahara, like Manabe, was a veteran of the Tokyo University meteorology department. Kasahara and Washington began by studying the advantages and drawbacks of the existing GCM efforts (GFDL, UCLA, and the lesser-known Livermore Atmospheric Model built by Charles ‘Chuck’ Leith at Lawrence Livermore National Laboratories⁶¹). They also reconsidered Richardson’s approach. They made

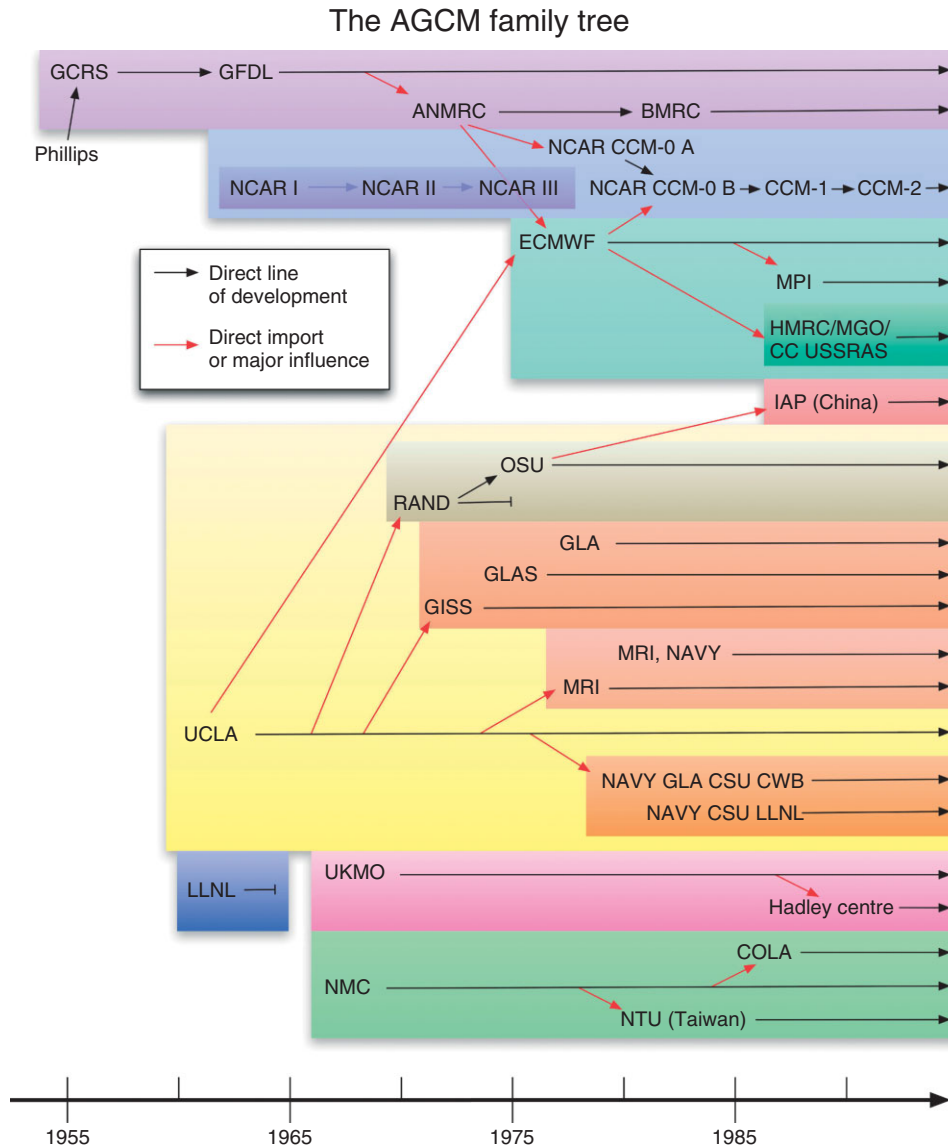


FIGURE 5 | The AGCM family tree.³⁴ *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* (Cambridge: MIT Press, 2010), p. 168. Graphic by Trevor Burnham. Acronym expansions and further information is available at pne.people.si.umich.edu/vastmachine/agcm.html.

an early decision to make a global (rather than hemispheric) model, and they adopted a *z*-coordinate system, in which the vertical coordinate is height rather than a pressure-related quantity. This allowed their GCM 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 and on rooting out sources of error in computers and computational schemes. Between 1963 and 1980, the group produced three major GCMs.^{62–66} NCAR’s Community Climate Model (CCM) series, an early spectral model, exemplifies the highly collaborative and international

character of climate modeling. The model’s first two versions, CCM-0A and CCM-0B, were respectively based on a spectral model constructed at the Australian Numerical Meteorological Research Center model and an early version of the European Center for Medium Range Weather Forecasts model. Several other groups adopted versions of the CCM in the late 1980s; NCAR made user manuals and code documentation widely available for all elements of the models beginning with CCM-0B. The CCM saw three major revisions and wide use until the middle 1990s, when NCAR began work on a successor, the Community Climate System Model (CCSM), a coupled atmosphere, ocean, land surface, and sea ice model.

THE GENERAL CIRCULATION OF CIRCULATION MODELS

Like ripples moving outward from the three pioneering groups (GFDL, UCLA, and NCAR), modelers, dynamical cores, model physics, numerical methods, and GCM computer code soon began to circulate around the world. By the early 1970s, a large number of institutions had established new general circulation modeling programs. In addition to those discussed above, the most active climate modeling centers today include Britain's Hadley Centre, Germany's Max Planck Institute, Japan's Earth Simulator Centre, and the Goddard Institute for Space Studies in the United States. Figure 5 shows the genealogy of atmospheric GCMs from Phillips' prototype through about 1995.

Figure 5 shows only part of this complicated story, and it does not capture the details of relationships among models. In some cases one lab imported another's computer code; in others, one lab adopted another's *mathematical* model, but programmed it from scratch for a different computer. Frequently, labs imported only part of an existing model (such as a dynamical core, a grid scheme, or a cloud parameterization) and built the rest themselves. The circuitous exchange of concepts, mathematical techniques, and computer code became entirely typical of computational meteorology and climatology after the middle 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 original GCM groups left to form new groups of their own, taking computer code with them. The availability of a widely shared, well standardized scientific computer language (FORTRAN) substantially facilitated these exchanges, as did the scientific-internationalist culture of meteorology.

Yet the number of GCMs and modeling groups worldwide grew slowly. This was largely because as modelers sought to increase model resolution and include more physical processes, the computer power they required continued to grow. More 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 near-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 highly trained staff of programmers and technical support personnel, as well as air-conditioned rooms and considerable amounts of electricity.

How many GCMs and climate modeling groups exist worldwide? The exact number can be expanded or contracted under various criteria. About 33 groups

submitted GCM output to the Atmospheric Model Intercomparison Project (AMIP) in the 1990s.⁶⁷ A few years later, however, only about 25 groups contributed coupled AOGCM outputs to the Coupled Model Intercomparison Project (CMIP)—reflecting the greater complexity and larger computational requirements of coupled models.⁶⁸ Notably, while the AMIP models included entries from Russia, Canada, Taiwan, China, and Korea, all of the CMIP simulations came from modeling groups based in Europe, Japan, Australia, and the USA, the historical leaders in climate modeling. The elite world of global climate simulation still includes no members from South America, Central America, Africa, the Middle East, or south Asia. Barriers to entry—including not only supercomputers, but also the knowledge and human infrastructure required to support research of this nature—remain very high.

COUPLING MODELS

Starting in the 1980s with coupled AOGCMs, climate modeling has moved in the direction of increasingly comprehensive models. Earth system models (ESMs) couple atmosphere–ocean GCMs to models of other climate-related systems, such as the land surface, the cryosphere (glaciers, sea ice, and snow cover), hydrology (lakes, rivers, evaporation, and rainfall), and vegetation. Meanwhile, integrated assessment models (IAMs) emerged from an environmental impact modeling tradition dating to the world dynamics models used in the 1972 Club of Rome report *The Limits to Growth*.⁶⁹ IAMs sought to incorporate climate change impacts, economic responses, and policy scenarios in a single modeling framework, typically composed of numerous components.

Initially, coupled models were created at individual laboratories one by one, on a craft basis. The proliferation of component models led to an increasing desire to 'mix and match' them, combining an ocean model from one lab with a sea ice model from another and an atmospheric model from a third. In response, in 2002 a group including NCAR, NOAA, NASA, and Department of Defense constituencies began developing an Earth System Modeling Framework (ESMF), essentially a set of software gateways which allow component models to interoperate.⁷⁰ Using the modeling framework, scientists can assemble new combinations of models, reuse model codes, regrid, and perform other modeling tasks without complex and time-consuming custom coding. Modeling frameworks mark a new trend in climate model evolution, heading toward greater transparency and a more 'open source' approach.

EVALUATING AND COMPARING CLIMATE MODELS

Modelers evaluate climate models in numerous ways. The most common technique all along has been to compare model output with climatological averages from observations. Another is to set parameters (such as greenhouse gas concentrations and the position of continents) to correspond with a known paleoclimate situation to see how accurately the model will reproduce a climate much different from the present one. Most recently, modelers have attempted to reproduce the climate of the 20th century; parameters are set to represent the transient increase in greenhouse gases and major volcanic eruptions.

Following the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988, modelers initiated a number of exercises in model evaluation. The Atmospheric Model Intercomparison Project, mentioned above, was among the first of these, established in 1989 at the Lawrence Livermore National Laboratory. AMIP required each modeling group to run its model using a specific set of ‘boundary conditions’, or parameters, and to provide a specific set of output variables in standard formats. Comparing model results with each other, as well as with observational data, allowed modelers to detect biases and helped to diagnose the reasons for them—not an easy thing to do in models containing hundreds or thousands of parameters.

Following AMIP, GCM intercomparison evolved into a series of more elaborate projects and a cycle formally linked to the IPCC assessment process, under the umbrella Program for Climate Model Diagnosis and Intercomparison.⁷¹ The current phase of CMIP, e.g., compares model simulations of the following:

1. Pre-industrial control run
2. Present-day control run
3. Climate of the 20th century experiment (realistic greenhouse gas increases)
4. 1% per year CO₂ increase to doubling and quadrupling
5. Stabilization at 550 ppm CO₂

as well as numerous others, prescribing well over 100 output fields the models should generate to permit direct comparison. By permitting regular, direct, and meaningful comparisons of the models with each other and with common data sets, these projects are transforming climate modeling from a craft activity of isolated individual groups into a more modular, standardized collective activity.

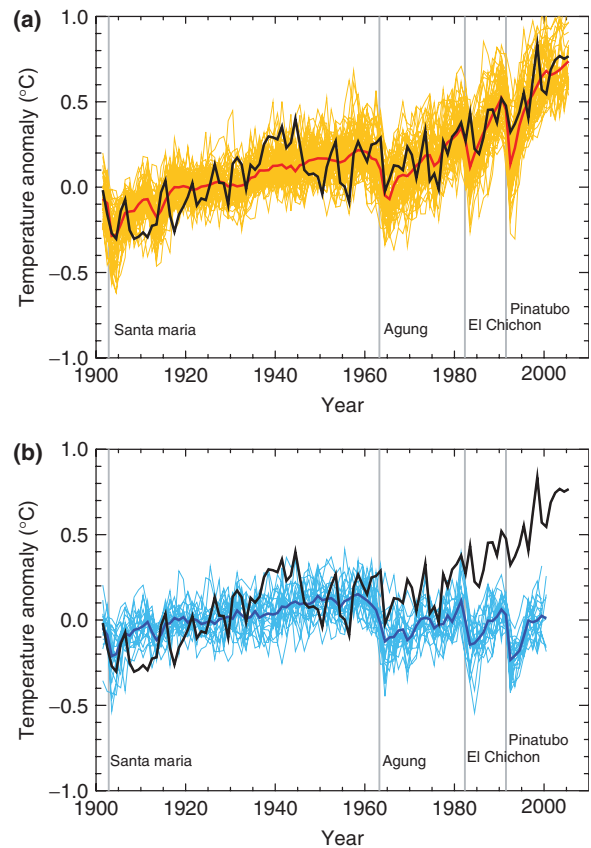


FIGURE 6 | Atmosphere–ocean general circulation model (AOGCM) simulations of 20th century global mean surface temperature anomaly with (a) and without (b) anthropogenic forcing. Black line in both graphs represents observations. Thick red (a) and blue (b) lines represent the trend across all model simulations. Original caption: Comparison between global mean surface temperature anomalies (°C) from observations (black) and AOGCM simulations forced with (a) both anthropogenic and natural forcings and (b) natural forcings only. All data are shown as global mean temperature anomalies relative to the period 1901–1950, as observed (black, Hadley Centre/Climatic Research Unit gridded surface temperature data set (HadCRUT3); Brohan et al., 2006) and, in (a) as obtained from 58 simulations produced by 14 models with both anthropogenic and natural forcings. The multi-model ensemble mean is shown as a thick red curve and individual simulations are shown as thin yellow curves. Vertical grey lines indicate the timing of major volcanic events. Those simulations that ended before 2005 were extended to 2005 by using the first few years of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) A1B scenario simulations that continued from the respective 20th-century simulations, where available. The simulated global mean temperature anomalies in (b) are from 19 simulations produced by five models with natural forcings only. The multi-model ensemble mean is shown as a thick blue curve and individual simulations are shown as thin blue curves. Simulations are selected that do not exhibit excessive drift in their control simulations (no more than 0.2°C per century). Each simulation was sampled so that coverage corresponds to that of the observations. (Reprinted with permission from Ref 38. Copyright 2007 Cambridge University Press.)

How do current GCM results compare with each other? How well do they track the 20th century climate record? What do they tell us about the relative roles of natural and anthropogenic factors? Figure 6 provides a glimpse of all of these comparisons simultaneously. In both charts, the thick black line represents the best available data for surface temperature. The thin lines graph the year-by-year outputs from numerous GCM simulations, which fluctuate, as expected, around the actual climate record. (No climate model *should* reproduce the record exactly, due to climate's natural variability.) The dashed lines mark the average trend from all the models together. Figure 6 shows that when both natural and anthropogenic forcings are included in present-day GCM simulations, their average trend tracks the 20th century observational record reasonably well. However, when anthropogenic forcings—greenhouse gases, aerosols, and other human activities that affect the atmosphere—are removed, the ensemble trend begins to fall below observed trend around 1960 and departs from it altogether by 1980. This is true not just of the models' average, but of every individual model run as well. None of the models compared could reproduce the most recent period of global warming without including human activities.

CONCLUSION

Climate models—theory-based representations of average atmospheric flows and processes—are the fundamental tools of modern climate science. Conceptual, analog, and mathematical models dominated until the advent of digital computers in the 1940s. Since the 1960s, GCMs—computer simulations of atmospheric flows and processes over long periods—have come to dominate climate science, although simpler models remain important both in their own right and as checks on sub-models included in GCMs. After 1975, climate simulations increasingly coupled atmospheric GCMs with ocean GCMs. From the 1990s to the present, models of other climatically significant processes have increasingly been coupled to AOGCMs, resulting in both ESMs and IAMs that simulate social, political, and economic aspects of the human influence on climate.

These trends have brought many disciplines together to seek realistic, potentially predictive models of climate change. Since 2000, research and operational agencies have begun to work together more closely, seeking a unified modeling framework for climate prediction. The result is an increasingly standardized, modular, global infrastructure for producing knowledge about Earth's climate, organized around simulation modeling.

REFERENCES

- Halley E. An historical account of the trade winds, and monsoons, observable in the seas between and near the Tropicks, with an attempt to assign the physical cause of the said winds. *Philos Trans R Soc Lond* 1686, 1:153–168.
- Hadley G. Concerning the cause of the general trade-winds. *Philos Trans R Soc Lond* 1735, 39:58–62.
- Dove HW. *Meteorologische Untersuchungen*. Berlin: Sanderischen Buchhandlung; 1837.
- Ferrel W. An essay on the winds and currents of the ocean. *Nashv J Med Surg* 1856, 11:287–301, 375–389.
- Chamberlin TCA. Group of hypotheses bearing on climatic changes. *J Geol* 1897, 5:653–683.
- Chamberlin TC. The influence of great epochs of limestone formation upon the constitution of the atmosphere. *J Geol* 1898, 6:609–621.
- Russell RJ. Climatic change through the ages. In: United States Department of Agriculture, ed. *Climate and Man*. Washington: U.S. Government Printing Office; 1941, 67–97.
- Brooks CEP. Geological and historical aspects of climatic change. In: Malone TF, ed. *Compendium of Meteorology*. Boston: American Meteorological Society; 1951, 1004–1018.
- Richardson LF. *Weather Prediction by Numerical Process*. Cambridge: Cambridge University Press; 1922.
- Fultz D. *Dynamics of Climate*. New York: Pergamon Press; 1960, 71–77.
- Hide R. Some experiments on thermal convection in a rotating liquid quarterly. *J R Meteorol Soc* 1953, 79:161.
- Kuo H-L. Theoretical findings concerning the effects of heating and rotation on the mechanism of energy release in rotating fluid systems. In: Pfeffer RL, ed. *Dynamics of Climate*. New York: Pergamon Press; 1960, 78–85.
- Lewis JM. Clarifying the dynamics of the general circulation: Phillips's 1956 experiment. *Bul Am Meteorol Soc* 1998, 79:39–60.
- Phillips NA. The general circulation of the atmosphere: a numerical experiment. *Q J R Meteorol Soc* 1956, 82:123–164.
- Adhémar AJ. *Les révolutions de la mer*. Privately published. Paris: 1842.

16. Croll J. *Climate and Time in Their Geological Relations*. Edinburgh: Adam and Charles Black; 1885.
17. Muller R, MacDonald GJ. *Ice Ages and Astronomical Causes: Data, Spectral Analysis, and Mechanisms*. New York: Springer; 2000.
18. Paillard D. Climate and the orbital parameters of the Earth. *C R Geosci* 2010, 342:273–285.
19. Fourier JBJ. *Théorie analytique de la chaleur*. Paris: F. Didot; 1822.
20. Arrhenius S. On the influence of carbonic acid in the air upon the temperature of the ground. *Philos Mag J Sci* 1896, 41:237–276.
21. Uppenbrink J. Arrhenius and global warming. *Science* 1996, 272:1122.
22. Callendar GS. The artificial production of carbon dioxide and its influence on temperature. *Q J R Meteorol Soc* 1938, 64:223–240.
23. Schneider SH, Dickinson RE. Climate modeling. *Rev Geophys Space Phys* 1974, 12:447–493. doi:10.1029/RG012i003p00447.
24. McGuffie K, Henderson-Sellers AA. *Climate Modelling Primer*. New York: John Wiley & Sons; 2005.
25. Weart SR. *The Discovery of Global Warming*. Cambridge: Harvard University Press; 2003.
26. Bjerknes V, Sandström JW, Hesselberg T, Devik OM. *Dynamic Meteorology and Hydrography*. Washington: Carnegie Institution of Washington; 1910.
27. Bjerknes V. *Fields of Force: Supplementary Lectures, Applications to Meteorology*. New York: Columbia University Press; 1906.
28. Lynch P. *The Emergence of Numerical Weather Prediction: Richardson's Dream*. New York: Cambridge University Press; 2006.
29. Nebeker F. *Calculating the Weather: Meteorology in the 20th Century*. New York: Academic Press; 1995.
30. Harper KC. *Weather by the Numbers: The Genesis of Modern Meteorology*. Cambridge: MIT Press; 2008.
31. Phillips TJ, Potter GL, Williamson DL, Cederwall RT, Boyle JS, Fiorino M, Hnilo JJ, Olson JG, Xie S, Yio JJ. Evaluating parameterizations in general circulation models: climate simulation meets weather prediction. *Bull Am Meteorol Soc* 2004, 85:1903–1915.
32. Shackley S. Epistemic lifestyles in climate change modeling. In: Miller CA, Edwards PN, eds. *Changing the Atmosphere: Expert Knowledge and Environmental Governance*. Cambridge: MIT Press; 2001, 107–134.
33. Edwards PN. Global climate science, uncertainty and politics: data-laden models, model-filtered data. *Sci Cult* 1999, 8:437–472. doi:10.1080/09505439909526558.
34. Edwards PNA. *Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*. Cambridge, MA: MIT Press; 2010.
35. Petersen A. *Simulating Nature: A Philosophical Study of Computer-Simulation Uncertainties and Their Role in Climate Science and Policy Advice*. Antwerp: Het Spinhuis; 2007.
36. Sundberg M. Parameterizations as boundary objects on the climate arena social. *Stud Sci* 2007, 37:473–488.
37. Arakawa A. The cumulus parameterization problem: past, present, and future. *J Clim* 2004, 17:2493–2525.
38. Intergovernmental Panel on Climate Change. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press; 2007.
39. Kurihara Y. Numerical integration of the primitive equations on a spherical grid. *Mon Weather Rev* 1965, 93:399–415.
40. Sadourny R, Arakawa A, Mintz Y. Integration of the nondivergent barotropic vorticity equation with an icosahedral-hexagonal grid for the sphere. *Mon Weather Rev* 1968, 96:351–356.
41. Silberman I. Planetary waves in the atmosphere. *J Atmos Sci* 1954, 11:27–34.
42. Platzman GW. The spectral form of the vorticity equation. *J Meteorol* 1960, 17:635–644.
43. Robert AJ. The integration of a spectral model of the atmosphere by the implicit method. In: World Meteorological Organization, International Union of Geodesy and Geophysics, eds. *Proceedings of the WMO IUGG symposium on numerical weather prediction in Tokyo, Japan, November 26–December 4, Tokyo, 1968*, Meteorological Society of Japan, VII-9–VII-24.
44. Orszag SA. Transform method for the calculation of vector-coupled sums: application to the spectral form of the vorticity equation. *J Atmos Sci* 1970, 27:890–895.
45. Orszag SA. Fourier series on spheres. *Mon Weather Rev* 1974, 102:56–75.
46. Eliassen E, MACHENHAUER B, RASMUSSEN E. *On a Numerical Method for Integration of the Hydrodynamical Equations with a Spectral Representation of the Horizontal Fields*; 1970.
47. Bourke W, McAvaney B, Puri K, Thurling R. Global modeling of atmospheric flow by spectral methods. In: Chang J, ed. *General Circulation Models of the Atmosphere*. San Francisco: Academic Press; 1977, 267–324.
48. Bourke WA. Multi-level spectral model. I. Formulation and hemispheric integrations. *Mon Weather Rev* 1974, 102:687–701.
49. Smagorinsky J. On the numerical integration of the primitive equations of motion for baroclinic flow in a closed region. *Mon Weather Rev* 1958, 86:457–466.
50. Smagorinsky J, Manabe S, Holloway JL. Numerical results from a nine-level general circulation model of the atmosphere. *Mon Weather Rev* 1965, 93:727–768.
51. Manabe S, Wetherald R. Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *J Atmos Sci* 1967, 24:241–259.

52. Smagorinsky J. The beginnings of numerical weather prediction and general circulation modeling: early recollections. *Adv Geophys* 1983, 25:3–37.
53. Manabe S, Bryan K. Climate calculations with a combined ocean-atmosphere model. *J Atmos Sci* 1969, 26:786–789.
54. Manabe S, Bryan K, Spelman MJA. Global ocean-atmosphere climate model: Part I. The atmospheric circulation. *J Phys Oceanogr* 1975, 5:3–29.
55. Manabe S. The dependence of atmospheric temperature on the concentration of carbon dioxide. In: Singer SF, ed. *Global Effects of Environmental Pollution*. Dallas: D. Reidel; 1970, 25–29.
56. Manabe S. Estimates of future change of climate due to the increase of carbon dioxide. In: Mathews WH, Kellogg WW, Robinson GD, eds. *Man's Impact on the Climate*. Cambridge: MIT Press; 1971, 250–264.
57. Manabe S, Stouffer RJ. Multiple-century response of a coupled ocean-atmosphere model to an increase of atmospheric carbon dioxide. *J Clim* 1994, 7:5–23.
58. Mintz Y. Design of some numerical general circulation experiments. *Bul Res Counc Isr* 1958, 76:67–114.
59. Arakawa A. Paul N. Edwards, July 17–18, 1997.
60. Arakawa A. A personal perspective on the early years of general circulation modeling at UCLA. In: Randall DA, ed. *General Circulation Model Development*. San Diego: Academic Press; 2000, 1–65.
61. Leith CE. *Methods in Computational Physics*. New York: Academic Press; 1965, 1–28.
62. Kasahara A, Washington WM. NCAR global general circulation model of the atmosphere. *Mon Weather Rev* 1967, 95:389–402.
63. Olinger JE, Welck RE, Kasahara A, Washington WM. *Description of NCAR Global Circulation Model*. Boulder: National Center for Atmospheric Research; 1970.
64. Kasahara A, Washington WM. General circulation experiments with a six-layer NCAR model, including orography, cloudiness and surface temperature calculations. *J Atmos Sci* 1971, 28:657–701.
65. Kasahara A, Sasamori T, Washington WM. Simulation experiments with a 12-layer stratospheric global circulation model. I. Dynamical effect of the earth's orography and thermal influence of continentality. *J Atmos Sci* 1973, 30:1229–1251.
66. Washington WM, Dickinson R, Ramanathan V, Mayer T, Williamson D, Williamson G, Wolski R. Preliminary atmospheric simulation with the third-generation NCAR general circulation model: January and July. In: Lawrence W, ed. *Report of the Jcc Conference on Climate Models: Performance, Intercomparison, and Sensitivity Studies*. Washington: WMO/ICSU Joint Organizing Committee & Global Atmospheric Research Programme; 1979, 95–138.
67. Atmospheric Model Intercomparison Project, Lawrence Livermore National Laboratory. Available at: <http://www-pcmdi.llnl.gov/projects/amip/index.php>. (Accessed December 2010).
68. Covey C, AchutaRao KM, Cubasch U, Jones P, Lambert SJ, Mann ME, Phillips TJ, Taylor KE. An overview of results from the coupled model intercomparison project. *Glob Planet Change* 2003, 37:103–133.
69. Meadows DH, Meadows DL, Randers J, Behrens III WW. *The Limits to Growth: a Report for the Club of Rome's Project on the Predicament of Mankind*. New York: Universe Books; 1972.
70. Hill C, DeLuca C, Balaji MS, da Silva A. The architecture of the earth system modeling framework. *Comput Sci Eng* 2004, 6:18–28.
71. Program on Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory. Available at: <http://www-pcmdi.llnl.gov>. (Accessed December 2010).

FURTHER READING

Edwards PN. *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*. Cambridge, MA: MIT Press; 2010.

Fleming JR. *Historical Essays on Meteorology, 1919–1995*. Boston, MA: American Meteorological Society; 1996.

Kalnay E. *Atmospheric Modeling, Data Assimilation and Predictability*. New York: Cambridge University Press; 2003.

Randall DA, ed. *General Circulation Model Development, Past Present and Future: The Proceedings of a Symposium in Honor of Akio Arakawa*. New York: Academic Press; 2000.

Weart SR. 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, College Park; 2008. Available at: <http://www.aip.org/history/climate/index.html>. (Accessed June 2010).