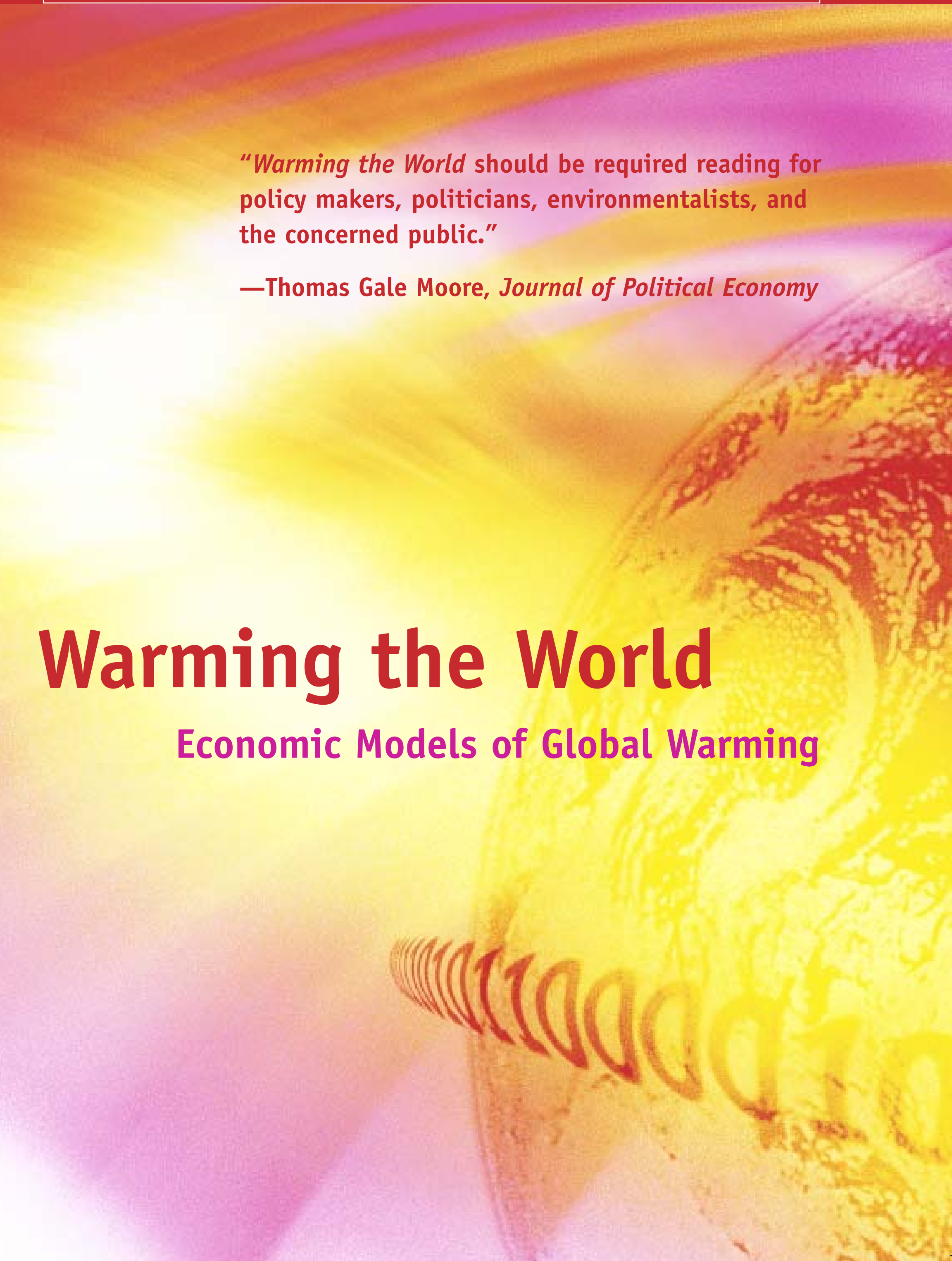
William D. Nordhaus • Joseph Boyer



"*Warming the World* should be required reading for policy makers, politicians, environmentalists, and the concerned public."

—Thomas Gale Moore, *Journal of Political Economy*

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Economic Models of Global Warming

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The MIT Press
Cambridge, Massachusetts
London, England

This book was set in Palatino by Best-set Typesetter Ltd., Hong Kong
Printed and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data

Nordhaus, William D.
Warming the world : economic models of global warming / William D. Nordhaus and Joseph Boyer.
p. cm.
Includes bibliographical references and index.
ISBN 0-262-14071-3 (hc. : alk. paper)
1. Global warming—Economic aspects—Mathematical models. 2. Economic development—Environmental aspects—Mathematical models. I. Boyer, Joseph, 1969–
II. Title.

QC981.8.G56.N67 2000
363.738′74—dc21 00-029230

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Preface

Dealing with complex scientific and economic issues has increasingly involved developing scientific and economic models that help analysts and decision makers understand likely future outcomes as well as the implications of alternative policies. This book presents the details of a pair of integrated-assessment models of the economics of climate change. The models, called RICE-99 (for the Regional Dynamic Integrated model of Climate and the Economy) and DICE-99 (for the Dynamic Integrated model of Climate and the Economy), build upon earlier work by Nordhaus and collaborators, particularly the DICE and RICE models constructed in the early 1990s. The purpose of this book is to lay out the logic and details of RICE-99 and DICE-99. Like an anatomy class, this description highlights internal structure of the models and the ways different segments are connected.

The book is organized into two parts. The first part describes RICE-99 and its globally aggregated companion, DICE-99. This part contains an introduction (chapter 1) and a brief description of RICE-99 (chapter 2) that includes all the model equations. The details of the derivation of these equations and their parameterization are presented in chapters 3 and 4. Chapters 1 through 4 present RICE-99, leaving explicit discussion of DICE-99 to chapter 5. Chapter 6 explains how the models are solved. Part II presents the major results of RICE-99 and applies it to the questions surrounding climate change. The appendixes provide a summary listing of the equations, a variable list, and the programs for the RICE-99 and DICE-99 models. The models and spreadsheets are also available on the Web.

Those interested in this exciting field will recognize that this book builds on earlier work of the authors and of many others. Although it bears the names of two authors, the intellectual inspiration and contribution of many should be recognized. Among those we thank for contributing directly or indirectly are Jesse Ausubel, Howard Gruenspecht, Henry Jacoby, Dale Jorgenson, Charles Kolstad, Alan Manne, Robert Mendelsohn, Nebojsa Nakicenovic, John Reilly, Richard Richels, Thomas Schelling, Richard Schmalensee, Stephen Schneider, Leo Schrattenholzer, Robert Stavins, Ferenc Toth, Karl Turekian, Paul Waggoner, John Weyant, Zili Yang, and Gary Yohe. Megan McCarthy and Ben Gillen provided valuable research assistance. This research was supported by the National Science Foundation and the Department of Energy. None of these is responsible for the errors, opinions, or flights of fancy in this work.

I

Developing the RICE and DICE Models

1 Introduction

"God does not play dice with the universe," was Albert Einstein's reaction to quantum mechanics. Yet humanity *is* playing dice with the natural environment through a multitude of interventions: emitting into the atmosphere trace gases like carbon dioxide that promise to change the global climate, adding ozone-depleting chemicals, engineering massive land-use changes, and depleting multitudes of species in their natural habitats, even as we create in the laboratory new organisms with unknown properties. In an earlier era, human societies learned to manage—or sometimes failed to learn and mismanaged—the grazing or water resources of their local environments. Today, as human activity increasingly affects global processes, we must learn to use wisely and protect economically our common geophysical and biological resources. This task of understanding and controlling interventions on a global scale is *managing the global commons*.

Climatologists and other scientists warn that the accumulations of carbon dioxide (CO_2) and other greenhouse gases (GHGs) are likely to lead to global warming and other significant climatic changes over the next century. This prospect has been sufficiently alarming that governments have undertaken, under the Kyoto Protocol of December 1997, to reduce their GHG emissions over the coming years. The Kyoto Protocol raises a number of fundamental issues: Are the emissions limitations proposed there sufficient, insufficient, or excessive? Is the mechanism proposed to combat global warming—limiting emissions from high-income countries—workable and desirable? Was it wise to omit developing countries? Is there a trajectory for the Kyoto Protocol that will lead to a comprehensive climate-change policy? Are other approaches, such as harmonized carbon taxes or geoengineering, worth considering? How does the approach in the Kyoto Protocol compare with the economist's dream of an "efficient" policy? And, perhaps most important, will these costly approaches sell in the political marketplace of the world's democracies and oligarchies?

Natural scientists have pondered many of the *scientific* questions associated with greenhouse warming for a century. But the *economic, political, and institutional* issues have only begun to be considered over the last decade. The intellectual challenge here is daunting—raising formidable issues of data, modeling, uncertainty, international coordination, and institutional design. In addition, the economic stakes are enormous. Several recent studies of the Kyoto Protocol put the price tag on abatement to be around $1 trillion in present value.[1] It is no hyperbole to say that the issue of greenhouse warming invokes the highest form of global citizenship—where nations are being called upon to sacrifice hundreds of billions of dollars of present consumption in an effort that will largely benefit people in other countries, where the benefit will not come until well into the next century and beyond, and where the threat is highly uncertain and based on modeling rather than direct observation.

The issue of global warming has proven one of the most controversial and difficult problems facing nations as they cross the bridge into the twenty-first century. Over the last decade, the issue has migrated from the scientific journals to White House conferences and world summit meetings. In response, a small navy of natural and social scientists has been mobilized to help improve our understanding. In parallel with the growing interest, industrial, environmental, and political groups have put their oars in the water to pull the ship in directions favorable to their ideologies or bottom lines.

Among the most impressive advances over the last decade has been the development of integrated-assessment economic models that analyze the problem of global warming from an economic point of view. Literally dozens of modeling groups around the world have brought to bear the tools of economics, mathematical modeling, decision theory, and related disciplines. Whereas a decade ago, not a single integrated dynamic model of the economics of climate change existed, there are now more than we can keep track of.

One of the earliest dynamic economic models of climate change was the DICE model (a Dynamic Integrated model of Climate and the Economy). Originally developed from a line of energy models, DICE integrated in an end-to-end fashion the economics, carbon cycle,

1. See the studies contained in Weyant 1999.

Table 1.1
Reference case output across model generations for the year 2100

	DICE-94	RICE-99
Industrial emissions (GtC/year)[1]	24.9	12.9
Output (trillions of 1990 U.S.$)	111.5	97.02
Population (billions)	9.8	10.7
Output per person (thousands of 1990 U.S.$)	11.4	9.1
Carbon intensity (tons carbon per $1,000 of GDP, 1990 U.S.$)	0.22	0.13
Temperature (degrees C above 1900)	3.39	2.42

Note: 1. "GtC" means billion metric tons of carbon.
Source: Runs of models as described in text.

climate science, and impacts in a highly aggregated model that allowed a weighing of the costs and benefits of taking steps to slow greenhouse warming. The first version of DICE was presented in 1990, and the results of the full model were described in Nordhaus 1994b. A regionalized version, known as RICE (a Regional dynamic Integrated model of Climate and the Economy), was developed and presented in Nordhaus and Yang 1996.

Although the basic structure of the DICE and RICE models has survived in the crucible of scientific criticism, further developments in both economics and the natural sciences suggest that major revisions of the earlier approaches would be useful. Although no simple solutions have been found, a number of small discoveries and large innovations in the natural and social sciences have come forth. Moreover, the past decade has seen major improvements in the underlying data on greenhouse-gas emissions and energy and economic data.

This book represents the fruits of the revision of the earlier models. The new models have benefited from a thorough overhaul while maintaining their basic structure. Table 1.1 compares projections of the major variables in RICE-99 with the earlier DICE-94 model for the reference case in 2100.[2]

The major changes from the old to the new models are the following:

1. The major methodological change is a respecification of the production relations. Whereas the earlier DICE and RICE models used a

2. The reference case represents the model's projections for what will happen if no government control over GHG emissions is imposed. See chapter 2, section four, or chapter 6 for more complete definition.

parameterized emissions–cost relationship, the new RICE model use a three-factor production function in capital, labor, and carbon-energy. The new RICE model develops an innovative technique for representing the demand for carbon fuels and uses existing energy-demand studies for calibration.

2. The new RICE model changes the treatment of energy supply to incorporate the exhaustion of fossil fuels. This approach treats the supply of fossil fuels explicitly and uses a market-determined process to drive the depletion of exhaustible carbon fuels. The new model incorporates a depletable supply of carbon fuels, with the marginal cost of extraction rising steeply after 6 trillion tons of carbon emissions.[3] (This would be the equivalent of burning about 9 trillion tons of coal.) With limited supplies, fossil fuel prices will eventually rise in the marketplace to choke off consumption of fossil fuels.

3. Most of the data have been updated by almost a decade to reflect data for 1994–98. The output growth in the models is generated by regional economic, energy, and population data and forecasts. The new model projects significantly lower reference CO_2 emissions over the next century than the earlier DICE and RICE models because of slower projected growth and a higher rate of decarbonization of the world economy.

4. The RICE/DICE-99 carbon-cycle model is now a three-box model, with carbon flows among the atmosphere, upper biosphere-shallow oceans, and deep oceans. (In earlier versions, carbon simply disappeared at a constant rate from the atmosphere.) The temperature dynamics in the new models remain unchanged from the earliest versions, as climate research has not produced compelling reasons to alter them. Forcings from non-CO_2 GHGs, and aerosols have been updated to reflect more recent projections. The projected global temperature change in the reference case turns out to be significantly lower in the current version of RICE. This is due to the inclusion of negative forcings from sulfates in RICE-99, the lower forcings from the chlorofluorocarbons, and the slower growth in CO_2 concentrations (see table 1.2).

3. We sometimes refer to carbon dioxide emissions and concentrations as "carbon emissions," "concentrations of carbon," or sometimes simply "emissions" or "concentrations." Both are measured in metric tons of carbon. We refer to metric tons of carbon as simply "tons of carbon." In some contexts, as noted, particularly when referring to coal, "tons" will mean short tons.

Table 1.2
Difference in radiative forcing across models, reference case, 2100

	Watts per m^2	Percent of total difference
Total difference (RICE-99 minus DICE-94)	–1.73	100.00
Carbon emissions and cycle		
Carbon emissions (GtC/year)[1]	–0.89	51.26
Starting carbon concentration	–0.06	3.25
Carbon cycle model	0.30	–17.49
Other anthropogenic forcings		
Chlorofluorocarbons	–0.42	24.28
Sulfate aerosols	–1.06	61.27
Other greenhouse gases	0.45	–26.01
Change in preindustrial carbon concentration in forcing equation	–0.06	3.43

Note: 1. "GtC" means billion metric tons of carbon.

5. The impacts of climate change have been revised significantly in the new models. The global impact is derived from regional impact estimates. These estimates are derived from an analysis that considers market, nonmarket, and potential catastrophic impacts. The resulting temperature damage function is more pessimistic than that of the original DICE model.

6. The RICE and DICE models were originally developed using the General Algebraic Modeling System software package. The new versions have been programmed both in GAMS and in an EXCEL spreadsheet version so that other researchers can easily understand and use the models.

This book lays out the revisions and their implications in detail. The underlying philosophy of the original DICE and RICE models remains unchanged: to develop small and transparent models that can be easily understood, can be modified as new data or results emerge, and will be useful for scientific, teaching, and policy purposes.

It is our hope that this book can help modelers and policymakers better understand the complex trade-offs involved in climate-change policy. In the end, good analysis cannot dictate policy, but it can help policymakers thread the needle between a ruinously expensive climate-change policy that today's citizens will find intolerable and a do-nothing policy that the future will curse us for.