

A Vast Machine

Computer Models, Climate Data, and the Politics of Global Warming

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**The MIT Press
Cambridge, Massachusetts
London, England**

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Set in Stone by Toppan Best-set Premedia Limited. Printed and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data

Edwards, Paul N.

A vast machine : computer models, climate data, and the politics of global warming / Paul N. Edwards.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-262-01392-5 (hardcover : alk. paper)

1. Weather forecasting. 2. Climatology—History. 3. Meteorology—History. 4. Climatology—Technological innovation. 5. Global temperature changes.

I. Title.

QC995.E296 2010

551.63—dc22

2009030678

10 9 8 7 6 5 4 3 2 1

Introduction

Unless you have been in a coma since 1988, you have certainly heard or read a story that goes something like this: Global warming is a myth. It's all model predictions, nothing but simulations. Before you believe it, wait for real data. "The climate-studies people always tend to overestimate their models," the physicist Freeman Dyson told an interviewer in April 2009. "They forget they are only models."¹ In the countless political controversies over climate change, the debate often shakes out into a contest: models versus data.

This supposed contest is at best an illusion, at worst a deliberate deception—because *without models, there are no data*. I'm not talking about the difference between "raw" and "cooked" data. I mean this literally. Today, no collection of signals or observations—even from satellites, which can "see" the whole planet—becomes global in time and space without first passing through a series of data models.

Since both observing systems and data models evolve, global data also change. We have not one data image of the global climate, but many. The past, or rather what we can know about the past, changes. And it will keep right on changing. I call this reverberation of data images "shimmering." Global data images have proliferated, yet they have also converged. They shimmer around a central line, a trend that tells us that Earth has already warmed by about 0.75°C (1.35°F) since 1900.

Nor is there any such thing as a pure climate simulation. Yes, we get a lot of knowledge from simulation models. But this book will show you that the models we use to project the future of climate are *not* pure theories, ungrounded in observation. Instead, they are filled with data—data that bind the models to measurable realities. Does that guarantee that the models are correct? Of course not. There is still a lot wrong with climate models, and many of the problems may never be solved. But the idea that you can avoid those problems by waiting for (model-independent) data

and the idea that climate models are fantasies untethered from atmospheric reality are utterly, completely wrong. *Everything we know about the world's climate—past, present, and future—we know through models.*

This book is a history of how scientists learned to understand the atmosphere, measure it, trace its past, and model its future. It isn't a work of advocacy. I am not going to try to convince you, as a scientist or an activist might, that climate change is real. Still, you will want me to lay my cards on the table, and it would be irresponsible of me not to do that. Yes, I think climate change is real, and I think it's the biggest threat the world faces now and will face for generations to come. Yet what I think about it is completely beside the point. Climate change is not a matter of opinion, belief, or ideology. This book is about how we came to know what we know about climate—how we make climate knowledge.

In the rest of this introduction, I will offer three avenues into this book. First, I will give a short summary of my argument, a quick preview of a very long movie. Next, I will give an idea about how to frame the argument in larger terms. (Think of 'frame' as a verb, not a noun; think of aiming a movie camera and choosing your focus, where you center the scene, and what you leave out of it.) Finally—after some caveats about what might surprise or disappoint you here—I will suggest several different ways to read this book, depending on who you are, what you already know, and what you might want to find out.

Climate Science as a Global Knowledge Infrastructure

Here is my argument, as briefly as I can make it: Climate is the history of weather—the average state of the atmosphere over periods of years, decades, centuries, and more. You can learn about climate in two ways. First, you can collect records from the past. We have sporadic instrument readings from the surface starting in the seventeenth century, systematic ones from the 1850s on, and good records from the air above the surface, obtained mainly from weather balloons and satellites, starting in the 1950s.² This book traces the history of efforts to gather weather and climate records for the whole planet. I call this *making global data*, and I call the effort it involves *data friction*. Second, you can try to understand climate as a physical system. If you succeed, not only can you explain how it works; you can also determine why it changes. And you can predict how it may change in the future. Understanding and predicting the climate is very difficult. In fact, it's one of the hardest challenges science has ever tackled, because it involves many interlocking systems, including the atmosphere, the

oceans, the cryosphere (ice and snow), land surfaces (soil, reflectance), and the biosphere (ecosystems, agriculture, etc.). You can't study global systems experimentally; they are too huge and complex. Instead, as I will show you, everything we know about the global climate depends on three types of computer models.

Simulation models are based on physical theory. Even after atmospheric physics became adequate to the task early in the twentieth century, *computational friction* prevented serious attempts to simulate weather or climate mathematically. By the late 1940s, with electronic digital computers, this began to change. Weather forecasters built numerical models to calculate the atmosphere's large-scale motions and predict the weather. Climate scientists then used similar techniques to simulate the global climate for long periods (years to decades). By changing the simulated forces and conditions, they also used models to predict how climate will change as human activity alters the composition of the atmosphere and other climate-related systems.

Reanalysis models come from weather forecasting. These models also simulate the weather, but unlike pure simulations they constrain their results with actual weather observations. Essentially, they produce a movie-like series of global weather forecasts, blending observations with simulation outputs to produce fully global, uniform data. Climate statistics derived from reanalysis cover the whole planet at all altitudes, unlike data from instruments alone. Since 1990, reanalysis of weather records has created a new source of global climate data.

What I call *data analysis models* (or *data models*, for short) are really a vast family of mathematical techniques, algorithms, and empirically derived adjustments to instrument readings.³ Philosophers of science use the phrase "models of data"; practicing scientists might say "data analysis." Data analysis models are used to process historical weather and climate records. Observing systems have changed so much and so often that you can only combine long-term records by modeling the effects of different instrument behaviors, data collection practices, weather station site changes, and hundreds of other factors. You also need models to adjust for the tremendous unevenness of observations in space and time. In this process, which I call *making data global*, coherent global data images are created from highly heterogeneous, time-varying observations.

The last part of my brief preview concerns the idea of a *climate knowledge infrastructure*. Systems for observing weather and climate originated in the nineteenth century, for the most part as national weather services. These developed as separate systems, but soon they linked their data

reporting through loosely coordinated international networks. The manual forecasting methods of that era focused mainly on regions rather than the whole world. Because processing them by hand would have taken far too long, such methods were not able to use vast quantities of data. When computerized weather forecasting arrived, in the mid 1950s, it required much more data—and soon it would require data from the whole planet. By the early 1960s, those needs, combined with the spur of Cold War politics and the lure of satellite technology, led to the World Weather Watch, an internetwork or web that combined numerous systems and networks into a functional system of global observing, telecommunication, data processing, and forecasting. This pattern of development—from systems to networks to webs—is visible in the histories of most large-scale infrastructures.

Weather forecasting and climatology diverged in the nineteenth century, developing different traditions and even different data sources. In the 1960s, climate modeling began to reunite the two fields. Here too, modeling shifted scientists' focus to the global scale. As in forecasting, existing data systems proved inadequate. One deficiency was the lack of data from the atmosphere above the ground, well sampled by weather balloons only after the late 1950s. Another problem, more complex, was the spotty, inconsistent, and poorly standardized record from surface stations. Investigators now had to make these data global. A long and painful process of *infrastructural inversion* began in the 1970s. Scientists turned the climate record upside down, reexamining every element of the observing system's history, often down to the level of individual measurements. Then, trying to reconstruct a history of the atmosphere, they digitized, interpolated, and processed those elements in many other ways.

Modeling outpaced empirically based knowledge of the global climate. By the 1970s, laboratories specializing in climate modeling had sprung up around the world, and climate models had gained a foothold in energy and environmental policy. As concerns about global warming mounted during the 1980s, scientists and policy makers institutionalized a knowledge-assessment process in the Intergovernmental Panel on Climate Change (IPCC). This process represents the most visible layer of the climate knowledge infrastructure.

Like most true infrastructures, the climate knowledge infrastructure is made up of many interlocking technical systems representing many links and layers of systems and structure, most of which long predate the

IPCC. The assessment process—now in the midst of its fifth cycle since 1990—has created imperatives, structures, and processes that link a vast array of knowledge producers and bring their disparate methods and products to bear on a common project. The assessments compare, combine, and interpret data and models to produce stable, reliable, widely shared knowledge about the global climate. This doesn't mean that controversies are suppressed; in fact, quite the opposite is true. The IPCC *brings controversy within consensus*, capturing the full range of expert opinion.

Climate knowledge is knowledge about the past. It's a form of history—the history of weather—and the infrastructure that creates climate knowledge works in the same way that historians work. What keeps historians in business? Why do they keep on writing new accounts of, say, the French Revolution or the Second World War? Don't we already know everything about those events? In fact we don't. There is always more to learn about the past. Historians continually discover previously unknown documents, letters, drawings, photographs, artifacts, and other kinds of evidence that reveal new aspects even of history's best-known episodes. On top of that, our perspective on the past keeps changing, for many reasons. We argue about how to interpret the evidence, finding flaws in earlier interpretations. And *we* keep changing. What we want to know about the past, what we hope to discover there, depends on who we are now.

Climate knowledge is like this too. People long ago observed climate and weather for their own reasons, within the knowledge frameworks of their times. You would like to use what they observed—not as they used it, but in new ways, with more precise, more powerful tools. How accurate were their measurements? Did they contain systematic errors? The numbers don't speak for themselves. So you dig into the history of data. You fight *metadata friction*, the difficulty of recovering contextual knowledge about old records. If you succeed, you find (perhaps) changes in station siting, faked logbooks, changes in instrumentation, misapplied standards, or a thousand other things that alter your understanding of the numbers in the records. Perhaps you come across a slightly different version of existing records, or a cache of previously unknown ones. You find flaws in previous interpretations of old data sets; perhaps you find new ways to correct them. You build new tools, gain new perspectives, and discover what you still don't know. And afterward, other investigators may follow in your path, discovering yet more about the past and altering your interpretation. In the words of T. S. Eliot,

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

The climate knowledge infrastructure is constantly opening itself up, reexamining every datum and data set, reanalyzing its data, adding to its metadata. Over time, countless iterations of that process have brought us shimmering data, an ever-expanding collection of global data images that will keep on growing, but never resolve into a single definitive record.

Yet these countless versions of the atmosphere's history have also converged. Could it be that one day some grossly different data image will emerge, in which the planet did not really warm across the period of historical records, or human activity played no significant role in climate change? Sure, it's possible; in science, never say never. But the chances of such a thing happening today are vanishingly small. We have a lot left to learn, but to the extent that anything so complex can ever be known, we know this. The infrastructure that supports climate knowledge is too large, too old, and too well developed.

Where are the politics in all this? Everywhere. A final thread that runs throughout this book is the idea of *infrastructural globalism*. In the context of meteorology, this refers to how the building of technical systems for gathering global data helped to create global institutions and ways of thinking globally. Building global observing systems required creating global intergovernmental organizations, such as the World Meteorological Organization and the Intergovernmental Panel on Climate Change. The Cold War, decolonization, and other aspects of international and world politics shaped the methods and practices of data collection, especially satellite systems.

As global warming rose to the top of the world's political agenda, the climate knowledge infrastructure itself became an object of intense political debates. Sides in these debates often saw the issue as one of models versus data. In the mid 1990s, environmental conservatives and climate-change skeptics promoted the idea that "sound science" must mean "incontrovertible proof by observational data," whereas models were inherently untrustworthy. But in global climate science, at least, this is a false dichotomy. The simplistic "models vs. data" debate lingers on, but in recent years it has been largely replaced by more sophisticated approaches. Amateur scientists and others dig deeply into models, data, and data modeling, sometimes joining the project of climate knowledge and sometimes

seeking to exploit its flaws for partisan purposes. Weblogs and “citizen science” websites now feature volunteer surveys of surface station biases, attempts to rewrite model code, and “audits” of climate data and models—infrastructural inversion, all over again. Outside the standard channels of peer-reviewed science, these sites nonetheless join the “controversy within consensus” model as mainstream science takes up and verifies their most significant results.

No longer under debate, however, are the fundamental frameworks of knowledge about the global climate: *how* we know what we know. Conceiving weather and climate as global phenomena helped promote an understanding of the world as a single physical system. Building the weather and climate knowledge infrastructures spread a specific way of making global knowledge—one whose techniques, values, and implications now extend not only throughout the sciences but far beyond.

Virtually any global thing you try to study will bring you up against the issues of *making global data*, *making data global*, and *data friction*. Studying anything that is planetary in scale—including human systems as well as natural systems—will put you in the business of *infrastructural globalism*. To understand the history of any such object, especially if you go back decades or longer, you will have to do some *infrastructural inversion*, and you will encounter *metadata friction*. Whatever you do, you will be using models of all sorts. These concepts frame this book’s larger meaning.

Monitoring, Modeling, and Memory

Today you can put instruments practically anywhere. Vast numbers of sensors *monitor* an equally vast range of phenomena, on every scale, from elementary particles to individual birds to Antarctic ozone levels to the solar wind. These sensors pour colossal volumes of digitized data into disk drives. Meanwhile, in many fields computer *models* complement or even replace laboratory experiments; analysis and simulation models have become principal means of data collection, prediction, and decision making. Third, vast data resources (scientific *memory*) are now increasingly available, though they are often distributed across thousands of research sites and institutions and in numerous incompatible formats.⁴

Computer models hold the key to transforming these information resources into knowledge. If you use a lot of sensors, you are going to need data models to make their signals into meaningful information. If you want to mine data created by somebody else and blend it with your own, you will need data models. If you want to do experiments on scales you

can't access or involving materials you can't handle, you will use a simulation model. If you want to look at long time scales, blending data collected at many places and times by many investigators into a common data set, you will need models to reconcile the differences.

Global knowledge based on global infrastructures for monitoring, modeling, and memory: this path, laid out by weather and climate science from the nineteenth century to the present, has since been followed by many other sciences. Increasingly, these sciences link with one another, sharing digital data and traversing each other's theoretical frameworks by means of computer models. Consider, as just one example, the Group on Earth Observations System of Systems (GEOSS), an initiative that emerged from the 2002 World Summit on Sustainable Development. The GEOSS inter-network links numerous global monitoring systems with modeling and memory of . . . well, practically everything on Earth. GEOSS's ultimate goal is "to transform earth system observations into socio-economic information of value."⁵ Anyone interested in any form of globalization, whether political, economic, historical, or cultural, will do well to attend to these new ways of thinking globally.

A Few Words about Words (and Numbers)

When I talk about *meteorology* and *meteorologists*, I'm not talking about the Weather Channel. I am talking about the spectrum of sciences and scientists that study the atmosphere, including forecasting, climate science, experimental studies, and other disciplines. When I say *anthropogenic*, I mean "of human origin," or "human-caused"; think *anthropos* (Greek for "human") and *genesis* (beginning). When I say *general circulation*, I'm talking about how the atmosphere moves ("circulates") around the planet, its typical patterns of motion on the global scale. *General circulation models* simulate this motion.

Climate sensitivity is a widely used benchmark for simulation experiments. Climate sensitivity is short for "how much the global average temperature will change when carbon dioxide concentrations double from their pre-industrial levels." Usually this is expressed as a range; 2–4.5°C is the current IPCC estimate of climate sensitivity. It now appears virtually inevitable that carbon dioxide concentrations will not only double but may triple or even quadruple before they decline. Hence, the climate sensitivity is just a signpost, not a marker for the likely peak concentration.

I use the metric system, the scientific standard. One degree Celsius ($^{\circ}\text{C}$) is equal to 1.8 degree Fahrenheit ($^{\circ}\text{F}$); water freezes at 0°C and boils at 100°C . A meter is a little more than a yard. A kilometer is about six tenths of a mile, so 100 kilometers is a little more than 60 miles.

This book has no glossary, but many are readily available. Two good ones are the online Glossary of Meteorology provided by the American Meteorological Society (amsglossary.allenpress.com/glossary/) and the one in the appendix to the IPCC's Working Group I Fourth Assessment Report (available at www.ipcc.ch).

How to Read This Book

I wanted to write a book that almost anyone could read and understand. At the same time, I wanted the book to appeal to scientists, and my fundamental argument requires going into some depth about weather and climate models, data, and their interactions. As a result, some people will find parts of the book too technical or too detailed, while others will find the same parts not technical or detailed enough. Here I briefly outline the book's structure, then describe three different ways you could read this book, depending on what kind of reader you are.

The book's sequence is roughly but not entirely chronological. Despite its length, it should be thought of as series of vignettes taken from a history so long and so complex that no linear narrative (and no single book) could hope to capture it. After chapter 7, most chapters carry one part of the story from some point in the 1950s to the present. Here is a map.

Chapter 1 outlines the book's conceptual framework and describes the arc of the argument.

Chapters 2–5 treat weather forecasting and climatology before 1945. These chapters provide background and introduce a series of concepts, especially the notions of data friction and computational friction.

Chapters 6 and 7 cover weather prediction and climate modeling from 1945 to 1970. This is the place to find explanations of how weather models and climate models work.

Chapters 8–10 recount how the weather information infrastructure developed between 1950 and 1980: how global weather data were collected ("making global data") and how they were analyzed and modeled to render global forecasts ("making data global"). Chapter 9 is an account of the World Weather Watch and the Global Atmospheric Research Program, the World Meteorological Organization's two major infrastructural

achievements through 1980. Chapter 10 develops the concept of *model-data symbiosis*.

Chapters 11 and 12 distinguish weather data from climate data and describe the reconstruction of historical temperature records. Chapter 11, the main subject of which is surface-station records, sweeps from the 1930s to the present. Chapter 12 describes the reunification of weather forecasting and climate science in the reanalysis projects begun in the late 1980s. (Reanalysis creates climate data from historical weather records.)

Chapter 13 returns to climate modeling, focusing on parameterization, tuning, and model validation. Taking a conceptual rather than a chronological approach, it focuses mainly on modeling issues of the period from 1980 to the present.

Chapters 14 and 15 discuss the interaction of models, data, and global atmospheric politics. Chapter 14 covers ozone depletion, nuclear winter, global warming, and other issues of the period 1960–1992, ending with the Framework Convention on Climate Change. Chapter 15 focuses on structural features of the politics of global warming since 1990.

The conclusion revisits the idea of a climate knowledge infrastructure and reflects on its larger meaning.

Most chapters begin and end with a short section written in an informal style. These sections try to draw out each chapter's central lessons briefly and readably, but do not necessarily rehearse the full argument. Reading them may help you decide how deeply to explore the chapter.

Say you are a “general reader”—not a scientist, but somebody who likes to read newspaper science sections or *Scientific American*, or who listens to *Science Friday* on National Public Radio. If you like to delve into historical background, chapters 2–5 and 14 should be relatively accessible. If you are more interested in how we know about climate change, begin with chapter 7 (perhaps skipping its more technical sections, those on pioneering climate models), then read chapters 11–13, chapter 15, and the conclusion.

If you are a scientist, and especially if you work in the atmospheric sciences, you probably already know a lot about current debates on climate change. You may care more about the history of models and data. For you, chapters 6–13 will be the core of the book—especially chapters 6 and 7, which describe the rise of computer modeling in weather forecasting and climate science. Chapter 15 and the conclusion may offer you some new ways to think about current debates.

If you are an academic or a student from a non-scientific discipline (such as history and philosophy of science, science and technology studies, or

political science), you will want to read the whole book. Historians will naturally be more interested in the parts relevant to their own periods. People with an epistemological bent will find chapters 10–13 most useful. If you are most interested in climate policy or controversy studies, chapters 11, 14, and 15 may be most rewarding for you.

What This Book Does Not Do

This book deliberately violates the received history of meteorology in a way that may upset the expectations of readers already versed in that history. Meteorology includes three main component disciplines: weather forecasting, climatology, and theoretical meteorology. Originally united, these disciplines split apart in the nineteenth century and developed in relative isolation until the advent of computer models after 1950. Computer modeling returned theoretical meteorology to a central role in forecasting, and it transformed climatology into what we now call climate science. Yet operational weather prediction's very different priorities still separated it institutionally and conceptually from climate science. Most histories of meteorology—especially the informal history that meteorologists recount to one another—accept this division at face value. As a consequence, the stories of weather forecasting, climatology, and theoretical meteorology are usually told separately.

In this book I bring the three narratives together in ways that may at first seem puzzling to some scientists. I do this because the arcs of those stories rejoined some time ago. Since 1960, computer models have been the fundamental tool of both weather forecasting and climate science, differing in details and in usage but not in underlying structure. Since 1990, reanalysis projects have reunited the previously separate streams of weather data and climate data, at least to a degree. More recently, operational climate prediction and the Earth System Modeling Framework (which allows model components to be readily exchanged among research labs and operational agencies) have signaled the beginning of a new stage in this reunification. Thus, to understand the infrastructure of climate knowledge you have to understand weather forecasting. Though still quite different in many ways, they are inseparable, and they are increasingly linked.

My deepest regret about the book is that it is not, as I once hoped it would be, a fully international history. Swedish, British, German, Japanese, and Soviet and Russian contributions, in particular, receive much less attention here than they deserve, and it would be possible to come away

from this book with an inflated view of the role of the United States in climate science and politics. My defense is that no scholar and no book can do everything. My hope is that I, along with many other writers, can continue to expand this story much as climate scientists have reconstructed climate history: with many iterations, as more evidence appears and as my colleagues find and correct the deficiencies. That's how good history works.

This is not a history of individuals, nor is it an ethnography. It contains few thoroughly drawn characters and few discussions of personal or group interactions. Instead, it is a history of systems, networks, and webs; of data, models, and knowledge flows. My goal is not to document details, but to provide an analytical perspective, a conceptual framework that makes some sense of things. For this reason, I have not attempted to systematically attribute credit for scientific advances, for organizational transformations, or for larger ideas and trends. In the time-honored scientific and scholarly tradition, I cite the most important publications and other works, but inevitably I will have passed over some of these. Many meteorologists maintain a remarkable awareness of their field's history, so these omissions will certainly disappoint some people. If you are one of them, please accept my apology; I intend no slight. I fully understand that everything I have described came about through the tireless work of individual human beings, many of whom dedicated their entire lives to building some part of this gigantic whole. I wish I had found a way to include them all.

My office and my computer's disk drive are crammed with excellent books and articles about meteorology and climate change written by other historians and social scientists. I have made such use of these works as I can, and have tried to gesture in their direction where I can't. In reaching out to a broad audience, I have left to one side what some of my colleagues may regard as important scholarly debates; these I will engage elsewhere.

My final caveat, which I will repeat frequently to avoid misunderstanding, is that this book treats only some pieces of the climate change puzzle. It focuses primarily on atmospheric models and the historical temperature record. These are the two most important ways we know about climate change, but many other lines of evidence, and many other kinds of models, play crucial parts in the knowledge infrastructure. Ultimately it is the convergence of all these lines of evidence, from numerous partly or completely independent disciplines and data sources, that underwrites the scientific consensus on global warming.

The Book's History

This book has been a long time coming. I first got interested in climate change in the mid 1980s, when I was in graduate school, in the context of global security issues. In 1994, as a junior faculty member at Stanford University, I began studying it in earnest under a National Science Foundation professional development fellowship. I am neither a meteorologist nor a computer scientist by training, although I worked as a computer operator and programmer in the mid 1970s, and although my first book, *The Closed World: Computers and the Politics of Discourse in Cold War America* (1996), took me deep into the history of computing. So I had to learn a lot. I took courses on climatology and studied the scientific literature intensively. I worked closely with my Stanford colleague Stephen Schneider, who provided what amounted to an intensive multi-year tutorial on climate science and politics. Over the years I attended countless scientific meetings.

Originally I planned to write a history of climate modeling, so I visited numerous climate laboratories and other facilities throughout the United States and in the United Kingdom, France, Switzerland, and Australia. During these visits I collected a large archive of documents. More than 800 documents are cited directly in this book, but my research bibliography runs to well over 5000 items. In addition to primary scientific articles, these include letters and other archival documents, email exchanges among scientists, “gray literature,” and a variety of photographs, PowerPoint presentations, and materials in other media.

Gray literature—conference proceedings, internal reports from climate laboratories, International Meteorological Organization and World Meteorological Organization publications, and similar items—has considerable importance in meteorology and is often cited in journal publications. Yet laying hands on any of the gray literature published before about 1995 is remarkably difficult. There are only a few well-stocked meteorological libraries in North America, and probably no more than two dozen in the whole world. Very few have the full set of WMO publications—especially operational manuals, whose earlier versions are routinely discarded when updated manuals arrive. Even the WMO’s library in Geneva no longer holds copies of some of that organization’s own publications. This fact matters in my story. Recently recovered older versions of WMO Publication 47 are now aiding in the reconstruction of weather records from ships (see chapter 11). Therefore, I spent many weeks in

meteorological libraries at the US National Center for Atmospheric Research, the Geophysical Fluid Dynamics Laboratory, Environment Canada, the Goddard Institute for Space Studies, UCLA's Department of Meteorology, the European Center for Medium Range Weather Forecasts, and the Australian Bureau of Meteorology Research Centre. I also made use of archives at the National Center for Atmospheric Research, the Massachusetts Institute of Technology, and the American Institute of Physics.

Between 1994 and 2001, I interviewed numerous scientists. In particular, I took lengthy oral histories from the first-generation climate modelers Cecil "Chuck" Leith, Syukuro Manabe, Warren Washington, Akira Kasahara, and Akio Arakawa. (I was not able to take oral histories from two other members of this first generation; Yale Mintz died in 1993, and by 1998, when I interviewed Joseph Smagorinsky, his Parkinson's Disease had progressed to the point that an oral history was no longer practicable. Fortunately, Smagorinsky had already written several excellent historical accounts of the events in which he was involved.) Transcripts of these oral histories are on deposit at the American Institute of Physics' Center for the History of Physics and are available for other researchers to use. The names of all my interviewees are listed in my acknowledgments. In the end, as I learned more and more about the field and as my focus shifted from the history of modeling to the larger topics this book covers, I decided to use most of those interviews as background rather than primary source material.

I made a deliberate decision not to pursue archival sources in great depth. Such sources do exist, particularly for events prior to about 1970, and I explored some of them rather thoroughly. Yet it quickly became clear to me that I needed to choose between ferreting out archival evidence and going where I wanted to go, namely toward a conceptual and long-historical view. Further, I decided that the most credible and relevant sources for this project were the same ones scientists use in their own work: peer-reviewed scientific journals; conference proceedings; documents published by such organizations as the WMO, the IPCC, and national science academies; and other primary professional literature.

Over the years, I have published a series of articles and another book: *Changing the Atmosphere: Expert Knowledge and Environmental Governance* (MIT Press, 2001), co-edited with Clark Miller. Bits and pieces of this previous work, all updated and revised, appear throughout *A Vast Machine*. As time went on, other research work and life events intervened, causing this project about global climate science to travel around the world with me.

I composed substantial parts of it during extended stays in France, the Netherlands, Australia, South Africa, and Namibia. The science continued to grow and change, as did the political context; the huge scale and scope of climate research made merely keeping up with the literature virtually a full-time job. My own perspective continued to shift as I developed the book's framework and further explored the intricate relationships between models and data. No one's understanding of this subject can ever be complete or finished, but here is mine, as done as I can do it and—like all knowledge—merely provisional.