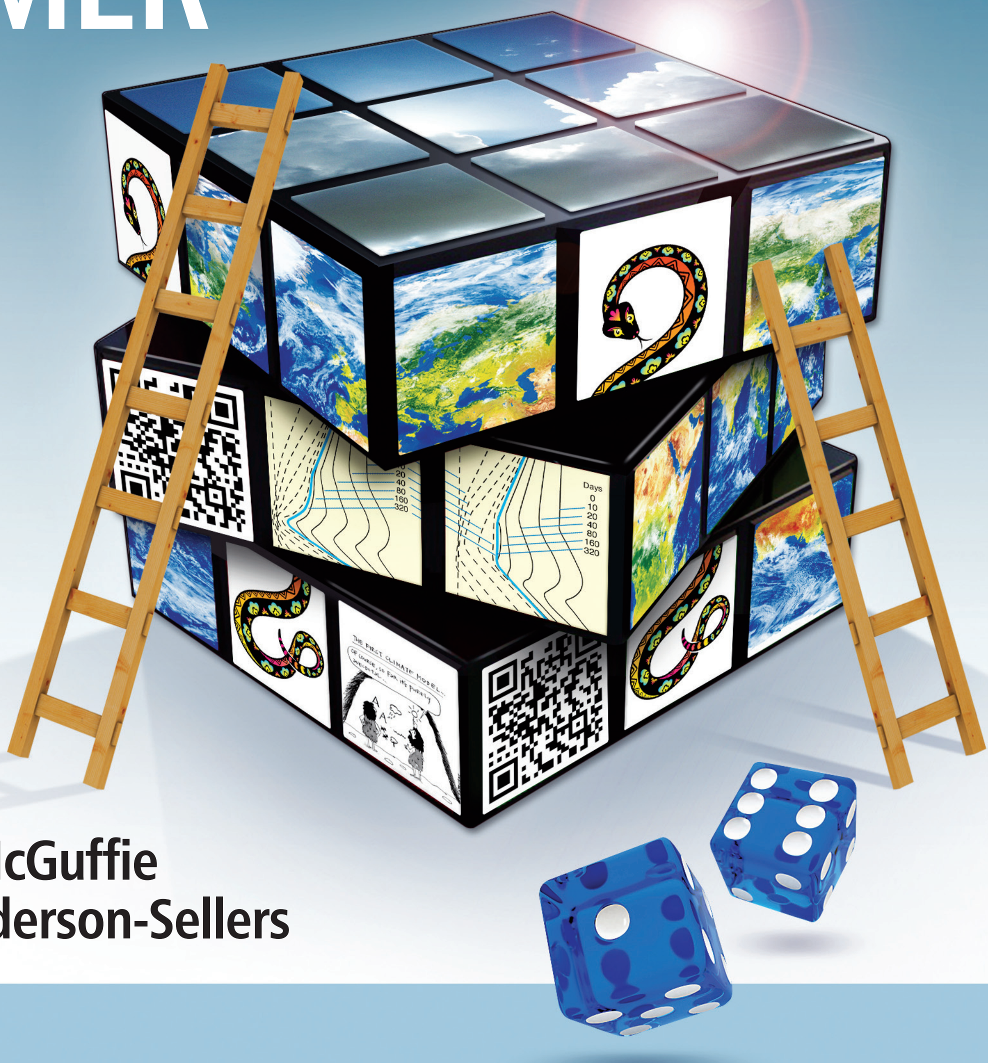
FOURTH EDITION

The CLIMATE MODELLING PRIMER



Kendal McGuffie
Ann Henderson-Sellers

with website

WILEY Blackwell

THE CLIMATE MODELLING PRIMER

THE CLIMATE MODELLING PRIMER

FOURTH EDITION

KENDAL McGUFFIE
UNIVERSITY OF TECHNOLOGY SYDNEY
AUSTRALIA

ANN HENDERSON-SELLERS
MACQUARIE UNIVERSITY
AUSTRALIA

WILEY Blackwell

Registered Office
John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Offices
9600 Garsington Road, Oxford, OX4 2DQ, UK
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK
111 River Street, Hoboken, NJ 07030-5774, USA

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com/wiley-blackwell.

Library of Congress Cataloging-in-Publication Data

McGuffie, K.
The climate modelling primer / Kendal McGuffie, Department of Applied Physics, University of Technology, Sydney, NSW, Australia, Ann Henderson-Sellers, Department of Environment and Geography, Macquarie University, North Ryde, NSW, Australia. – Fourth edition.
pages cm
Includes bibliographical references and index.
ISBN 978-1-119-94336-5 (cloth : alk. paper) – ISBN 978-1-119-94337-2 (pbk. : alk. paper) – ISBN 978-1-118-74684-4 (epdf) – ISBN 978-1-118-74707-0 – ISBN 978-1-118-74712-4 (cs) – ISBN 978-1-118-74718-6 (epub) – ISBN (invalid) 978-1-118-74719-3 (emobi) 1. Climatology–Mathematical models. I. Henderson-Sellers, A. II. Title.
QC981. M482 2014
551.601′1–dc23
2013030746

A catalogue record for this book is available from the British Library.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Cover image: Ladders iStock File #13915338 © luchschen. Sky iStock File #99665 © Lumnicence. World iStock File #3112747 © janrysavy. Dice iStock File #9926268 © creisinger. All other images courtesy of the authors.

Set in 10/12pt Avenir by SPi Publisher Services, Pondicherry, India

1 2014

CONTENTS

PREFACE vii

ACKNOWLEDGEMENTS xv

ABOUT THE COMPANION WEBSITE xvi

1 **Why Model Climate?** 3

2 **The Evolution of Climate Models** 69

3 **Energy Balance Models** 139

4 **Intermediate Complexity Models** 199

5 **Coupled Climate System Models** 281

6 **Through the Looking Glass** 371

COLLECTED ENDNOTES 393

HINTS AND SOLUTIONS 401

LIST OF ABBREVIATIONS 402

LIST OF SYMBOLS 406

BIBLIOGRAPHY 407

INDEX 431

PREFACE

Today, climate modelling affects everyone, everywhere. Today, the Worldwide Web contains myriad resources for anyone interested in climate modelling. These include videoed talks by world experts, fantastic simulations made using some of the world's most modern models and links that allow an interested beginner to actively participate in climate modelling themselves. This pervasive electronic environment means that our fourth edition of *The Climate Modelling Primer* is quite different from its predecessors. This latest edition still represents the culmination of more than a quarter of a century of learning about how to model climate but we have re-oriented the book towards engaging readers in an interactive experience, making use of internet resources such as scannable QR (quick response) codes and links to websites, articles, etc. Times change, and today's climate model beginners more frequently wish to know how models work in order to allow them to understand model simulations properly, rather than themselves wanting to build, run or own a climate model. In response to this need, we suggest activities, such as developing a 'treasure chest' collection, writing blogs and addressing local community meetings that are designed to appeal to anyone wishing to develop their understanding of climate modelling science.

Climate modelling may seem to be about computers and technology but it is also very much about people. How models evolve and how well they are understood and who trusts their results depend critically on the scientists who build them, the funders who support them, the policy analysts who use them and the communicators who explain their outputs. This has always been true but today the emphasis has shifted from a scientific activity with little apparent public scrutiny to one about which *everyone* has an opinion. Many of these are less fully informed than they wish. *The Climate Modelling Primer* is dedicated to these people: readers who hope to gain understanding about 21st-century climate modelling.

Our *Climate Modelling Primer* (CMP) has greatly evolved since the first edition published in 1987. In keeping with the rapid development of climate models, modelling techniques and tools, the model environment, and indeed climate modellers themselves, every CMP version has changed. The first edition contained a 'floppy' disk that was, at the time, quite revolutionary. The second edition included a CD offering a small number of visualisations from actual climate model runs: a novel concept in 1997. The third edition also included a CD and we developed a dedicated website (www.climatemodellingprimer.net/). Now a classic, *The Climate Modelling Primer* can be considered as a guide to the rules and riddles of climate change science for those who need to know how models work and what they can deliver. Today, this audience includes virtually all thoughtful citizens and certainly all our political leaders.

This fourth edition aims to reach out by delivering information in a user-centred format. We take as our premise that each reader (each climate modelling student) intends to increase their understanding of climate models. Throughout the *Primer* we will examine climate modelling from the premise that 'all models are wrong; the practical question is how wrong do they have to be to not be useful' (Box and Draper 1987). Naturally, climate prediction will be important but we will endeavour to draw attention to the other strengths and benefits of climate modelling throughout this text.

The book encourages learning by including a number of specific tools in every chapter:

- A clear statement of learning objectives at the beginning of each chapter
- Illustrative climate model understanding insets such as speed dating, model validation, feedback and so-called 'wiring' diagrams
- Technical/mathematical boxes that explain underpinning theory more fully
- Practical communication exercises about climate modelling as a 'learn by doing' enterprise

- Downloadable, easy-to-use climate models to explore concepts
- Biographies of people who are/have been important in climate modelling
- Short exercises that summarise the chapter's content and consolidate learning by means of research and review questions
- A closing 'Showcase Study' that highlights some of the main points in the chapter

Below we demonstrate how these aspects will appear in this fourth edition of *The Climate Modelling Primer*.

Learning Objectives – for the whole book

After studying this book you will:

- be familiar with the history of climate modelling and understand its aims for the future
- understand how climate models are used in simulations of past, future and current climates at a variety of scales
- be able to assess a wide range of communication forms employed to share results from climate model simulations with different audiences
- recognise the variety of confidence and uncertainty measures associated with climate model outputs and know how to interpret them
- appreciate the ways in which results from climate models affect 21st-century policy, laws, international trade and human development.

These items are reviewed as Learning Outcomes for this book in Chapter 6.

Illustrative climate model understanding boxes

These are exercises to be appreciated; indeed, we hope, enjoyed. We encourage you to dip into them.

Illustrative climate model understanding

Boiling a frog

There is a well-known story about what allegedly happens if you boil a frog. Take a quick look on the web to source a few examples of this such as cartoons, sketches, etc.; for example, boiling the frog movie: http://www.climatemodellingprimer.net/l/k001.htm

There are two lessons to draw from this modern parable: the first emphasises the relationship between speed of change and response to it. The second exploits humorous comparisons between frogs and people to point out wisdom and awareness.

In terms of climate modelling, the question is – which of these illustrations has value in explaining or demonstrating characteristics of models?

This might be the place to explain that we are referencing material differently in this edition. We offer a very short literature history at the end of each chapter – this is a background historical overview of the topics in that chapter. All our other literature citations are in the form of endnotes – gathered at the end of the book. These and other reference material are collected in a complete Bibliography, also at the end of the book.

Technical/mathematical boxes

These usually include mathematical developments that are worked outside the main text because they can be followed or not as the reader prefers. So you can skip these if you wish. For example:

Tech Box 1

Very simple climate model (static version)

The simplest global climate model can be written as follows:

$$(1-\alpha)\frac{S}{4} = \varepsilon\tau_a\sigma T^4 \qquad \text{(Tech Box Eq 1)}$$

Using values of $S = 1370\,\mathrm{W\,m^{-2}}$, $\alpha = 0.3$, $\varepsilon\tau_a = 0.62$ and $\sigma = 5.67\times10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$ gives for T (the globally averaged surface temperature) a value of 287 K, or about 14°C, close to Earth's average surface temperature today.

Climate Model Communication Box 1

Write a blog (diary) or tweet: action

If you already have a blog or can 'blog' in a group site, that's great. If not, either create one (this is simple) or write a personal diary. Or you may prefer to 'tweet'.

Your task is to create blog entries about 10 different aspects of climate models during the time it takes you to work through this book. Each entry has to be at least 100 words long and with a great headline. If you prefer to 'tweet', then create 50 tweets in total: five per topic.

If you are unfamiliar with blogging or tweeting, the first step is not to write yourself but to hunt the web for blog entries that you like. Collect at least 10 entries you like, as different as possible (i.e. by different people; about different topics; written with different audiences in mind). List why you like each of these entries and try to develop a set of 'good characteristics' from this list that will help you to write interesting blogs yourself. Discuss your ideas with someone who is a successful blogger.

Your goal is to influence others. Consider how you might try to measure this.

Practical communication about climate modelling: learning by doing

Our hope in proposing an example 'climate model communication' idea in each chapter is to encourage sharing of modelling concepts and of climate model understanding. In all aspects of life, nothing better aids understanding than the process of trying to explain something to someone else. We have an undisguised second motive in making these suggestions – we hope that readers of our *Primer* will assist in widening community appreciation of all that climate models can do – and all they cannot!

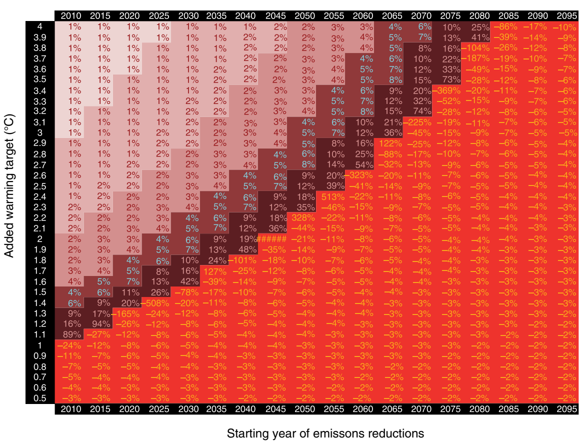
A, B, C to R, S, T of climate modelling

At the end of most chapters, we invite reader review and involvement following the topics: **R**, Reasons for climate modelling; **S**, Signposts to understanding; and **T**, Treasures of climate model discovery and insight.

To encourage personal learning, we are employing an old technique that may be unexpected in this context: a collector's chest. The goal is that as you read the *Primer* you collect climate modelling treasures: a small set of illustrations that you find persuasive, pretty and memorable. Beginning a great treasure collection will be the Climate Modelling Communication task in Chapter 1. One of the authors' examples is mostly a collection of web links. When these occur in this edition, we also give QR code pictures: point your smartphone at the QR code here to view one of these simulations: http://www.climatemodellingprimer.net/l/k002.htm

Downloadable, easy-to-use climate models to explore concepts

The downloadable models can be found on www.climatemodellingprimer.net. One is a simple energy balance model (EBM); another spreadsheet model illuminates anthropogenic climate change mitigation options. In Chapter 2, we explore the latter simple model, which calculates the required emission reduction rate (% per year) as a function of the desired climate target and the start date. In this figure, temperature limit goals are unachievable in the lower right, bright red area. Climate control 'targets' (resulting warming above preindustrial temperatures) rise exponentially as a function of start date (year) of any proposed reduction scheme. This is a screen snapshot from one of our spreadsheet models.



Biographies of people who are/have been important in climate modelling

Our 'meet the modeller' biography boxes are genuine introductions to real people. The first example we've chosen for this Preface may seem a little odd – our short biography is of Isaac Asimov (Biography Box 1). We chose Dr Asimov for a couple of reasons, as well as the fact that we both love his science fiction. Asimov has influenced people we mention in the *Primer* (read the biography to find out who). He also pushes science to close to its limits in his concept of psychohistory: a series of mathematical

Biography Box 1

Meet the modeller: Isaac Asimov

Isaac Asimov (2 January 1920 – 6 April 1992) was an American scientist, famous author and professor of biochemistry at Boston University. A prolific writer, he is renowned for the fact that he published books in all 10 major categories of the Dewey Decimal (library) System. He is credited by the *Oxford English Dictionary* with the introduction of the words robotics, positronic (his robotic brains were positronic) and psychohistory (the theory of large numbers of intelligent agents invented by Hari Seldon as the basis of the *Foundation* series).

Isaac Asimov described Carl Sagan as one of only two people he ever met whose intellect surpassed his own. The other, he claimed, was the computer scientist and artificial intelligence expert Marvin Minsky. Paul Krugman, a Nobel Laureate in Economics, has stated that it was Asimov's concept of psychohistory that inspired him to become an economist (Krugman 2010).

Read more

Asimov, I. (1980) *In Joy Still Felt: The Autobiography of Isaac Asimov, 1954–1978*. New York: Doubleday/Avon. pp. 217, 302.

Asimov, I. (1988) *Prelude to Foundation*. New York: Bantam Books.

Watch

Asimov on life-long learning: http://www.climatemodellingprimer.net/l/k003.htm

Biography Box 2

Meet a modeller: Ann Henderson-Sellers and Kendal McGuffie

Climate modelling leadership: AH-S conducted the world's first climate model simulation of tropical deforestation in 1982, which led to the quantification of the role of forests in large-scale climate change. KMcG and AH-S worked together in the late 1980s/early 1990s to deliver one of the first digital intercomparisons of climate model results through the Model Evaluation Consortium for Climate Assessment (MECCA) Analysis Team (see 2nd edition of the CMP's CD for these results).

Popular recognition: This is their seventh joint book if you include the one they co-wrote about hiking the Australian Great North Walk – a history of the 250 km bush track connecting the New South Wales cities of Newcastle and Sydney.

Kendal McGuffie and Ann Henderson-Sellers. Photo source: K. McGuffie and A. Henderson-Sellers.

Climate modelling connectivity: Ann owes much of her understanding of climate models to Jim Hansen and of the land surface to Bob Dickinson. Both Kendal and Ann have worked closely with Greg Holland, the respected mesoscale modeller, including in the co-authorship of the definitive paper published in 1998 in the *Bulletin of the American Meteorological Society*.

Life and times: Kendal McGuffie is an Associate Professor and Head of the School of Physics and Advanced Materials at the University of Technology, Sydney. He graduated from the University of Edinburgh with a BSc in Physics and went on to complete a PhD at the University of Liverpool on cloud and radiation interactions. His first paper resulted from what his supervisor considered to be an excessive fascination with the hysteresis cycle of snow albedo. He has also researched tracking the hydrological cycle using stable water isotopes and conducted observational studies of tropical convection in association with the development of novel observational platforms for tropical cyclone monitoring.

Ann Henderson-Sellers was one of the founders of model-based analysis of the land surface in climate, contributing fundamentally to understanding anthropogenic climate change. Thirty years ago, she co-created (with Mo Wilson) the first digital dataset of vegetation and soil and, in 1992, she designed and co-ordinated the first international intercomparison of climate modules. She has held many positions, including being the Director of the United Nation's World Climate Research Programme culminating in its contributions to the IPCC being recognised in the Nobel Peace Prize for 2007.

Together these researchers have contributed to a wide variety of aspects of climate: explaining models, evaluating simulations and rescuing data; for example, between 1985 and 1995 they jointly identified and accessed archival sources that showed cloudiness increasing over the 20th century. They also share random godchildren, an electric car, pleasure in movie going, a penguin and a chocolate Raisin.

Read more

Henderson-Sellers, A., Zhang, H., Berz, G., et al. (1998) Tropical cyclones and global climate change: a post-IPCC assessment. Bull Am Meteorol Soc 79(1), 19–38.

Henderson-Sellers, A., McGuffie, K. (eds) (2012) *The Future of the World's Climate*. Amsterdam: Elsevier Scientific. (Winner of the Atmospheric Science Librarians International (ASLI) Choice Award for 2012.)

Watch

Communicating climate change: hurricane hazards' honesty (KMcG and AH-S), 2011, Rhodes:http://www.climatemodellingprimer.net/l/k004.htm laws by means of which one can predict the future of civilisations. This idea is interesting today because we are now asking how far into unexpected and so far unexplored domains might climate models be useful: to predict human health, to construct policy about limits to population growth, or to frame political debate about geoengineering?

Our second reason for including biographies of well-known climate modellers, beyond the obvious one of introduction, is to try to mention some of the personal connections among folks in this field. Although there are many modellers today, this community grew quite fast from a tiny origin. Tracing some modeller links illuminates how some models seem more closely related than others. For anyone interested in family histories, there are fascinating tales to unravel of relationships, break-ups and long-lost siblings.

Speaking of links, it is time to introduce ourselves (Biography Box 2).

As another example of the QR codes we will use throughout the *Primer*, here is a link to a talk by one of our most beloved modellers – check him out. http://www.climate-modellingprimer.net/l/k005.htm

Chapter summary

At the end of every chapter we offer a two-part set of exercises: the first part is questions that can be answered – say in a report or essay. The second part contains more open-ended questions to prompt discussion. This is also the very last section of the book – reviewing and reflecting on learning gained from the book as a whole.

All these collected summary topics can be pursued by an individual or as part of class or group learning.

1 Summary: research and review

Review topic and question

Write a 200-word description of any climate model or climate model simulation you know about that is suitable for a public blog or a newspaper column. For example, model predictions of future climate changes relevant to where you live.

Discussion topic

Assess the success of either your communication (in your response to the above invitation) or our description of what will be found in this book. Did the communication mostly focus on how models work, on the confidence or uncertainties of predictions, on the development that underpins models or on the actions that are demanded by the results of the simulation?

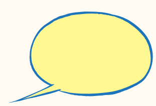
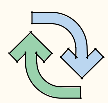
Rate the success of either communication on a scale of 1 (dreadful) to 10 (fully successful).

Chapter closing showcase

Here we list the boxes that appear in the six chapters of *The Climate Modelling Primer* and give a hint about the topics they illustrate. As well as the biography boxes and the technical (mathematical) material boxes, there are eight sets of explanatory boxes that involve the reader in thought, further study or research.

1. Speed Dating: Meet a Model – a very quick 'meet and greet' of a real model
2. CSI (climate simulation intrigues) in sets of four per chapter

Table 1 Boxes in the book. The boxed material in Chapters 1–5 (and also in Chapter 6, but not boxed) can be checked and cross-referenced using this summary

Chapter	Speed Dating: Meet a Model	CSI: Climate Simulation Intrigues	Climate Model Validation	Spotlight – probing models	Climate Model Communication	Feedback Diagrams	Wiring the World	Showcase – end of chapter study
Purpose of study elements	Quick 'chat' with a range of models	4-box set outlining a climate intrigue	How models are evaluated and verified	Examination of one aspect of a model	Sharing understanding of modelling	Components and links: vital parts of model construction and comprehension		Review and thought prompter
Task	Fast greeting	Quick read	Discussion prep	Details of models	Action / participate	Developing diagram power		Review and discuss
Time (each)	3 minutes	2 minutes each box	15–30 minutes	20–30 minutes	20 minutes to days	A few minutes or longer		1–1.5 hours
1: Why Model Climate?	Gamers' climate model	Weirdness of water	Regional climate simulation	Palaeoclimates and Palaeo-MIP (model intercomparison project)	Modellers' meeting and 'Alien' magazines	Meet the 'CLAW'	ATLAS @ CERN and Coastal Councils	Radiation testing: satellites versus models
2: Evolution of Climate Models	Lorenz's butterfly	Co-evolving computers and climate	Hansen's famous 1981 climate prediction – correct	Discipline is born: climate models' first review	Climate models in the arts	Cloudiness: defogging cloud schemes	Ocean warming and CMIP management	Desertification when the Sahel was 1970s news
3: Energy Balance Models	Daisyworld	Clouds and the cryosphere	Quadrupling, not doubling, CO_2	Energy balance models in 1976	Local councils	Sea-ice	Original and briefer 'Bretherton'	Martian climate
4: Inter-mediate Complexity Models	Model's 'IMAGE'	Committing to confidence	Milankovitch – climate and the Sun	'MAGICC' of aerosols	Policy making using climate model results	Tall grass carbon	Energy wiring in MESSAGE and REMIND	Economics of 'RICE'
5: Coupled Climate System Models	A community of climate modellers	International climate law	Cloud water ice – changing representations	Forcing and feedbacks	Mass media portrayal of climate models	Ocean circulation	Nitrogen cycle and Baltic sea linkages	Coupling climate to the land
6: Through the Looking Glass (in text, not boxes)	Weather at home do-it-yourself prediction	Still curiouser character-istics of water	Attributing extremes to climate change	Perturbed physics ensembles probed	Conference participation or video making	Deforesting the Amazon	Gaia and wheel of intelligence	Citizen science – people join Climate Prediction.net
Icon								

ATLAS, A Toroidal LHC (Large Hadron Collider) Apparatus; CERN, Conseil Européen pour la Recherche Nucléaire; CLAW, paper identified by authors' names: Charlson, Lovelock, Andreae, Warren; CMIP, coupled model intercomparison project; IMAGE, Integrated Model to Assess the Global Environment/Integrated Model to Assess the Greenhouse Effect; MAGICC, Model for the Assessment of Greenhouse-gas Induced Climate Change; MESSAGE, Model for Energy Supply Strategy Alternatives and their General Environmental Impact; REMIND, Refined Model of Investment and Technological Development; RICE, Regional Integrated model of Climate and the Ecology.

3. Model Validation – comparing observations and model results
4. Spotlight on Climate Models – probing one aspect of important climate modelling papers
5. Climate Model Communication – ideas to tempt climate model sharing
6. Feedback diagrams – connecting components
7. Wiring the World – describing relationships
8. Showcases – climate model paper highlight at the end of each chapter

Throughout the book, these boxes offer reviews and forward glimpses (Table 1).

There are a number of 'routes' through this book. We hope you will begin with Chapter 1 but, beware, it contains lots of ideas and material, much of which is explained in subsequent chapters. If you come across stuff you don't fully follow, don't worry too much just there. For example, if you need to find out about the skill and capability of today's models, go to Chapter 5 but we also recommend reading Chapter 1 on 'why model'. If you want to try modelling for yourself then read Chapter 3 with a preliminary scan of Chapter 2 on the evolutionary history of climate modelling and download the simple models described. Chapter 4 is rather mathematical but if you really need to know the ingredients of modelling, then it is your study text, after an introduction in Chapter 1 or 2.

Finally, we still enjoy learning about climate models and their applications and we do very much hope that our readers will share some of our enjoyment in this new, fourth edition of *The Climate Modelling Primer*.

Kendal McGuffie and Ann Henderson-Sellers
Sydney

ACKNOWLEDGEMENTS

We are, as ever, immensely grateful to Brian who seems always ready and willing to set aside his own research and book writing in order to help us with ours. Without him we would have poor spelling, terrible punctuation and a whole lot of muddled science – thanks for everything Bri!

We also wish to thank all our reader-reviewers of this edition. Drs Liam Phelan and Huqiang Zhang were especially helpful in their comments, criticisms, edits and enthusiastic support. We are also grateful to (in alphabetical order): Dr Jean-François Exbrayat, Dr Supriya Mathew, Dr Debasish PaiMazumder, Martin Rice, Dr Maria Tsukernik, and Martin Vezér. They all made very useful contributions to the editing phase. This edition could have included mistakes from earlier editions if it were not for the diligent feedback received from many earlier readers, many of whom joined us in the Model Evaluation Consortium for Climate Assessment Analysis Team (pictured below) – thank you all.

Despite these acknowledgements, we must, of course, assume full responsibility for any remaining imperfect explanations and for any errors that may have crept in. Please contact us via the web page (http://www.climatemodellingprimer.net) and let us know if you find any of these.

We have drawn on a very wide variety of published material. Specific credits are given where the figure, table or quotation is used, coupled with all references being listed in full in the Bibliography at the end of the book. Fiona Katauskas (fionakatauskas.com) drew most of the cartoons. 'Why cutting down forests reduces rainfall' is reproduced by permission of Cathy Wilcox, Fairfax Media.

ABOUT THE COMPANION WEBSITE

This book is accompanied by a companion website:

www.wiley.com/go/mcguffie/climatemodellingprimer

The website includes:

- Figures from the book
- Tables from the book

The authors also operate a website:

www.climatemodellingprimer.net

It is frequently updated and contains:

- All the hot-linked QR code addresses
- Updates and corrections to this and earlier editions
- All the downloadable computer models
- Readers' feedback

Vocabulary of Climate

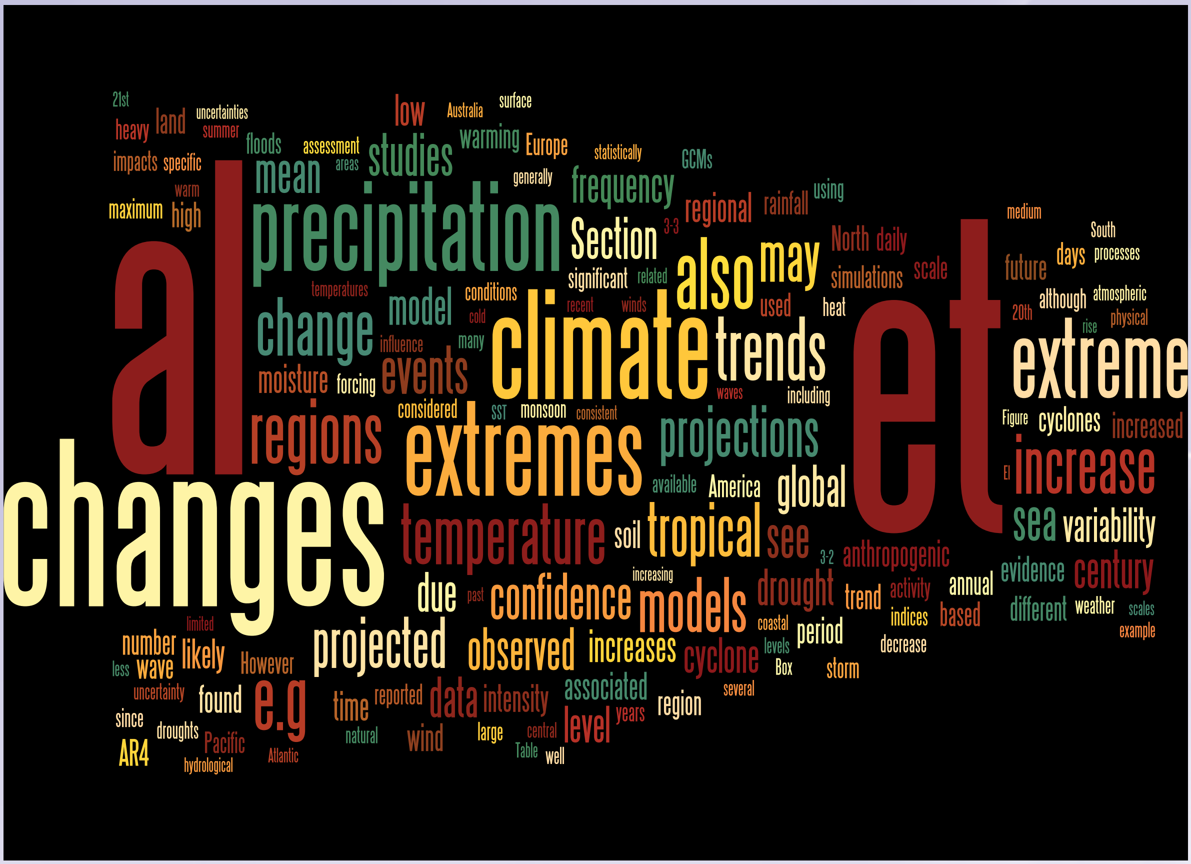


Plate 1.1 Vocabulary of climate. How we discuss climate today is illustrated in this 'wordle',[1] created by Neville Nicholls using the text in Chapter 3 of the 2012 Intergovernmental Panel on Climate Change (IPCC) Report on Climate Extremes.[2] Most of the work drawn upon is collaborative, so the phrase 'et al.' indicating with others dominates. Interestingly, *precipitation* is more frequently used (larger) than *temperature; projected* and *projections* occur much more often than *evidence*; and, relevant for this book, *models* and *confidence* are both fairly important.

1 Why Model Climate?

'All models are wrong, but some are useful.' (Box and Draper 1987, p4)

'The strongest arguments prove nothing so long as the conclusions are not verified by experience. Experimental science is the queen of sciences and the goal of all speculation.' (Roger Bacon ca. 1214–1294)

Plate 1.2 Eclipse 2012 – the climate is driven first and foremost by solar radiation.

LEARNING OBJECTIVES

After completing this chapter, you will be able to:

- recognise the many reasons for having models
- track the history of climate theory becoming fact
- list the factors affecting planetary scale climate
- explain the concept of climate feedback and give examples
- recognise the mechanisms whereby persistent and widespread life affects climate.

The Climate Modelling Primer, Fourth Edition. Kendal McGuffie and Ann Henderson-Sellers.

Companion website: www.wiley.com/go/mcguffie/climatemodellingprimer

1.1 Introduction

This book is entitled *The Climate Modelling Primer*, a title that presupposes modelling to be a useful exercise, and that readers are familiar with the idea of models and the reasons for participating in modelling. We assume you are interested in building or testing models or in exploiting their results. This foundation chapter tests these assumptions by examining the important question, 'Why model climate?'. We try to answer this question in three ways: first by looking at reasons for modelling in general; by applying a selection of these reasons to climate modelling; and then by taking a very different view of Earth's climate, from a distant galaxy, and using this metaphorical alien climate scoping to investigate some of the fundamental ingredients of planetary climates and thus of climate models. In this opening chapter we cover a wide variety of topics quite quickly to give a sense of the wonderful breadth of climate models and their achievements. In doing this we do not define or explain in much detail because these explanations constitute the rest of this book. If you come across a concept you wish to understand better, you can locate a further description of it using the index or checking the summary of boxed material at the end of the Preface.

The characteristics of climate and hence those that climate models must try to reproduce can be thought of as a primer – or perhaps an A, B, C – as outlined in Table 1.1.

- ***A is for astronomy***: any planet or moon with a climate is constrained by fundamental astrophysical conditions.
- ***B is for boundary and for biology***: climate becomes interesting to model most often when it relates to living systems and where it touches boundaries.
- ***C is for comprehension***: the reasons for constructing, operating and analysing climate models are ultimately to try to understand climate change and variability.

To encourage personal learning, we are employing an old technique that may be unexpected in this context. It is a 'collector's chest'. In the 18th and 19th centuries, such collector's chests were built to hold and attractively display novel collections of scientific specimens. Many voyages of discovery included natural scientists who would have carried their rare and curious samples home in such sturdy wooden chests. Our example (Figure 1.1), the Macquarie collector's chest, was

Table 1.1 A primer, or 'A, B, C', of climate modelling

A, B, C	Aspects of climate modelling
A: Astronomy	Astrophysical attributes – orbit, atmosphere, radiative budget, existence/ prevalence of water …
B: Biology and boundaries	Life and climate, surface conditions, volcanic activity …
C: Comprehension	Prediction, testing theories, raising questions, bracketing outcomes, directing data collection, disciplining policy …

Figure 1.1 The Macquarie collector's chest. Collections like these were for display and specifically designed as attractive and persuasive depictions of unusual places. Source: Mitchell Library. State Library of NSW – XR 69.

Table 1.2 The *Primer* authors' climate modelling treasures, following the items in the old collector's chest shown in Figure 1.1

Type	Old chest	Authors' treasure collection
Visual	Paintings	The cartoon by Cathy Wilcox illustrating the CMP authors' research on Amazonian deforestation that was published on the front page of our local newspaper
Personal experience	Butterflies, beetles, etc.	Results from the Model Evaluation Consortium for Climate Assessment intercomparisons created in 1992. These were probably the first global climate model intercomparisons (e.g. videos on CD in CMP2)
Oceans	Algae and seaweeds	Movie featuring the ocean near where we live – 'Finding Nemo' (2003 and in 3D in 2012), especially for its depiction of the East Australian Current – the one that carries the turtles
Change behaviour	Exotic stuffed birds	Photos from visits to the melting Mont Blanc glacier when the authors lived in Geneva
Pretty things	Arrangements of sea-shells	Art work on the cover of *The Future of the World's Climate*, a book the CMP authors edited in 2011–12. Both the art itself and the quotation it contains
How it works	Artefacts	An antiquarian water band spectroscope that KMcG bought for AH-S's birthday that shows water vapour absorption bands (an in-your-hand greenhouse demonstrator)

almost certainly intended as a special presentation piece to celebrate the colony of New South Wales once the Governor, to whom it was given, arrived back in the UK. If you are not keen on stuffed birds and old seaweed, another type of treasure collection still to be found in some homes is the heritage quilt, and a still more modern version is scrapbooking.

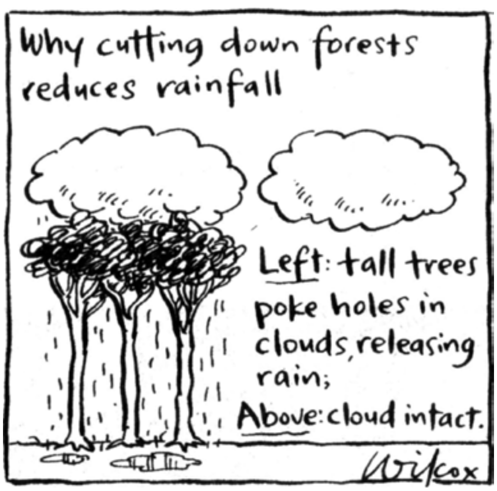
Climate Modelling Primer (CMP) readers are welcome to use whichever analogy they prefer: collector's chest, heirloom or heritage quilt or digital scrapbook. The goal is that, as you read the *Primer*, you collect climate-modelling treasures: a small set of illustrations that you find persuasive, pretty and memorable. These can be real objects such as diagrams, papers, cartoons, printouts, etc. or virtual links as in our example at the end of this chapter (see Table 1.11). The point of the collection is to assist recall of aspects of climate modelling that you may find difficult to understand or perhaps that you find challenging to explain. Each collection is, therefore, rather personal, but not private, because like Governor Lachlan Macquarie's chest, it will contain amazing illustrations selected for explaining, remembering and sharing. To begin your great treasure collection, we offer you the tangible version of ours (the authors') in Table 1.2 and later we introduce our e-chest version.

At the end of this chapter, we give another of our collection examples and then each *Primer* reader is on their own to collect the best (most interesting) items for themselves.

1.2 What is a climate model?

In the broadest sense, models are for learning about the world (in our case, the climate) and the learning takes place in the construction and the manipulation of the model, as anyone who has watched a child build idealised houses or spaceships with Lego™, or built with it themselves, will know. Climate models are, likewise, idealised representations of a complicated and complex reality through which our understanding of the climate has significantly expanded. All models involve some ignoring, distorting and approximating, but gradually they allow us to build understanding of the system being modelled. A child's Lego construction typically contains the essential elements of the real object, improves with attention to detail, helps them understand the real world, but is never confused with the real thing.

In the past few decades, the boundaries of the climate system that we are modelling have become much less clear. This evolution, though not inhibiting in itself, is exemplified by a quick survey of the term 'climate' in textbooks a century apart – say 1910 and 2010. In the former, climate is viewed as constant and stable – the average weather of a place or region defined in terms of unchanging seasons, crops, habitability, etc. In the latter, climate is typically viewed as a planet-wide characteristic, undeniably variable but also subject to change; climate is a topic of huge discussion, if not outright dispute. Consequently, what climate modelling involves has changed and will, no doubt, continue to change. Nonetheless, most people share an understanding of what a 'climate model' entails. Here, we use the analogy of a cooking recipe.



1.2.1 Climate modelling and cooking: feeding good

Issue: *cooking is an interesting analogy for climate modelling.*
Message: *the best meals, and models, depend on many characteristics: fine ingredients, the chef's skill and the consumer's attitude, e.g. palate, hunger/desire and ambience.*

Making a meal and constructing a climate model share, perhaps, three or four essential steps: selecting the ingredients, combining and processing them, the evaluation (appreciating the fruits of the kitchen) and, often, considering repeating the recipe. As with any recipe, you can vary the ingredients of a climate model a little and create a similar dish or change a lot and cook up something altogether different. This analogy encourages additional comparisons: some ingredients are essential, some optional; frequently the order of the steps must be followed rather rigorously; evaluation is a vital part of the process (why cook if no-one eats?) but is poorly quantified; and, finally, success does not guarantee repeating good outcomes, but is a hopeful sign (Table 1.3). Cooking and modelling share another important feature: it is quite possible to understand how a good meal is constructed and appreciate it without having the detailed culinary skills to replicate it. So it is with models. This *Primer* is for nourishment and budding food connoisseurs but not really for chefs.

In this chapter, we intend to take a very quick look at a large selection of climate models. If you are happy to think of this *Primer* as a recipe book, then this chapter serves as kitchen preparation – we can consider the menu, possible ingredients, tools (even including a dishpan!) and, most

Speed Date Box 1

Gamers go-for-it: the 2007 Climate Challenge

Meet: http://www.climatemodellingprimer.net/l/k101.htm

Name and date of birth: *Climate Challenge* is a web-based computer game created by the game development company Red Redemption in 2007 and sponsored by the BBC.

Fame factor: This game was created in response to the growing awareness of the role that climate models would play in international negotiation by the worldwide mass media. The BBC was plugging into public interest in the run-up to the famous 15th Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) in Copenhagen in December 2007.

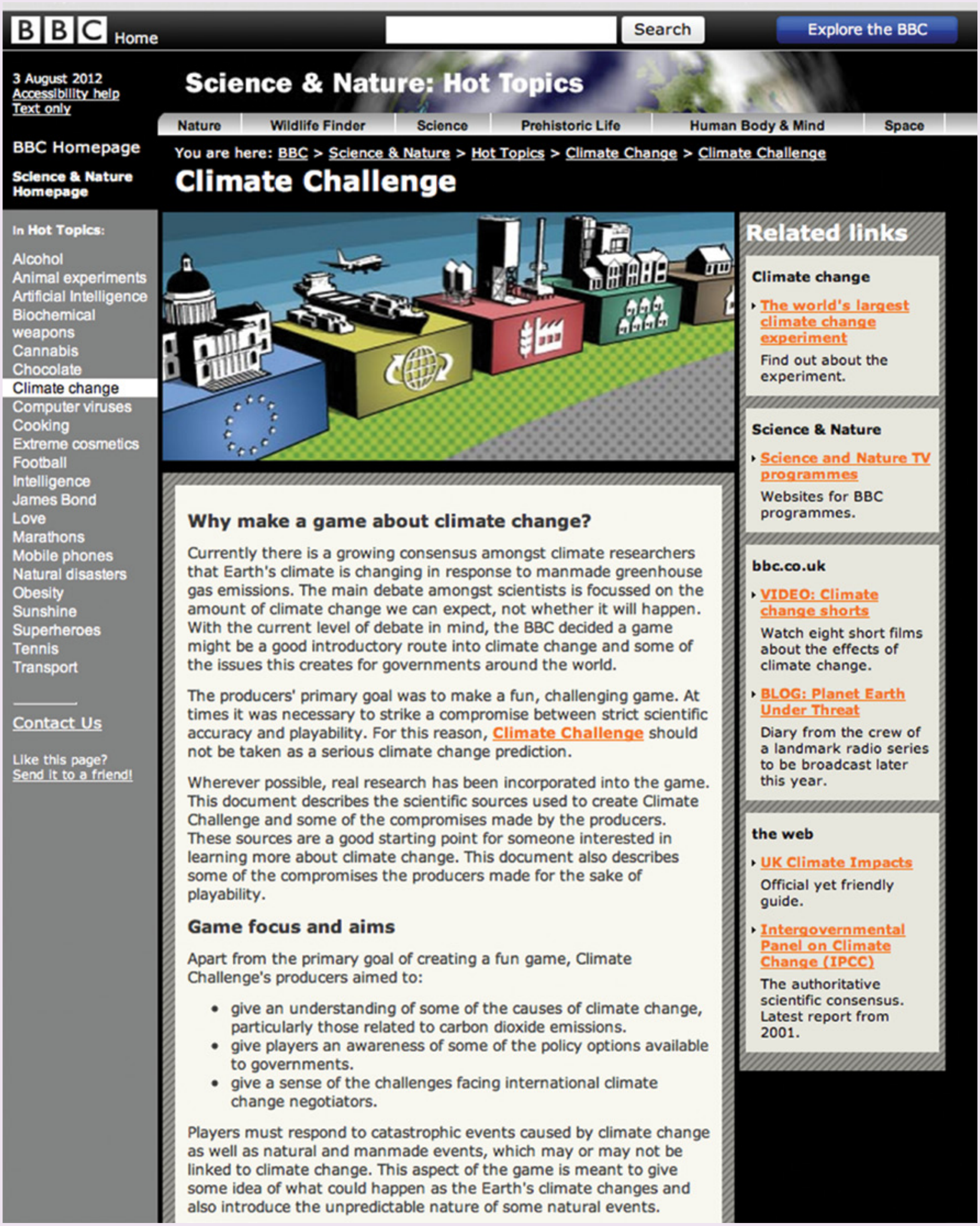
Looks: *Climate Challenge* is fun: fairly fast but also thought-provoking and open-ended. Each player works through simulations occupying this century (2000–2100) in which you (the player) become the President of all 'European nations'. Your goal is two-fold: radically reduce your country's CO_2 emissions and also manage to remain popular enough to stay in office. The popularity catch is the true reality of the climate challenge for the world's politicians. The science in *Climate Challenge* is sound, having been developed at Oxford University using the UK Meteorological Office's global climate model.

In the game, each simulation (round) lasts 10 turns, each spanning a decade between 1990 and 2090. Progress is measured by four world resources plus gas emissions: money (in millions of euros); energy (in megawatt hours); food stocks (in millions of tonnes); water (in trillions of litres); and carbon dioxide (CO_2) emissions (in millions of tonnes or teragrams). A turn consists of selecting up to five policy cards, each of which will use up or add certain resources. For example, 'Import Food' adds food but costs euros and energy and adds to the CO_2 emissions. Similarly, 'Require Energy Efficient Appliances' costs euros but adds energy and reduces CO_2 emissions. Particular policies unlock other cards such as planting large forests. But disasters can strike, draining resources unexpectedly and forcing the player to choose between a very expensive, unpopular policy and an expensive, very unpopular policy.

Coverage: Every policy has an approval rating and, if enough citizens are unhappy with your performance, you will be voted out, which ends the game. Between turns, a newspaper page provides feedback on your progress and public opinion. There was a six-part TV series created at the time the game went live (2007) co-produced by One Planet Pictures (UK) and dev.tv (Switzerland) http://www.climatemodellingprimer.net/l/k102.htm

On a date: Your date goal is to reduce CO_2 emissions to the target levels agreed by the global community and also to keep your electorate happy. Periodically, you (the player) have to meet other world leaders at the Climate Change Summit and vote on setting new global emissions limits. This is not unlike the UNFCCC COP meetings. If other leaders feel that you/Europe is not doing enough, they will be less inclined to reduce their own emissions and you will have to subsidise them, an expensive way to buy votes. There is a fierce sense of reality to this climate model speed date.

(*Continued*)



BBC Home | Search | Explore the BBC

3 August 2012
Accessibility help
Text only

Science & Nature: Hot Topics

Nature | Wildlife Finder | Science | Prehistoric Life | Human Body & Mind | Space

BBC Homepage

Science & Nature Homepage

You are here: BBC > Science & Nature > Hot Topics > Climate Change > Climate Challenge

Climate Challenge

In Hot Topics:

Alcohol
Animal experiments
Artificial Intelligence
Biochemical weapons
Cannabis
Chocolate
Climate change
Computer viruses
Cooking
Extreme cosmetics
Football
Intelligence
James Bond
Love
Marathons
Mobile phones
Natural disasters
Obesity
Sunshine
Superheroes
Tennis
Transport

Contact Us

Like this page?
Send it to a friend!

Why make a game about climate change?

Currently there is a growing consensus amongst climate researchers that Earth's climate is changing in response to manmade greenhouse gas emissions. The main debate amongst scientists is focussed on the amount of climate change we can expect, not whether it will happen. With the current level of debate in mind, the BBC decided a game might be a good introductory route into climate change and some of the issues this creates for governments around the world.

The producers' primary goal was to make a fun, challenging game. At times it was necessary to strike a compromise between strict scientific accuracy and playability. For this reason, Climate Challenge should not be taken as a serious climate change prediction.

Wherever possible, real research has been incorporated into the game. This document describes the scientific sources used to create Climate Challenge and some of the compromises made by the producers. These sources are a good starting point for someone interested in learning more about climate change. This document also describes some of the compromises the producers made for the sake of playability.

Game focus and aims

Apart from the primary goal of creating a fun game, Climate Challenge's producers aimed to:

- give an understanding of some of the causes of climate change, particularly those related to carbon dioxide emissions.
- give players an awareness of some of the policy options available to governments.
- give a sense of the challenges facing international climate change negotiators.

Players must respond to catastrophic events caused by climate change as well as natural and manmade events, which may or may not be linked to climate change. This aspect of the game is meant to give some idea of what could happen as the Earth's climate changes and also introduce the unpredictable nature of some natural events.

Related links

Climate change
- The world's largest climate change experiment
Find out about the experiment.

Science & Nature
- Science and Nature TV programmes
Websites for BBC programmes.

bbc.co.uk
- VIDEO: Climate change shorts
Watch eight short films about the effects of climate change.
- BLOG: Planet Earth Under Threat
Diary from the crew of a landmark radio series to be broadcast later this year.

the web
- UK Climate Impacts
Official yet friendly guide.
- Intergovernmental Panel on Climate Change (IPCC)
The authoritative scientific consensus. Latest report from 2001.

Figure source: www.bbc.co.uk

Table 1.3 Components of recipes for cooking and for climate modelling

Characteristics	Meal	Climate model
Ingredients	Some essential, some optional	Some essential, some optional
Method	Ordered and quantified	Ordered and quantified
Evaluation	Does it resemble the photo? How does it taste? Did anyone get sick? High nutritional value?	Can it simulate present day? How about a different geological era? Are there aspects that are wrong? Can it predict?
Repetition	Are changes possible or desirable?	Are changes possible or desirable?

importantly, how to combine ingredients to create a value-delivering climate model. Throughout, please take our analogy with a 'pinch of salt' (pun intended). Remember that not all dishes win favour with all diners and from time to time our desire for, and pleasure in, different meals differs. This is as true for climate models as for food. Models can be as different as peanut butter sandwiches and crème caramel; they please differently and typically cannot readily substitute for one another.

A quick review of Figure 1.2 underlines that just having a menu or list of ingredients (for a modern climate model this might comprise atmosphere, land, ocean, sea-ice, aerosols, carbon cycling, vegetation, chemistry, nitrogen, ice sheets and more) does not get the meal ready. All modellers also need the recipe for constructing each dish. The nature of these climate model ingredients will be the subject of most of the rest of this book. How to create a climate model will depend to a very great measure on what the modeller and user want to predict or understand. Different models demand different methodologies and there are a number of ways of illustrating this; we have chosen here to highlight the strengths and weaknesses of climate models by examining why people build and use them.

1.2.2 Climate models are much more than code

Climate models are first and foremost collections of software (computer code). As such, they require platforms (hardware) on which to operate and as the conduit for displaying their results. All collections of software (bundles) and hardware (machines) have relationships (human interfaces) with people: their developers and their users. A neat analogy between climate models and smartphone apps illustrates the synergies among people, platforms and software. Table 1.4 compares the benefits and challenges of nifty phone apps and of climate models.

The tension between competitiveness and customer universality of implementation is not limited to smartphones and climate models. The same discussion surrounded the development of CDs, DVDs and, before that, vinyl records and 19th-century railway gauges. Users usually want applications to be straightforward and then frequently wish to add on or to mix and match while developers generally regard their system as 'delicate' or, at the least, worthy of protection.

In the case of smartphones and climate models, some drawbacks – those of infrastructure – can be reduced by intentionally creating applications (phone apps and models) that work on all available systems. National, and even international, planning could encourage this. Other problems – especially those arising from poor development and testing or from user misapplication – are less easy to fix. In both cases, the first customer complaints (both (a)s in Table 1.4) might be fixable by developing an upgrade that solves the problem. However, the second criticisms (the (b)s in Table 1.4) are more to do with the fundamental design: this outcome was not intended to be delivered. Of course, most systems can be modified to do whatever

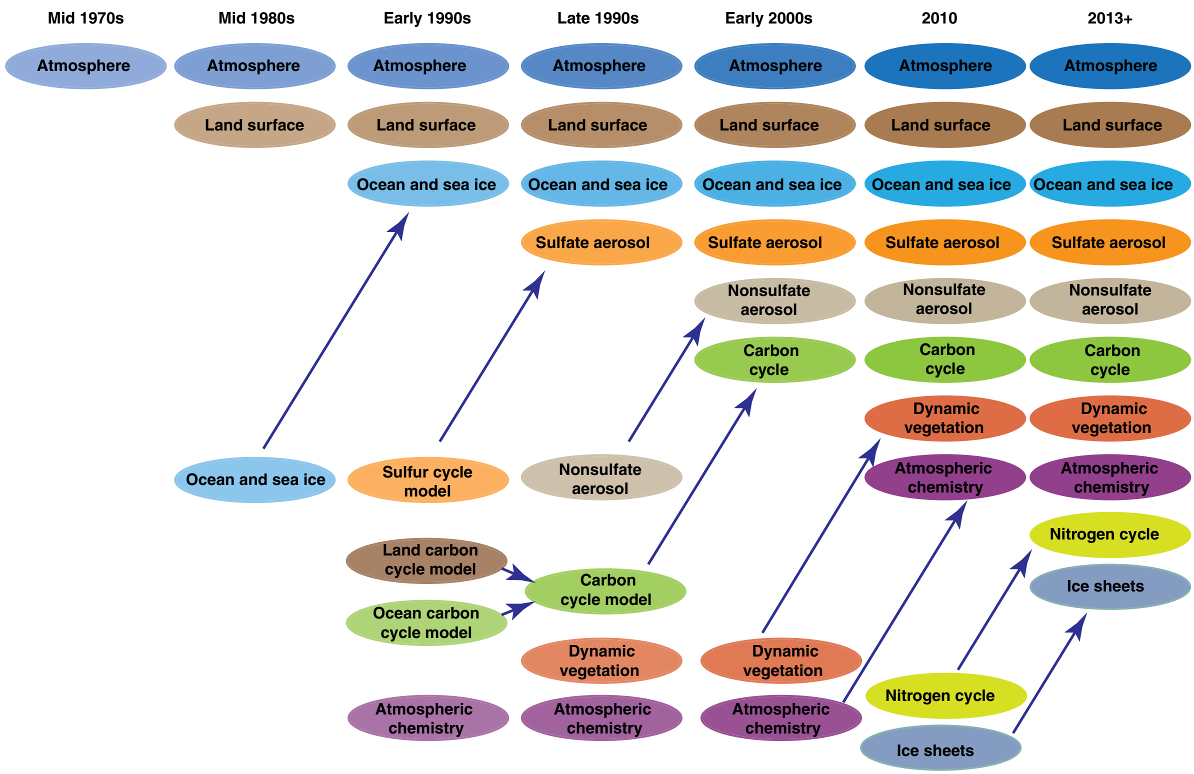


Figure 1.2 Changing list of components (ingredients) of climate models as it evolved over the past half-century. This diagram is not a recipe because it does not tell how to make the model; it is just the list of ingredients. As such, it comprises only the first step in climate modelling construction. Source: Extended and modified from IPCC 2001.

Table 1.4 Comparison between a climate model and a smartphone navigation 'app' (application). Both benefit from users who extend their comfort zone but also suffer from failure of the developers to standardise across platforms and from users' misapplication

Code (software)	Intended platform (hardware and its software)	Example use	Challenges	Criticisms
Navigation app	iPhone™	Finding a coffee shop	May not work on Android™	(a) Doesn't work in a covered mall (b) Doesn't play music
Climate model	Supercomputer	Reforestation opportunities under global warming	May not give the same results on large array of PCs	(a) Little use for sea-ice projection (b) Doesn't include cost-benefit values

their designers wish but some care has to go into decisions to add features 'because we can' or 'because they were requested'. The analogy holds, as climate model users resemble smartphone owners inasmuch as they need to have some understanding of what an app can (and cannot) do before setting out to use it for an important task.

1.3 Multiple reasons for climate modelling

In order to identify a set of reasons for conducting climate modelling, we review why people undertake modelling of all types for wide-ranging tasks. In a series of lectures in 2008, Joshua Epstein[3] described how everyone models all the time but relatively few people recognise their actions as model construction and exploitation. Developing the ideas of George Box, Epstein outlines how modelling outcomes can be very broad and lists 16 reasons for building or using a model, other than the obvious one of prediction.

To begin to answer the question 'Why model climate?', we have modified and reduced Epstein's list to just 10 compelling reasons for being interested in climate modelling. These are listed in Table 1.5.

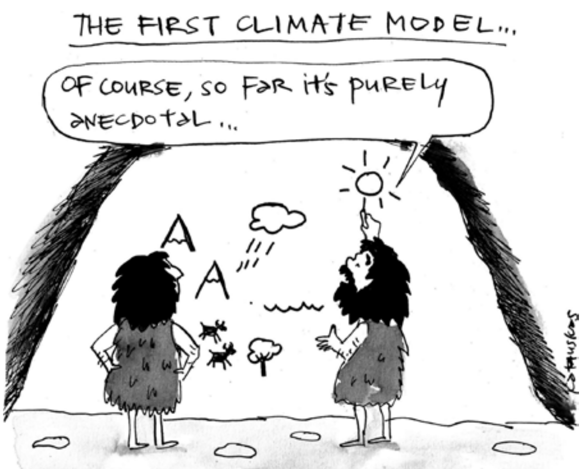
While some readers might have expected this book to focus primarily on climate model predictions, other strengths and benefits of climate modelling comprise a large proportion of this text. In particular, we examine climate modelling from the premise that 'all models are wrong; the practical question is how wrong do they have to be to not be useful'.[4] That we can and do, in our daily lives, obtain reliable knowledge from unrealistic models seems paradoxical at first. Dick Levins argued the case for believing that 'our truth is the intersection of independent lies'.[5] He proposed that, in order to overcome challenges of modelling complex systems, scientists often treat the same problem with several alternative independent models. Despite unrealistic aspects of their design, if such models are sufficiently independent and still yield similar results, one can infer some degree of confirmation.

Throughout *The Climate Modelling Primer*, we will refer to the 10 reasons for building, running and exploiting climate models, their strengths and their weaknesses. For example, the explanatory value of climate models is as important as their use for prediction. There are many ways of illustrating this, such as the case of simulation of ocean–atmosphere oscillations, the most well known of these being the El Niño–Southern Oscillation (ENSO). Coupling the oceans into climate models has permitted the examination of some of the prevalent decadal variability in climate. However, while many large-scale oscillations in the ocean–atmosphere components of the climate system are now recognised and these oscillations can be reproduced (that is, described) by today's models, modellers are only just beginning to see benefits of the extra complexity. For example, during the 2000s, the Interdecadal Pacific Oscillation reversed, cooling the Pacific and stalling the human-produced rise of the global average temperature. Climate models can now reproduce this stall and explore its implications for future climate prediction. Using different initialising conditions affected the simulations of the decadal climate changes.[6] In other words, as models become more complete, this completeness tends to improve skill of predictions and increase understanding of climate behaviour.

Table 1.5 Top 10 reasons for climate modelling (in addition to prediction)

No.	Reason
1	Climate models test the robustness of prevailing theory
2	Climate models illuminate salient features and core uncertainties
3	Climate models reveal the apparently simple to be complex and vice versa
4	Climate models raise new questions and suggest analogies
5	Climate models expose prevailing wisdom as compatible or incompatible with existing data and hence direct collection of new data
6	Climate models explain
7	Climate models bound (bracket) outcomes within plausible ranges
8	Climate models train practitioners and educate the general public
9	Climate models discipline the policy dialogue
10	Climate models encourage sensible thinking and informed discussion

We approve of, and try to uphold, the idea of modelling as a means of enhancing learning and understanding, above the desire for prediction. We encourage our readers to consider our 10 climate modelling reasons, comparing them with Epstein's original 16. Throughout the book, we will point out prediction, explanation and other successes and failures of climate models and we encourage readers to create their own lists of examples that interest them, which illustrate how different types of models, most of which we construct and use almost unconsciously, underpin our lives and add value.



Reflection on Learning 1.1

Recognise the many reasons for having models

Virtually all models of importance for the future of Earth and its people exist and operate in a complicated, nested framework that also encompasses economics, human development, politics and policies on adaptation to manage exposure to natural and human-induced extremes and disasters. Climate models are no exception (Figure 1.3).

Climate models assist in assessments of exposure and vulnerability of human society and natural ecosystems to climate. They also allow evaluation of the comparative influence of natural climate variability and anthropogenic climate disturbance as well as encouraging development of resilience to risks that cannot be eliminated. Outcomes from climate models are today contributing to and influencing demand for policies regarding greenhouse gas emissions and the potential for mitigation of anthropogenic climate change. When thinking about why a model was developed and how its results are used, it is vital to remember this broad context. ■

Figure 1.3 Schematic of the connections between climate, disaster, development and vulnerability. Many models, including climate models, contribute to our understanding of these interdependencies. Source: IPCC (2012). Reproduced with permission from the IPCC.