standing current plans for weather modification and geoengineering. Today's planetary engineers, he argues, imagine themselves as technological pioneers and are unaware of decades, if not centuries, of similar speculations. More critically, technological solutions for global warming have the potential to distract policy-makers and citizens from strategies based on changing regulatory regimes and people's behavior.

When it comes to addressing climate change, technological fixes remain attractive to many conservative and libertarian politicians and economists. Fleming proposes instead a middle path that seeks neither dominion over weather nor a diminishment of dangers that environmental problems pose for the 21st century. Acknowledging previous attempts at climate control can offer researchers and policy-makers some valuable historical lessons. *Fixing the Sky* provides an essential foundation for understanding the long and dubious scientific tradition from which plans for climate control hail.

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HISTORY AND PHILOSOPHY OF SCIENCE

Computing the Climate and More

Richard C. J. Somerville

As a thought experiment, imagine an alternative history of our planet, one in which the digital electronic computer had never been invented. Then ask yourself how our ability to understand 21st-century climate change would have been affected. Because fossil fuels were already dominant in the precomputer era before World War II, it seems likely that even in this alternative history they would power our global energy system. So human-caused climate change would presumably now be well under way, much as it is today. Burning coal, oil, and natural gas would still produce a significant increase in the amount of carbon dioxide in the atmosphere, which would drive an altered greenhouse effect and shift climates around the globe. In this hypothetical world without computers, however, climate science would surely have achieved only a relatively primitive level of understanding. Researchers would have neither the observational evidence to adequately document climate change nor the scientific tools to understand and predict it. In our actual world, that plentiful evidence and those powerful tools both rely heavily on computer models.

A Vast Machine
Computer Models, Climate Data, and the Politics of Global Warming
by Paul N. Edwards
MIT Press, Cambridge, MA, 2010. 546 pp. $32.95, £24.95. ISBN 9780262013925.

Science in the Age of Computer Simulation
by Eric B. Winsberg
University of Chicago Press, Chicago, 2010. 164 pp. $66. ISBN 9780226902029. Paper, $24. ISBN 9780226902043.

A Vast Machine explores the ramifications of this key insight. Paul N. Edwards (a historian of science and technology at the University of Michigan) has written a book that is both a history of modern climate science and an analysis of the relation between that science and today's concerns about global warming. Climate contrarians often assert that computer simulations of climate are unreliable and that climate science should instead deal with observations of the actual climate. Although their primary motivation may be opposition to possible policies, their stated concern is usually a distrust of mainstream climate science. The contrarians insist that this science ought not to depend on an analysis of virtual climates produced by models, which are, after all, mere computer programs. Edwards, however, makes the reader understand that models play a central role in producing nearly all the climate observations that scientists use. For example, converting satellite measurements of atmospheric radiances into "observations" of temperature is a complex task involving models. In six short words, the central message of this book is "without models, there are no data."

Edwards traces the development of modern models of the climate system, research that branched off from numerical weather prediction in the 1950s. Such weather prediction relies on computer simulations that start with observations of present meteoro-

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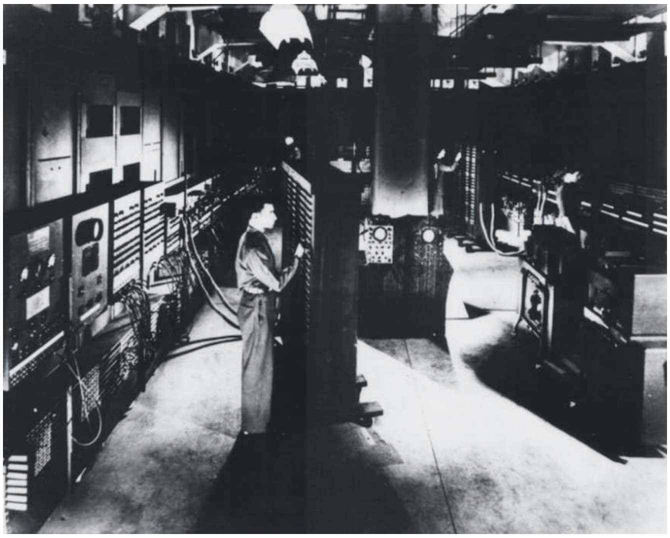
logical conditions and calculate the detailed evolution of the state of the atmosphere (temperature, pressure, winds, and humidity) for up to about two weeks. This model-centered process is the basis of the daily weather forecasts that appear on television, radio, and the Internet and in newspapers. Present-day climate models are usually more comprehensive physically. Typically, such models simulate a complex, interactive system comprising not only the atmosphere but also oceans, snow and ice, land surfaces, and biogeochemical processes. Compared with weather forecast models, climate models also simulate far longer time periods, from months to millennia.

A Vast Machine does an especially good job at recounting details of the historical evolution of these models, without drowning the reader in jargon and, amazingly, without using any mathematics at all. Edwards has interviewed many of the pioneers in the field and has clearly explored the research literature extensively. His account will be readily accessible to that legendary target, the general reader, a broadly educated person interested in science and technology, among other things. Such a reader will, I expect, be particularly interested in Edwards's penetrating analysis of the role of climate science and models in the current political and policy discussion of how best to meet the imposing challenges of confronting man-made climate change.

The book will also fascinate members of the climate modeling research community. Although I have worked in this field for more than 40 years, I encountered many surprising and fascinating nuggets—including the disclosure that one celebrated early climate modeler never learned to program computers. Edwards's coverage does have a few limitations. He primarily emphasizes contributions from scientists in the United States, as he acknowledges, and he focuses much more strongly on the atmosphere than on other important components of the climate system. Within these limitations, the author's impressive scholarship and command of his material have produced a truly magisterial account.

Science in the Age of Computer Simulation is a very different book, and it may primarily intrigue a very different audience. In it, Eric Winsberg (a philosopher of science at the University of South Florida) considers the rise in the importance of computer simulations, not only in climate research but throughout science in general. His concern "is as much about what philosophers of science should learn in the age of simulation as it is about what philosophy can contribute to our understanding of how the digital computer is transforming science." He is interested in issues such as the relationship between experiment and computer simulation. He asks, for example, under what conditions should we expect a computer simulation to be reliable?



Computing power for early modeling. ENIAC filled a large room, consumed 140 kilowatts, and contained some 18,000 fragile vacuum tubes.

Such questions, while of broad importance to science in general, are also highly relevant to climate modeling, and here it may be helpful to establish some historical context. Computer simulations in science began after World War II and were at first confined to meteorology and nuclear weapons research. John von Neumann, a towering figure in 20th-century mathematics and mathematical physics, understood immediately that these two seemingly disparate fields are scientifically closely connected: both being centrally concerned with highly nonlinear fluid dynamics. And in both, carrying out controlled experiments and making measurements present great difficulties. The ENIAC (Electronic Numerical Integrator and Computer), the most important American computer during this period, was completed in late 1945 and initially used for hydrogen bomb calculations. Primitive by modern standards, it had a tiny memory and could carry out fewer than 400 typical multiplications per second. One early numerical weather prediction actually calculated not the meteorological conditions at Earth's surface but atmospheric circulation at an altitude of about 5500 meters. In 1950, such a prediction on the ENIAC required some 24 hours of computing time to produce a 24-hour forecast.

The crude but promising early computer simulations astonished meteorologists and led rapidly to operational numerical weather forecasts in the mid-1950s, first in Sweden and the United States. Some scientists also foresaw a new role for modeling. Von Neumann himself explicitly stated that computer simulations might "replace certain experimental procedures in some selected parts of mathematical physics." Indeed, when carrying out simulations routinely in many fields of science, researchers today often speak of "numerical experiments."

Winsberg comes at this issue from the perspective of a philosopher. He reminds us that philosophy of science has historically always drawn its motivations and directions from the science of the day. He notes that computer simulation now occupies a centrally important place in many fields of science. However, as he points out, such simulations typically are carried out within the constraints of existing fundamental theory, rather than changing or revolutionizing theory. Winsberg suggests that philosophy of science, in these contemporary scientific circumstances, ought now to concern itself with the subject of simulating complex phenomena within existing theory, as opposed to its traditional focus on the creation of novel scientific theories.

In *Science in the Age of Computer Simulation*, Winsberg explores this new direction in depth, with extensive references to both philosophical and scientific developments. He concludes,

> [W]hat we might call the ontological relationship between simulations and experiments is quite complicated. Is it true that simulations are, after all, a particular species of experiment? I have tried to argue against this claim, while at the same time insisting that the differences between simulation and experiment are more subtle than some of the critics of the claim have suggested. Most important, I have tried to argue that we should disconnect questions about the identity of simulations and experiments from questions of the epistemic power of simulations.

Such provocative findings, and Winsberg's exceptionally readable account of the reasoning that led him to them, will interest many general readers as well as scientists and philosophers of science.

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