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Book review: Beyond Global Warming: How Numerical Models Revealed the Secrets of Climate Change. Syukuro Manabe and Anthony J. Broccoli. 208 pp. Princeton U. P., Princeton, NJ. 2020. Price $35 (hardcover) ISBN 978-0-691-18516-3. (John C. H. Chiang, Reviewer).

For climate science, the year 2021 stands out for two reasons. The first is the publication of the Working Group I contribution to the Intergovernmental Panel on Climate Change 6th report, announced with international fanfare, which renews the public's engagement with science of global warming. The second is the awarding of the Nobel Prize for Physics to two physical climate scientists, Syukoro Manabe and Klaus Hasselmann. Manabe's Nobel citation highlights his role in "the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming." As luck would have it, Manabe's book is on precisely this subject. Written with his longtime collaborator Anthony Broccoli - a distinguished climate scientist in his own right - the authors describe the role of numerical modeling in the development of the science of global warming, highlighting contributions for which Manabe played a pivotal role. The book thus provides a valuable account of the scientific work that ultimately led to Manabe's honor.

The title *Beyond Global Warming* speaks to the authors' belief that the greatest benefit of climate modeling is not about predicting future climate, but rather providing a deeper insight into the mechanisms of global climate and how it responds to forcing. Indeed, the book is mostly devoted to communicating key physical concepts gleaned from climate model studies (the book is based on lecture notes for a graduate course that Manabe taught at Princeton). However, the authors also take a historical approach in linking the earliest studies of the late 19th and early 20th century to their own efforts and those of their colleagues in the second half of the 20th century, thus bridging the history that led to the current Earth System models used today. As such, the book occupies a curious space between standard climate dynamics texts that introduce the science but without the historical context, and popular accounts of global warming science (e.g. Spencer Weart's *The Discovery of Global Warming*) that delve into the history but with a relatively light treatment of the underlying physical concepts.

It seems appropriate to first summarize what the book covers. Chapter 1 begins with a textbook rendition of the greenhouse effect. However, this chapter sets the stage for the detailed look at the development of climate modeling and its applications that occupies the rest of the book. Chapter 2 recounts the earliest works by Arrhenius and Callendar using simple energy-balance models to estimate the warming due to increased greenhouse gases. A key lesson learned from this early model was that vertical atmospheric processes are important, thus leading to the seminal 1-D model studies (Chapter 3) by Manabe and colleagues on radiative and radiative-convective equilibrium and response to CO2 forcing. The success of the 1-D models encouraged the development of 3-D general circulation models (Chapter 4) of the atmosphere, thereby enabling the first numerical simulations exploring global climate changes (Chapter 5). Chapter 6 is devoted to an exploration of climate sensitivity – that is, the global mean surface temperature change due to a doubling of atmospheric CO2 concentration – and various feedbacks that determine this quantity. The reader is then transported to a climate of the distant past, with the first attempts at modeling of the most recent ice age (Chapter 7) and a comparison of these simulations to paleoclimate proxy estimates of ocean surface temperature. Chapter 8 is devoted to the development of the global ocean model and its coupling to the atmospheric model to obtain a self-consistent model of the atmosphere-land-ocean system, exploring how the deep ocean (as part of the global climate system) then responds to atmospheric CO2 changes (Chapter 9). The book closes with a discussion of how the global water cycle changes in the face of global warming (Chapter 10).

The book caters to a wider audience by being light on equations, choosing instead to describe physical insights through detailed descriptions aided by diagrams. The authors walk the reader through various concepts, conveying the subtlety and richness of the underlying physics. As such, having a college physics background, or at least a very good physical intuition, is needed to appreciate the contents. However, minimizing the mathematics shouldn't be confused with minimizing the depth of coverage: for those wanting to simmer in the details, this is a wonderful reference. Some atmospheric and climate science jargon is used in the book that wasn't adequately defined: a glossary would have been helpful, but these days a quick Google search probably works just as well.

In reading how the early climate models evolved, I was impressed by the ingenuity with which the modelers worked around the severe constraints in computational power. Approximations (aka parameterizations) were formulated to represent physical processes either could not be spatially resolved and/or were imperfectly understood at the time. As a graduate student, I read a copy of the (handwritten!) notes describing the climate model from the Geophysical Fluid Dynamics Laboratory where Manabe worked, and this book reminded me of the simple yet ingenious parameterizations that they used: for example, convective adjustment to represent the net effect of small-scale convection at the model grid scale, and the unforgettable 'bucket model' for modeling land hydrological processes. While the authors did not articulate the emotional aspects of their scientific journey, the historical narrative did help me imagine being part of that discovery process. What wonder and excitement they must have felt when they saw that that the simulated temperature and precipitation looked remarkably like that of the actual Earth!

An unusual aspect of this book is the detail offered on the nitty-gritty of modeling: how the model is configured and run, how the output is dissected, and so forth. All this is quite familiar to those engaged in climate modeling, but I have not seen this level of detail in a book before. I wonder how informative this is to the casual reader: I might have preferred less technical detail in favor of more detail on the historical context, but that could be because I am all too familiar with the former. A casual reader might appreciate seeing the technical details to get a sense of the strengths and weaknesses of climate modeling.

The benefits of using this book for teaching are obvious to me. For my undergraduate climate and earth science courses, I would use parts of the book to complement existing texts: the detailed descriptions offered would help students understand the deeper physical meaning of various climate processes. For a graduate seminar, I can imagine offering a semester-long course on climate modeling based on the original papers referenced in the book, and with the book providing the overarching scientific and historical narrative.

I started my own academic journey with the intention of entering a 'traditional' field within physics, but switched to climate science during my graduate studies when I was introduced to the world of climate modeling. The global atmospheric and oceanic processes they represented captured my imagination, and I was intrigued by the possibility they afforded to explore the workings of Earth’s climate. Manabe and Broccoli’s book show how this possibility was fully realized by the pioneers of climate modeling, and how their explorations ultimately led to the discovery of global warming and its ramifications. Climate modeling today is driven by the need for predicting future changes, so the emphasis now tilts towards engineering with increasing complexity of incorporated processes into Earth System models and increasing spatial resolution aided by supercomputers with lots of data storage. However, the book serves as a powerful reminder of how curiosity-driven explorations with simpler models are still valuable, and indeed needed, for providing new insights on the physical world in which we all live and depend upon.

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