Changing the Atmosphere

Expert Knowledge and Environmental Governance

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Representing the Global Atmosphere: Computer Models, Data, and Knowledge about Climate Change

Paul N. Edwards

If the idea of a truly *global* environmental problem required a poster child, climate change would certainly top the list of candidates.

Political and scientific narratives of the last decade almost always frame climate change as a genuinely planetary risk. The UN Framework Convention on Climate Change (FCCC) defines the threatened climate system as "the totality of the atmosphere, hydrosphere, biosphere, and geosphere and their interactions" (United Nations 1992, Article 1). This way of framing the issue notes that the causes of climate change, such as fossil fuel combustion, deforestation, and rice and cattle agriculture, extend across the face of the planet. They are embedded in core sectors of modern economic systems and affect the daily activities of everyone on the planet. The global-risk perspective emphasizes that the projected consequences of climate change will implicate virtually all human communities and natural ecosystems. In the early twenty-first century, then, climate change can be put forward as the quintessential global environmental problem.

Yet when the human risks posed by rising atmospheric concentrations of carbon dioxide were first (re)discovered in the late 1950s and early 1960s, they were often understood primarily in local or regional, rather than global, terms. As with other environmental problems, such as earthquakes, urban smog, and drought, the consequences of climate change would, it was thought, affect some places more severely than others. In most places, on this view, people would simply adapt (as they always have) to such changes. Thus a 1966 report by the U.S. National Research Council (NRC) expressed complacency about climate change:

> It is perhaps worth noting that, even in the more extreme estimates of the possible climatic consequences of increased atmospheric CO_2, the calculated temperature changes have been of the order of a few degrees, generally less than five or ten. From glacial-geologic data, it is known with some certainty that North America and Europe have, since the last maximum of the Wisconsin Glaciation, experienced climates that have averaged several degrees warmer than the present. As mentioned earlier, *although some of the natural climatic changes have had locally catastrophic effects, they did not stop the steady evolution of civilization.* (National Academy of Sciences 1966, emphasis added; see Miller, forthcoming, detailing the local framing of climate change and the subsequent transition to global framing)

Even two decades later, in its 1983 report *Changing Climate*, the NRC once again stressed that climate change not only could, but for pragmatic purposes *should*, be defined "flexibly" in local terms:

> Viewed in terms of energy, global pollution, and worldwide environmental damage, the "CO_2 problem" appears intractable. Viewed as a problem of changes in local environmental factors—rainfall, river flow, sea level—the myriad of individual incremental problems take their place among the other stresses to which nations and individuals adapt. It is important to be flexible both in definition of the issue, which is really more climate change than CO_2, and in maintaining a variety of alternative options for response. (National Research Council 1983, 3)

Yet by the mid-1980s, most conceptions of climate change painted its risks almost exclusively in global terms.

How, and why, did scientific and political discourses about the human risks of climate change shift the emphasis from local to global concerns? To answer this question, this chapter will explore in detail the history of the competing, and contested, representations of climate through which the contemporary debate has been structured.

One clue comes from an important scientific paradigm shift. Historically, the science of climatology consisted primarily of record keeping and analysis of climate trends at a particular location (see Miller, forthcoming). Although a global conception of *weather* had developed by the early 1900s, climatology continued for decades along this rather separate, particularistic track. Even in the 1960s and 1970s, the primary scientific tools for representing climate remained the long-term statistical databases compiled by climatologists. But in the decade between about 1965 and 1975, the locally oriented climatologists were rapidly displaced by a new breed of global modelers. By the late 1970s, computer-based climate models—conceptually almost identical to the weather models in use since the 1950s, although used differently (see below)—had come to dominate climatological discourse. With this change, the very meaning of *climate* shifted from a local to a global understanding. The term *climatology* gradually fell from favor (although it is still used), replaced by the term *climate science*. This shift reflected the new model-based, globally oriented paradigm.

Today, climate models are essential not only for predicting future climates, but also for attributing the causes of climatic change in the recent past. Without a model of what would have happened *without* anthropogenic (human-caused) atmospheric change, scientists cannot separate out the effects of rising greenhouse gas concentrations from natural climatic variability. The inherent variability of weather makes it impossible to attribute individual storms, floods, droughts, or hurricanes to changes in the global climate. Only by coupling statistical analyses to climate modeling exercises have scientists been able to isolate and display the "fingerprint" of global warming in changing weather patterns around the world.

Because of its long-term, statistical character, even local climate change is difficult to grasp experientially. A few hot summers, an unusual spate of major storms, or even a decade-long drought can be elements of "normal," regional climate variation, rather than signals of long-term climate change. By the same token, *global* climate change cannot be grasped experientially at all. The most commonly cited figure in climate change debates—change in the average global temperature—has no correlate in anyone's actual living conditions. Thus, while public awareness and understanding of climate change have always depended on the work of the scientific community, they do so more now than ever before. Knowledge of climate change, in the contemporary sense of the term, comes *only* from science; in Bruno Latour's phrase, climate modeling has become an "obligatory passage point" for knowledge of climate change. Furthermore, knowledge about changes in the global climate system depends on very many sciences, from meteorology to oceanography to ecology. The theories, models, standards of evidence, and data sets of these various contributors are often quite different, not to mention contested. Modern climate science is a multidisciplinary and interdisciplinary field, rather than the specialty of statistical climatology.

The increasingly complex articulation between a science-based, descriptive understanding and normative climate politics—where the global climate is seen as a system in which political intervention could be both important and effective—has generated unprecedented interdisciplinary scientific collaboration and political coordination. These phenomena require historical explanation. At the same time, they present an opportunity to grapple with the central question of knowledge-power relationships at the interfaces between local, national, and global communities. How have scientists tied the wide-ranging strands of their work together? How have their efforts linked up with the formation of new transnational scientific and political communities? How have particular representations of climate linked multiple communities of researchers, government officials, and citizens? How have national efforts differed and conflicted, and how have these differences been handled in the international community? These are the kinds of questions to which a science studies theoretical approach may offer new and different answers.

This chapter begins to approach these questions, and also serves as an introduction to climate science concepts treated throughout this volume. To do so, it focuses on two key "boundary objects" in this enormous and enormously confusing arena: computer models of the atmosphere and global satellite data sets. Boundary objects are things, theories, symbols, or other entities used by multiple communities; although they may have different meanings and functions for each group, they provide conceptual and pragmatic links that bind the communities together (Star and Griesemer 1989). Computer models and global data sets play this role for many of the scientific and political groups focused on climate change.

Computer models are arguably the single most important tool of global climate science. They range in size from simple programs that can run on a desktop computer to ultracomplicated simulation models of the entire Earth system, which strain the capacities of even the most powerful supercomputers. Much of climate science could not exist without them, since planetary-scale processes cannot be studied by controlled laboratory experiments. Instead, climate science relies on global "experiments" performed on models to provide it with insights into the dynamics of the atmospheric system as a whole.

Satellite data—covering many facets of the atmosphere, and a smaller number of characteristics of the Earth's oceans, ice, snow, and land surfaces—are likewise central to contemporary scientific understandings of the entire planet. Although many other forms of data are collected on a worldwide basis (from surface stations, radar, weather balloons, ships, and so on), their coverage is far less uniform, less easily standardized, and less easily collected in a single location. The huge size of global data sets makes it impossible to process or understand them in any detail without the aid of computers (Edwards 1999). In fact, global data sets of the relevant density cannot even be collected without the aid of computerized interpolation models that mediate between raw instrument readings and usable data formats. I will return to this issue below.

I begin this chapter by sketching the history of atmospheric modeling and its relation to the development of global data networks. Second, I describe how modern climate models work and discuss some of the key problems faced by modelers. Third, I examine the extremely fuzzy boundaries between models and data in global climate science, and the major role of computer models in binding them into a coherent system of knowledge with a global, rather than a local or regional, basis. Finally, I explore some implications of the primary role given to computer models in representing the global atmosphere.

Climate Science: Concepts and Tools

Since most of the chapters in this book discuss climate modeling in one way or another, I will begin by describing briefly the scientific concepts on which the models are based and how these models work. I purposely ignore scientific controversies, since many of these are treated in detail by later chapters. In any case, at this level of generality there is little debate.

Scientific Principles

The principal sources of atmospheric science lie in various branches of physics: theories of the behavior of gases (pressure, temperature), the radiation absorption and emission characteristics of different gases, and turbulent fluid (gas) flows.

The earth is bathed in a constant flood of solar energy, all of which it ultimately reradiates into space. One key aspect of climate, the Earth's temperature, is therefore a matter of what climate scientists call *energy balance*: all the energy that goes into the system must, eventually, come out again. The atmosphere forms a blanket of gases (primarily nitrogen, oxygen, and water vapor) capable of absorbing and holding a great deal of this incoming energy as heat. The oceans, too, absorb and retain heat. They play a major role in the overall climate system, "damping" the system's response to change with their enormous heat-retention capacity (far larger than the atmosphere's). In theory, if the earth had no atmosphere its average surface temperature would be about –19°C. Instead, the heat retained in the atmosphere maintains it at the current global average of about 15°C.

Under the influence of solar heating and the earth's rotation, both the atmosphere and the oceans "circulate," carrying heat around the globe in currents of air and water. The *general circulation* refers to the motion and state of the entire atmosphere (or ocean); it is sometimes (more aptly) termed the *global* circulation. Ultimately, the circulation conducts heat from the equator, which receives the greatest amount of incoming energy from the sun, to the poles, where more heat is radiated into space than is received. Since weather moves freely around the globe and changes with considerable speed, only by modeling the general circulation can meteorologists hope to understand the evolution of weather over more than a couple of days.

The earth's wobble on its axis in relation to the sun, atmospheric and oceanic turbulence, and many other factors render circulation patterns highly complex. In the short term (hours to weeks), such patterns are experienced as weather: rain, dry spells, clouds, hurricanes. Long-term patterns (occurring over months to decades, and beyond) are known as *climate*, and include such phenomena as the seasons, with their regular annual changes in temperature and precipitation; prevailing regional climates (deserts, tropics, ice caps, and so forth); multiyear climatic variations (droughts, the El Niño/Southern Oscillation, and so on); and very long term climate changes such as ice ages.

Models

Climate models are mathematical simulations, based on physical principles, of these long-term atmospheric conditions. Although many discussions in this book (and in public debates) focus on the most complicated, supercomputer-based climate models, in fact there is a wide range of complexity, sometimes referred to by scientists as the *hierarchy of models*.

The simplest, "zero-dimensional" models rely solely on the principle of energy balance discussed above (and are called *energy-balance models*). Using measured values for such factors as solar radiation and concentrations of the atmosphere's constituent gases, they compute (for example) a single global average temperature, treating the earth as if it were a point mass. Models this basic may involve only a few equations and can readily be solved by hand. One- and two-dimensional energy-balance models also exist.[1] Another class of two-dimensional models, called *radiative-convective*, calculates the atmosphere's vertical temperature structure. In these models, temperature is computed as a function of latitude and either longitude (a second horizontal dimension) or air pressure (the vertical dimension). Many two-dimensional models remain relatively simple—typically, a few hundred to a few thousand lines of computer code—compared to the three-dimensional[2] models known as *atmospheric general circulation models* (GCMs, or AGCMs to distinguish them from OGCMs, which model the oceanic general circulation).

Contemporary atmospheric GCMs are typically expressed in some 30,000 to 60,000 lines of FORTRAN code. They represent the atmosphere as a three-dimensional lattice or "grid."[3] Typically, the grid resolution at the surface is 3°–5° latitude by 6°–8° longitude. (This translates roughly into squares or rectangles 300 to 500 km on a side.) Eight to twenty layers of varying depth represent the vertical dimension up to a height of 20 km or so, with more layers at lower altitudes, where the atmosphere is denser and most weather occurs. Equations of state compute the effect of various forces (radiation, convective heating, and so on) on the air masses and moisture (clouds and water vapor) within each grid box. Equations of motion compute the direction and speed of the air's movement into the surrounding grid boxes. AGCMs usually also include representations of certain aspects of the land surface, such as elevation and albedo (reflectance). In addition, they usually include some representation of the oceans, which may be as simple as a shallow, one-layer "swamp" ocean with fixed surface temperature. Today's most sophisticated models dynamically couple AGCMs to full-scale OGCMs of equivalent complexity. In addition, they may also include models of sea ice, snow cover, vegetation, agriculture, and other phenomena with important effects on climate; such models are sometimes known as *Earth systems models* (ESMs).

Such models demand enormous computational power. The first GCMs required twenty-four hours of computer time in order to simulate a single day of global circulation. By the mid-1970s, faster computers reduced the time to about twelve hours per simulated year. For a typical climate modeling run of twenty simulated years, a GCM still required as much as 240 hours—ten continuous days—of expensive supercomputer time. Although computer speeds continue to increase, these long run times have declined little since then. Modelers prefer, instead, to represent more variables, increase resolution, and carry out longer runs (Chervin 1990).

Modern weather forecasters also use GCMs. Weather forecasters use the highest possible model resolution, because their purpose is prediction and because their model runs are only a few days. Ideally, weather models must resolve relatively small-scale processes, such as the formation and motion of clouds. Grid cells as small as 60 km on a side are common in the best modern weather GCMs. They are initialized with observational data, such as temperature, humidity, and wind speed, from a wide range of sources, including surface weather stations, satellites, and radiosondes (weather balloons). The models then calculate the likely evolution of this observed initial state over short periods (hours to days).

Climate modelers, by contrast, use *coarse-grid* GCMs that cannot simulate clouds and many other atmospheric processes directly; climate scientists refer to such phenomena as *sub-grid-scale* processes. This necessitates *parameterization*, or representation of small-scale events by large-scale variables (Hack 1992; Kiehl 1992). In addition, when used for climate research, GCMs generally are not initialized with observational data. Instead, GCMs are autonomous simulations that generate their own "climates," starting—in principle, if not in practice—with only a few empirically derived inputs such as solar radiation, gas composition of the atmosphere, sea surface temperatures, and orbital precession. These simulated climates must be run until they stabilize, then compared with observed long-term trends and phenomena in the earth's climate system. This requires multidecade, even millennia-long time series (Manabe and Stouffer 1994, 1979, 1994; Wigley, Pearman, and Kelly 1992). These features of climate modeling lead to uncertainties and epistemological issues discussed by several contributors to this volume. I will return to them below, after sketching the place of general circulation modeling in the history of climate science and politics.

Computer Models and Global Data Networks

The concept of anthropogenic climate change has surprisingly deep historical roots, reaching back over 100 years. In this section, I discuss the history of climate modeling and its role in the emergence of climate change as a political issue.

Early Theories of Climatic Change

Scientific theories of climate change date to the mid-nineteenth century. In 1824, Jean-Baptiste Joseph Fourier hypothesized that the atmosphere retains heat, keeping the earth's surface temperature far higher than it would be if the earth had no atmosphere or if the atmosphere contained no water vapor or carbon dioxide (CO_2). Fourier likened the heating action of the atmosphere to a "hothouse," thus christening what we now call the *greenhouse effect*.

Physicist John Tyndall, in Great Britain, first calculated the radiative potential of CO_2 in 1863. His result paved the way for the Swedish scientist Svante Arrhenius, in 1896, to make the first calculation of the contribution of carbon dioxide to the earth's surface temperature. In 1900, another British scientist, T. C. Chamberlin, published a sweeping theory of climatic change over geological time scales, with CO_2 as the basic mechanism. Chamberlin argued that volcanic eruptions produce CO_2, warming the earth; the weathering of rocks absorbs the gas, accounting for glacial cycles. Chamberlin's idea that CO_2 was the *determining* factor in global climate change is no longer current. Orbital cycles, water vapor, ocean currents, and other factors are today believed to be more important. Yet Chamberlin did identify one of the basic mechanisms.

In 1903 Arrhenius went on to calculate that the CO_2 added to the atmosphere by human combustion of fossil fuels might eventually raise the earth's temperature substantially. In fact, he predicted that if the amount of CO_2 in the atmosphere were to double, the global average temperature would rise somewhere between 1.5° and 4°C. Even the most sophisticated modern climate models run on supercomputers still predict approximately this same range of probable change.

Arrhenius, perhaps since he lived in a very cold place, thought that such a global warming might be a good thing. But in his time, world consumption of fossil fuels remained low enough that this seemed merely an idle speculation, not a near-term possibility. Tellingly, Arrhenius also computed the effect of *decreasing* CO_2 on the atmosphere. He noted that natural factors might also produce such a change.

Although these scientists never thought of climate change as a political concern, in fact concern about anthropogenic climate change long predates the modern concept of greenhouse warming. James R. Fleming, Nico Stehr, Hans von Storch, and Moritz Flügel have uncovered numerous historical episodes of attribution of climatic changes to human causes. For example, in the Middle Ages climate anomalies were sometimes explained by the church as a divine response to human sin (Stehr, von Storch, and Flügel 1995), while Thomas Jefferson apparently believed that clearing land for agriculture altered the climate of the early United States in favorable ways (Fleming 1998). Similarly, Richard Grove (1997) has argued that some nineteenth-century colonial forest policies were predicated on a "dessicationist" theory of relations between deforestation and local, regional, and even continental climate change. According to Grove, these policies are the direct ancestors of some modern forest-conservation agendas. Grove also shows that colonial meteorologists in India and Australia developed early theories of global "teleconnections" (long-distance interactions of ocean currents and weather patterns, such as El Niño) by observing coincidence between Indian and Australian droughts.

The episode that perhaps most nearly resembles modern climate politics occurred in the 1890s, when German scientists Edward

Brückner and Julius Hann argued (separately) that human-induced climatic warming was already occurring in Europe and America as a result of deforestation and other causes. They based their speculations on trends derived from observations, rather than from physical theories of the atmosphere. Brückner thought that crop failures, economic crises, and epidemics would result, and argued that countries should undertake vast reforestation programs to counteract the trend. Prussia, Italy, and France established government reforestation committees as a result, while scientific societies debated the issue in the United States. In the end the issue fizzled, but it stands as a remarkable precursor to modern climate politics (Stehr and von Storch 2000).

Numerical Weather Prediction

Through most of this century, the history of climate politics is intimately linked with the history of numerical models of the atmosphere, initially created to forecast weather.

Toward the end of the nineteenth century, meteorology began to build theoretical foundations. By the early 1900s, the Norwegian meteorologist Vilhelm Bjerknes could argue that atmospheric physics had advanced sufficiently to allow weather to be forecast using calculations. He developed a set of seven differential equations, derived from basic physics, whose simultaneous solution would predict the large-scale movements of the atmosphere. Today these are known as the *primitive equations*.

Bjerknes proposed a *graphical calculus*, based on weather maps, for solving the equations. This analog technique made no attempt to treat the problem numerically, a feat far beyond the capacities of human or mechanical computers of the day. Although forecasters continued to use and develop his methods until the 1950s, both the lack of faster calculating methods and the dearth of accurate observational data limited their success (Nebeker 1995).

Richardson's "Forecast Factory" In 1922, the English mathematician Lewis Fry Richardson developed the first numerical weather prediction (NWP) system. His calculating techniques—finite difference solutions of differential equations in a gridded space—were the same ones employed by the first generations of GCM builders. Richardson's method, based on simplified versions of Bjerknes's equations, reduced the necessary calculations to a level where manual solution could be contemplated. Still, the task remained fantastically large. His own attempt to calculate weather for a single eight-hour period took six weeks and ended in failure.

His model's enormous calculation requirements led Richardson to propose a fanciful solution he called the *forecast-factory*. The "factory"—really more like a vast orchestral performance—would have filled a huge stadium with 64,000 people. Each one, armed with a mechanical calculator, would perform one element of the calculation. A leader, stationed in the center, would coordinate the forecast using colored signal lights and a telegraph system. Yet even with this impossible apparatus, Richardson thought he would probably be able to calculate weather only about as fast as it actually happens (Richardson 1922). Only in the 1940s, when digital computers made possible automatic calculation on an unprecedented scale, did Richardson's technique become practical.

Operational Computer Forecasting The Princeton mathematician John von Neumann was among the earliest computer pioneers. Engaged in computer simulations of nuclear weapons explosions, he immediately saw parallels to weather prediction. (Both are nonlinear problems in fluid dynamics.) In 1946, von Neumann began to advocate the application of computers to weather prediction (Aspray 1990). As a committed opponent of Soviet-bloc communism and a key member of the World War II–era national security establishment, von Neumann hoped that weather modeling might lead to weather control. This, he believed, might be used as a weapon of war. Soviet harvests, for example, might be ruined by a U.S.-induced drought (Kwa 1994; Kwa, chapter 5, this volume; von Neumann 1955). On this basis, von Neumann sold weather research to military funding agencies.

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

The Meteorology Project ran its first computerized weather forecast on the ENIAC in 1950. Although not identical to Richardson's, the group's model followed his in representing the atmosphere as a grid, calculating changes on a regular time step, and employing finite difference methods to solve differential equations numerically. The 1950 forecasts, covering North America and part of the surrounding ocean, used a two-dimensional grid with 270 points about 700 km apart. The time step was three hours. Results, while far from perfect, were good enough to justify further work (Charney, Fjörtoft, and von Neumann 1950; Platzman 1979). Anticipating future success, Charney and his colleagues convinced the Weather Bureau, the Air Force, and the Navy to establish a Joint Numerical Weather Prediction (JNWP) Unit in 1954.

In December of that year, an independent effort at the Royal Swedish Air Force Weather Service became first in the world to use computer models for routine real-time weather forecasting (i.e., with broadcast of forecasts in advance of weather), using a model developed at the University of Stockholm (Bergthorsson et al. 1955; University of Stockholm Institute of Meteorology 1954). Routine computer forecasting began in the United States in mid-1955 (Nebeker 1995).

General Circulation Modeling

As late as the 1970s, the weather models used by forecasters were still regional or continental (vs. hemispherical or global) in scale, and they made no attempt to look ahead further than a few days. Calculations for numerical weather forecasts were limited to what could be accomplished in a couple of hours on then-primitive digital computers.

Yet for theoretical meteorologists, more interested in causal patterns than in real-time forecasting, general circulation modeling rapidly became a kind of holy grail. By mid-1955 Norman Phillips had completed a two-layer computer model of the general circulation (Phillips 1956). Despite its primitive nature, Phillips's model is now often regarded as the first working GCM. Like other early GCMs, this model employed major simplifying assumptions, modifying the equations to reduce the number of variables and calculations. As computer power grew, the need for simplifying assumptions diminished (although as we will see, it has hardly vanished). Between the late 1950s and the early 1960s, a number of separate groups in the United States, England, and Germany began—more or less independently—to build many-leveled, three-dimensional GCMs based on the full Bjerknes/Richardson primitive equations.

The General Circulation Research Section of the U.S. Weather Bureau became the first laboratory to build a continuing program in general circulation modeling. It opened in 1955, under the direction of Joseph Smagorinsky. Smagorinsky felt that his charge was to continue with the final step of the von Neumann/Charney computer modeling program: a three-dimensional, global, primitive-equation general circulation model of the atmosphere (Smagorinsky 1983). The lab—renamed the Geophysical Fluid Dynamics Laboratory (GFDL) in 1963—moved to Princeton University in 1968, where it remains.

Beginning in 1959, Smagorinsky and his colleagues, especially the Japanese émigré Syukuro Manabe, proceeded to develop a nine-level primitive-equation GCM, still hemispheric (Manabe 1967; Manabe, Smagorinsky, and Strickler 1965; Smagorinsky 1963). Other important general circulation modeling groups formed during the 1960s at UCLA, the U.S. National Center for Atmospheric Research, the United Kingdom Meteorological Office, and elsewhere.

By the end of the decade, general circulation modeling was firmly established as a basic research tool of meteorology and climate science. The European Center for Medium Range Weather Forecasts (ECMWF), founded in 1975, was the first to employ a *global* general circulation model in operational weather forecasting, beginning in 1979. Today, most weather forecasting centers around the world get global and regional weather data from the ECMWF and a few other large centers; they may use these data as is, or plug them into their own regional models. GCMs have not replaced simpler models altogether; in fact, many climate modelers play off one- and two-dimensional models against GCMs in the course of their research. But GCMs' sophistication and their apparent realism—as the highest-resolution theoretical representations presently available of the general circulation—have earned them a possibly inordinate prestige. Perhaps ironically, this is somewhat less true in the modeling community than among the "consumers" of model results in politics, the media, nongovernmental organizations—and academic communities, such as the one responsible for the book you are presently reading—working on climate science and climate change.

Data for Numerical Models

Modeling is, of course, only one part of the story of meteorology and climate science. The collection and processing of weather data (and its derivative, climate data) is the other. Once meteorology had provided theories of the general circulation, scientists confronted the problem of acquiring data commensurate with the models' needs and capabilities. As computers became the tools of choice for this purpose, this task evolved in unprecedented ways that fundamentally transformed the atmospheric sciences.

As Miller and Edwards note in chapter 1 of this volume, international agreements to share weather observations date to the 1878 founding of the International Meteorological Organization (IMO). Long before World War II, standard coding systems had been worked out to facilitate transfer of this information. In 1951, under the United Nations, the IMO became the World Meteorological Organization (WMO). Both organizations developed and promoted data distribution systems and standardized observational techniques.

Computerized weather prediction brought vastly intensified needs for data and for ways to handle those data. Weather models required information about the state of the atmosphere from ground level to very high altitudes. Ideally, data would be collected from locations as near as possible to the points on the models' three-dimensional grids. But in the 1950s, such data were simply unavailable. Observation stations, concentrated in urban regions, provided only very scattered and irregularly spaced coverage of the world's oceans and sparsely populated land areas.

In addition, the mere acquisition of weather information was only one step toward real-time numerical forecasting. The computer programs were useless without well-structured, reliable data *in digital form*. Most weather data, at that time, were collected by analog instruments (e.g., mercury thermometers or barometers). A human instrument reader converted them into numbers (digits) and charted them on maps, interpolating intermediate values, by eye or with simple calculating aids. The time delays inherent in this analog-digital data conversion were magnified by delays in long-distance communication. All of this imposed limitations on the scale of operational weather forecasting and left the global general circulation out of reach of predictive models.

In 1954 "gathering, plotting, analyzing and feeding the necessary information for a 24-hour forecast into a computer [took] between 10 and 12 hours," with another hour required for computation ("Long-Range Weather Forecasts by Computer," 1954). Well into the 1960s, even in the industrialized world, much weather data was hand-recorded and hand-processed before being entered into computers (Collins 1969). Data distributed in potentially machine-readable form, such as teletype, often arrived in a Babel of different formats, necessitating conversions (World Meteorological Organization 1962). Much of the available data was never used, since the time required to code it for the computer would have delayed forecasts beyond their short useful lifetimes.

Meteorologists had always engaged in "smoothing" data (eliminating anomalous data points). Another standard practice was the interpolation of intermediate values from known ones. To feed the grids of computerized weather models, this activity became a central element of meteorological work. By the 1960s, it was being automated. The methods did not really change, but their automation required explicit, computer-programmable theories of error, anomaly, and interpolation. The effect was simultaneously to render this data "massage" invisible (Filippov 1969).

By the early 1960s, atmospheric scientists realized that the core issue of their discipline had been turned on its head by the computer. In the very recent past, through the data networks built for World War II, they had acquired far more data than they could ever hope to use. But now, already, they did not have enough of it—at least not in the right formats (standard, computer processable), from the right places (uniform grid points), and at the right times (on the uniform time steps used by the models). The computer, which had created the possibility of NWP, now also became a tool for refining, correcting, and shaping data to fit the models' needs.

Global Data Networks and Anthropogenic Climate Change

The International Geophysical Year (IGY), a UN-sponsored program of global cooperative experiments to learn about the earth's physical systems, including the atmosphere and the oceans (see Miller, chapter 6, this volume), began in 1957. As it opened, the theory of carbon dioxide–induced global warming was finding renewed scientific attention. Suess had already concluded that fossil fuel combustion was producing so much carbon that some of it remained in the atmosphere, causing a continual rise in the atmospheric concentration of carbon dioxide (Suess 1953). Plass aroused new interest in carbon dioxide as a factor in climate change (Plass 1956).

Suess and Revelle predicted that fossil fuels might soon induce rapid changes in world climate. They wrote, in 1957, that humanity was conducting, unawares, "a great geophysical experiment" on the Earth's climate (Revelle and Suess 1957). To track the "experiment's" progress, Revelle proposed a monitoring station for atmospheric CO_2 at Mauna Loa, Hawaii, as part of the IGY. The Mauna Loa station, along with another station in Antarctica, has since documented a steady annual rise in the atmospheric concentration of CO_2, due primarily to human activities.

The IGY's meteorological component focused most of its attention on the global general circulation problem. Three pole-to-pole chains of atmospheric observing stations were established along the meridians 10°E (Europe/Africa), 70°–80°W (the Americas), and 140°W (Japan/Australia). Dividing the globe roughly into thirds, these stations coordinated their observations to collect data simultaneously on specially designated "Regular World Days" and "World Meteorological Intervals." An atmospheric rocketry program retrieved information from very high altitudes. Data from all aspects of the IGY were deposited at three World Data Centres, major repositories of climatological information to this day (Comité Spécial de l'Année Géophysique Internationale 1958; Jones 1959).

The IGY efforts represent the first global data networks conceived on a scale to match the developing atmospheric models (see Miller, chapter 6, this volume). Nevertheless, even these covered the Southern Hemisphere only sparsely. They marked the start of a trend toward global programs such as the World Weather Watch (WWW) and the Global Atmospheric Research Program (GARP). WWW, coordinated by the WMO, eventually linked global data collection from satellites, rockets, buoys, radiosondes, and commercial aircraft as well as conventional observing stations. This was necessary, according to one participant, because "currently conventional methods . . . will never be sufficient if the state of the atmosphere over the whole globe is to be observed at reasonable cost with the time and space resolution which can be used with advantage in computer-assisted research and forecasting" (Robinson 1967, 410). GARP's roots lay in a 1961 U.S. proposal for "further co-operative efforts between all nations in weather prediction and eventually in weather control," backed by President John F. Kennedy (Robinson 1967, 409). Among GARP's chief organizers was Joseph Smagorinsky, founder of GFDL and builder of the first primitive-equation GCM. With the participation of scientists from the United States, the Soviet Union, and many other nations, GARP eventually sponsored a series of regional and global observations and experiments. At the height of the Cold War, the IGY and these successors marked a new era of international cooperation in meteorology.

Despite the interesting links between climate change concerns, the IGY, and the construction of global digital data networks, the concrete issue of climate change had little, if any, effect on data networks until the 1970s. Instead, the early impetus came from the desire of both weather forecasters and theoretical meteorologists to achieve better coverage of the globe. The former were motivated by practical concerns of forecasting. But the latter hoped to achieve a grander goal: modeling the detailed dynamics of the global atmosphere.

By 1969, the WMO had called for extending the global atmospheric data network to monitor pollutants that might change the climate, such as CO_2 and particulate aerosols. Anthropogenic climate change began to become a public policy issue within the U.S. government (and, soon afterward, in some other industrialized nations; see the seven country studies in Edwards and Miller, forthcoming). However, it was almost two decades before global warming became a genuine public concern at the level of mass politics. Meanwhile, attempts continued to build models capable of "realistically" representing the global climate, and to construct data sets accurate enough to distinguish "signals" of long-term climatic change from the "noise" of natural climatic variation. These goals were tightly intertwined. Without global data sets, modelers could neither validate nor parameterize their models. Without computers and satellites, uniformly gridded global data sets could not even be created, much less manipulated. Without NWP models and GCMs, these data could not be understood.

The UN Conference on the Human Environment, held in Stockholm in 1972, approved plans for an extended global data network "with little discussion" (Hart and Victor 1993). During the rest of the 1970s, increasingly sophisticated data collection and processing networks developed in tandem with GCMs and weather models at NCAR, ECMWF, the U.S. National Meteorological Center, and numerous other locations (virtually all in the industrialized world).

Models and Global Atmospheric Politics Scientific concerns about climate change allowed climate science to ride the 1970s political wave of environmentalism. By no means was this a cynical attempt at self-promotion; for many, it represented genuine alarm aroused by significant scientific results. Nevertheless, these worries provided practical reasons for accelerating expensive research programs. But in the 1970s, the immaturity of climate science and climate models made consensus on anthropogenic global warming impossible. Climate theorists did not agree on the relative roles of such factors as solar variability, sunspots, and cloud feedbacks in climate change; global *cooling*, some argued, was also a possibility (Edwards and Lahsen, forthcoming). Chaotic qualities of the climate system added to the uncertainty over model results.

Nevertheless, by the late 1970s climate change had begun to generate an ever-broadening circle of scientific and policy concerns. At the First World Climate Conference in 1979, WMO scientists established the World Climate Programme to coordinate and develop climate research and climate data. The "nuclear winter" issue of the early 1980s and the Antarctic "ozone hole" discovered in 1986 were the first events to elevate the general issue of anthropogenic atmospheric change to the level of front-page news (Edwards and Lahsen, forthcoming; Morrisette 1989; Schneider 1989). Both issues created an awareness that human actions were capable of causing sudden, potentially catastrophic changes in the atmosphere not just regionally, but on a global scale. The Cold War fizzled to a close, leaving a sort of "apocalypse gap" in popular political consciousness, which was readily filled by global warming scenarios. As the basis of key scientific results, computer models played substantial—even decisive—roles in the nuclear winter and ozone depletion issues as well as in climate change.

In 1985, at Villach, Austria, an influential climate-science conference recommended policy studies of climate change mitigation techniques, including international treaties. Ozone depletion concerns resulted in a near-comprehensive international ban on chlorofluorocarbons, completed in 1990 after just five years of negotiation. In 1988, the WMO and the UN Environment Program formed the Intergovernmental Panel on Climate Change (IPCC). The group, consisting of experts on climate, ecology, and environmental and social impacts from around the world, was asked to serve as the scientific adviser for international climate negotiations. In 1990 the organization released its first report, designed as input to the Second World Climate Conference held later that year. The report noted a qualified consensus on two points. First, greenhouse gas concentrations were rising rapidly due to human activities. Second, if this trend continued, global average temperatures were likely to rise somewhere between 1.5° and 4°C by about 2050 AD.

The IPCC played a crucial role in the 1992 UN Conference on Environment and Development (UNCED). The UNCED produced the landmark FCCC. Signed by 165 nations, the Framework Convention entered into force in early 1994. It sets voluntary goals for stabilizing greenhouse gas emissions. More important, the FCCC requires signatories to prepare national greenhouse gas emission inventories and commits them to ongoing negotiations toward an international treaty on climate change (Bodansky 1993). The IPCC continues to provide scientific input to the periodic Conferences of Parties to the FCCC. An era of global atmospheric politics had dawned, with computer models at its very core (Bodansky 1994; Donoghue 1994).

Associated with the political arrival of the climate change issue was a trend toward ever more comprehensive global models, from two directions. The first, *Earth system* or *Earth systems* models (ESMs), was a direct extension of natural-science efforts to couple oceanic and atmospheric general circulation models. The goal is to couple models of other climate-related systems (land surface, sea ice, and so on) to an

OAGCM, eventually capturing all of the major elements of the total climate system—including anthropogenic effects such as agriculture and artificial greenhouse gas release (Schneider 1994; Trenberth 1992; Turner, Moss, and Skole 1993). In general, sophisticated models of human socioeconomic activities have been last in line for integration into ESMs, which focus most of their effort on natural systems. Most of these models descend from existing GCM efforts. The second type, *integrated assessment models* (IAMs), aims to simulate the impacts of climate change on human society, and the costs and benefits of possible mitigations (Alcamo 1994; Dowlatabadi and Morgan 1993; Hope 1993; Rotmans 1990, 1992). IAMs typically do not incorporate GCMs directly. Instead, they rely either on selected and aggregated GCM outputs or on much simpler energy-balance climate models. Their purpose is to allow rough, rapid analysis of the possible effects of various politicoeconomic scenarios on climate change. IAM developers generally spend much more of their energy than climate system modelers do on the social, political, and economic elements of their models, relying for the natural-systems side on outputs from other efforts based in the natural sciences.

IAMs incorporate empirically derived trends, heuristics, and unproven or qualitative theories into their modeling techniques far more freely than do climate and Earth system models. Their goal is comparison of policy scenarios and forecasting of trends, not prediction at statistically significant levels; this is the point of the term *assessment*. Not all IAM outputs are global in scope—for example, the first IMAGE model focused primarily on the Netherlands (Rotmans 1990). Many IAM builders hope that their models—unlike the hypercomplex, supercomputer-based ESMs—will be simple, transparent, and portable enough that policymakers, or perhaps their staffers or administrative agencies, can engage with the models directly. If so, they could observe for themselves, on a desktop computer, the differential effects of various politicoeconomic scenarios, such as carbon taxes, population stabilization, or reforestation efforts, on global change. The idea is to offer policymakers an effective way to learn a set of *heuristics*—a quasi-intuitive "feel" or rule of thumb based on, yet not fully determined by, data-driven analysis—for global change policy options. Table 2.1 compares a first-generation

Table 2.1
Comparison of the GENESIS Earth system model and the IMAGE integrated assessment model

GENESIS	IMAGE
• Origin: previous NCAR climate models	• Origin: Ph.D. thesis
• Orientation: natural/physical science	• Orientation: policy analysis tool
• Based on sophisticated, high-resolution atmospheric GCM; other models added later	• Simple, one- or two-dimensional atmospheric models; modular; built as integrated unit
• Parameterization: moderate, relatively model-specific	• Parameterization: extreme, literature-based
• Approach to terrestrial biosphere: potential vegetation, to be modified later by agriculture model	• Approach to terrestrial biosphere: actual land use; mosaic of natural and human-altered landscapes
• Typical experiments: regional climate change due to CO_2 doubling; paleoclimate	• Typical experiments: impacts of IPCC scenarios on Dutch coastal defenses; emissions scenarios
• Technology: supercomputers	• Technology: PCs
• Architecture: partially modular, model-specific, but publicly available and user-manipulable within limits	• Architecture: highly modular, open, links easily with other models, user-manipulable
• Institutional context: Interdisciplinary Climate Systems Group, Climate and Global Dynamics Division, NCAR, USA	• Institutional context: National Institute for Public Health and Environmental Protection (RIVM), Netherlands
• Audience/accessibility: climate science community	• Audience/accessibility: climate science community, terrestrial ecosystems community, policymakers, educators
• Funding: EPA; NSF	• Funding: RIVM, European Economic Community

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Earth system model (GENESIS) with a first-generation integrated assessment model (IMAGE).

ESMs and IAMs have become focal points in a relatively new, very broad effort to integrate results and methods from many different sciences. Social, behavioral, economic, and policy sciences are part of this mix, albeit more so in IAMs than in ESMs. Doing this kind of modeling means that each discipline—often extending to members of policy communities, such as regulatory agencies—must ultimately embody its data and principles in computer code that can "talk" to the model's other modules (i.e., perform "intermodel handoffs"). Thus IAMs and ESMs are increasingly the foci of an emerging *epistemic community*.

This is Peter Haas's term for a knowledge-based professional group that shares a set of beliefs about cause-and-effect relationships and a set of practices for testing and confirming them. Crucially, an epistemic community also shares a set of values and an interpretive framework; these guide the group in drawing policy conclusions from their knowledge. Its ability to stake an authoritative claim to knowledge is what gives an epistemic community its power (Haas 1990a, 55–63; 1990b). In the arena of global-change science, where wholly empirical methods are infeasible, computer modeling has become *the* central practice for evaluating truth claims. It lies at the center of the epistemic community of global change science. Other, roughly equivalent ways of describing the fundamental role of models in climate science/policy communities would be as supports for climate-change discourse (Edwards 1996a) and as boundary objects in a knowledge exchange system (Star and Griesemer 1989).

Whether or not they are ever used directly by policymakers, ESMs and IAMs in fact contribute substantially to the basis of global change politics, in the important sense that they serve as a central organizing principle for a large, growing, epistemologically coherent community. This community shares the crucial belief that *global* natural systems may be significantly affected by human activities—a belief to which few would have subscribed three decades ago. It also, in general, shares the values that such systems are worth preserving and that rational political decision making can be achieved, at least to some degree, which could preserve them (Jasanoff and Wynne 1998). Integrated model building contributes directly to this base of common assumptions, to a scientific macroparadigm that accepts computer simulation as a substitute for (infeasible) traditional forms of experimentation, and to a network of individuals, laboratories, and institutions such as the U.S. Global Change Research Program and the IPCC. The models help to create a public space, including shared knowledge, shared values, and access to common tools and data, for consensus building on global change issues. In this very important, entirely nonpejorative sense, comprehensive model building—as the core representation of the global atmosphere—is simultaneously scientific and political (Edwards 1996b; Jasanoff 1990).

Techniques and Problems of "Global" Representation

As climate change became a major public issue in the last decade, an acrimonious debate about the relationship between models and data moved from the scientific arena into the mass media. IPCC "consensus" opinion met intense opposition from a small but vocal "contrarian" group, especially in the United States. These skeptics raised many objections to models, from poor parameterization of cloud feedbacks to differences between the observed warming to date (about 0.5°C) and model calculations showing a 1°C warming for the same period (White 1990). Recently, GCMs incorporating particulate aerosol effects have aligned more closely with observations; the IPCC's most recent report states that "the balance of evidence suggests a discernible human influence on global climate" (Houghton et al. 1996, 5). But despite the appearance of scientific consensus and moves toward a binding emissions-limitation treaty at the international level, debate continues into the present, with skeptics arguing that models cannot be trusted without higher levels of observational confirmation (Edwards and Lahsen, forthcoming).

These debates are simultaneously scientific, political, and epistemological. They go to the heart of the question of what we know about the world and how we can know it. At the same time, by projecting the extent and impacts of climatic change in the future, and by locating it in data about the past, they set the stage for policy choices. In this section, I explore some of the epistemological issues behind these debates. While I will focus on GCMs, my conclusions apply equally to ESMs, IAMs, and other kinds of models as well. The surprising upshot

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of this discussion is that *all* important knowledge and choice about climate change depends fundamentally on modeling.

Model Resolution and the Computational Bottleneck

GCMs recompute the state of the entire atmosphere every fifteen to thirty simulated minutes. This process is extremely computationally intensive. At each time step, hundreds to thousands of complex calculations must be performed on each of the tens of thousands of grid boxes. This consumes vast quantities of supercomputer time; a typical state-of-the-art GCM currently requires tens to hundreds of hours for a full-length "run" of twenty to a hundred simulated years. In principle, climate modelers could achieve far better results with high-resolution NWP models. But the number of model calculations increases exponentially with higher resolutions. This creates a computational bottleneck, forcing GCM builders to make trade-offs between a model's resolution and its complexity.

"Complexity" here refers to two related things: the number of phenomena simulated, and the level of detail at which they are modeled. Existing models do not directly simulate a vast number of basic atmospheric events. The most important of these is the formation of clouds, which form typically on scales of a few kilometers or less. Clouds are believed to play many key roles in climate, such as trapping heat at night or reflecting it back into space during the day. These phenomena are notoriously difficult to study empirically, and their role in climate remains controversial. Clouds are not yet perfectly modeled even with NWP techniques. Other phenomena not well captured at GCM resolutions are the activity of the planetary boundary layer (the layer of air nearest the earth's surface) and many factors relating to the land surface, such as its roughness and elevation. (For example, many current models represent the entire region between the Sierra Nevada range in California and the Rocky Mountains as a single plateau of uniform elevation.)

Their low resolution is one reason for the high levels of uncertainty surrounding climate models. Techniques for getting the most out of these low-resolution models have improved them, but have also been intensely controversial. The next section reviews some of these techniques and the associated problems and controversies.

Parameterization and Tuning

Most of the major issues in climate modeling stem from the problem of scale described above. All sub-grid-scale processes must be represented parametrically, or *parameterized.* For example, rather than represent cloud formation in terms of convection columns, cloud condensation nuclei, and other direct causes, a GCM typically calculates the amount of cloud cover within a grid box as some function of temperature and humidity. This approach embodies what is known as the *closure assumption.* This is the postulate that small-scale processes can ultimately be represented accurately *in terms of the large-scale variables available to the models.*

Parameterization is controversial, and its effects on the activity of models are not entirely encouraging (Shackley et al. 1998). For example, some cloud parameterization schemes in early GCMs resulted in cloud "blinking," an oscillation between the presence and absence of cloud cover in a given grid box at each time step when certain variables happened to be just at the critical threshold. Real clouds do not, of course, behave like this. The question is whether and how unrealistic behavior of this sort in one element of the model affects the quality of overall model results.

Another example of a parameterized function is atmospheric absorption of solar radiation, the energy driver for the entire climate system. Atmospheric molecules absorb solar energy at particular frequencies known as spectrographic "lines."

> The contribution of each narrow absorption line must be accounted for to model the transfer of radiation.... There are tens of thousands of such lines arising from all the absorbing gases in the atmosphere. Thus, to include all lines in a parameter of absorption would require an explicit summing over all lines at each model level and horizontal location. These types of calculations can be performed on present day supercomputers and are called line-by-line models. (Kiehl 1992, 338)

But such modeling is too computationally expensive. Instead, absorption is represented in GCMs by coefficients that implicitly integrate all the absorption lines.

In an ideal model, the only fixed conditions would be the distribution and altitude of continental surfaces. All other variables, such as sea surface temperature, land surface albedo (reflectance), cloud formation, and so on would be generated internally by the model itself from the lower-level physical properties of air, water, and other basic constituents of the climate system. To say that current GCMs are far from reaching this goal is a vast understatement. Instead, "virtually all physical processes operating in the atmosphere require parameterization" in models (Kiehl 1992, 336). Generating these parameters is therefore the largest part of the modeler's work.

Climate modelers do this partly by reviewing the meteorological literature and observational data to try to determine how small-scale processes and large-scale variables might be related. When they succeed in finding such relations, they call the resulting parameters *physically based*. Often, however, they do not find direct links to large-scale physical variables. In this common case, modelers invent ad hoc schemes that provide the models with the necessary connections. For example, one method of cloud parameterization represents all the cumulus clouds in a given region as a single "bulk" cloud (Yanai, Esbensen, and Chu 1973). In addition, observed patterns exist that can be mathematically described, but whose physics are not understood. These, too, are represented in the models as parameters.

Another, very important part of modelers' work is known as *tuning* the parameters. *Tuning* means adjusting the values of coefficients and even, sometimes, reconstructing equations to produce a better overall model result. "Better" may mean that the result agrees more closely with observations, or that it more closely corresponds with the modeler's judgment about what one modeler called the *physical plausibility* of the change. In some cases parameters fit relatively well with observed data. In others—as in the case of cloud parameterizations—the connection is so uncertain that tuning is *required*. Such parameters are said to be "highly tunable." Since many parameters interact with others, tuning is a complex process. Changing a coefficient in one parameter may push the behavior of others outside an acceptable range.

Flux Adjustment

Today's most sophisticated climate models couple atmospheric general circulation models with general circulation models of the oceans. The latter operate on principles much like those of atmospheric GCMs. These "coupled" models, known as OAGCMs, must somehow provide for the exchanges or "fluxes" of heat, momentum (wind and surface resistance), and water (precipitation, evaporation) between the ocean and the atmosphere. Empirical knowledge of these fluxes is not very good, but their values have profound effects on model behavior.

Most OAGCMs include ad hoc terms, known as *flux adjustments*, that modify and correct the overall model results to bring them more closely into line with observations. Without them, the models' climates drift out of line with observed values and patterns (Meehl 1992). These adjustments are "nonphysical" model terms, in modelers' language, although they are also characterized as "empirically determined" (Houghton et al. 1995, 237, 34); they are an excellent example of "highly tunable" parameters. Recently the National Center for Atmospheric Research introduced the first OAGCM that does not require flux adjustments (Kerr 1997).

Parameterization and tuning are, in effect, scientific art forms whose connection to physical theory and observational data varies widely. As one modeler told me in a confidential interview,

> Sure, all the time you find things that you realize are ambiguous or at least arguable, and you arbitrarily change them. I've actually put in arguable things, and you do that all the time. You just can't afford to model all processes at the level of detail where there'd be no argument. So you have to parameterize, and lump in the whole result as a crude parameter.

Common Code: GCMs as a Family

One final issue about GCMs concerns their relationships with each other. Because of their complexity and expense, the total number of atmospheric GCMs is not large—probably fewer than fifty worldwide. Many of these models share a common heritage (Edwards 2000). Typically, one modeling group "borrows" another group's model and modifies it. This avoids unnecessary replication of effort, but it also means that the "new" models may retain problematic elements of those from which they were created. Several modelers told me that substantial segments of the computer code in modern GCMs remain unchanged from the original models of the 1960s. This may be one reason for the fact that some systematic errors in GCMs are common to virtually all extant models (Boer 1992; World Meteorological Organization 1991).

Data-Laden Models

Simulation models are typically described as theoretical constructs, deriving their results from equations representing physical laws (Oreskes, Shrader-Frechette, and Belitz 1994). In this conception—shared by most modelers—models use basic information about key physical variables only as a starting point (what modelers call *initial conditions*.)[4] However, as the foregoing discussion has shown, the reality of climate modeling practice is at best an approximation of this goal.

Many of the basic physical laws governing atmospheric behavior are well understood and relatively uncontroversial. Modelers call these the *primitive equations*. But the huge range of spatial and temporal scales involved—from the molecular to the global, from milliseconds to millennia—makes it impossible to build models from these principles alone. Schneider notes that

> even our most sophisticated "first principles" models contain "empirical statistical" elements within the model structure. . . . We can describe the known physical laws mathematically, at least in principle. In practice, however, solving these equations in full, explicit detail is impossible. First, the possible scales of motion in the atmospheric and oceanic components range from the submolecular to the global. Second are the interactions of energy transfers among the different scales of motion. Finally, many scales of disturbance are inherently unstable; small disturbances, for example, grow rapidly in size if conditions are favorable. (Schneider 1992, 19)

Hence the necessity of parameterization, much of which can be described as the integration of observationally derived approximations or heuristics into the model core. Schneider sometimes refers to parameters as "semiempirical," an intriguingly vague description that highlights their fuzzy relationship with observational data. For the foreseeable future, all GCMs will contain many of these "semiempirical" values and equations. Thus we might say that GCMs are *data-laden*.

I use this phrase symmetrically with the well-known observation that data are "theory-laden" (Hanson 1958; Popper [1934] 1959). In one sense there is nothing odd about this, since theory in the physical sciences always includes constants (such as the gravitational constant or the sun's energy output) derived from empirical measurements. However, physical-science practice normally attempts to explain large-scale phenomena as an outcome of smaller-scale processes. The "data-ladenness" I describe here refers to the inclusion of large-scale, empirical statistical data in models, which necessarily goes against the reductionist imperative of the physical sciences.

Model-Filtered Data

Global climatological data sets are deeply problematic.

Some of the reasons are obvious. Many kinds of measurements, from many different instruments, are necessary to make up a data set that covers the entire global atmosphere in three dimensions and over many years. These measurements are taken under a vast variety of conditions, which differ for reasons that are not only physical (e.g., Antarctic vs. temperate zones), but social (differing levels of understanding, technical skill, and experience in different countries) and historical (changes in techniques, instrumentation, and so on over time).

Fairly good records of land and sea surface meteorology exist for the last hundred years, but changes over time in instrument quality, location, number, and measurement techniques create many uncertainties. For example, most thermometers are located on land and clustered in urban regions, where "heat island" effects raise local temperatures above the regional average. Meteorological records at sea tend to be drawn from shipping lanes, ignoring the globe's less traveled areas. For the last several decades, records from the atmosphere above the surface have been drawn from increasingly extensive commercial aircraft, radiosonde (weather balloon), and rawinsonde (radar-tracked radiosonde) networks, but these too are concentrated in particular areas. Coverage in the tropics and in the Southern Hemisphere is particularly poor. Heroic efforts continue to purify these data by estimating and correcting for systematic errors (Houghton et al. 1996, 133–192). For example, satellite data are being used to estimate the effects of urban heat island bias on global surface temperature data (Johnson et al. 1994); historical sea surface temperatures have been corrected for the effects of different kinds of buckets used to draw water samples (Folland and Parker 1995); and problems with rawinsonde data are being addressed by comparisons with satellite data and corrections for various sampling errors (Parker and Cox 1995).

Among the chief tools of this data-filtering process are what we might call *intermediate models*. These include models of instrument behavior, interpolation techniques (for converting actual observations into gridded data), techniques for automatic rejection of anomalous data points, and many other methods (Christy, Spencer, and McNider 1995; Hurrell and Trenberth 1997; Jenne 1998; Karl, Knight, and Christy 1994). Recently, a number of laboratories have used computer models to produce "reanalyses" that attempt to calibrate, correlate, and smooth data from multiple sources into long-term, internally consistent global climatological data (ECMWF Re-Analysis Project 1995; NASA Goddard Space Flight Center 1998; National Oceanic and Atmospheric Administration 1999).

Satellites and Global Data Sets Unlike all others, satellite data have the signal advantage of being genuinely global in scope. Weather satellites overfly the entire globe at least twice every day. This total coverage makes satellite data extremely attractive to climate modelers. "We don't care about a beautiful data set from just one point," one modeler told me. "It's not much use to us. We have one person whose almost entire job is taking satellite data sets and putting them into files that it's easy for us to compare our stuff to."

Yet satellite data are also problematic. Satellites provide only proxy measurements of temperature; these may be distorted by optical effects. In addition, their lifespans are short (two to five years) and their instruments may drift out of calibration over time. A number of scientists, including one responsible for satellite data analysis at a major climate modeling group, told me that the quality of these data was not very good. One said that their main practical value has been for television weather images. Nevertheless, the satellite data are generally regarded as the most reliable global observational record.

Here too, the solution to problems in these data is a suite of intermediate models. Statistical models filter out "signals" from noise; models of atmospheric structure and chemistry are used to disaggregate radiances detected at the top of the atmosphere into their sources in the various atmospheric layers and chemical constituents below. In addition, models are used to "grid" the data and to combine them with other data sources. Among the most important data sources are the twice-daily atmospheric analyses of the U.S. National Meteorological Center and the European Centre for Medium-Range Weather Forecasting. These atmospheric analyses "incorporate observational data from both the surface and from satellites into a 4-D data assimilation system that uses a numerical weather prediction model to carry forward information from previous analyses, giving global uniformly gridded data" (Kiehl 1992, 367–368). Thus the twice-daily periods of actual observation are transformed into twenty-four-hour data sets *by computer models.*[5]

Conclusion: Modeling as World Building

The model-data relationship in climate science is thus exceptionally complex. Models contain "semiempirical" parameters, or heuristic principles derived from observations. Meanwhile, global data sets are derived from direct observations by modeling. Since the problems of scale that create this situation are present in all global dynamic processes, the same could be said of all world-scale models. These facts about data and models have a number of important but rarely noticed consequences for climate change concerns.

First, it is *models*, rather than data, that are global. They make inaccurate, incomplete, inconsistent, poorly calibrated, and temporally brief data *function as* global by correcting, interpolating, completing, and gridding them. The sheer size of global data sets makes it unlikely that much could be learned from them without the computer models that make them comprehensible. Furthermore, global uniformly gridded data would never have been generated in the first place without the models that required data in that form. The dynamics of the earth's atmosphere could not be understood without them—at least not at a level of detail that would confer the ability to make long-term projections.

Second, the structure of knowledge about the past (data) and knowledge about the future (model projections) exhibits a surprising symmetry in the climate change field. Models, often the same ones used for future projections, are required to produce global data in the first place (Suppes, 1962, called these *models of data*). The youth of the climate field means that data sets remain in flux, not only because new data are acquired but because intermediate models continue to evolve. Yet detecting climatic change in the historical record depends on comparing a present state against a past baseline—which in this case remains a moving target. Because detection requires a long historical record, there is no alternative other than model-based reanalysis. Forecasts of future climate change rely on comparisons with the same (shifting) baseline.

Third, even if the historical record were absolutely firm, so that future trends could be projected "directly" from the data, forecasts of climatic change would still necessarily rely on modeling. This is the case because in a highly complex system with multiple feedbacks, there is no a priori reason to suppose that any given historical trend will continue on the same path. In effect, extrapolating directly from data trends would itself be a model of atmospheric behavior—but one without any basis in physical theory. The point here is that without *some* model of atmospheric behavior—even this primitive and almost certainly false one—the exact shape of the curve of global climate change could not be projected at all.

Fourth, modeling is necessary to separate human from natural contributions to climate change. For example, major volcanic eruptions, such as those of El Chichón (1982) and Mount Pinatubo (1991), can inject vast quantities of particulate aerosols into the stratosphere, causing cooling near the surface and warming in the stratosphere that can last several years. To understand the human role in global climate change, the effects of these and other natural events must be extracted from the global data. This can only be done through modeling.

Finally, *models offer the only practical way to discern the effects of policy choices about climate change.* As a thought experiment, imagine that a strong, comprehensive climate change policy (regulating, say, not only greenhouse gas emissions and energy efficiency, but agriculture, forestry, population, and economic development) were somehow instituted tomorrow and continued for fifty years. At the end of that time, how would we measure its success or failure? The only way to do so would be to compare the historical record with models of what would have happened had the policy never been introduced. This point is important, since it indicates one potential role for models that has rarely been highlighted.

For all these reasons, computer models are, and will remain, the historical, social, and epistemic core of the climate science/policy community. Without them, we would know little if anything about the causes and possible future consequences of climate change. At least as importantly, from a science-studies viewpoint, the global epistemic community that now surrounds the climate change issue would have lacked a fundamental organizing principle.

As I have shown, this point has sociological and historical ramifications as well as epistemological ones. Climate science communities developed around the practice of computer modeling. By its nature—resource-intensive "big science"—this practice limited the number of expert groups and focused them on a common strategy of "parameterization" and model-based experimentation. With the growth of computer power and the expansion of political interest in (and funding for) climate science, especially in the last decade, related sciences began to cluster around the models, using them as a common language for scientific integration. At the same time, policy communities came to depend on (and at least in part to trust) models for advice. Thus global modeling does not merely represent, but in a social and semiotic sense *constructs*, the global atmosphere.

Notes

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1. Zero-dimensional models compute energy balances as if the earth were a single point in space rather than a volume. One-dimensional models usually compute according to latitudinal bands (without vertical depth). Two-dimensional models add either longitude (horizontal east-west) or air pressure (vertical) dimensions to produce a grid (horizontal or vertical). Three-dimensional models extend the grid either longitudinally or vertically to produce a gridded volume.

2. The designation *three-dimensional* is slightly misleading. Most GCMs are really four-dimensional, the fourth dimension being time.

3. The most popular modern modeling technique, the spectral transform method, does not use grids in this simple Cartesian sense. Spectral models represent the atmosphere as a series of interacting waves. They are mathematically complex and difficult to grasp intuitively, but for my purposes here, this simple description is adequate.

4. This sense of the term applies mainly to *mathematical* models; it is worth pointing out that this is not the only important sense of the term. Analog models, in which one physical system is used to model another (by "analogy"), may be largely nontheoretical. Early experiments in climate modeling sometimes used analog models, such as dishpans (representing the earth) filled with fluids (representing the atmosphere) rotating above a heat source (representing the sun) (Hide 1953). Today, analog models have virtually disappeared from the field, although one might argue that climate studies of other planets serve a similar purpose.

5. Long-term, contemporary data sets are not the only ones against which to test climate models. The seasonal cycle provides a well-known, reasonably well-understood benchmark. Paleoclimatic (prehistoric) data from a variety of "proxy" sources, such as tree rings, ice cores, and fossilized pollen, are also available. Model inputs can be set to the different conditions (orbital precession, trace gas concentration, and so on) of past periods and evaluated by how well they simulate the paleoclimatic record. Naturally, the level of detail in paleoclimatic data is far lower than in contemporary instrumental observations.