Vocabulary of Climate

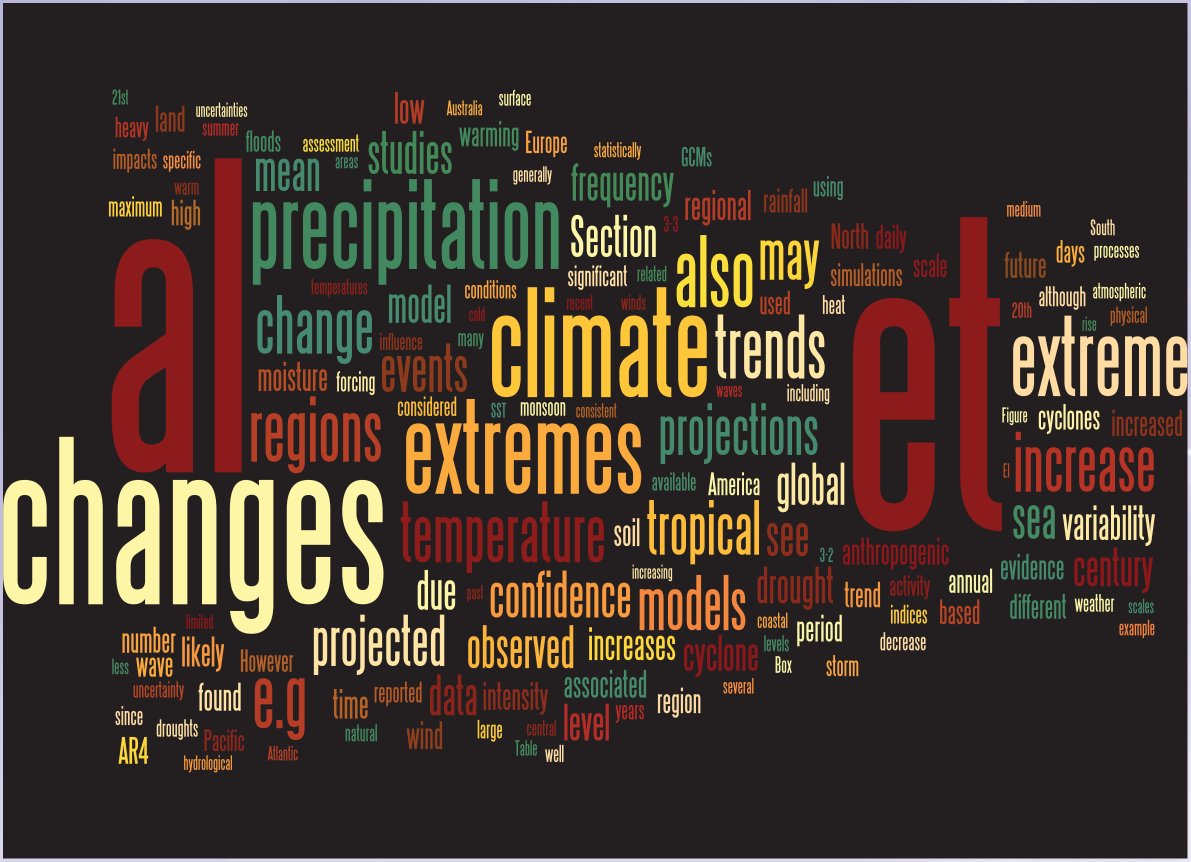


Plate 1.1 Vocabulary of climate. How we discuss climate today is illustrated in this 'wordle',[1] created by Neville Nicholls using the text in Chapter 3 of the 2012 Intergovernmental Panel on Climate Change (IPCC) Report on Climate Extremes.[2] Most of the work drawn upon is collaborative, so the phrase '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.

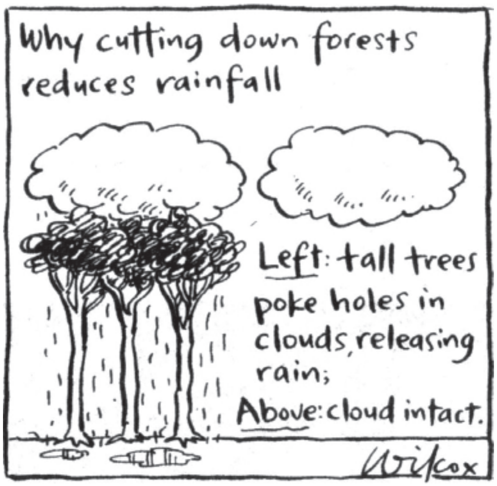
Climate Modelling Primer (CMP) readers are welcome to use whichever analogy they prefer: collector's chest, heirloom or heritage quilt or digital scrapbook. The goal is that, as you read the *Primer*, you collect climate-modelling treasures: a small set of illustrations that you find persuasive, pretty 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.

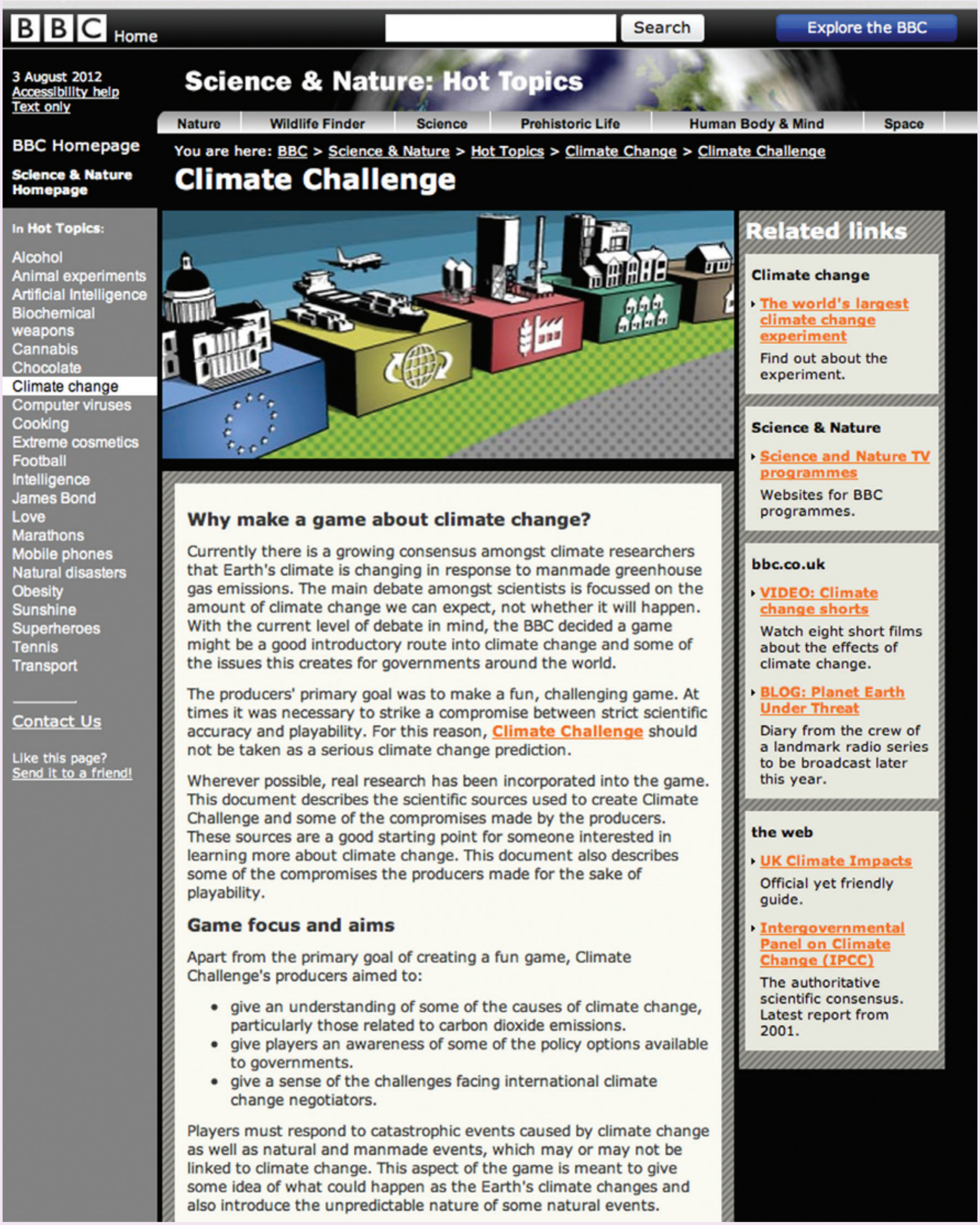
Looks: *Climate Challenge* is fun: fairly fast but also thought-provoking and open-ended. Each player works through simulations occupying this century (2000–2100) in which you (the player) become the President of all 'European nations'. Your goal is two-fold: radically reduce your country's CO_2 emissions 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*)



3 August 2012
Accessibility help
Text only

BBC Homepage

Science & Nature Homepage

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!

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

Climate Challenge

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

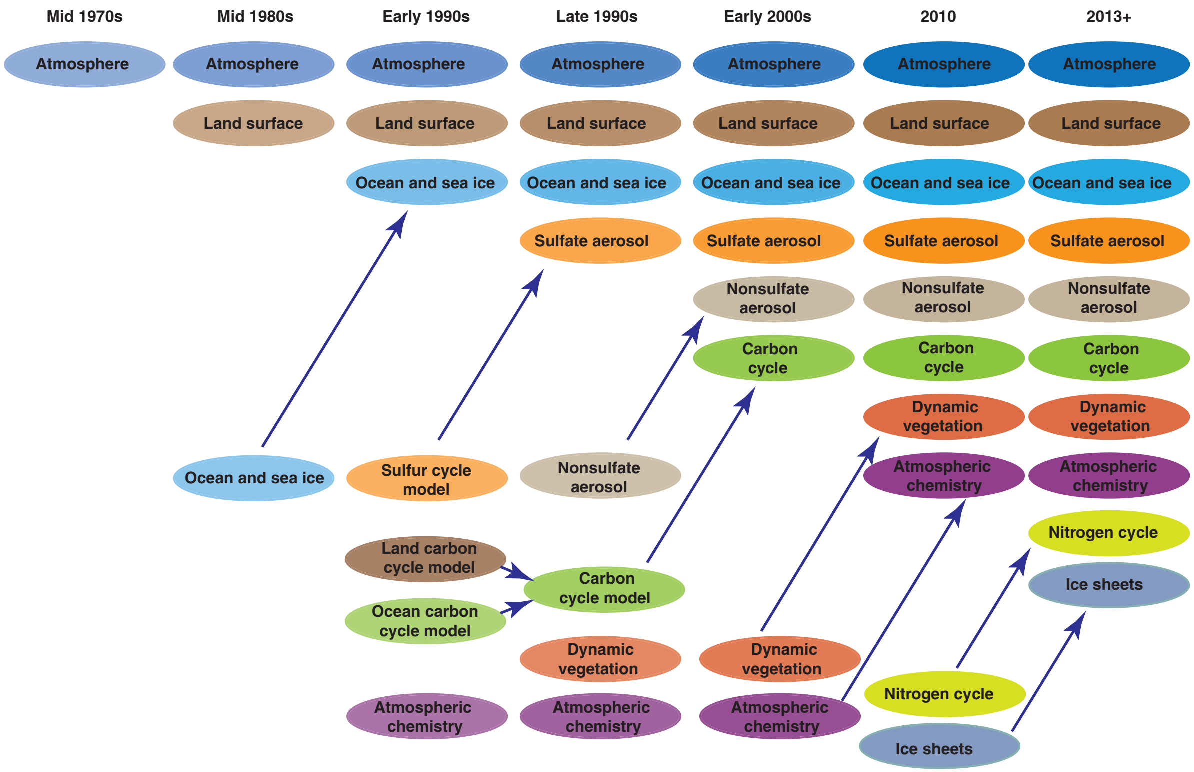


Figure 1.2 Changing list of components (ingredients) of climate models as it evolved over the past half-century. This diagram is not a recipe because it does not tell how to make the model; it is just the list of ingredients. As such, it comprises only the first step in climate modelling construction.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

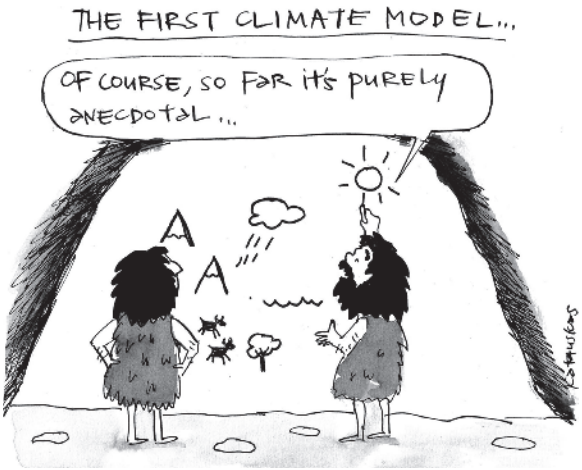
While some readers might have expected this book to focus primarily on climate model predictions, other strengths and benefits of climate modelling comprise a large proportion of this text. In particular, we examine climate modelling from the premise that 'all models are wrong; the practical question 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.



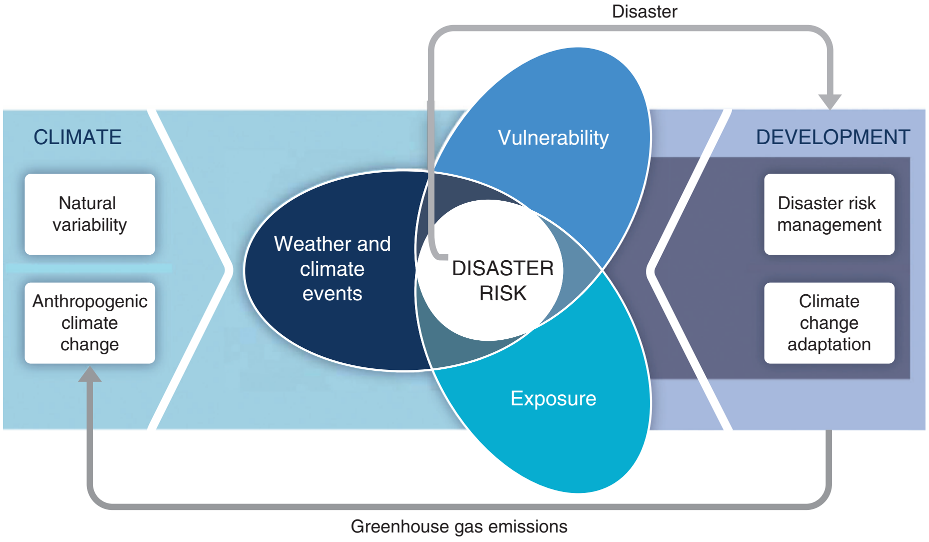
Reflection on Learning 1.1

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.



Tech Box 1.1

Watch a climate model 'flower'

Take a glimpse at the behaviour of 'ready-to-use' climate models by running a web-based climate model – for example, DaisyWorld: http://www.climate-modellingprimer.net/l/k103.htm Can you identify or discover:

1. any of the equations this model uses?
2. its starting conditions and whether these can be changed by a user (by you)?
3. the time characteristics, i.e. what timestep the model uses and what time period it can simulate?

Compare what you found out about this model with the same attributes for the speed dating model 'Climate Challenge 2007' (see Speed Date Box 1).

Before we can begin to discuss the reasons for modelling, we need to specify what constitutes a model, in our case, a climate model. We shall begin here by asserting that all climate models need three things: (i) one or more relationships (equations) that relate the output to the input; (ii) specified starting (or initial) conditions; and (iii) some time characteristics, usually the time increment the model uses and the time period covered.

All models are simplifications. Although climate models may appear to be straightforward, in construction and ease of use, they produce a surprisingly rich array of simulated climates. The act of simplification is a fundamental characteristic of modelling. The British physicist and mathematician, Lord Kelvin said in 1889:

> `.. when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind.' (Lord Kelvin aka William Thomson, 1st Baron, in Popular Lectures and Addresses, London, 1889, v. I, p73.)

However, as Epstein emphasises, apparent simplicity can be deceptive. Coming closer to modern thinking, check out the explanation of what a model is in Isaac Asimov's sci-fi story *Prelude to Foundation* (Asimov, 1988, p 162).

1.3.1 Climate models test the robustness of prevailing theory

***Issue**: global warming seen through a Victorian rainband spectroscope.*
***Message**: models contribute to examining how theories work and how observations test them – comparing gravity and greenhouse.*

Most, if not all, models perform roles other than prediction. Consider the part played by climate models in confirming[7] the 'theory' of global warming. The reason for the creation of some of the earliest climate models was to be able to examine the consequences of the proposal that addition of greenhouse gases to the atmosphere will result in additional warming. Investigating this theory of surface temperature increase as a result of heat absorption and re-emission by atmospheric greenhouse gases has involved models for centuries. Some of the earliest models, real tools that detected absorption by gases, passed from the laboratory to everyday shops (Figure 1.4a).

The concept of global (or greenhouse) warming emerged around 150 years after the idea of gravitation.[8] It was 1838 when French physicist Claude Pouillet described how the Earth's atmosphere increases the surface temperature. The theory was also confirmed by observations – in

(a)

CTOBER 21, 1886 [PRICE SIXPENCE

[All Rights are Reserved

GRACE'S NEW DIRECT VISION SPECTROSCOPE.

MR. JOHN BROWNING begs to direct attention to the advantages of this very powerful, portable, and efficient Instrument, which will divide the Sodium lines or the D lines in the Solar Spectrum, and show the Rain-Band *as Separate Lines*; it is provided with a fine motion focusing arrangement, and it is applicable to every purpose for which a Direct Vision Spectroscope can be used.

Price in Morocco Leather Case, £3 8s. 6d.

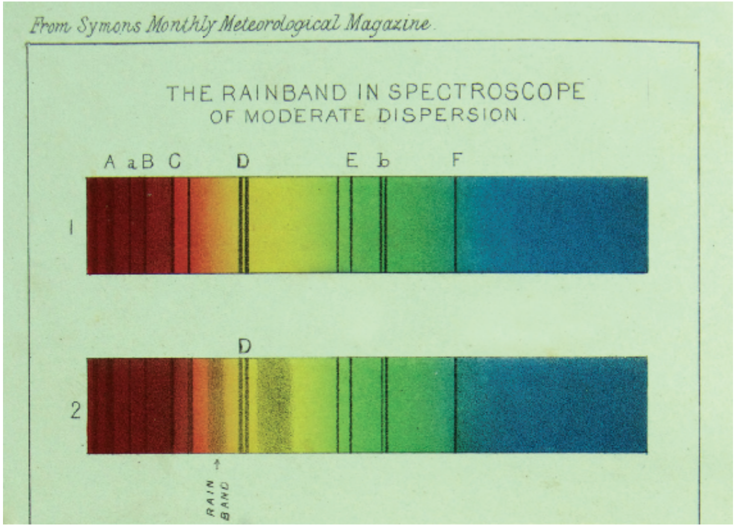
Illustrated Catalogue of Spectroscopes sent post free, Sixpence.

JOHN BROWNING,

Optical and Physical Instrument Maker to H.M. Government,

63, STRAND, LONDON, W.C.

(b)



From Symons Monthly Meteorological Magazine

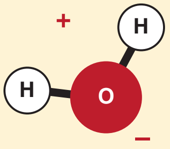
THE RAINBAND IN SPECTROSCOPE
OF MODERATE DISPERSION

Figure 1.4 (a) 1880s' advertising copy for a spectroscope: a hand-held Victorian scientific toy marketed as a tool for rain prediction, offered for only 3 pounds, 8 shillings and 6 pence. The Grace's 'New Direct Vision Spectroscope' is said to have advantages of being 'very powerful, portable and efficient' and able to 'divide the Sodium lines or the D lines in the Solar Spectrum and show the Rain Band as Separate Lines'. Source: Browning (1883). (b) Possibly the earliest use of remote sensing in meteorology: a so-called 'rain-band' spectrum from 6th July 1881. The spectroscope splits daylight into its (rainbow) spectrum. Dark lines, caused by the preferential absorption by water vapour of light at these wavelengths (labelled rainband), appear superimposed on the spectrum as the amount of water vapour increases (grey stippled bands), an indication of imminent rain.

CSI Box 1.1

Weirdness of Water: Great greenhouse gas

Water vapour is the strongest greenhouse gas in our atmosphere. This happens because water molecules (H_2O) form so that the oxygen atom is pushed to one vertex and the two hydrogen atoms to others. This configuration causes a dipole charge on the molecule: the oxygen end is partially negatively and the hydrogen end partially positively charged. This charge separation of the water molecule has many important consequences. From the point of greenhouse warming, it means that when an H_2O vapour molecule rotates or vibrates there is an interaction with electromagnetic radiation, the heat energy emitted from the Earth's surface. This interaction involves absorption and emission of radiation in a large number of water vapour 'spectral lines', making water vapour a significant greenhouse gas.



1859, scientist John Tyndall conducted a set of early spectroscopy experiments demonstrating that water vapour and carbon dioxide absorb infrared radiation. The construction of a 'model' of laboratory spectroscopy applied to the Earth's atmosphere was to become the popular 'toy' of the late 19th century (Figure 1.4a). An instrument, termed a rainband spectroscope, capable of 'fingerprinting' gaseous absorption became quite a fad around 1870. These pocket spectroscopes designed specifically to display the so-called 'rainband' were created and marketed as supposedly useful tools for the prediction of rain.[9] They permitted any curious citizen to see a colourful 'rainbow' spectrum embellished with several dozen dark absorption lines (Figure 1.4b).

Danish physicist Niels Bohr concluded that the formation of these spectral lines occurs when elements or compounds interact with radiation, either absorbing the radiation and increasing their energy by a discrete amount or lowering their energy and emitting a parcel of radiation. Based on such fundamental foundations, spectroscopy, the documentation and analysis of these spectra, is now used in laboratories to determine constituents of samples in forensic analysis, and by astronomers to detect chemical species in space.

From this established understanding of the behaviour of atoms came questions concerning the effect of the additional heat from the atmospheric gases re-radiated back to a planetary surface.

Reflection on Learning 1.2

Track the history of scientific theory becoming fact

Review the history of the two theories of gravitation and greenhouse as they pass through almost identical steps (Table 1.6). General (i.e. widespread) acceptance proceeds from speculation through objections and improvements (usually scientific), past vindicated prediction to sensitivity analysis pertaining to predictive skill. Along the path, theories collect communities of adherents beginning in science, incorporating lay people, encompass the general public and even move into portrayal in art and popular culture. For example, greenhouse was used to make predictions that were later observed: in the 1950s, Harvard University professor Richard Goody[10] anticipated that the surface temperature of Venus would be very high, though this was not verified until 1967 by the Soviet Union's probe, *Venera 4*.

Consider carefully what you think 'proof' of a 'theory' entails. What constituency needs to accept such 'proof'; is this a democratic decision or some other process? In this book, we present a series of boxes entitled 'Climate Model Validation'. What do you think about the concept of 'validation' of a model? ■

Table 1.6 Model involvement in testing the theories of global warming and its history compared to those of gravitation

Theory 'proving'	Gravitation	Global (greenhouse) warming
Origin	300+ years old (Newton, 1687)	~180 years old (Pouillet, 1838) or older (Mariotte, 1681)
Predictions	Neptune (1824) from Uranus	Industrial warming (Arrhenius, 1896) Venus 'hot house' (Goody, 1952)
Objections raised	Newton disliked 'action at a distance'	Clouds, especially their feedbacks, are very poor (cf. Lindzen et al. 2001)
Prediction conflicts	Precession of Mercury's perihelion (1859)	Different values deduced for climate sensitivity: 3 K (IPCC), 3–4 K (Hansen)
Improvements	Special relativity (1905): $E=mc^2$	Aerosols included in IPCC AR3 (2001d); carbon feedbacks included in IPCC AR4 (2007d)
Acceptability: (i) to lay people	Everyday mechanics is Newtonian	Earth is habitable because of greenhouse gases
(ii) to scientists	Eddington proves General Relativity (1919) and space agencies use in space programmes	Human disturbance demonstrated by Keeling's CO_2 observations from 1958 and by temperature increases since ~1990
(iii) broad public	Stephen Hawking and Star Trek	Bill McKibben and the '350.org' movement

Source: Henderson-Sellers (2012). Reproduced with permission of Elsevier.

1.3.2 Climate models illuminate salient features and core uncertainties

***Issue**: Goldilocks and rotating dishpans.*
***Message**: models illustrate and help analyse planet-wide complex flows that redistribute energy.*

Climate modelling has two parent groups: first, the astronomers who probe energy-absorbing gases and analyse stellar radiation; and, second, the weather forecasters who hope to extend their predictions beyond days into months and years. This mixed parentage has produced odd lurches and happy combinations in the understanding of climate and how to simulate it.[11]

One example we can use is water. From the point of view of astronomy, water is considered essential for life. The climatically habitable zone (or circumstellar habitable zone, CHZ) is the region around any star within which it is theoretically possible for a planet with sufficient atmospheric pressure to retain liquid water on its surface. This habitable zone has to be neither 'too hot' nor 'too cold' but 'exactly right' so that it has come to be called the 'Goldilocks' zone'.[12]

Astronomers try to identify planets occurring inside the CHZ of stars and recently estimated that 6% of close stars have planets in the CHZ.[13] They use this 'zone' to sift their observations for possible life-bearing planets and moons since water in its three phase states is a helpful (if not essential) component of climatic stability (Figure 1.5).

Water is very unusual: it is the only natural substance on Earth that co-occurs in all three physical states (liquid, solid and gas). The properties

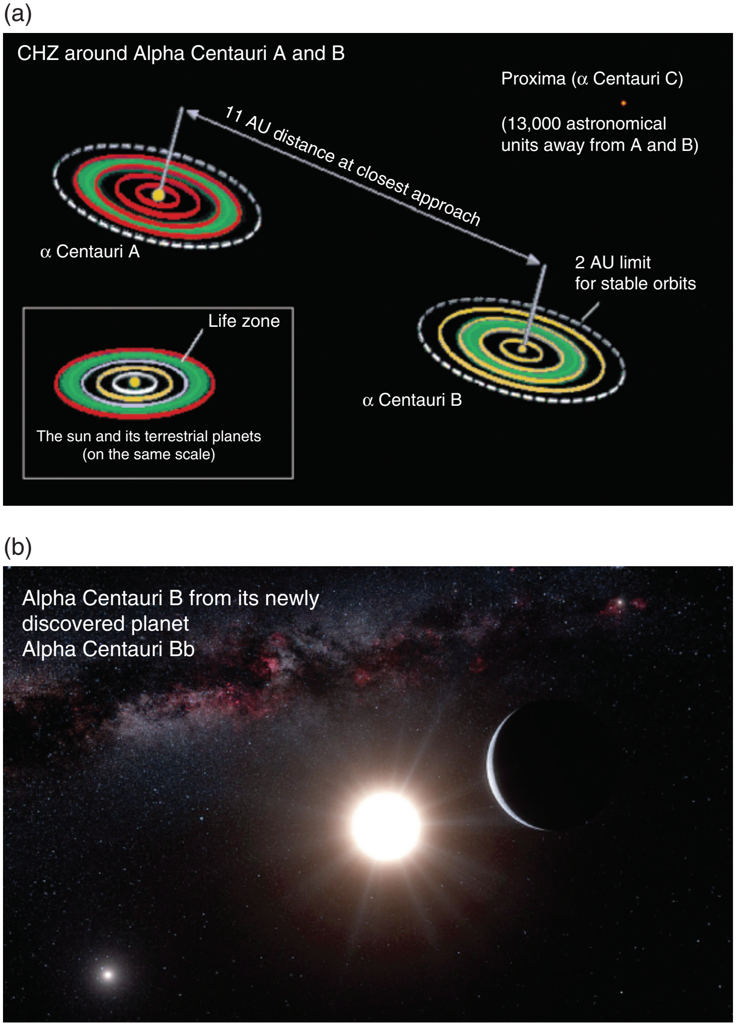


Figure 1.5 (a) Schematic of the circumstellar habitable zone (CHZ – in green) around Earth's two nearest neighbouring stellar systems: Alpha Centauri A and B, together with (b) an artist's impression of how the latter star might look from its newly discovered planet: Alpha Centauri Bb.[14] In other words, if alien life occurs in this constellation it is most likely to be found in one of these green zones and such life probably views its 'sun' much as this depiction.[15] Source: (a) CHZs of Alpha Centauri A and B from Beech (2012). Reproduced with permission of Oxford University Press. (b) Artist impression by ESO/L. (http://www.eso.org/public/archives/images/screen/eso1241a.jpg). L. Calçada/Nick Risinger (skysurvey.org).

of water that give rise to this include the unusually large latent heats of both condensation and solidification; its unusually large specific heat (which means that water bodies absorb heat and retain it well); the 'chaining' behaviour of molecules in the vapour phase, which causes surface 'stickiness', dimer absorption and many more fascinating characteristics.

Climate models are usually assumed to be numerical simulations run on computers. However, there are analogue[16] models that illuminate fundamental aspects of the climate system: one is the double pendulum, another is the now famous 'rotating dishpan'. This latter climate model is, as its name suggests, a piece of apparatus comprising a cylindrical pan mounted on a turntable. The aim is to simulate the combined effects of planetary rotation (spinning the dish) and of an imposed equator-to-pole temperature gradient (heating the edge and cooling the centre) on the motion of the fluid in the cylinder. Laboratory experiments of this kind began in the 1950s (see, for example, the work of Raymond Hide[17] of the UK Meteorological Office and David Fultz of the University of Chicago[18]) and remain an important tool for weather and climate analysis.

In the classic dishpan experiment, the motion of the water in the cylinder is tracked using coloured objects or dye and, as the dish is rotated, a variety of patterns is seen when viewed with a camera rotating with the dish. At low speeds, the flow is around the dish but, as the rotation speed increases, waves develop, extending almost from the centre to the perimeter and incorporating smaller, closed circulations. Patterns can be made clearer by dropping two colours of dye into the water – one close to the cold centre and another near to the warmed periphery. The dishpan's shift from zonal to wave-like flow is closely analogous to observed shifts in upper tropospheric dynamics (Figure 1.6).

These patterns of flow, functions of the pole-to-equator temperature gradient and the speed of rotation, are found in all planetary atmospheres and in oceans, although the latter are constrained by continents. The differential heating (the fact that the equator is heated more than the poles) drives the meridional circulation – termed the Hadley Cell in the low latitudes of the Earth's atmosphere and Rossby waves in the mid-latitudes. The ocean circulation possesses elements of this equator-to-pole energy movement complicated by continental boundaries and the presence of density and salinity differences (Figure 1.7).

The fundamental characteristics of all atmospheres and oceans (fluids) on all astronomical bodies (planets, moons and even stars) are heating as a result of radiation imbalance (incoming absorbed not equal to outgoing emitted) at different latitudes and fluid flow carrying energy to resolve this imbalance.

CSI Box 1.2

Weirdness of Water: Water, water, everywhere

'Earth,' say observers, especially those lucky enough to have viewed it from outside, would be better named 'Water'. Almost three-quarters (~71%) of Earth's surface is water, the brightest features are frozen water, and the atmosphere is frequently cloudy. The character of our 'Blue Marble' is controlled by water and, importantly for climate modelling, by water's phase transitions: changes of state from ice to liquid, and to vapour and back again. Water's very large latent (hidden) heat of vaporisation (2270 kJ kg^{-1}), a result of the extensive hydrogen bonding between its molecules, moderates climate because large energies are required to change state. Water's high specific heat (4187 J kg^{-1} K^{-1}) means that oceans take a long time to warm and to cool, offering climate change buffering. Water ice is (very unusually) less dense than its liquid state, so lakes and oceans freeze top first, separating atmosphere from water.

Photo source: NASA.

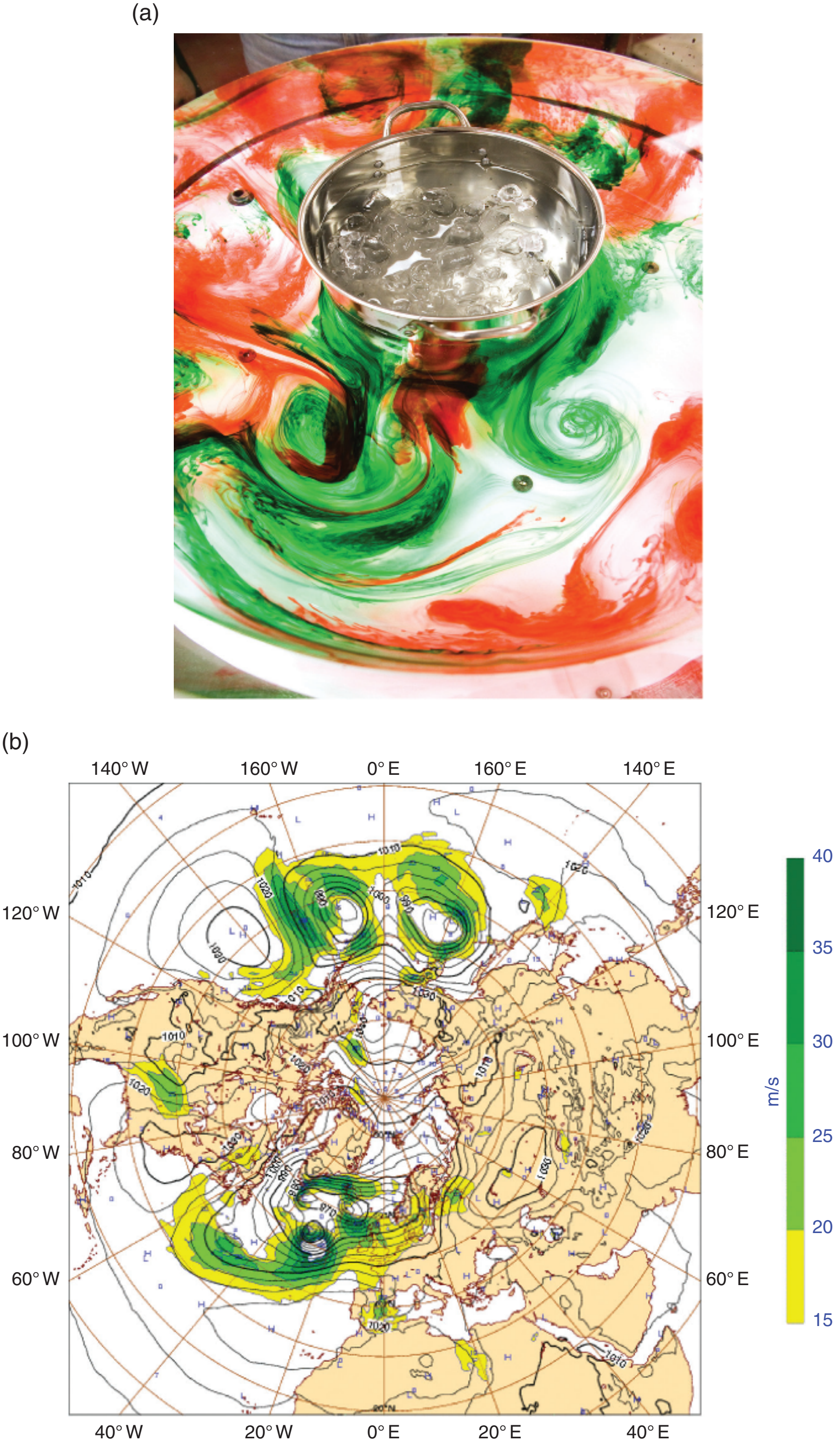


Figure 1.6 Dishpan planets: rotating tank experiments capture the main features of atmospheric circulation. (a) Patterns of tracer (dye) injected as drops into a spinning tank from the warm outside edge (*red*) and from the chilled centre (*green*). Source: Jason Smith, University of Chicago. (b) Weather forecast chart for the Northern Hemisphere for 28 January 2013 showing the isobars of mean sea-level pressure and the 850 hPa wind speed in yellow-green. Source: European Centre for Medium-Range Weather Forecasts (ECMWF): www.ecmwf.int/. © ECMWF.

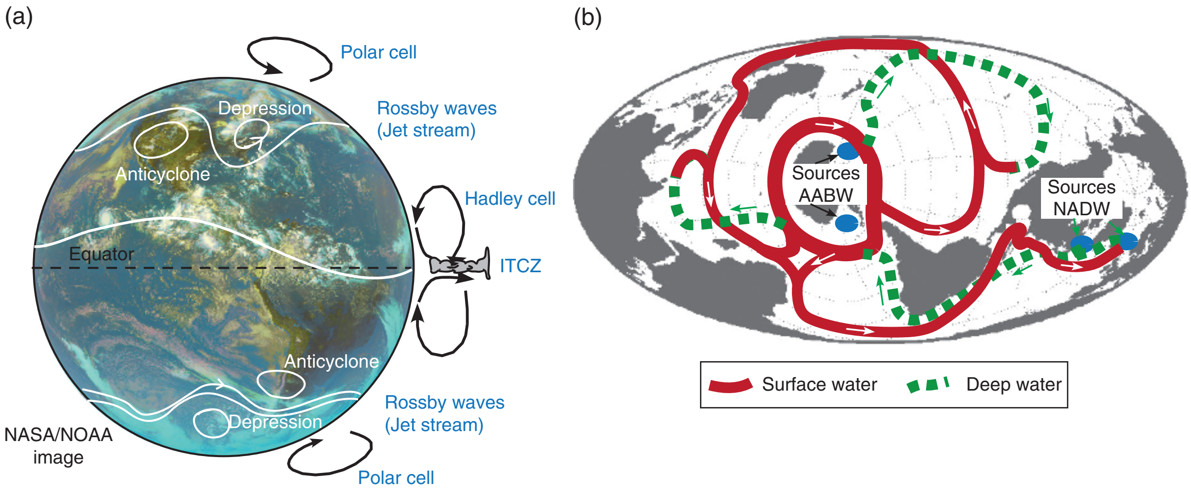


Figure 1.7 Primary features of the atmospheric and oceanic circulation. (a) The atmospheric circulation is determined primarily by the net radiation budgets (excess in the tropics, Inter-tropical Convergence Zone [ITCZ], and deficit near the poles) and the rotation of the Earth (especially the Rossby waves). (b) The thermohaline circulation of the ocean, often referred to as the 'ocean conveyor', results in the movement of water throughout the major ocean basins of the world over periods of hundreds to thousands of years. Green dashed lines follow deep ocean water, from their sources off the Greenland and Antarctic coasts, North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) respectively, as it transforms into middle layer and finally surface water (*red*) and closes the ocean circulation system.

Climate Model Communication Box 1.1

Modelling hobbyists meeting

This communication exercise is also known as the 'CEO in the lift (elevator)' speech. It comprises a very quick (2-minute) explanation of what you do and why, in your view, it is important. For this example, please imagine you have been invited to a "modelling hobbyists' convention" – a gathering of all types of modellers. At the opening social, you are asked what you model. Try to explain, in terms that a fanatical model train set owner, say, could understand, what climate modellers do and how their activities are interesting and worthwhile. Use no more than 100 words, or out loud less than 2 minutes of speech. An interesting place to check out if you are using jargon is at http://www.climatemodellingprimer.net/l/k104.htm.

Reflection on Learning 1.3

List the factors affecting planetary scale climate

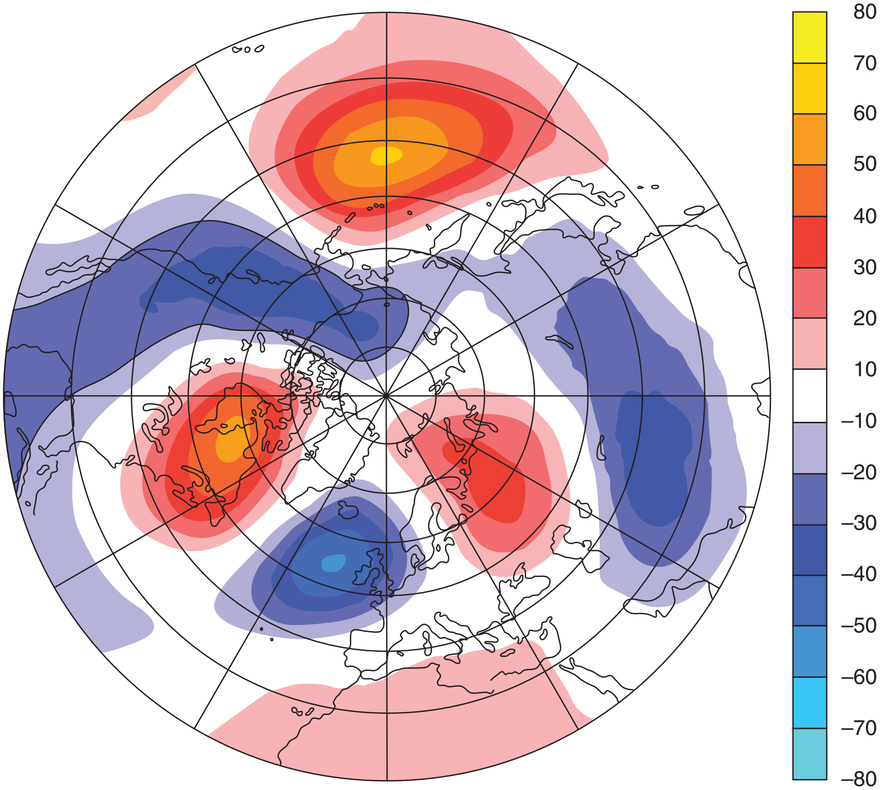
Climate is controlled by universal laws including conservation and the three laws of thermodynamics, which C.P. Snow once wittily summarised as 'you can't win, you can't break even, and you can't get out of the game'. For planets, these basic rules include (i) radiation in equals radiation out; and (ii) axial spin adds a Coriolis twist to equator-to-pole flows. From such basic rules, modellers and experimentalists design beautifully elegant and extraordinarily pretty demonstrations of the wonder of planetary-scale circulation in the atmosphere and the oceans (Figure 1.8). ■

1.3.3 Climate models reveal the apparently simple to be complex and vice versa

***Issue**: the butterfly effect seen in the swing of a double pendulum.*

***Message**: models capture essential features and illustrate unexpected behaviour as seen in chaotic attractors.*

Figure 1.8 Climate models are designed to represent the major circulation features of the atmosphere and ocean. For example, this atmospheric simulation of the stationary eddy component (the departure from the zonal mean) of the 500 hPa geopotential height (m) in boreal (northern) winter (DJF) uses a coupled climate model (the EC-Earth model). Source: After Hazeleger et al. (2012). Reproduced with permission of Springer Science+Business Media.



Tech Box 1.2

View the Lorenz Attractor unfolding

See: http://www.climatemodellingprimer.net/l/k105.htm

This video allows the viewer to witness the dynamic 3D evolution of the Lorenz Attractor. The simulation consists of 5000 spheres, the colour of which changes as the iterations continue. The equations being solved are as identified by Edward Lorenz in 1963.[19] We will be properly introduced to this extraordinary model in Chapter 2, Speed Date Box 2.

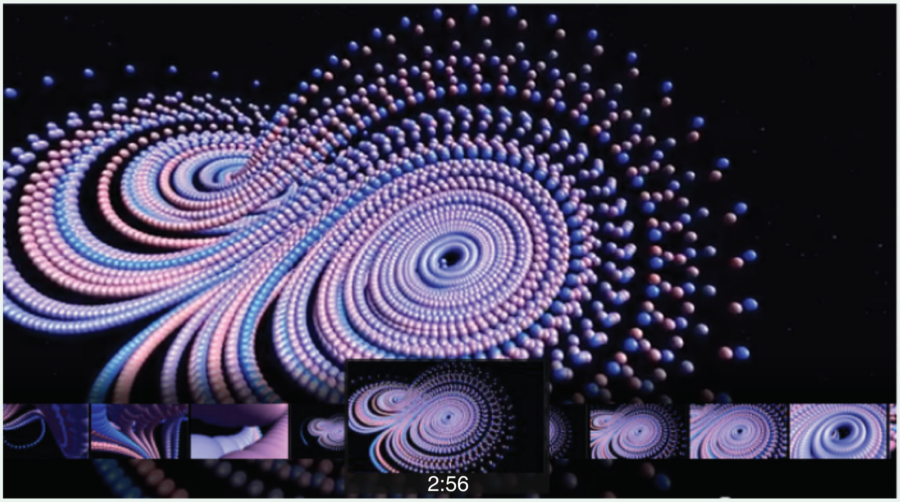


Figure source: http://www.youtube.com/watch?v=iu4RdmBVdps&feature=fvwrel.

Massachusetts Institute of Technology mathematician Edward Lorenz is famous for what has become known as the 'butterfly effect', although he actually used the metaphor of a seagull's wing.[20] The term describes the chaotic amplification of a tiny disturbance, which means for climate models that a small change in the initial conditions can result in a quite different final state (Tech Box 1.2).

The model Lorenz used, which led him to publish the first description of this now famous effect and which has since been found in virtually every branch of predictive science, consists of just three equations. Although Henri Poincaré had noted the notion of chaotic unpredictability, it was not until Lorenz's seminal work in 1963[21] that the true nature of behaviour constrained by what we now know of as 'fractionally dimensioned geometry' became clear. Thus, the salient feature of climate (and many other) models is the inherent unpredictability of the systems they describe. The core uncertainty is in the final outcome of each simulation. As Lorenz himself discovered, minute differences in initial conditions translate into completely diverse final outcomes.

It is fairly easy to simulate chaotic behaviour with a real (physical) model – one that you can build yourself. A double pendulum consists of two rigid links (sticks) of very little mass with point

Biography Box 1.1

Meet the modeller: Edward N. Lorenz

Leadership: Lorenz was the first to recognise what is now called chaotic behaviour. His discovery overthrew the status quo in climate science, requiring that all climate modellers understand the complexity of the system they study.

Popular recognition: Lorenz was famously responsible for naming the 'butterfly effect'. He claimed that this phrase arose as a consequence of his failure to provide a title for a talk in 1972. To plug the title gap, the organiser creatively listed, 'Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?'.

Climate modelling connectivity: Lorenz's 1963 work, which laid the foundation for the field of chaotic systems, used a truncated form of the atmospheric convection equations of Barry Saltzman, another giant intellect in early climate modelling.

Life and times: Edward Norton Lorenz (23 May 1917 – 16 April 2008) was an American mathematician and meteorologist and for many years a professor at MIT. In the early 1960s, Lorenz realised that small differences in a dynamic system such as the atmosphere – or a model of the atmosphere – could trigger vast and often unsuspected results. It has been said that his profoundly influential work delivered one of the most dramatic changes in our view of nature since Sir Isaac Newton. Speaking soon after his death, Kerry Emanuel, also of MIT, said, 'Ed put the last nail in the coffin of the Cartesian universe and fomented what some have called the third scientific revolution of the 20th century'.

Read more

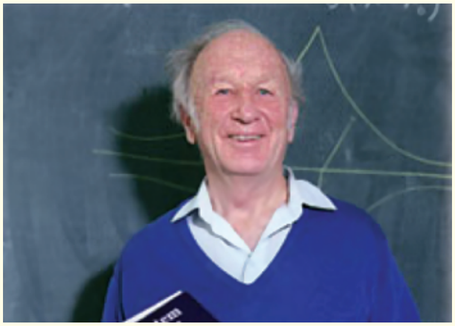
Gleick, J. (1987) *Chaos: Making a New Science*. London: Vintage.

Lewis, J.M. (2005) Roots of ensemble forecasting. Mon Weather Rev 133, 1865–1885.

Lorenz, E. (1963) Deterministic nonperiodic flow. J Atmos Sci 20, 130–141.

Watch

http://www.climatemodellingprimer.net/l/k109.htm



Ed Lorenz in 1994. Photo source: © UCAR, photo by Curt Zukosky.

weights attached to their ends. These links (sticks) are confined to two-dimensional rotational motion about their joint. Initially the motion appears regular but chaotic movements always occur with the end point of the pendulum eventually covering the whole space available to it for a given starting energy (Tech Box 1.3).

Although first simulated in simple climate models in the 1960s, the 'strange attractor' behaviour (see Tech Boxes 1.2 and 1.3) that has come to characterise climate dynamics has been discovered in ecology and, more recently, socio-economic systems.[22] For example, Figure 1.9 shows discontinuous transitions in the value of supply of money market derivatives (*s*) as a function of the number (*n*) of derivatives being traded and the risk (ε) of the various banks operating in a complicated international financial system.[23]

Tech Box 1.3

Craft a double pendulum or crochet a Lorenz Manifold

Build a simple device that exhibits chaotic behaviour: an excellent science project or chaotic climate conversation starter.

1 Build a double pendulum

Build it – find out how to create one here: http://www.climatemodellingprimer.net/l/k106.htm

Get the PDF for this project: http://www.climatemodellingprimer.net/l/k107.htm

2 Crochet your own Lorenz Manifold[24]

Find out how to create this folded surface in wool: http://www.climatemodellingprimer.net/l/k108.htm

Consider how these two hobbyists' activities relate to one another, i.e. what links the behaviour of the double pendulum to the Lorenz manifold surface.

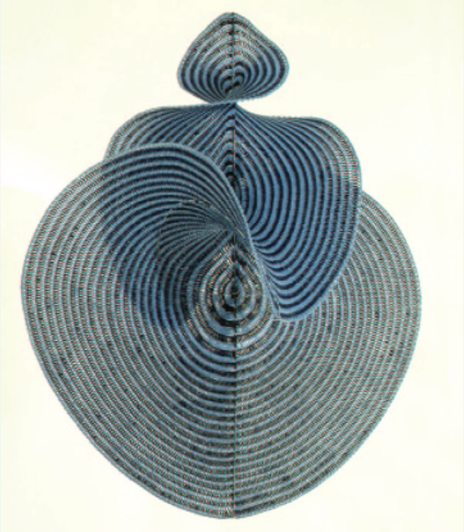


Figure source: Osinga and Krauskopf (2004). Reproduced with permission of Springer Science+Business Media.

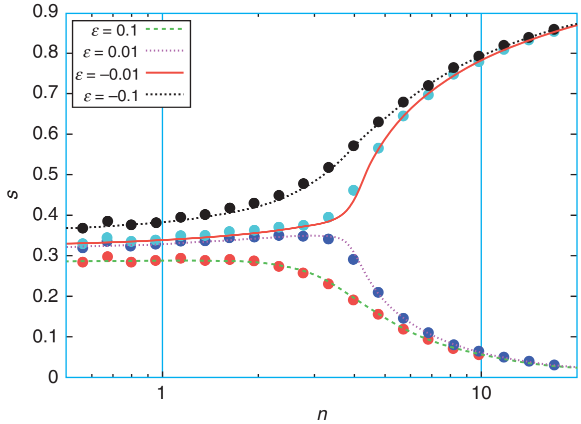


Figure 1.9 Complex systems exhibit instabilities. Here international trading in financial derivatives is seen to behave discontinuously. The average supply of any one derivative, *s*, at competitive equilibrium as a function of the number, *n*, of different derivatives being traded, for various values of banks' risk premium, *ε*. The two 'branches' can be viewed as similar to the strange attractors seen in the simulation described in Tech Box 1.2. Source: Haldane and May (2011). Reproduced with permission of Nature Publishing Group.

1.3.4 Climate models raise new questions and suggest analogies

Issue*: positive and negative feedback seen in a poorly rigged microphone system.*

Message*: social and physical systems with feedbacks grow anomalies and also dampen them so models have to capture this behaviour.*

The term 'feedback' originates in early electronics. In 1909, Nobel Laureate Karl Ferdinand

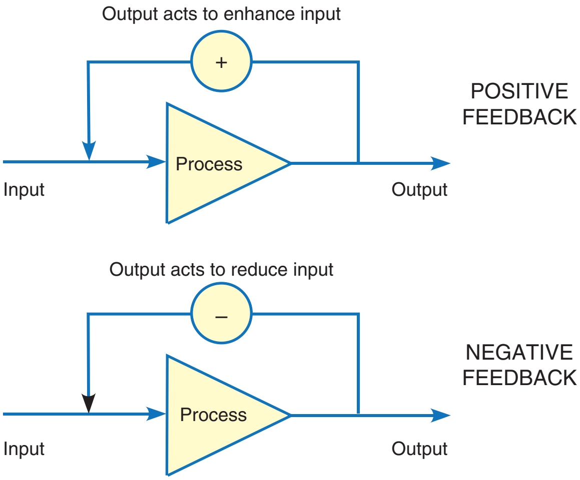


Figure 1.10 Types of feedback. Feedback processes can be classified as positive or negative. In positive feedback, a portion of the output is fed back to the input and acts to further stimulate the process. In the case of negative feedback, the portion of the output is subtracted from the input and acts to dampen the process

Braun used the term *feed-back* to describe undesired coupling between elements of an electronic circuit. In the broadest sense, a feedback occurs when a portion of the output from the action of a system is added to the input and subsequently alters the output. The result of such a loop system can either be an amplification of the process, resulting in the familiar amplifier howl, or a dampening, which is used for control in almost every modern amplifier circuit. These feedbacks are labelled positive and negative respectively. In a climate situation, positive feedbacks act to grow an initial perturbation whereas negative feedbacks reduce the perturbation (Figure 1.10).

Today, 'feedback' has become closely associated with climate; for example, most people recognise its use in the phrase 'ice-albedo feedback' even though they might not be able to define the word 'albedo' (see Chapter 3). In the mass media, feedback, as the reinforcement of the impacts of warming on Arctic sea-ice, is in common usage: as the ice-albedo feedback operates as temperatures rise, the sea-ice melts. This leads to a greater area of dark ocean as the amount of bright ice decreases. Dark surfaces absorb more sunlight than the ice so the ocean warms still further, making it harder to reform sea-ice and tending to reinforce the first effect.

The importance of the sign of a feedback process can be simply illustrated by considering the impact of self-image on diet. Someone slightly overweight who eats for consolation can become depressed by their increased food intake and so eat more and rapidly become enmeshed in a detrimental, positive feedback effect. On the other hand, perception of a different kind can be used to illustrate negative feedback. As a city grows, there is a tendency for immigration but the additional influx of industry, cars and people is often detrimental to the environment, so that it may be balanced by an outflow of wealthier inhabitants, with a potentially negative impact on the central city's economy by reducing investment. Because feedback mechanisms act to further enlarge or suppress the initial disturbance, their incorporation into models of climate is essential. Early in the story of climate modelling, the concept of feedback was recognised as important (Feedback Box 1).

Positive feedback magnifies changes and can lead to the crossing of thresholds beyond which a new state is entered from which return is not achievable by removing (or reversing) the original disturbance. This idea of positive feedback reinforcing an initial perturbation has been exploited in many areas such as social systems – for example, in riot situations where unintentional reinforcement (maybe by introducing law enforcement personnel) tends to further enrage crowds.

Nobel Prize winner Thomas Schelling expanded upon the 'tipping point' concept in the 1970s and a very readable account of such phenomena is found in the book *The Tipping Point: How Little Things Can Make a Big Difference.*[25] This lists many examples of this threshold-crossing concept and focuses, in particular, on examples where small changes create big effects. The tipping point from which the book takes its title is that point in a system's development where a small change leads to a huge effect in a rapid timeframe and spreads through the system in a contagious fashion. This was shown in Figure 1.9 for world markets in banking derivatives.

Feedback Box 1

The 'CLAW'

Read: Charlson, R.J., Lovelock, J.E., Andreae, M.E., Warren, S.G. (1987) Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate. Nature 326, 655–661.

This paper is famous for presenting the first testable Gaia Hypothesis[26] (that living things 'work' to modify the climate) and for being among the first to discuss the impact of aerosols (small droplets or particles) on the climate (the addition of aerosols to cool climate is at the heart of many geoengineering proposals). The paper concludes that counteracting the warming due to doubling of atmospheric CO_2 requires approximately a doubling of cloud condensation nuclei (CCN). The paper's fame has resulted in it being referred to by the acronym built from the first letters of the authors' family names: Charlson, Lovelock, Andreae and Warren: 'CLAW'. Here, we focus on its depiction of the biologically driven climate feedback mechanism: dimethylsulfide (DMS), produced by oceanic plankton and oxidised in the atmosphere to form a sulfate aerosol that is the main source of CCN over the oceans. The albedo (reflectance) of clouds is altered by changes in CCN density and so biological modification of the climate ensues. The diagram shows how measurable quantities (in rectangles) are changed by processes (in ovals) where the signs show the effect of a positive change of the quantity in the preceding rectangle.

The CLAW authors note that the least certain of the depicted processes is the effect of cloud albedo on DMS emission – they show this oval (lower right corner of figure) with either plus or minus impact. This must be positive if climate regulation is to occur. Thus, if the initial disturbance is, say, an increase in solar radiation, this prompts more DMS; DMS is oxidised to sulfate aerosols; more aerosols mean more CCN; this increases the cloud droplet number; hence the clouds become brighter and so reflect more solar radiation; and so the initial disturbance is dampened. In Gaian terms, the plankton act to reduce (i.e. diminish) the disturbance to the climate.

The CLAW hypothesis has its own entry in Wikipedia and there is now an 'anti-CLAW' mechanism created by Jim Lovelock, one of the authors of this paper and the co-inventor of the Gaia Hypothesis.

The way in which the feedback diagram is drawn here (from the CLAW paper) follows a terminology originally proposed by William Kellogg. Questions that the figure raises include:

1. Can this feedback system be drawn more simply?
2. Does this version show a positive or a negative feedback?

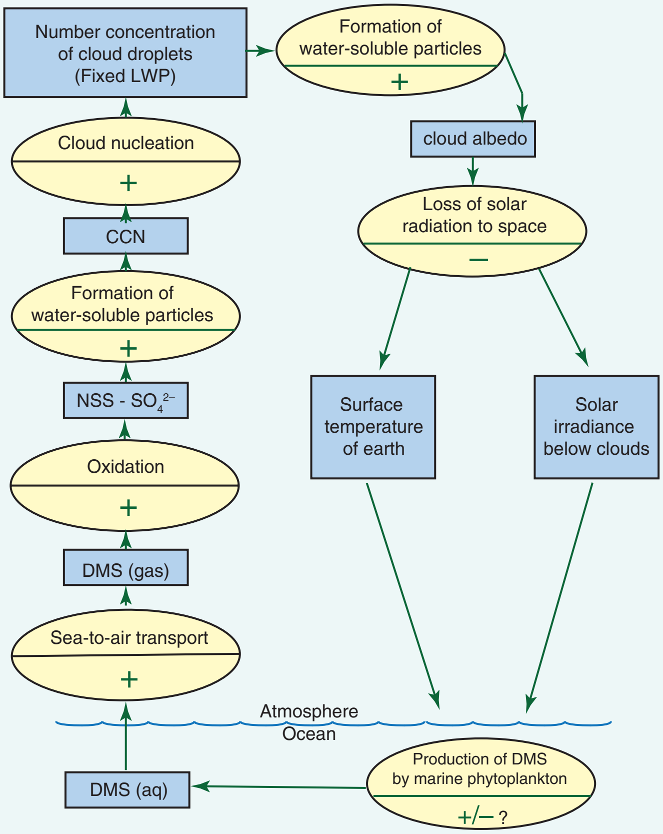


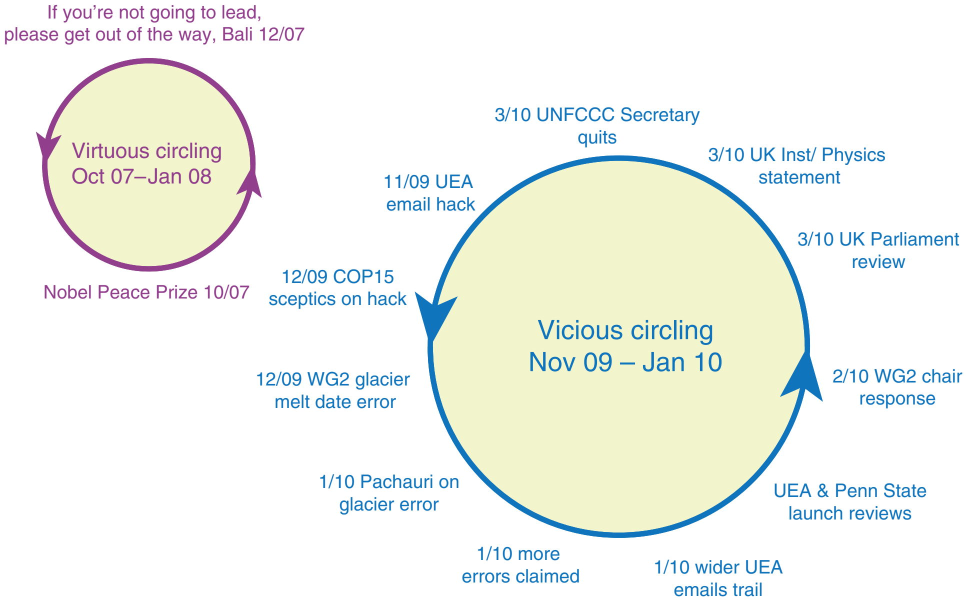
Figure source: Charlson et al. (1987). Reproduced with permission of Nature Publishing Group.

Climate change entered a different regime in 2007 with the publication of the Intergovernmental Panel on Climate Change's (IPCC's) Fourth Assessment Report (AR4) and the joint award of the Nobel Peace Prize to Al Gore and the IPCC. People no longer asked 'whether' human activities are changing the climate but the more urgent questions of: 'how fast?', 'with what impacts?' and 'demanding what responses?'. In late 2007, a virtuous cycle reinforced the public's recognition of the need for urgent action to mitigate change. Positive feedback, including in the media, showed climate change to be a risk management problem to be solved by all nations (Figure 1.11).

The mass media reversed (from virtuous to vicious) the direction of their positive feedback on anthropogenic climate change late in 2009.[27] This time, the character of public perception of anthropogenic climate change was transformed by media coverage of what was an inconsequential error in Working Group Two IPCC AR4 and selected contents of the Climatic Research Unit of the UK's University of East Anglia stolen emails trail.[28] The press pushed public perception past a social tipping point in December 2009. The weak Copenhagen Accord (2009) and the reduced pressure for climate mitigation legislation felt by world leaders are symptoms of the new social state resulting from crossing this irrevocable social threshold.

The true integrity question about anthropogenic climate change is really whether, and with what priority and pressure, urgently required actions are agreed and taken. Models are a key component to these decisions.

Figure 1.11 Virtuous and vicious circles created by a positive feedback that operated around two UNFCCC COP meetings (in 2007 and 2009). Public understanding and political will were reinforced through media coverage of the issue of anthropogenic climate change in two strong processes of positive feedback in 2007 and 2009. In the virtuous case, positive feedback strengthens public belief in the reality of climate change and, thus, the political will to respond to the threat at COP13 in Bali in December 2007. In the vicious case, a media clamour of positive feedback strengthens public interest in IPCC errors and in claims (later refuted) of abuse of the processes of IPCC and, thus, greatly reduces the political will to respond to the global warming threat at COP15 in Copenhagen in December 2009. Source: After Henderson-Sellers (2010). Reproduced with permission of Springer Science+Business Media.

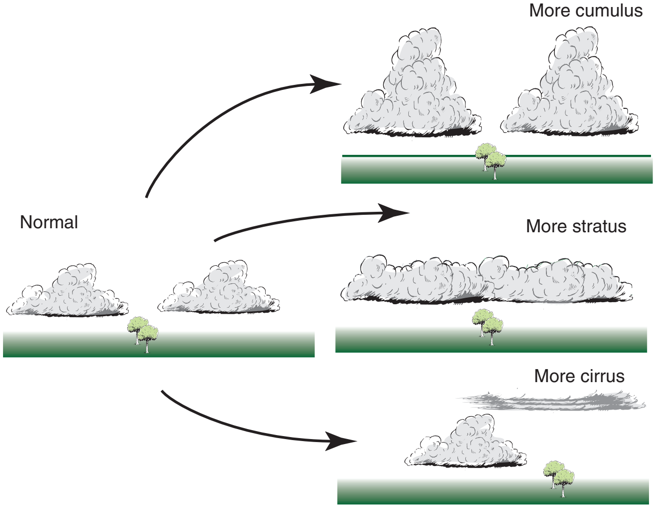


Reflection on Learning 1.4

Explain the concept of climate feedback and give examples

Clouds are important: clouds can be gloomy but they also create beautiful sunsets. Clouds are important in climate: they control radiation input (because of their high albedos) and they also play a large part in the emitted infrared radiation (because of their height in the atmosphere and hence lower temperatures). Clouds are important in climate modelling: cloudiness changes as other factors alter. However, correct (valid and robust) parameterisation of clouds in climate models has yet to be achieved. For example, Figure 1.12 illustrates how cloudiness might change: will 'more cloud' mean more stratus (low level and hence cooler), more cumulus (can be towering and very bright) or more cirrus (thin and high)? Each of these changes involves dynamical and thermodynamical feedbacks as illustrated here for the case of a change in the amount of cumulus convection. ■

(a) Types of cloud feedback



(b) Factors associated with cloud feedback

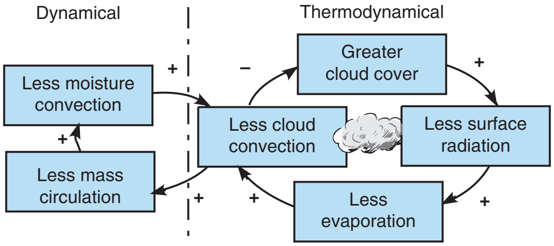


Figure 1.12 Cloud-climate interactions. (a) When climate shifts cause (for example) 'more cloud', this can be manifested in many ways: as more low-level layer cloud (stratus), as more towering tall cloud (cumulus) or as more high thin cloud (cirrus). The cloud could either be more extensive vertically or more extensive horizontally. Each of these 'cloud increases' creates a very different radiation effect and hence a different feedback onto climate. (b) Examples of dynamical and thermodynamical feedbacks and their directions in the case of a change in the amount of cumulus cloud convection. Source: Modified from Henderson-Sellers and Robinson (1986). Reproduced with permission of Longmans.

Tech Box 1.4

Planetary climate model – effective temperature and surface temperature

The simplest global climate model can be written as follows:

$$(1-\alpha)\frac{S}{4} = \sigma T_e^4 \qquad (1.1)$$

Using values of $S = 1370\,\mathrm{W\,m^{-2}}$, $\alpha = 0.3$ and $\sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$ gives for T_e (the planetary-wide effective temperature) a value of 255 K, or –18°C, in good agreement with the Earth's average effective (not surface) radiative temperature today.

If there are greenhouse gases in the planet's atmosphere then its surface temperature is the sum of this effective temperature and the greenhouse warming caused by these gases' absorption and re-emission of infrared radiation.

$$T_s = T_e + \Delta T \qquad (1.2)$$

Today's greenhouse effect, ΔT, of around +34°C delivers a global mean surface temperature of 289 K.

1.3.5 Climate models expose prevailing wisdom as compatible or incompatible with existing data and hence direct collection of new data

Issue*: geological evidence of massive climate change (e.g. Snowball Earth).*

Message*: models test theories about early Earth glaciations – evaluating the impact of strong positive feedbacks and climate recovery.*

An effective positive feedback mechanism was discussed in the previous section. Climate models can be shown to be instrumental in probing data by reference to the phenomenon of 'Snowball Earth'. At its simplest, the Snowball Earth idea refers to occasions in the geological record when glacial formations appear to have covered the whole Earth, or at least are found in locations at or near the equator, as well as at mid- and high latitudes. These periods are not fully agreed, but seem to begin with a Pre-Cambrian glaciation (the Huronian) that occurred between 2.1 and 2.4 billion years ago, followed by three Neo-Proterozoic glaciations dated between 650 and 800 million years ago. Although there is some dispute about the geographical extent of the glacial deposits, the climate model-based topic is fairly independent of these.

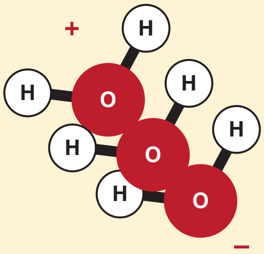
The question posed by widespread geological evidence of early global glaciation is, can a fully glaciated Earth 'recover', i.e. warm up, so that large-scale oceans are once again unfrozen? It has been noted above that the ice-albedo feedback is positive or reinforcing. Once a fully glaciated Earth occurs, almost any climate model will struggle to deglaciate.

Using a very simple climate model (Tech Box 1.4), it is straightforward to pinpoint the aspects of climate that must be modified to alter a trajectory. This very simple model shows that globally averaged mean surface temperature depends on only two factors susceptible to speedy (near real-time) modification: the albedo and the greenhouse effect.

Changing the global albedo from today's value of 0.3 to a much larger value, commensurate with a global glaciation of, say, 0.8, gives an effective temperature for the planet of 186 K. Adding today's greenhouse increment lifts this to only 220 K (or –53°C). This is a 'best case' since the albedo might have been higher and the solar radiation (*S*) was certainly lower in the past. These climate model calculations underline how easy it is to encourage persistent glaciation. However,

CSI Box 1.3

Weirdness of Water: Buddy, can you spare a dime-r



Understanding water means picturing its molecular construction: four hydrogen bonds produces an open three-dimensional network – a tetrahedron; the dipole charge on each water molecule means that they are attracted to one another. This molecular form and mutual cohesion are the source of many of the weird properties of water of great significance to Earth, to life and to climate simulation. For example, water's high melting and boiling point temperatures; and its large specific and latent heat capacities. Generally, water prefers to 'hang together' but it also dissolves a very wide range of substances, giving rise to its name 'universal solvent'. The smallest water molecule cluster contains only two water molecules: it is the dimer. Water vapour dimer absorption contributes to greenhouse warming and, although it has been known to experimentalists for many years, it remains a challenge to properly code into radiative transfer modules of climate models.

the geological record also shows that these glaciated periods stopped. Can this simple model be used to suggest how this could have occurred? A greenhouse temperature boost of around 100 K is required to defrost Snowball Earth. Since we know that the greenhouse effect on Venus is roughly +500 K,[29] this heating is by no means impossible, but it does raise interesting questions about the geological mechanisms that cycled CO_2 (or other greenhouse gases) in and out of the atmosphere on three or four occasions during Earth's history.

This geological puzzle persists and tempts climate modellers to probe its possible causes and effects. Large mixing ratios of carbon dioxide can be related to sedimentary rocks later deposited and the stark facets of the simple calculations above can be ameliorated by, for example, postulating a lower albedo on the snowball – say because of dust deposited following large volcanic eruptions or by arguing that world oceans would not fully freeze and might maintain near zero (°C) water temperatures overlain by wet (and hence grey rather than bright white) sea-ice. The former hypothetical situation has been termed 'Dustball' or 'Mudball Earth' while the latter has the name 'Slushball'.[30] Both have been extensively examined using all types of climate models from very simple to fully coupled.[31] The climate modelling barrier to freeze-thaw shifts has also prompted additional geological hypotheses – for example, involving changed chemistry of the Earth's atmosphere.

New geochemical data show two significant increases in atmospheric O_2 levels at around 2.4–2.3 and 0.8–0.6 billion years ago, times that coincide with the Snowball Earth glacial evidence. The geochemical story tells of oceanic sulfate concentrations increasing in accord with greater O_2 levels, while levels of methane, a strong greenhouse gas, appear to be the mirror inverse of atmospheric O_2 levels. These so-called 'oxic transitions' are characterised by significant disturbances in the carbon cycle. A plausible case can be made linking the delay between the appearance of oxygenic photosynthesis and oxygenation of the atmosphere to active scavenging of newly created O_2 out of the early atmosphere.

1.3.6 Climate models explain

Issue: *radiation controls climate.*
Message: *models calculate the impact of insolation changes – glacial/interglacial cycles follow solar input.*

The orbit of the Earth is an ellipse around the Sun, which lies at one of the foci. There are several different ways in which the orbital configuration can change to affect the received radiation and thus the climate. These 'Milankovitch[32] variations' describe the changing parameters of the Earth's orbit around the Sun. They are: (i) changes in eccentricity; (ii) changes in obliquity; and (iii) changes in orbital precession (Figure 1.13). The Earth's orbit becomes more eccentric (elliptical) and then more circular in a pseudo-cyclic way, completing the cycle in about 110,000 years. The mean annual incident flux varies as a function of the eccentricity of the orbit, E. For a larger value of E, there is a smaller incident annual flux. The current value of E is 0.017. In the last 5 million years, it has varied from 0.000,483 to 0.060,791, resulting in changes in the incident flux of +0.014% to –0.170% (~0.19 W m^{-2} and ~2.3 W m^{-2} respectively) from the current value.

The obliquity, the tilt of the Earth's axis of rotation, is the angle between the Earth's axis and the plane of the ecliptic (the plane in which the Earth and other bodies of the solar system orbit the Sun). This tilt varies from about 22° to 24.5°, with a period of about 40,000 years. The current value is 23.5°. Seasonal variations depend upon the obliquity: if the obliquity is large, so is the range of seasonality. Although the total received radiation is not altered, a greater seasonal variation in received flux is accompanied by a smaller meridional gradient in the annual radiation. (Recall that the meridional net radiation imbalance drives atmospheric and ocean circulations – see Figure 1.7.)

Owing to gravitational interaction with the other planets, primarily Jupiter, the perihelion (the point of the Earth's elliptical orbit closest to the Sun) moves in space so that the ellipse is moved around in space. This orbital precession will cause a progressive change in the time of the equinoxes. These changes occur in such a way that two main periodicities are apparent: 23,000 years and 18,800 years. This change, like that of obliquity, does not alter the total radiation received but does affect its temporal and spatial distribution. For example, perihelion is currently on 5 January, in the middle of the Northern Hemisphere winter, but 11,000–15,000 years from now it will occur in July. At the present-day value of eccentricity, there is a range of ~6% in the solar radiation incident at the top of the atmosphere between perihelion and aphelion (i.e. ~1411 to 1329 W m^{-2}).

Spectral analysis of long-term temperature data, such as the records in Figure 1.13b, has shown the existence of cycles with periods of ~20,000, ~40,000 and ~100,000 years (Figure 1.13c). These correspond closely with the Milankovitch cycles. The strongest signal in the observational data, however, is the 100,000-year cycle. This cycle corresponds to that of eccentricity variations in the Earth's orbit but eccentricity variations produce the smallest insolation changes resulting in a challenge for climate models. Modelling results have suggested that the present configuration of the landmasses in the Northern Hemisphere may favour rapid development of ice caps when conditions favour cool Northern Hemisphere summers. Almost certainly, these external changes in insolation trigger feedback effects in the climate system that demand correct incorporation into models.

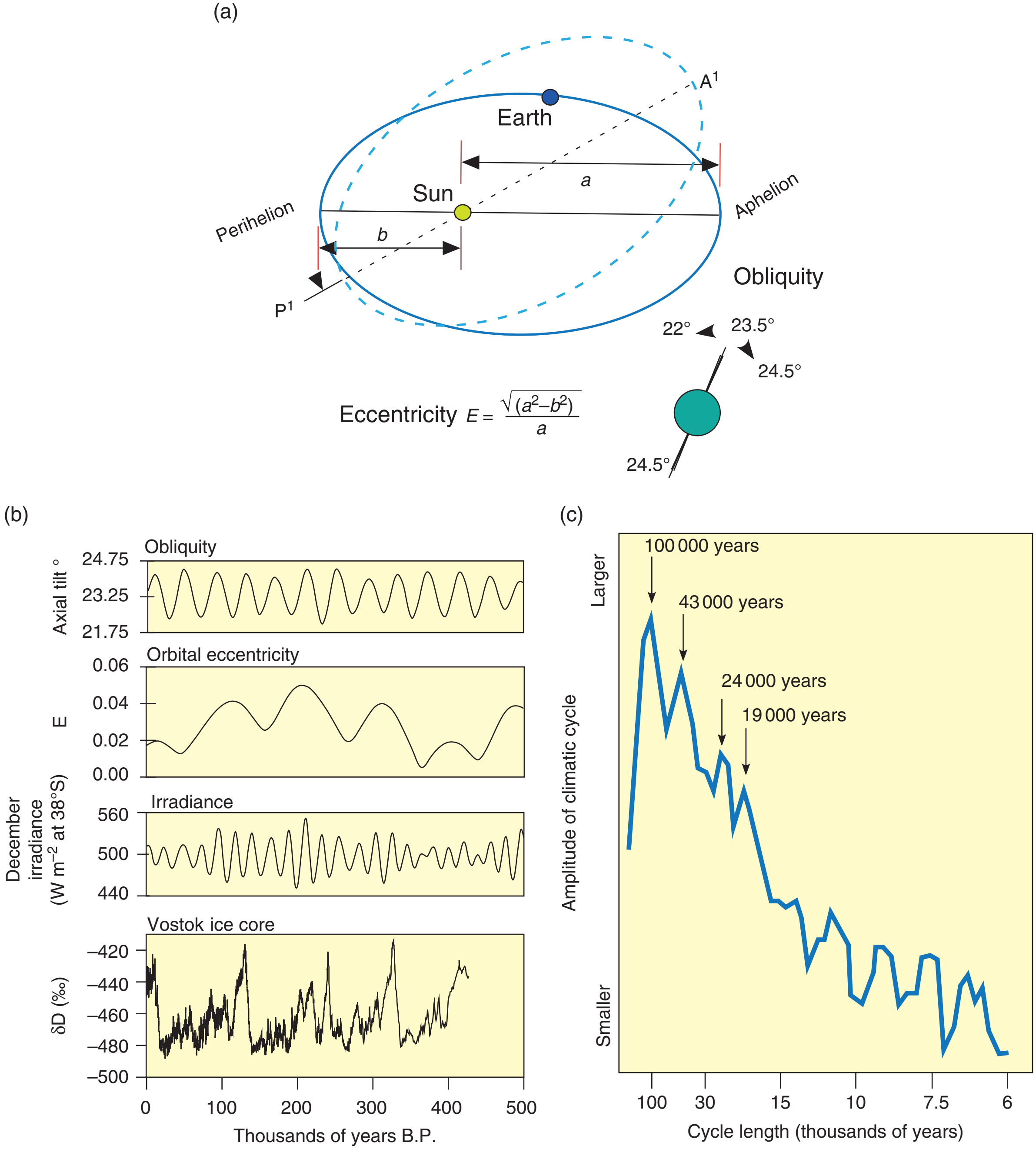


Figure 1.13 Milankovitch variations in incident solar radiation control the climate. (a) Schematic diagram showing the variations in the three orbital components: obliquity (axial tilt), orbital eccentricity and precession of the perihelion. (b) Variations in these three components over the last 500,000 years together with δD proxy temperature record from the Vostok Ice Core. (c) A spectrum of climatic variations over the last 500,000 years. The graph shows the importance of the climatic cycles of 100,000 years (eccentricity), 43,000 years (obliquity) and 24,000 and 19,000 years (precession of the location of perihelion). The curve is constructed from an isotopic record of two Indian Ocean cores. Source: Imbrie and Imbrie (1979). Reproduced with permission.

Spotlight on Climate Models Box 1

Palaeoclimate modelling challenge

Read: Braconnot, P., Harrison, S.P., Kageyama, M., et al. (2012) Evaluation of climate models using palaeoclimatic data. Nature Clim Change 11, 1–8.

The Palaeoclimate Modelling Intercomparison Project (PMIP), by applying palaeo-evaluation to simulations made by climate models used for future predictions, provides quasi-independent assessments of model performance. If adequate confidence can be placed in the palaeo data, it may be possible to determine whether a model is sufficiently sensitive to changes in atmospheric composition or how well it computes the strength of feedbacks that modify the model response to disturbances. This is the basis for the investigation by Braconnot et al. spotlighted here.

These authors review the evidence for two aspects of palaeoclimate: the change in the mean annual precipitation (MAP) for the mid-Holocene and the change in mean temperature of the coldest month (MTCO) for the last glacial maximum (LGM). These are assessed for different regions: for MAP over five monsoon regions (North Africa, India, East Asia, North America and South America) and for MTCO over five regions (western North America, eastern North America, Europe, Asia and the tropics). There is a great deal of detail given by Braconnot et al. in the supplementary information linked from the publication itself. Their analyses might prompt questions such as: how hard is it to reconstruct precipitation from palaeo data and how do scientists reconstruct the temperature of the coldest month from palaeo data? The figure shows how precipitation anomalies (as MAPs) compare for the five monsoon regions and among the three phases of PMIP and the palaeoclimate reconstructions. An AGCM is an atmospheric (only) global climate model; OAGCM is an ocean-atmospheric model; and OAVGCM is a global climate model with ocean, atmosphere and interactive vegetation.

Braconnot et al. conclude that evaluation of climate simulations against palaeo data shows that models reproduce the direction and large-scale patterns of past changes in climate, but tend to underestimate the magnitude of regional changes. However, thoughtful inspection of this figure may raise questions such as: Why is the range (shown by the whiskers of the box plots) so much greater for the reconstructions than for the models? And, since the range of observations (truth) is so large, does it matter that the three PMIP simulation sets differ a little?

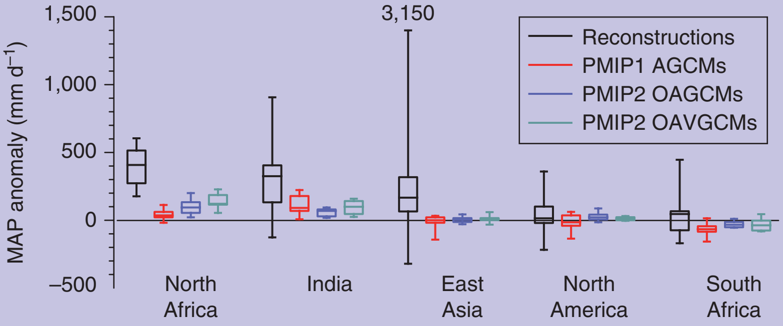


Figure source: Braconnot et al. (2012). Reproduced with permission of Nature Publishing Group.

(*Continued*)

Discussion question

Climate modellers tackle the need to 'validate' their models in three main ways: by examining how climate models perform when simulating a few recent decades to no more than a century; by evaluating components of the full models (e.g. rainfall or radiation) and testing the predictions of these components against observations for a short period (usually no more than a year); and by hind-casting past climates and assessing how well the model predictions compare with reconstructions of these palaeoclimates. Each of these techniques has its own problems and they share the primary challenge of defining 'how good is good enough?'. Which of these validation techniques do you believe to be most valuable and why?

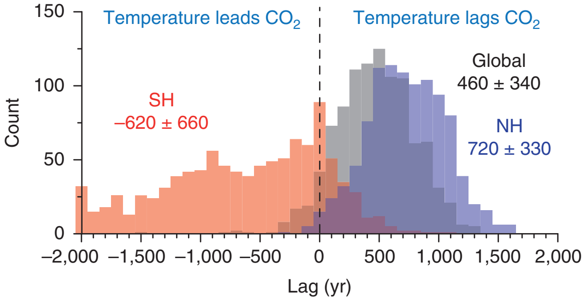


Figure 1.14 Frequency of occurrence (counts) of leading and lagging (years) of atmospheric CO_2 concentration and temperature for the global (grey), Northern Hemisphere (NH; blue) and Southern Hemisphere (SH; red) during the Pleistocene ice ages (20–10 kyr ago). CO_2 concentration leads the global temperature for the vast majority of the time (90% of the simulations) and lags it in only 6% of the 1000 Monte Carlo experiments. Differences between the respective temperature changes of the Northern Hemisphere and Southern Hemisphere are linked to the strength of the Atlantic Meridional Overturning Circulation (AMOC) recorded in marine sediments. The overall picture is of global temperatures being led by CO_2 concentrations with an antiphased hemispheric temperature response to ocean circulation changes superimposed on this globally in-phase warming. Source: Shakun et al. (2012). Reproduced with permission of Nature Publishing Group.

The identification of orbital frequencies in changes in global ice volume (measured using the marine oxygen isotope ($^{18}O/^{16}O$) record as a proxy) demonstrated in the 1970s that climate responds to the Earth's astronomical attitude to the Sun. It also posed interesting challenges for climate modellers: how is it that the smallest insolation change creates the largest climate swings and how are latitudinal changes in solar energy transmitted to the whole planet? Analysis in the 1980s of CO_2 in air trapped in Antarctic ice revealed that greenhouse gas concentrations also increased and decreased over the last glacial cycle. However, neither observations nor models could tease out the exact relationship among greenhouse gases, solar insolation and climate.

Specifically, proxy data were variously interpreted to suggest that CO_2 was the primary driver of the ice ages, a more modest feedback on warming and a consequence rather than cause of past climate change.

Climate models contributed to this confusion partly because they had to use snapshot simulations rather than through time re-creations and so could not distinguish the timing of changes in various forcings relative to responses. In 2012, a combined analysis of proxy data and new climate model simulations suggested that the local Antarctic temperature was strongly correlated with and seems to have slightly led changes in CO_2 concentration (Figure 1.14).[33] Whether this conclusion fully explains the causes of the Pleistocene ice ages remains to be seen.

1.3.7 Climate models bound (bracket) outcomes within plausible ranges

Issue: *land use matters for climate.*
Message: *models pinpoint how tropical deforestation and desertification can alter climate but also in which locations the atmosphere is dominant.*

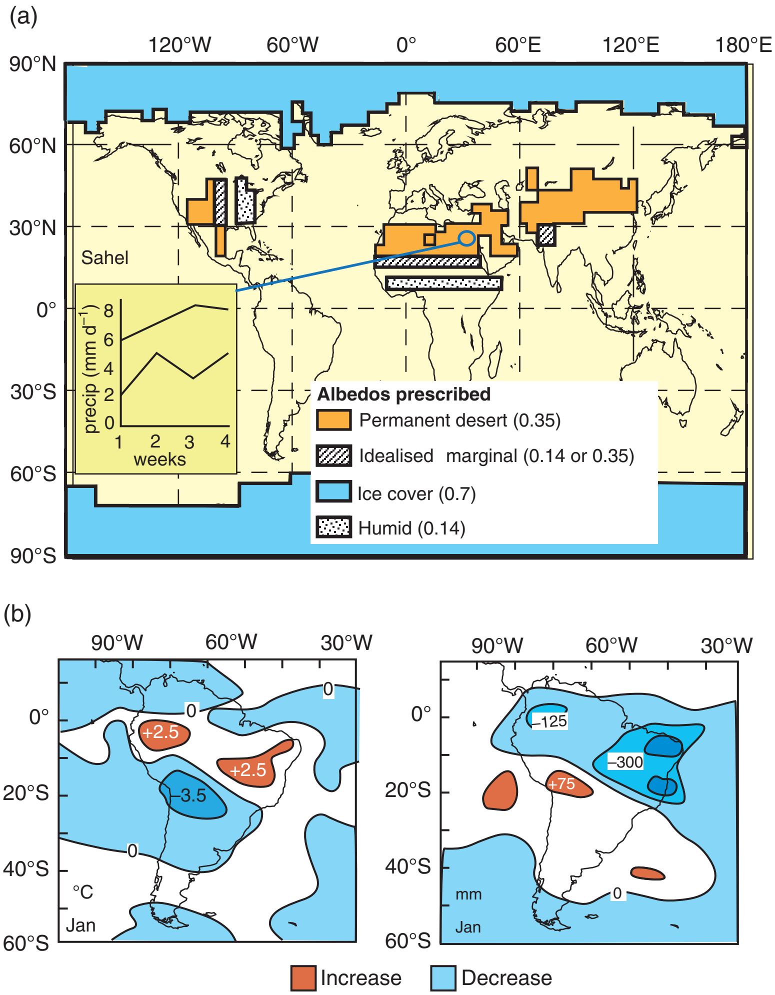


Figure 1.15 Historical modelling of the impact of land-use change on climate. (a) Areas for which albedo changes were made in a set of 1970s GCM experiments, by Charney, designed to examine desertification. The inset graph shows the rainfall resulting from increasing the surface albedo from 0.14 to 0.35 in the Sahel region when free evaporation was permitted. (b) Simulated temperature (*left*) and precipitation (*right*) changes following replacement of the Amazon tropical moist forest by scrub grassland in a 1980s GCM. These are 5-year means from the end of a 6-year deforestation experiment. Areas of significant increase or decrease (using Student's *t*) are shown. Source: (a) Henderson-Sellers and Wilson (1983). Reproduced with permission of the American Geophysical Union.

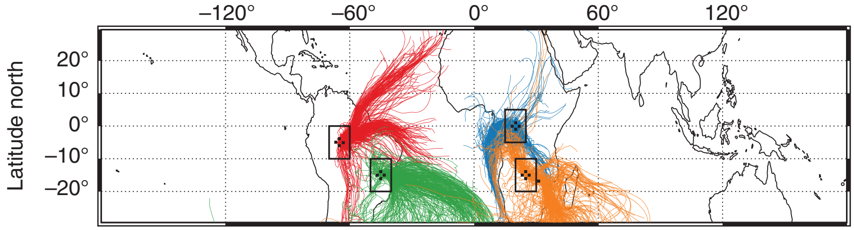


Figure 1.16 Climate model investigation of the transport of moisture into tropical regions of interest (four boxes) shown as 10-day back-trajectories of air arriving daily during one example year (2001) calculated using the ECMWF model. Source: Spracklen et al. (2012). Reproduced with permission of Nature Publishing Group.

Humans are now recognised as major agents in regional-scale changes of the character of the Earth's surface. These include desertification, re- and deforestation, urbanisation and engineering of major rivers, lakes and dams. Climate modellers have investigated the climatic effect of such changes in the nature of the Earth's continental surface for over 40 years. The more recent evaluations not only demonstrate human disturbance of climate flowing from land-surface changes but also allow consideration of possible mitigation techniques to try to restore aspects of regional climate previously disturbed.

Desertification is a problem affecting millions of people. The sparse vegetation natural to arid and semi-arid areas can be easily removed as a result of relatively minor changes in the climate or by direct influence of human activity such as overgrazing or poor agricultural practices. Removal of vegetation and exposure of bare soil increase albedo and decrease soil water storage, because of increased run-off. Less moisture available at the surface means decreased latent heat flux, leading to an increase in surface temperature. On the other hand, the increased albedo produces a net radiative loss. In climate model calculations, the latter effect appears to dominate and the radiation deficit causes large-scale subsidence. In this descending air, cloud and precipitation formation tend to be suppressed and aridity increases (Figure 1.15a). This global simulation involves a surface albedo change for a group of semi-arid areas. It can be seen that an increase in surface albedo does seem to decrease rainfall. Use of a global model emphasises that all parts of the climate system are interlinked. Although this particular model includes many simplifications, the results are illustrative of the types of surface-induced climatic effects that are captured by models.

At present, around 30% of the land surface of the Earth is forested and about 10% is cultivated. However, the amount of forest, particularly in the tropics, is rapidly being reduced while reforestation is prevalent in mid-latitudes. As a consequence, the surface characteristics of large areas are being greatly modified. Modellers have attempted to examine the climatic effects of forest planting and clearance. The change in surface character can be especially noticeable when forests are replaced by cropland. One area that is undergoing deforestation is the Amazon Basin in South America. The important change in deforestation is in the surface hydrological characteristics, since the evapotranspiration from a forested area can be many times greater than from adjacent open ground. Most climate model simulations of Amazonian deforestation show a reduction in moisture recycling (because of the lack of the moist forest canopy), which reduces precipitation markedly (Figure 1.15b). However, the available global model experiments do not agree on whether an increase in surface temperature occurs. The largest impacts are the local and regional effects on the climate, which could exacerbate the effects of soil impoverishment and reduced biodiversity accompanying the deforestation. It has proved possible to detect impacts resulting from tropical deforestation propagating to the global scale by increasing the length of the integrations and adding ensemble members to the suite of simulations studied.[34]

From the early 1970s, when Jule Charney calculated the possible impact of marginal desert land use, past the first deforestation simulation in the 1980s to the present day, climate models have been used in combination with observations to obtain an increasingly persuasive case for reduction of human impact in vulnerable regions.[35] For example, Figure 1.16 illustrates a modelling result (here back trajectories from four tropical forests (boxes)) obtained by combining satellite observations of tropical precipitation and vegetation density with model simulations of atmospheric transport to evaluate the effect of forests on tropical rainfall.[36] This model analysis established that in more than 60% of the tropical land surface, air that has passed over dense and areally extensive vegetation in the preceding few days produces at least twice as much rain as air that has not crossed forests.

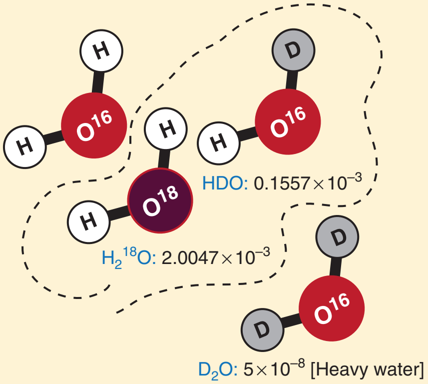
Water occurs in different isotopologue forms (see CSI Box 1.4) that can be traced in both models and in the real world. Figure 1.17 illustrates the likelihood (bracketed by observations in this case) that water in the Alamo River (white circle) is derived from different locations in western North America. Warm colours indicate locations at which the modelled precipitation

CSI Box 1.4

Weirdness of Water: Isotopes and isotopologues

Water's isotopologues (not isotopes because water is a compound, not an element) arise from bonding among the various isotopes of hydrogen and oxygen. Because these isotopologues can be separately identified, they provide climate modellers with tracking and process measurement capabilities.[37] For example, the 'heavy' water isotope ($^1H^2H^{16}O$) binds more strongly to other water molecules and so requires more kinetic energy than its common cousin ($^1H^1H^{16}O$) to evaporate. As a consequence, water vapour above an open water surface, such as an ocean, will contain relatively fewer 'heavy' water molecules than the ocean itself. As the moist air mass moves across a continent, the 'heavy' water molecules will tend to precipitate out more readily, further depleting the water vapour of 'heavy' water.

Isotopic depletion, now in proxy analyses, aids climate modelling through determining the global temperature fluctuations during ice ages to measuring the biospheric recycling of water in tropical forests. ($D = {}^2H$).



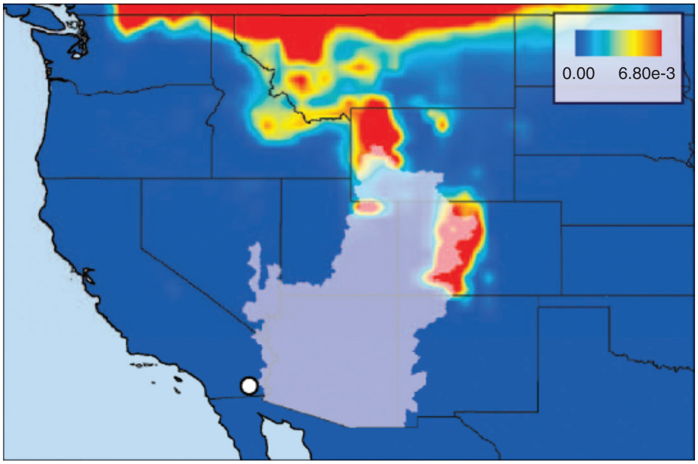


Figure 1.17 Combining model simulation and data analysis can provide greater insight than either technique applied separately. Output from the Isoscapes Modeling, Analysis and Prediction (IsoMAP) showing the relative likelihood (unit-less ranging from red (very likely) to deep blue (unlikely)) that water in the Alamo River (*white circle*) is derived from different locations in western North America. Source: Bowen et al. (2012). Reproduced with permission of the American Geophysical Union.

isotope ratios are more similar to the isotopic character of the river water, than the blue colours. This analysis shows that a large fraction of the water in the Alamo River is derived from the distant headwaters of the Colorado River drainage basin.

1.3.8 Climate models train practitioners and educate the general public

Issue*: when is a model ready to inform, e.g. nuclear winter?*
Message*: models illuminate policy choices and also become embroiled in policy disputes.*

It is frequently noted that weather plays an important role in warfare: there are many stories and anecdotes from the Second World War, the most famous being the weather forecast for the D-Day landings. The impact of climate forecast on warfare, or rather the possibility of war, is less well known but at least as important. This case of climate modelling informing military options relates to the issue of Mutually Assured Destruction (MAD) that, it was believed, stopped the Soviet Union and the United States of America from embarking on nuclear conflict during the Cold War because, once begun, the obliteration would be complete. The premise of MAD naturally tempted military advisors to propose more limited war strategies until a climate model demonstrated unequivocally that even this was doomed.

The basic theory of what has come to be termed 'nuclear winter' is that nuclear explosions themselves, and to a much greater extent the ensuing fires, would cause massive injection of soot (black aerosols) into the atmosphere.[38] This effect was well known, and had been observed during earlier conflicts. However, climate models further improved understanding by permitting consideration of the effect of the height of the injection (up to 10–15 km above the surface) and then allowing calculation of the resulting impacts of these dark upper tropospheric aerosols. The models showed that the dark particles tended to absorb solar radiation, warming the air and pushing the smoke still higher. Once in the stratosphere, this black aerosol would persist for many years, as the tropospheric removal process of rain washout would not be available. The smoke stays high and absorbs sunlight, so that the surface temperature drops and sets up a positive feedback loop, encouraging these conditions to continue (Figure 1.18).

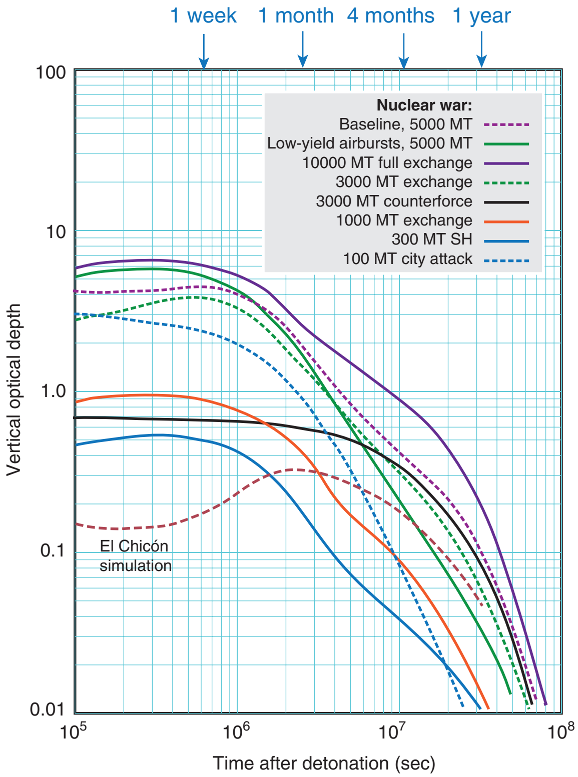


Figure 1.18 Climate model results can become iconic. This famous simulation is from a paper known as 'TTAPS' and shows the time evolution of the disturbing effect of nuclear war on the atmospheric climate. Optical depths (i.e. scattering plus absorption) calculated by a one-dimensional radiative-convective model for wavelength of 550 nm are compared for a natural disturbance (the El Chichón volcanic eruption) and a range of nuclear war scenarios. Optical depths of ≤0.1 are negligible; those ~1.0 are significant and when >2 there are serious consequences. Source: Turco et al. (1983).

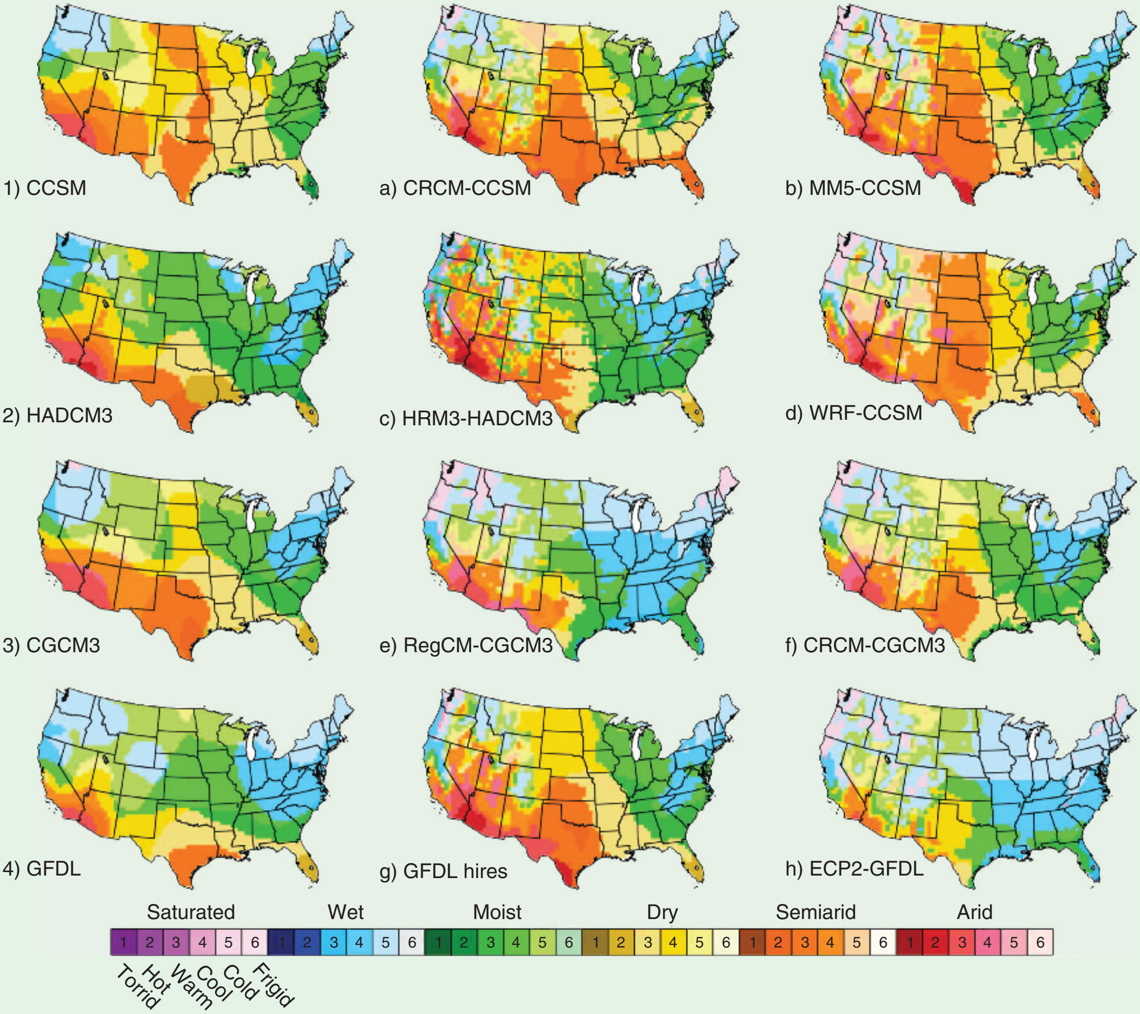
Although there were earlier accounts of this process, the public and policy recognition mostly arose when a famous climate modelling paper known now by the initials of its authors as TTAPS (Richard P. Turco, Owen Toon, Thomas P. Ackerman, James B. Pollack and Carl Sagan) was published in the journal *Science* in 1983.[39] The model employed was a one-dimensional radiative–convective model extending (unusually) to the mesopause. As such, it permitted the prediction of the vertical characteristics of the

Model Validation Box 1

Regionalising climate with Thornthwaite

Read: Elguindi, N., Grundstein, A. (2012) An integrated approach to assessing 21st century climate change over the contiguous U.S. using the NARCCAP RCM output. Clim Change 117, 809–827.

How to test the veracity of predictions made by climate models has been a challenge since the first models were used. Side-by-side comparison of pictures (usually maps) of output variables was the earliest



1) CCSM a) CRCM-CCSM b) MM5-CCSM

2) HADCM3 c) HRM3-HADCM3 d) WRF-CCSM

3) CGCM3 e) RegCM-CGCM3 f) CRCM-CGCM3

4) GFDL g) GFDL hires h) ECP2-GFDL

Figure source: Elguindi and Grundstein (2013). Reproduced with permission of Springer Science+Business Media.

(*Continued*)

method employed. This simple 'by eye' comparison was slightly improved by mapping not just a single parameter but a compound variable composed of more than one element of the predicted climate. The earliest of these evaluations exploited 'climate regimes' most commonly due to three researchers: Holdridge, Köppen and Thornthwaite. These climate classifications date back to the middle of the 20th century and have been quite widely applied.

In the 2012 paper by Elguindi and Grundstein, the Thornthwaite classification is employed to facilitate a comparison among predicted climates for the continental USA using six regional climate models (RegCMs) forced by coupled global climate models (GCMs). The authors select the models they investigate from RegCMs participating in NARCCAP (North American Regional Climate Change Assessment Program). Each model was run for 30 years for the current climate (1971–2000), and 30 years simulating the future climate (2041–2070) using the A2 scenario from the Special Report on Emissions Scenarios of the Intergovernmental Panel on Climate Change.[41] The figure shows the 'current' climate (1971–2000) simulated by four AOGCMs (1–4 in left column) and the RegCMs (a–h) in the centre and right columns.

It is common to find that higher resolution in models gives rise to better climate simulation in areas of rapidly changing topography (e.g. mountains). Does this expected 'improvement' show in the figure? With reference to the future climate predictions, Elguindi and Grundstein find that 'the U.S. will become drier, particularly across the Midwest as the moisture boundary shifts eastward, and in the Appalachian region'. There are a number of ways that prediction of the 'current' climate may be evaluated. Thinking about these, can you suggest what hazards might affect such attempts to 'validate' the predictions shown in this figure?

Discussion preparation questions

1. How easy do you find it to compare model predictions 'by eye'?
2. Research climate classifications and their use for evaluating climate model predictions.

global climate following a large-scale nuclear war but not regional impacts. While this geographical limitation was serious, and has since been resolved by using general circulation models, the main point – that such a conflict is equally unwinnable because the surface cooling is global and profound – carried into the mass media as well as affecting military and policy strategies.

There arose a muddled controversy when in 1986 two different modellers, Starley Thompson and Stephen Schneider, wrote a paper entitled 'Nuclear Winter Reappraised'.[40] Review of this paper shows that the goal was not to discredit the TTAPS conclusions but to slightly ameliorate them – neatly dubbed a 'nuclear autumn' (rather than winter). The media and policy fallout (pun intended) from the perceived dispute among climate models was a modest presage for the later sceptic-driven discussion about global warming. As with the science on nuclear fallout, the science about climate change is often misconstrued as being controversial among experts whereas there is widespread consensus on the overarching points of social concern.

That the original TTAPS results altered military practitioners' views is undeniable. The interest of the general public is also clear in the media trail from science paper, via policy documents to more generally accessible policy journals (e.g. *Foreign Affairs*), to the mass media. Many subsequent climate simulations have shown that the original TTAPS theory is, by and large, correct although the details differ as a function of such aspects as the regional input of aerosol and the time of year investigated. The main point, frequently underlined by climate scientists, is that, in addition to the large number of deaths and massive infrastructure disruption resulting from a nuclear exchange, there is a major climate disturbance that is most likely to persist for years if not decades. Carl Sagan underscored the climatic disturbance of large-scale fires arising from bombs or incendiary devices in relation to the Iran-Iraq war in the early 1990s. More recently, global and regional model simulations have determined that oil-well fires are unlikely to create extensive enough smoke plumes to result in their lofting above the tropopause, but extensive burning of towns and cities could produce such plumes. To date, development of large enough smoke plumes that are self-heating and thus self-lofting through the troposphere to the stratosphere, where they become stuck, remains a modelled result observationally unsupported.[42]

1.3.9 Climate models discipline the policy dialogue

Issue: *global climate governance, e.g. the Montréal Protocol.*
Message: *models simulate the chemical disruption of a natural atmospheric balance and also reveal how much a good international treaty has benefitted Earth.*

The successful Montréal Protocol is often offered as a template for future limit-setting measures to curb greenhouse gas increases. Even though it is not at all clear that this is a good analogy for carbon dioxide and other greenhouse gas emission reductions, the way in which stratospheric ozone depletion came to be understood and its subsequent protection by means of international treaty are a vindication of climate modelling. The amount of ozone in the stratosphere is the result of a dynamic balance between photochemical production and loss. The chemistry is catalysed by chlorine ions (Cl) and/or bromine ions (Br). The shorthand form of this stratospheric chemical cycle is a chlorine atom changes an ozone molecule to oxygen:

$$\mathrm{Cl} + \mathrm{O_3} \rightarrow \mathrm{ClO} + \mathrm{O_2}$$

and then this ClO reacts with nascent oxygen (O) to release the original chlorine atom:

$$\mathrm{ClO} + \mathrm{O} \rightarrow \mathrm{Cl} + \mathrm{O_2}$$

These reactions can repeat and continue to destroy ozone.

There are a number of famous names involved with the story of ozone depletion above both poles and the investigation of chemistry that makes this occur and the international treaty (the Montréal Protocol) that caused the discontinuation of industrial production of the chlorofluorocarbons (CFCs). Three well-known atmospheric scientists, Paul Crutzen, Mario Molina and Sherwood (Sheri) Rowland, were awarded the 1995 Nobel Prize for Chemistry for their work on this problem. Widespread alarm about how CFCs might affect the Earth's atmosphere arose following the publication of a landmark observationally based paper by Farman, Gardiner and Shanklin in *Nature* in 1985.[43] Other important climate scientists involved in disentangling this chemistry and observing the Antarctic depletion include James Lovelock and Susan Solomon.

Climate models have been used to show that the Montréal Protocol has not only averted further damage to the ozone layer[44] but has helped prevent significant regional climate change (Figure 1.19).

Chemistry-climate models have been used to analyse the effects of the Montréal Protocol, i.e. the effectiveness of the ozone recovery that this treaty delivered.[45] Figure 1.19 shows the paired comparison predictions from one such climate model. In one simulation, the emission of ozone-depleting substances was prescribed according to the restrictions of the Montréal Protocol as compared with a second model run in which the ozone-depleting substances grew by 3% annually. This model predicts that the Montréal Protocol will have saved up to 80% of the global annual total ozone by the end of the 21st century. Further analysis of the simulations concludes that without this Protocol, by 2100, the mesosphere and stratosphere cool down by 40°C and 20°C, respectively, as a consequence of dramatic ozone depletion. Finally, without the Montréal Protocol, ultraviolet (UV) radiation undergoes a five-fold increase in populated areas in the 21st century, resulting in much greater incidence of skin cancers in many high-latitude regions.

Biography Box 1.2

Meet the modeller: Stephen H. Schneider

Leadership: a pioneer in modelling, Schneider possessed the rare gift of being able to explain the complexities of climate science and, rarer still, the willingness to use it to benefit everyone. He was the greatest populariser of climate.

Popular recognition: a frequent contributor to the media, Schneider coined the term 'mediarology' to describe the challenges of successfully communicating science to the public. He spoke fast, unerringly and with unbounded enthusiasm – always!

Climate modelling connectivity: Schneider was advisor, mentor, co-worker and friend to a very large number of climate modellers, from Jim Hansen in the 1970s to Bob Dickinson in the 1980s, and most recently with his wife, Terry Root, on the impacts of human-caused climate change on the distribution and abundance of many species.

Life and times: Stephen H. Schneider (11 February 1945 – 19 July 2010) was a professor at Stanford University from where he led assessment initiatives for the IPCC, founded and edited the journal *Climatic Change*, and wrote hundreds of books and papers on climate. Schneider was withering about those exploiting uncertainty in order to undermine public belief in all types of scientific consensus. In one of his last books, *Science as a Contact Sport*, he describes developing a positive, practical policy that will bring climate change back under our control, help the economy with a new generation of green energy jobs and productivity, and reduce the dependence on fossil fuels and, ultimately, ensure a future for ourselves and our children.

Read more

Mastrandrea, M.D., Schneider, S.H. (2010) *Preparing for Climate Change*. Cambridge, MA: MIT Press.

Schneider, S.H. (2009) *Science as a Contact Sport: Inside the Battle to Save the Earth's Climate*. Washington, DC: National Geographic Society.

http://www.climatemodellingprimer.net/l/k110.htm

http://www.climatemodellingprimer.net/l/k111.htm

Watch

Schneider argues for immediate action on climate:

http://www.climatemodellingprimer.net/l/k112.htm

http://www.climatemodellingprimer.net/l/k113.htm

IPCC Synthesis Report Scoping Meeting held in Liège, Belgium, August 2010, dedicated to Steve Schneider's memory. Photo source: Jean-Pascal van Ypersele.

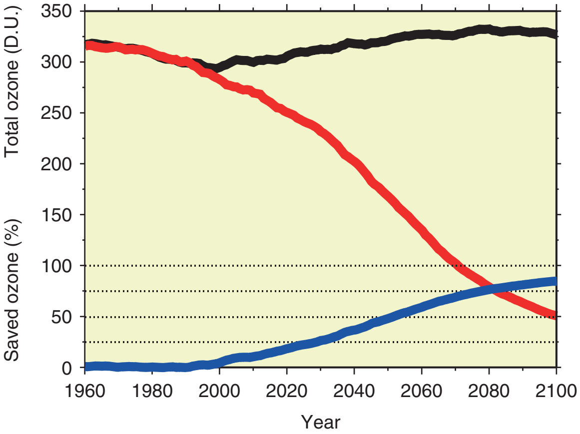


Figure 1.19 Climate model simulations can contribute to improved global governance by illustrating the effect of changed laws or proposed legislation changes. Here, the positive impact of the Montréal Protocol is shown in the time evolution of the global, annual mean total ozone with (*black*) and without (*red*) the Protocol. Total ozone saved by the Montréal Protocol limitations (%) is represented by the blue line. Source: After Egorova et al. (2012).

1.3.10 Climate models encourage sensible thinking and informed discussion

Issue: *Geoengineering as an economic problem.* ***Message***: *models allow public discussion of the possibility and timing of intervention to reduce global warming.*

Today's society discusses a host of ideas around the issue of global warming, ranging from sceptics' disruption of informed discussion[46] through to setting carbon taxes at a level that promises reduction in CO_2 emissions and the challenge of prioritising adaptation investments to try to defend future generations while not upsetting the current generation's lifestyle.

The idea of large-scale, planetary modification to relieve, or even resolve, a pollution problem is anathema to some people. Indeed, there is a group of climate modellers who still refuse to work on the implications of geoengineering because they argue that this research has the potential to reduce society's willingness to act to reduce greenhouse gas emissions. This refusal is a stark, perhaps even extreme, example of climate models informing discussion. However, the larger majority of modellers accept (albeit in many cases very reluctantly) that examining the costs and consequences of trying to engineer the planet to reduce the impacts of global warming may become necessary.

Using a very simple climate model, it is straightforward to pinpoint the aspects of climate that must be modified to alter the most likely global warming trajectory. The very simple climate model introduced in Tech Box 1.4 shows that globally averaged mean surface temperature depends on only two factors susceptible to speedy (near real-time) modification: the albedo and the greenhouse effect. Thus, there are only two ways to try to engineer away the greenhouse warming: either reduce the absorbed solar radiation or remove some of the polluting greenhouse gases. These two techniques are frequently abbreviated as solar radiation management (SRM) and carbon dioxide removal (CDR). The radiation terms upon which the techniques have to work are shown in Figure 1.20. As the width of the arrows indicates magnitude, it can be seen that operating on the solar radiation near the top of the atmosphere or the heat absorbed by the ground from the atmosphere (both ~324 $W\,m^{-2}$) is similarly challenging, at least in energy terms.

Carbon dioxide removal techniques encompass activities already under way such as protecting vibrant forests as effective carbon sinks, moving to non-fossil fuel energy sources, enriching agricultural land so that more carbon is retained in soils, and by scrubbing CO_2 out of the air. CDR also involves much less wholesome proposals such as increasing oceanic uptake of CO_2, for example by fertilisation of the oceans with naturally scarce nutrients, or by forcing a more energetic oceanic upwelling. SRM also ranges from apparently benign to much more intrusive techniques: colouring roofs white or encouraging crops with higher albedos through to inserting large amounts of sulfate aerosols into the stratosphere to scatter sunlight back to space or even erecting solar shields beyond the atmosphere.

Over the past decade there has been a series of assessments of both of these technique types. In all cases, climate models have been used to evaluate the degree of change possible and, importantly, the likely consequences of the

Biography Box 1.3

Meet the modeller: Susan Solomon

Leadership: Solomon's climate leadership was most clearly demonstrated in 2007 as co-chair (with Dr Qin Dahe) of Working Group 1 of the UN's Intergovernmental Panel on Climate Change during its production of the report that concluded 'unequivocally' that the world is warming.

Popular recognition: In *Time Magazine*'s 2008 Top 100 list of the world's most influential people. Susan has been honoured by having two geological features in Antarctica – the Solomon Glacier (78°23′S, 162°30′E) and Solomon Saddle (78°23′S, 162°39′E) – named in recognition of her achievements as a scientist.

Climate modelling connectivity: Solomon shares a place in the National Oceanic and Atmospheric Administration's Top 10 History Makers with Joseph Smagorinksy.

Life and times: Solomon is internationally recognised as a leader in atmospheric science. She won acclaim for her perceptive explanation of the cause of the Antarctic ozone hole. In the 1980s and 1990s she led expeditions to Antarctica and her popular book *The Coldest March* was in the 2001 Books of the Year lists of *The New York Times, The Economist* and *The Independent*. In Antarctica, her team overcame the challenges of scientific study during the polar winter, confirming the ozone depletion's cause: the chemicals known as chlorofluorocarbons (CFCs). Solomon developed a new method for evaluating the ozone depletion potentials used as a scale for regulating compounds that damage the ozone layer. These conclusions helped lead to a global ban on CFCs.

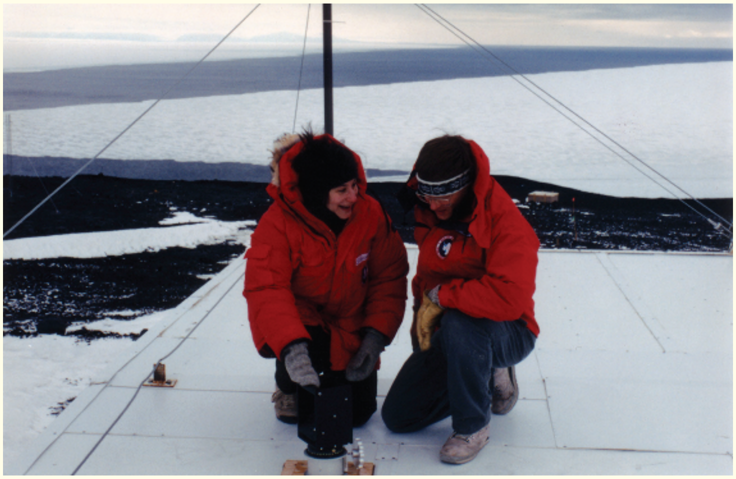
Read more

Solomon S. (2002) *The Coldest March: Scott's Fatal Antarctic Expedition*. New Haven, CT: Yale University Press. www.coldestmarch.com

Time Magazine's 'most influential people': http://www.climatemodellingprimer.net/l/k114.htm

Watch

2010 Darsh T. Wasan Lecture: http://www.climatemodellingprimer.net/l/k115.htm



Susan Solomon (left) and colleague at McMurdo Station. Photo source: Alexandra Weaver.

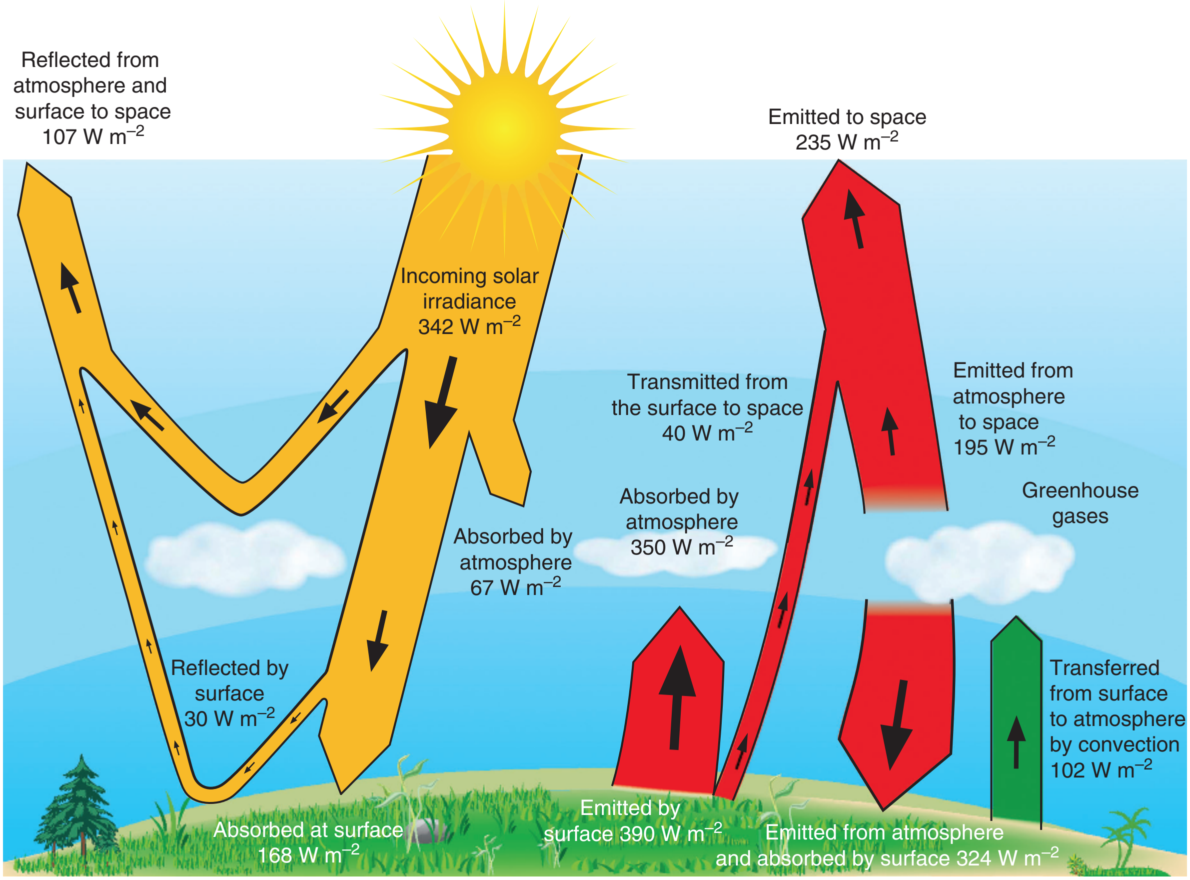


Figure 1.20 Globally averaged energy budget of the Earth: solar in yellow; thermal (heat) in red and moisture (evaporation) in green. Climate models are frequently evaluated in terms of their ability to represent these fluxes. Climatic disturbances that alter components of the energy budget are also simulated using climate models; for example, the impact of geoengineering climate control proposals such as solar radiation management (SRM) and carbon dioxide removal (CDR) techniques. Source: Shepherd et al. (2009) and Trenberth et al. (2009). Reproduced with permission of the American Meteorological Society.

particular proposed proactive engineering.[47] Generally, CDR techniques have more champions because, if successful, they result in removal of the problem – too much CO_2 in the atmosphere. However, their outcomes are more difficult to anticipate and, at present, are also believed likely to take longer to undertake and to achieve reduction of greenhouse gas loading. SRM techniques are usually quicker and easier to undertake but carry with them two disadvantages: they do not solve the problem and by further (albeit differently) altering the climate, they may themselves cause additional climate disturbances. Table 1.7 is one example of the application of climate models to the evaluation of aspects of possible SRM techniques. Evaluation includes how much energy reduction is delivered, how much each W m^{-2} costs, the likely side-effects and the risk associated with these. Selecting the 'best' tool depends on the confidence placed in such estimates.

There is one other aspect of geoengineering as probed and revealed by climate models: the possibility that such techniques might need to be applied very quickly if a so-called 'tipping point' seems very close (see Section 1.3.4). This is illustrated in Figure 1.21 showing the planetary boundaries for the Earth.[48] The 2009 planetary boundaries concept is based on the notion that transgressing one or more planetary boundaries is deleterious and may be catastrophic for life on Earth because

Table 1.7 Comparison of conventional mitigation costs, risks and extent of control offered versus a variety of SRM proposals. Control methods are ranked (roughly) in order of preference taking into account the risks and costs as well as the ability of the method to deliver full removal of the impact of anthropogenic warming

Global warming control mechanism	Possible side-effects and risk	Annual cost ($billions per W m^{-2})	Max. forcing (W m^{-2})	Notes and references
Conventional mitigation	Reduction in crop yields (low)	200	–2 to –5	Stabilise CO_2 at 450–550 ppm. Stern (2007) estimates 1% of global GDP per year
Space-based reflectors	Control failure (high) Regional climate change (medium) Reduction in crop yields (low)	5	Any	Launch costs of \$5000 kg^{-1} assumed, and replacing reflectors every 30 years (launch mass of 100,000 tons) (Keith 2000)
Stratospheric aerosols	Control failure (high) Regional climate change (medium) Changes in stratospheric chemistry (medium)	0.2	Any	Injection of 1 Tg H_2S pa by aircraft (Robock et al. 2009, Lenton and Vaughan 2009) 1.5 to 5 TgS yr^{-1} to offset 2× CO_2
Desert surface albedo	Regional climate change (high) Ecosystem impacts (high)	1000	–3	Maintenance and ecological issues likely render this impracticable (Gaskill 2004)
Cloud albedo	Control failure (high) Regional climate change (high)	0.2	–4	Operating costs of 300–400 autonomous vessels pa seeding clouds with seawater droplets dispersed from ocean
Grassland and crop albedo	Regional climate change (medium) Reduction in crop yields (low)	Not known	–1	Incentives for growing high-albedo varieties and cultural effects not known (Lenton and Vaughan 2009)
Human settlement albedo	Regional climate change (low)	2000	–0.2	Painting urban surfaces white every decade (Lenton and Vaughan 2009)

Source: Shepherd et al. (2009). Reproduced with permission of The Royal Society.

Notes:

[1] Costs in \$$10^9$ (billions) given per year and per unit of radiative forcing, i.e. \$$10^9$ yr^{-1} per W m^{-2}.

[2] 'Control failure' relates to the failure of the geoengineering control. As the aim of SRM techniques is to reduce absorbed solar radiation, failure could lead to a rapid warming much more difficult to adapt to than the climate change in the absence of geoengineering. Control methods that produce the largest negative radiative forcing and which rely on advanced technology carry the largest risks of failure.

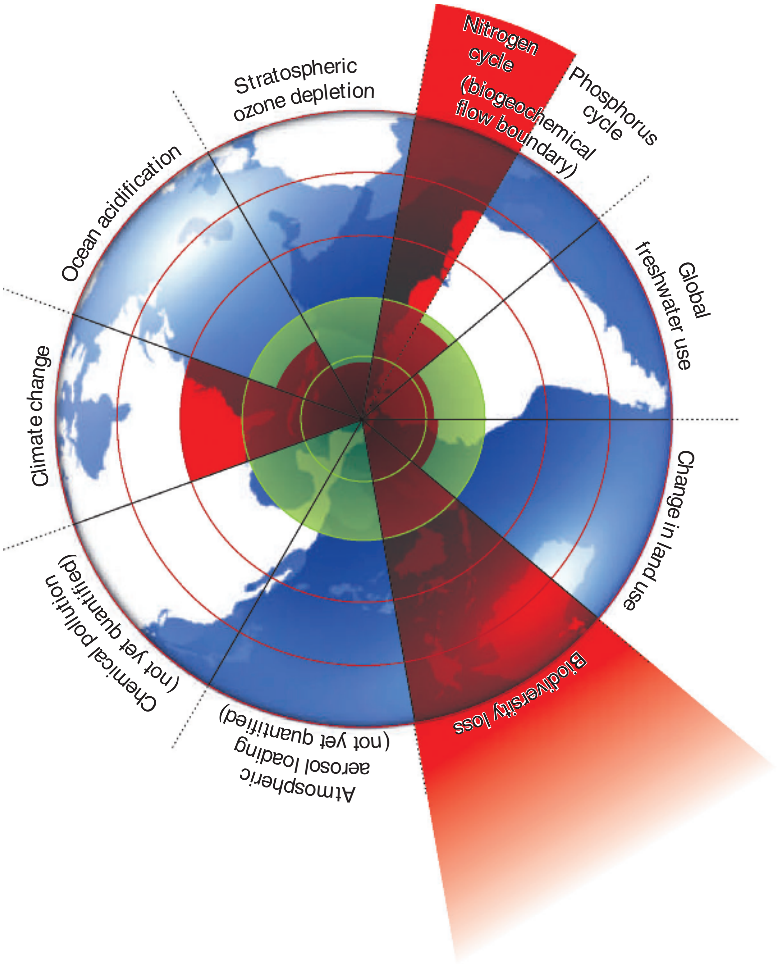


Figure 1.21 Sectoral view of the Earth's climate in terms of (*inner green*) humanity's 'safe operating space' and the red wedges indicating already-crossed boundaries of three critical systems. Of the nine planetary sectors, the boundaries already transgressed (*red*) are of climate change, biodiversity loss and human interference with the nitrogen cycle. Atmospheric aerosol loading and chemical pollution boundaries are not yet quantified while ocean acidification, stratospheric ozone depletion, global freshwater use and changes in land use remain 'safe', as does the biogeochemical flow boundary associated with phosphorus cycling. Source: After Rockström et al. (2009a). Reproduced with permission of Nature Publishing Group.

of the risk that crossing thresholds will trigger non-linear, abrupt environmental change within continental- to planetary-scale systems. The nine planetary boundaries together define a 'safe space' for climate on Earth: (i) climate change; (ii) ocean acidification; (iii) stratospheric ozone depletion; (iv) biogeochemical nitrogen and phosphorus cycles; (v) global freshwater use; (vi) land-use change; (vii) biodiversity loss; (viii) chemical pollution; and (ix) atmospheric aerosol loading.

1.4 Climate models: sound components in careful combination

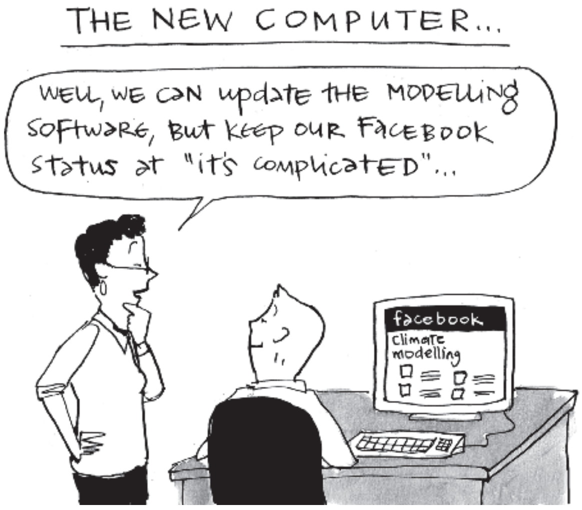
***Issue**: climate modelling has many aspects including clever coding, fast/large platforms, modellers' funding, skill and motivation and user specifications.*

***Message**: community understanding of the strengths and weaknesses of climate models is increasing and demands continued encouragement.*

The overview in Section 1.3 of the many ways in which climate models are used can help to refine the 'recipe' view of climate modelling. Figure 1.2 showed a long list of ingredients incorporated into climate models ranging from the atmosphere through to ice sheets and nitrogen cycling. On the other hand, in this chapter we have been introduced to very simple climate models containing as few as only three components: the simple radiative budget model (see Tech Box 1.4) uses albedo, solar radiation and a greenhouse increment to compute surface temperature and Lorenz's model (see Tech Box 1.2) computes just the three directional components of wind. This apparent conflict between complexity and use of climate models pervades today's literature and even the media and the arts. There is no rule that gives the amount of detail required in any particular model.

1.4.1 Ingredients and method

The real challenge of turning good cooking into great cuisine is how ingredients are combined – in fact, the chemistry of cookery. In this chapter, we have glimpsed the extraordinarily complex behaviour that can arise from apparently straightforward combination of model ingredients. Since as few as three ingredients can produce what seem like bizarre climate outcomes, caution is necessary when analysing results of even apparently simple models. We take our kitchen analogy just a little further to examine another important feature of climate systems and hence of climate models: the concept of equilibration time. A pot of hot water removed from a stove will re-equilibrate with the room environment in a characteristic time that depends upon the difference in temperature of the pot contents and the room, as well as the size and shape of the pot and the contents of the pot. Such characteristic times are a vital component of climate and thus of climate models.



It is common to express equilibration times in terms of the time it would take a system or subsystem to reduce an imposed disturbance to a fraction 1/e ≈0.37 of the disturbed value, termed the e-folding time. A smaller temperature difference, a smaller pot or a larger surface-to-volume ratio of the container will result in relatively shorter e-folding times. Large e-folding times characterise subsystems that respond only very slowly. Table 1.8 lists equilibration times for a range of subsystems of the climate system. The longest times are those for the deep ocean, the glaciers and ice sheets (hundreds to thousands of years), while the remaining elements of the climate system have equilibration times ranging from days to years.

Often the importance of feedback effects depends upon the timescale of behaviour of the subsystems they affect and so the concept of timescale of response is crucially important to all aspects of climate modelling. This timescale is variously referred to as the equilibration time, the response time, the relaxation time or the adjustment time. It is a measure of the time the subsystem takes to re-equilibrate following a small perturbation to it. A short equilibration timescale indicates that the subsystem responds very quickly to perturbations and can therefore be viewed as being quasi-instantaneously equilibrated with an adjacent subsystem with a much longer equilibration time. The very long equilibration times of the deep ocean and ice sheets pose a particularly difficult problem for climate modellers. The methods by which the short response time of the atmospheric features

Wiring the World Box 1

Real wires and the real world

Climate models have to embrace very many components and relationships. These have to be clearly identified and the links defined before a climate model is constructed and checked repeatedly during its evolution and use. Connections among model

(a)

(b)

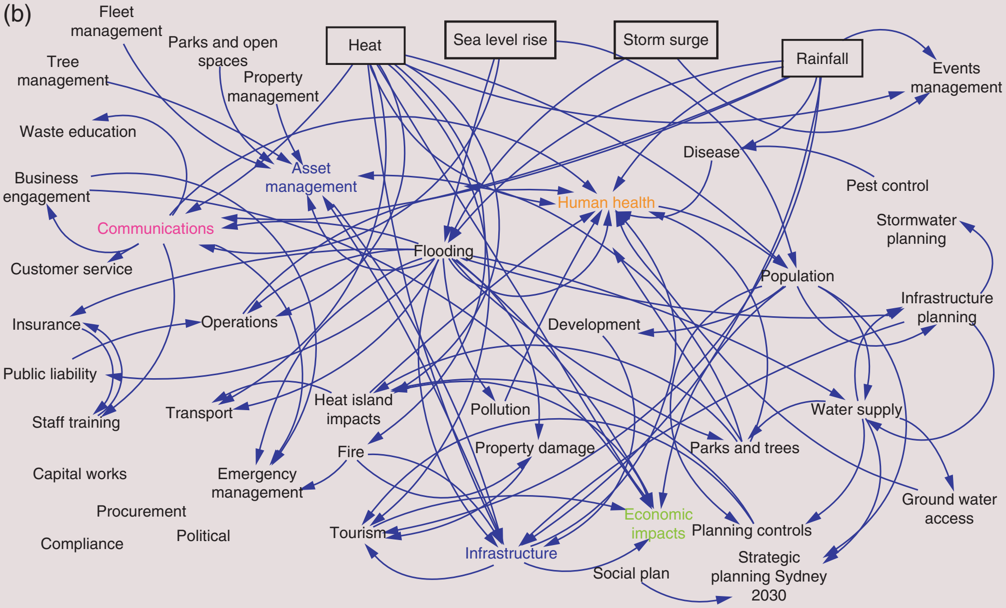


Figure source: (a) CERN. © 2013 CERN. (b) Sydney Coastal Councils Group. Reproduced with permission of the Sydney Coastal Councils Group.

(*Continued*)

components' organisation can be described in a variety of different ways: a common form is the so-called 'wiring diagram'. Any electrical system has a wiring diagram; the more complicated the electrical connections, the more frightening the wiring, and the diagram. We were pretty amazed when we witnessed the mass of electrical wires inside the CERN[49] ATLAS experiment in 2007, just before it was sealed for experimentation. ATLAS is 45 metres long, over 25 metres high and weighs about 7000 tonnes (the same as the Eiffel Tower or a hundred empty 747 aeroplanes). Its wiring (pictured in (a)) is pretty hairy!

Descriptions, including models, of complicated systems need (1) very many connections (wires) and (2) very careful checks of connections (wiring). In 'Wiring the World' boxes in each chapter, we illustrate and examine this type of 'components and links' diagram. It is important to recognise the difference between a wiring diagram and a feedback diagram (the latter will also feature in boxes).

The local government fact sheet from which the picture (b) is taken claims that it represents key climate change drivers, the impacts of climate change, likely management responses and the relationships between these.[50] This is a wiring diagram but it may not quite satisfy the needs of climate modelling. Most of our 'Wiring the World' diagrams are those that underpin construction of models or are used to analyse their results.

Wiring the World: two minute thought prompts

- If you had to check the wiring of one of CERN's experiments, how would you go about it?
- Suppose the second picture (b) was to be made the basis of a climate model. Are there aspects you would change, items to add or remove and why?

Table 1.8 Equilibration times for several subsystems of the climate system

Climatic domain	Seconds	Equivalent
Atmosphere		
Free	10^6	10 days
Boundary layer	10^5	24 hours
Ocean		
Mixed layer	10^6–10^7	Months–years
Deep	10^{10}	300 years
Sea-ice	10^6–10^{10}	Days–100s of years
Continents		
Snow and surface ice layer	10^5	24 hours
Lakes and rivers	10^6	10 days
Soil/vegetation	10^6–10^{10}	Days–100s of years
Mountain glaciers	10^{10}	300 years
Ice sheets	10^{11}	3000 years
Earth's mantle	10^{15}	30 million years

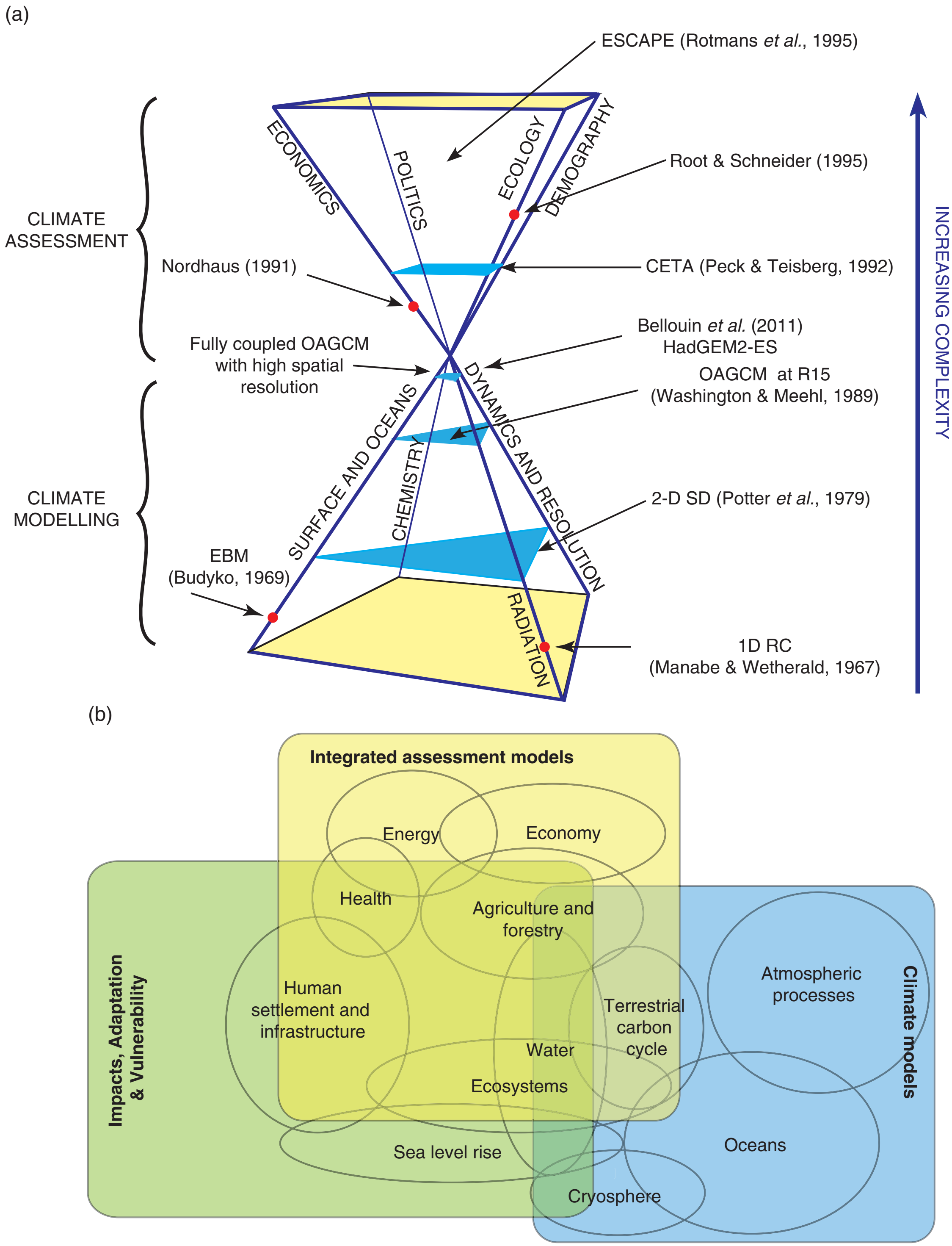


Figure 1.22 Climate model type schematics showing 'categories' of climate models and underlining the recognition that assessment of consequences dominates many modelling activities. (a) Balancing of climate assessment models on the pinnacle of climate models with examples. (b) Categorisation by model application following the IPCC Working Group structure of science (models), impacts (vulnerability) and responses (assessment). Source: (b) Moss et al. (2010). Reproduced with permission of Nature Publishing Group.

can be linked to the much slower response time of the ocean and ice sheets are discussed later in this book. Understanding feedbacks can only come through careful examination of the action of likely perturbations and the relative equilibration times of various parts of the climate system. The very wide range of timescales in the climate system is reflected in the wide range of climate model types described in this book.

Our last use of the cooking and climate modelling analogy is to illustrate the mixed, changing and sometimes confusing terminology. Recipe instructions frequently differ according to culture and over time: for example, 'browning', crisping', 'toasting' and 'flashing under the grill'. In the discussion of Table 1.8, the rich terminology around equilibration was noted. This unsettled naming is also a feature of the last decade's climate models. For example, Figure 1.22 illustrates two ways of representing the breadth of climate models that operate today: (a) balancing of climate assessment models on the pinnacle of climate models and (b) categorisation by model application. There is an old-fashioned convention that discusses 'physical' or 'physically based' models. This means climate models that are mostly based on physical laws (radiation, fluid dynamics, etc.), even though, as Figure 1.22a illustrates, these models have for some time included aspects of chemistry and biology. The 'assessment' area of climate modelling is almost as confusing, with integrated assessment models (IAMs), impacts models and earth system models of intermediate complexity (EMICs). Sometimes, the latter are solely physical models, which incorporate climate elements with long response times, say parts of the cryosphere, not yet included in the parameterisations of global climate models (GCMs) (discussed in Chapters 3 and 4). Our conclusion is that, as with recipes, while it would be less confusing for novices if everyone used the same terms, this 'one size fits all' does not exist now and, frankly, probably never should.

The climate system, and therefore any model designed to represent it, can be described in a wide variety of ways: in terms of subsystems (see Figure 1.22b) and their directions and types of interactions; in terms of characteristics such as equilibration times (such as Table 1.8); to capture the feedbacks (i.e. the processes and interactions) and how they enlarge or dampen disturbance; and in terms of their intended application (see Figure 1.22a).

1.4.2 Climate model prediction: getting the right result for the correct reason

Throughout the *Primer* we will be examining predictions made by climate models and reviewing their skill. Climate models come in an almost bewilderingly wide variety of types: written descriptive (hot dry summer and warm wet winter); in laboratories (such as the rotating dishpan analogue model); and of course many types of numerical climate models. Demonstration of some aspects of climate modelling is most usefully accomplished by visualisation developed out of analogue representations as well as the simulation-based videos which abound on the web. Making a real model work in your office, laboratory or home is a persuasive means of demonstrating skill (Table 1.9).

The omission and inclusion of parameters, processes and timescales in climate models are vexed. The 'gotcha' rule applies strongly to climate modelling: the overlooked can be critical. We have highlighted the way in which climate models incorporate many of the very strange and extreme properties of water in this chapter – the harder you look at water, the weirder it becomes.

1.4.3 Climate models pushing the envelope

As this chapter has illustrated, climate models, modellers and modelling take many forms and deliver to wide-ranging audiences. Since it is very hard to try to define what is, and therefore is not, a 'climate model', we demonstrate the breadth of the discipline today by posing two possibly outrageous questions of the family of climate models.

- Can climate models tell us about extraterrestrial life or them about us?
- Can climate models inform global governance?

Table 1.9 Summary of models used in this chapter as examples of the top 10 reasons for undertaking climate modelling

Climate model type: laboratory (L) or numerical (N)	Section	Reason for modelling	Example in this chapter
Rainband spectroscope (L)	1.3.1	Test theory	Global warming
Rotating dishpan (L)	1.3.2	Illuminate features and uncertainties	Goldilocks zone and planetary waves
Double pendulum (L)	1.3.3	Show complex can be simple and vice versa	Butterfly effect
Microphone circuit (L)	1.3.4	Raise questions, suggest analogies	Feedbacks
0D Energy Balance Model (N)	1.3.5	Agree (disagree) with data	Early Earth Snowball
Monte Carlo Simulation (N)	1.3.6	Explain	Milankovitch and CO_2 lead/lag temperatures
Global Circulation Model (N)	1.3.7	Bracket ranges of outcomes	Deforestation/ desertification
Single Column Radiative Convective Model (N)	1.3.8	Train professionals and public	Nuclear winter
Chemistry-Climate Model (N)	1.3.9	Discipline policy	Montréal Protocol
Economic models (N)	1.3.10	Encourage sensible thinking	Geoengineering
Multiple models in assessment (N)	1.4.1	Prediction	Risk assessment

Alien climate modelling

In May 2012, NASA scientists determined that our galaxy will collide with the Andromeda Nebula[51] in about 4 billion years, about as far into the future as the period of a water-based climate on Earth but less than the age of our solar system (around 5 billion years). This forthcoming collision is not a cause for alarm, or even much interest, on Earth, but imagine that in Andromeda, a galaxy far, far away….. an alien life form has been asked to apply climate modelling to assess the likelihood of sentient beings inhabiting a smallish planetary system discovered by the astronomers on her world to be orbiting a rather ordinary star – the one we call the Sun. This conjectured 'alien' process is not very far-fetched. Right now, we (Earthlings) are already examining planets that orbit distant stars to evaluate their atmospheric make-up and hence the likelihood that they host life. For example, the June 2012 transit of Venus offered an important opportunity for the orbiting Hubble telescope to be trained on an object in our solar system specifically to aid in correcting and confirming our ability to evaluate the atmospheric constituents of very distant exoplanets. A little closer to home, as *Curiosity* (the NASA explorer) tours the Martian surface, experiments with climate models are being used to interpret its findings in terms of the likelihood of widespread life there.[52]

Our imaginary alien researcher knows how to detect the possibility of intelligent life because she studied this in high school. The evaluation on Andromeda happens in two parts: A – the astrophysics and B – the beings. In (A) a well-tuned software package automatically tests the physics of the stellar system and the chemistry of the atmospheres of the planets and larger satellites (moons) in that stellar system. If this delivers likely living planets, our alien researcher begins (B) in which she seeks for evidence of persistence of climatically stable conditions that can be construed to be imposed (controlled by sentient beings). This search is in accord with the Andromedan view that the clearest demonstration of intelligent life's emergence is integration with planetary systems.

Any search for intelligent life assesses the star type, which determines its radiance characteristics and development. It is believed in Andromeda that single stars (i.e. not binaries or trinary star systems) are more likely to host planets and moons in climatically stable zones (see Figure 1.5). Planets are known to form from the debris remaining in the proto-stellar disc, following stellar condensation. Close to most stars, silicates and minerals accrete, building planets that are smaller and denser (rocky planets) while, at larger distances from the star, accretion is of ice cores that then capture surrounding gas, creating gas giants. All of these may have moons (satellites) that are large enough to retain an atmosphere over astronomical timescales, i.e. many billions of years.

Assessments are undertaken of planets and moons large enough to have retained an atmosphere for most (preferably all) of the lifetime of their star. Once a planet (or moon) is discovered to have an atmosphere, its physical properties are checked, especially rotation rate, eccentricity of its orbit around the star, axial obliquity, and the presence of a magnetic field (see Figure 1.13). These are important because:

- the rotation rate determines the length of days/nights – no preferred value is sought but phase-locked planets (where the rotation rate is equal to the stellar orbital period, i.e. day length equals year) are avoided because these worlds have massive day/night climate contrasts
- the eccentricity of the orbit determines how large the seasonal changes are – the more nearly circular, the smaller the seasonal contrast; extremely eccentric orbits may give rise to less habitable climates
- the axial obliquity (or tilt of the planetary axis to the plane in which planets and star exist) also contributes to the seasonality. Combinations of large obliquity and large eccentricity can lead to extreme and persistent 'ice' ages
- the existence of a magnetic field around the planet protects its atmosphere and surface from destructive stellar emanations and is therefore believed to be a useful contributor to overall habitability.

The astrophysical and chemical assessments above are well known to us but how aliens might evaluate our activities can only be conjecture. The radiative signature of the biosphere may have two components: non-sentient and sentient. Chemical disequilibrium, a sign of living systems,[53] can be detected in absorption/emission lines in spectra (see Figure 1.4b). Lovelock[54] deduced as long ago as 1965 that a planet bearing life can be easily distinguished from a sterile one and he concluded:

> '… atmospheric analysis, is simple and practical as well as important in the general problem of detection of life. A detailed and accurate knowledge of the composition of the planetary atmosphere can directly indicate the presence of life in terms of chemical disequilibrium.' (p569)

Emissions directly attributable to sentient life can also be sought. Radio wavelength radiation (TV and radio programmes) have first to be separated from naturally occurring radio waves and then, perhaps, such a data stream might reveal the existence, even behaviour, of sentient beings. Andromedans incorporate social science in their climate evaluation and, indeed, some aspects of sociology and economics are being incorporated into our climate models.

Biography Box 1.4

Meet the modeller: Carl Sagan

Leadership: Sagan, while popularly recognised for astronomy, led climate-modelling science in a number of ways. Perhaps the most important was his role in the famous 'Nuclear Winter' assessment. The simulated climatic effect of a nuclear war is that large amounts of smoke and soot ejected into the upper atmosphere reduce sunlight for many months or even years, plunging the whole world into very low temperatures and, it was argued, making any such nuclear detonation a global catastrophe.

Popular recognition: The very popular PBS series *Cosmos*; and his novel *Contact* is the basis for the 1997 film of the same name starring Jodi Foster that ends with the dedication 'For Carl'.

Climate modelling connectivity: Carl Sagan and Lyn Margulis, the co-inventor (with James Lovelock) of the Gaia Hypothesis of planetary climatic stability, were co-workers and once married.

Life and times: Carl E. Sagan (9 November 1934 – 20 December 1996), the American astronomer and science communicator, wrote seminal papers on planetary habitability and climate stability. He was a renowned communicator about science and an advocate for both the environment and for humanity. Sagan's interest in the evolution of life began during his undergraduate studies when he worked with the geneticist H.J. Muller and wrote a thesis on the origins of life with physical chemist H.C. Urey. Sagan was linked to many searches for extraterrestrial life, including the famous 'Arecibo message' that he co-wrote with Frank Drake. This radio message was transmitted to space from the Arecibo radio telescope on 16 November 1974, aimed at informing potential extraterrestrials about Earth.

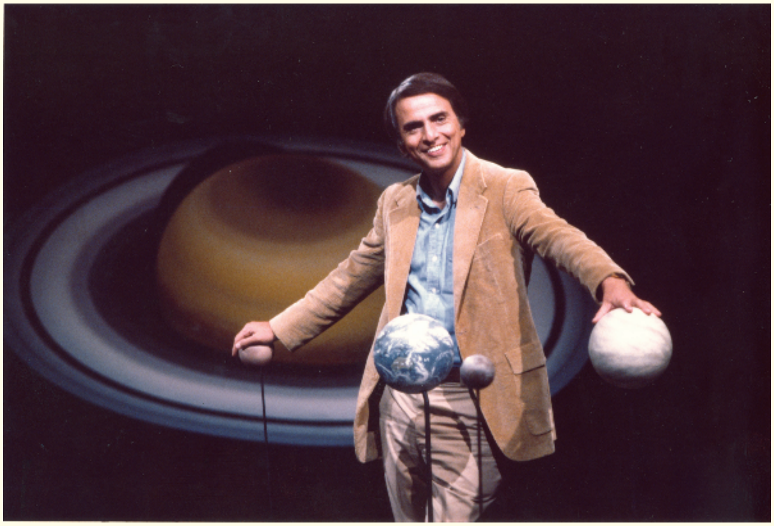
Read more

TTAPS paper: Turco, R., Toon, O., Ackerman, T., Pollack, J., Sagan, C. (1983) Nuclear winter: global consequences of multiple nuclear explosions. Science 222, 4630, 1283–1292. www.jstor.org/stable/1691639

Watch

Carl Sagan, Stephen Hawking and Arthur C. Clarke. God, the universe and everything else (1988). http://www.climatemodellingprimer.net/l/k116.htm

Carl Sagan's last (1996) interview: http://www.climatemodellingprimer.net/l/k117.htm LINK 1.17



Carl Sagan. Photo source: © Druyan-Sagan Ass, Inc.

Climate Model Communication Box 1.2

Climate modelling shared with non-professionals

Bringing about changes in global governance demands widespread public support. Such support depends on how effectively issues of environmental degradation, including climate changes, are understood. In this activity, you read articles with which you are unfamiliar. Choose a well-known 'professional' journal or magazine (e.g. *Economist, National Geographic, New Yorker, Rolling Stone, Foreign Affairs*) that has an audience very different from your knowledge base – something you would not normally read but professional people access. There are two parts to this task: familiarising yourself with the 'aliens' who read this magazine and evaluation of their characterisation of climate modelling.

1. Evaluating the magazine generally

From one recent issue, carefully answer the following questions.

- Who reads this journal? Give reasons for your answer using examples and quotes from the publication. (Less than 200 words)
- What level of climate, environmental and modelling knowledge do you need to understand this magazine's articles (high school, university, postgraduate or professionally trained)? Give reasons and examples to illustrate your answer. (Less than 200 words)

2. Characterisation of climate modelling in this magazine

Find at least one (preferably two) articles from the past 5 years in this magazine that describe climate models or predictions made using them. Give the full references of these.

Write a review of one article (500 words maximum) that explains:

- the aim of the article
- how the author describes the climate models used
- the audience for the article
- how the author makes use of layout features such as diagrams and tables
- your personal opinion (with reasons) on the worth of the article.

Global governance outcomes from climate modelling

Another aspect of climate modelling that warrants thought is the use of model results to encourage, or even mandate, global changes to governance structures and laws. In Section 1.3.9, the example of the Montréal Protocol was raised as both a successful result of scientific understanding (and modelling) of the atmospheric changes and their consequences, and as a possible template for global structures to limit CO_2 emissions. There are sound arguments in favour of governance changes in the transgression of three of the boundaries[55] identified in Figure 1.21: the rate of biodiversity loss, the rate of transformation of the nitrogen cycle and climate change.

Hope of global governance improvement depends on whether members of the general public are confident enough about climate model results to pursue discussions on additions to or changes in international law. This, in turn, depends on climate modellers informing policy – a challenge that the IPCC has faced for many years.

In addition to the Earth system boundaries argument, the issue of geoengineering of the climate (see Section 1.3.10) has already prompted calls for much improved global governance before any experiments are undertaken on planetary-scale climate engineering.

In the lead-up to the UN Conference on Sustainable Development in June 2012 (known as Rio + 20), and the High-Level Summit on the Millennium Development Goals in 2013, there has been a growing debate on how to draw up renewed and expanded global development goals that bring together the twin objectives of

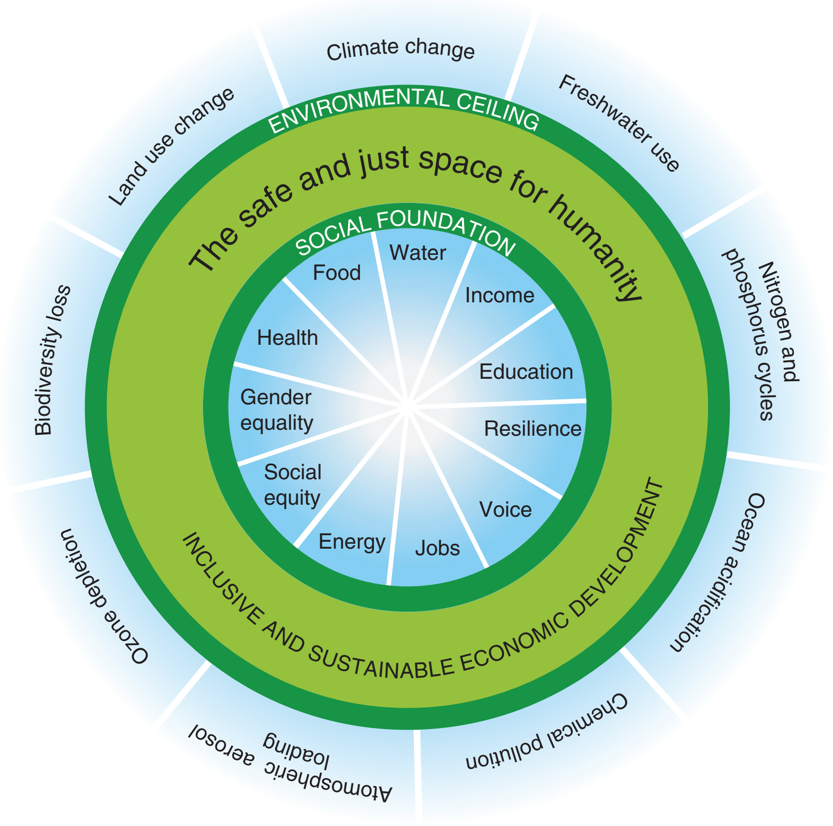


Figure 1.23 Diagrammatic combining of the environmental sectors (*outside*) of the 'safe operating space' of Rockström et al. (see Figure 1.21) with societal sectors (*inside*) likely to be involved in managing the Earth's systems, i.e. provision of a human systems' underpinning of the planetary boundaries. Source: Raworth (2012).

poverty eradication and environmental sustainability. The case that members of the general public are confident enough about climate model results to pursue discussions on the most appropriate way of dealing with the consequences of large-scale climate change is presumed in a recent Oxfam Discussion Paper: 'Living in the Donut' by Kate Raworth.[56] The establishment of biogeochemical and physical boundaries depends on climate models. In the Rio + 20 paper, Oxfam extends this concept, adding human factors to the planetary ones to create a single framework. The social foundation forms an inner boundary, below which are many dimensions of human deprivation. The environmental ceiling forms an outer boundary, beyond which are many dimensions of environmental degradation. Between the two boundaries lies an area, shaped like a doughnut, that represents an environmentally safe and socially just space in which humanity can thrive (Figure 1.23).

This last section has strongly stretched the idea of what can flow from climate modelling: into the Andromeda Nebula and into human systems, especially those that inform international law. Maybe this is going too far but models of all sorts already inform international negotiations and we saw (Section 1.3.8) that climate model simulations have affected warfare.

It may be that rules of civilisation development[57] may come to be included in climate or 'Earth system' models in the future. Around the world, some early adopters among climate modellers are currently examining the relationships between the number of agents and the complexity of their interactions.

Reflection on Learning 1.5

Recognise the mechanisms whereby persistent and widespread life affects climate

As long ago as 1965,[58] James Lovelock pointed out that any planet bearing life must differ very substantially from a sterile one in at least two ways: an 'extreme departure from an inorganic steady-state equilibrium of chemical potential' and a planet-wide orderliness of structures and of events which are 'utterly improbable on a basis of thermodynamic equilibrium'. Thus, before any human probe alighted on any foreign planet, Lovelock described a simple life detection scheme: '… a detailed and accurate knowledge of the composition of the planetary atmosphere can directly indicate the presence of life in terms of chemical disequilibrium'. This life detection system underlines how critical life is to the climate while the very need to detect distant non-Earth life is suggestive of how important climate is for life. Recent Earth system model developments are functionally dependent upon clear representation of climate-life interactions and interdependencies (Figure 1.24). ■

1.5 Climate modelling: about this book

Issue: *climate models are being, and will continue to be, used and abused.*
Message: *this* Primer *is designed to develop better-informed climate model users.*

In this first chapter, we have tried to identify why people model, how these motivations relate to the skill of climate modellers and to the challenge faced by users of their model output. It is also important to mention here what this book is *not* about. This is not a book on global (or greenhouse) warming, although the core lessons can help one better understand the role of models in studies about climate change. In this last section, we explain our goals for readers and indicate our own views.

1.5.1 Climate modelling: read the label and exercise care

The most important reason for modelling is to understand and then explain. This chapter considered the reasons for climate modelling,

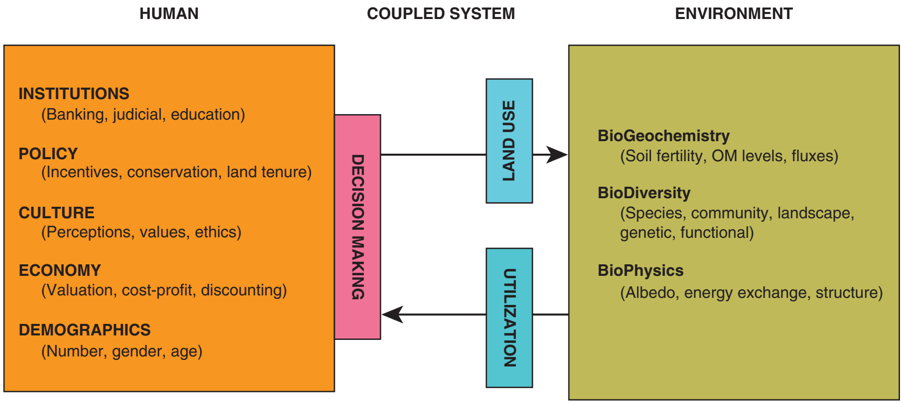


Figure 1.24 This simplified 'interacting boxes' diagram shows some two-way interactions between the human (*left*) and environmental (*right*) subsystems. This representation of the relationships between environmental and human systems can be compared with the sectoral structure in Figure 1.23. The question for climate modellers is how much of this diagram must be incorporated into a climate model. Source: Nobre et al. (2010). Reproduced with permission of the American Meteorological Society.

Table 1.10 *The Climate Modelling Primer* or A, B, C together with questions that models can and do tackle

	Components	Climate model question
A: Astronomy		
How astrophysics defines climate	Orbit	Is the Earth's astrophysics compatible with its 4 billion year climatic stability?
	Atmosphere	Can atmospheric species depletion/increase be explained?
	Radiative budget	How does greenhouse warming interact with astronomical variations in insolation?
	Water	Is water essential for long-term climate stability?
B: Biology and Boundaries		
How life affects climate and where to place climate boundaries	Life and climate	Is pervasive life always revealed by chemical disequilibrium?
	Climatic boundary conditions	Climate models include and exclude aspects of 'planet-wide' systems. How are these boundaries selected?
	Climate modification and awareness of passive climate control	Can climate model results make a compelling case that people are significant climate modifiers?
C: Comprehension		
How climate models lead to understanding	Test theories and bracket ranges of outcomes	If models are used to test theories, how are models tested?
	Illuminate features and reveal uncertainties	Do analogue models predict?
	Show that complex can be simple and vice versa	If model results are very variable, how can predictions be understood?
	Raise questions, suggest new data requirements	Models both use data and demand data – can the paradox of data 'double-dipping' be resolved?
	Encourage sensible policies	Many global challenges are informed by modelling, climate and economic simulations having at least commensurate validity

including viewing planetary climate from far away with the intention of identifying the main (and hopefully most important) characteristics of climate and hence of climate models. The characteristics of climate and thus the features that most climate models endeavour to capture can be thought of as a primer – or perhaps an A, B, C (Table 1.10). Any planet or moon with a 'climate' will most likely satisfy some fundamental astrophysical conditions. This climate becomes interesting to modellers most often when it relates to living systems. These may either passively (without knowledge) or actively (like us) alter the natural climate. Our reason for constructing, operating and analysing climate models is finally to try to understand them and, through them, the climate.

In our view, all the best reasons for modelling climate involve improving explanations and sharing these aspects of climatic characteristics with wider communities. A great example appeared in the magazine *Rolling Stone* in August 2012.[59] By Bill McKibben of 350.org fame, this broad audience story is powerfully entitled 'Global Warming's Terrifying New Math: three simple numbers that add up to global catastrophe – and that make clear who the real enemy is'.

As noted above, this *Primer* is not primarily about the effects of anthropogenic greenhouse gas emissions. As scientists, we concur with the 2012 American Meteorological Society statement.[60] In another way, the *Primer* is very much about human climate change because to understand our future climate we (policy makers, voters, commuters, in fact everyone) must understand a little about climate modelling. As Kevin Trenberth[61] points out, climate scientists are frequently asked about an event 'Is it caused by climate change?'. But this is the wrong question and, being poorly posed, has no satisfactory answer. Trenberth's answer, with which we wholeheartedly agree, is 'all weather events are affected by climate change because the environment in which they occur is warmer and moister than it used to be' (p283).

1.5.2 *The Climate Modelling Primer*

In one sense, this book develops the background material required for understanding of the most complex type of climate model, the fully coupled climate system model, by illustrating principles in other, simpler, model types. Chapter 2 contains a history of climate modelling and provides an introduction to all the types of models to be discussed in subsequent chapters. The other chapters are concerned with different model types, their development and applications. Throughout, we have taken climate models to be predictive descriptions of regional- to global-scale phenomena; hence, empirically based 'models' such as crop prediction equations and water resource management codes have not been included.

It is necessary to introduce the concept of energy balance, especially planetary radiation balance, before one-dimensional energy balance models (Chapter 3) can be understood. In Chapter 4, models that intentionally consider only a few of the important processes of the climate system are examined. These simpler models are used to gain deeper understanding of the nature of feedbacks and forcings within the climate system. These models, which have enjoyed a significant renaissance in the last 15 years, are now widely known as earth system models of intermediate complexity (EMICs).

One way to think about the book is that it begins with simpler models and works towards more complex ones. This is true but the structure also introduces elements of the climate system as they are needed. For example, clouds and the cryosphere (ice, snow and ice clouds) are important for energy balance models (EBMs) and so time is invested in glaciers and their modelling in Chapter 3. The way radiation interacts with the atmosphere is explained in Chapter 4, together with an introduction to the components of the oceanic circulation necessary for climate simulation. Chapter 5 takes a more 'how to build it' approach, looking at the way in which climate computations are undertaken in computers. By this point, the reader is, hopefully, well prepared to understand the way in which energy transfers, ocean and atmosphere dynamics, biological processes and chemical changes are included in coupled three-dimensional models of the climate system. We also address how these results can be integrated with assessments (both of model prediction skills and of likely impacts of climate changes) in the development of social and economic policies.

Throughout the book, an effort will be made to underline the importance of simpler models in understanding the complex interactions between various components of the climate system. Complicated three-dimensional models are only

Climate Model Showcase Box 1

Checking 20 climate models

Read: Bender, F.A-M., Rodhe, H., Charlson, R.J., Ekman, A.M.L., Loeb, N. (2006) 22 views of the global albedo – comparison between 20 GCMs and two satellites. Tellus 58A, 320–330.

A basic premise of all climate modelling is that, at the top of the atmosphere, there is an approximate balance between incoming and outgoing radiation, given by $0 \approx C\ \partial T_e/\partial t = \pi R^2 S(1-\alpha) - 4\pi R^2 \sigma\ T_e^4$. Here, the first term on the right represents the fraction of the incident solar radiation, after the fraction α (the planetary albedo) is reflected back to space. The second term represents the outgoing long-wave radiation, with its Stefan–Boltzmann dependence on the effective radiative temperature, T_e. C is the Earth's total heat capacity, S the solar constant, R the Earth's radius and σ the Stefan–Boltzmann constant.

It is known that many of these terms change over time; for example, the solar 'constant' varies in accordance with solar fluctuations and as a function of changes in the Earth's orbit. This paper examines one of these variables: the Earth's planetary (i.e. viewed from outside the atmosphere) albedo, α. The investigation is interesting because it compares this albedo as observed by two different satellite sets and as computed by 20 different GCMs. This comparison of the Earth's global albedo is undertaken for the recent past: from the mid-1980s to the early 2000s. The GCM simulations are derived from 20th-century re-creations using historical forcings that differ somewhat between GCMs, but the effects of the differences are considered unimportant for the purposes of this comparison.

The two satellite measurement campaigns are the Earth Radiation Budget Experiment (ERBE), giving data from February 1985 to May 1989, and the Clouds and the Earth's Radiant Energy System (CERES), with data from March 2000 to December 2003. The 20 coupled ocean-atmosphere GCMs performed their simulations of the 20th century in support of the IPCC Fourth Assessment Report and archived their model descriptions and the results at the Program for Climate Model Diagnostics and Intercomparison (PCMDI: http://www.climatemodellingprimer.net/l/k125.htm). These archives of observations and simulations allow a comprehensive comparison of the planetary albedo (α) in data and predictions made by 20 current GCMs at the time in use for the IPCC assessments.

The climate models do not do well, as the figure shows. GCM-derived albedos are almost consistently higher than the values observed by satellites. For the period with global ERBE

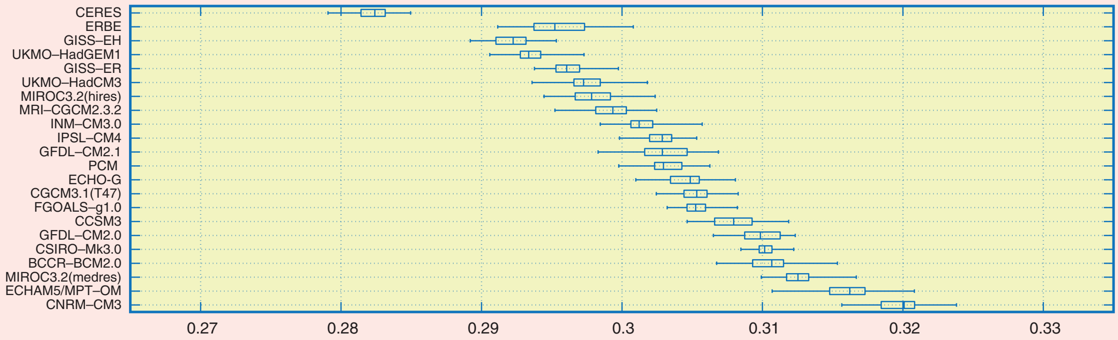


Figure source: Bender et al. (2006). Reproduced with permission of John Wiley & Sons Ltd.

(*Continued*)

data (February 1985–May 1989), the modelled global mean albedo is on average 0.009 above the measured global mean. This corresponds to a difference in radiative flux of almost 3 W m^{-2}. The mean level of global mean albedo according to CERES (using data from the first 4 years of this century) is an additional ca. 0.012 below the ERBE mean, corresponding to an additional flux difference of ca. 4 W m^{-2}. The authors undertake a detailed regional analysis, concluding that the seasonal variations of albedo in subtropical areas dominated by low-level stratus clouds and in dry deserts in subtropical areas are the most poorly simulated by the models.

This study gives rise to a range of issues, including how useful are efforts to evaluate climate model performance and, since essentially all climate models are tuned to existing observations, what value of planetary albedo should be employed in low-resolution climate models such as energy balance models (EBMs).

Review

Find other evaluations of climate model adequacy and try to determine if these have changed over the past two decades.

Discussion questions

1. It is recognised that climate modellers use all the data they can find to set parameters and correct formulations; in other words, to tune the models. Can this tuning be removed (or accounted for) in evaluation tests? Can such observations be used to evaluate the adequacy of the models?
2. How much difference do you think is 'reasonable' between the GCMs' albedo and the two sources of observations used in this multi-model evaluation? Why do you choose this value? Much greater regional, than global, discrepancies (between models and data) were found. Why do you think this happened? Is this finding likely to hold for other climate parameters?
3. This study is about evaluating GCMs in terms of the planetary albedo they calculate. In other climate models, this planetary albedo is specified. What do the observations suggest about specifying a single unchanging value for this parameter? Is the planetary albedo unchanging and, if so, what is the cause of such stability? Can this apparent global stability be disturbed by human impact or is the system resilient?

one, not necessarily the best, tool for climate study. The literature contains many fascinating examples of very simple models being used to demonstrate failures and illustrate processes in much more complex systems. However, any introduction to climate modelling must stress the crucial role played by computers. Without the recent growth in computational power and the reduction in computing costs, most of the developments in climate modelling that have taken place over the last five decades could not have happened.

A fully coupled climate model (also called an ocean–atmosphere-biosphere general circulation model – OABGCM) takes about 25–30 person-years to code, and the code requires continual updating as new ideas are implemented and as advances in computer science are accommodated. Most modellers who currently perform experiments with the most complex of models modify only particular components of the models. The size and detail in these models mean that only through a sharing of effort can progress be made. As the models have become increasingly complex, application of the principles of software engineering has become an essential part of the process and has made it easier to upgrade and exchange parts of the models. In an uncannily symbiotic lock-step, computers and climate models co-develop.

The exponential growth of the Worldwide Web and the access to information it enables have become a fundamental part of life and, thus, also of climate modelling. This has pros and cons: it allows global access and has led to the widespread use (and sometimes abuse) of climate model results. At the beginning of this chapter, we introduced the idea of a 'treasure chest' of climate modelling examples and illustrated how each reader might develop such a personal collection with our analogue version (see Table 1.2). The Web encourages an e-treasure collection, perhaps a little like the Macquarie treasure chest (see Figure 1.1). Table 1.11 shows the *Primer* authors' climate modelling e-treasures.

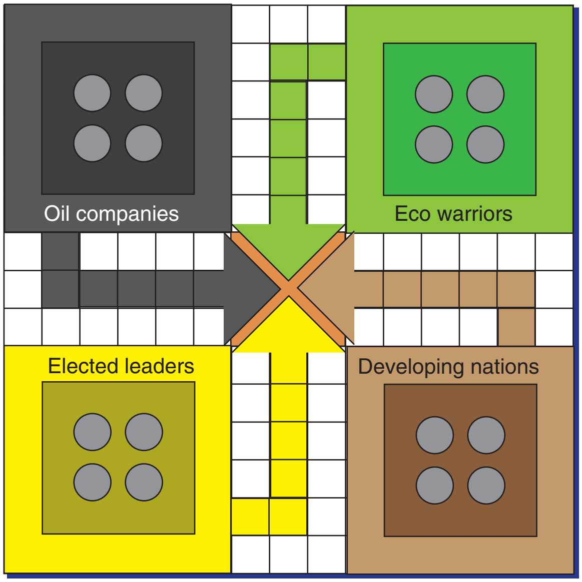
We encourage reflection to lock in learning. At the end of the book, we have gathered some final examples of aspects of climate modelling we believe this book illuminates. We also hope that our examples of personal climate modelling treasures will encourage or even inspire your collection. Remember, your goal as you read through

Table 1.11 *The Primer* authors' climate modelling e-treasure collection (compared with the 'real-world' items given in Table 1.2)

Type	Old chest	Authors' e-treasure collection	QR codes
Visual	Paintings	Write a climate change limerick: for inspiration, see http://www.climatemodellingprimer.net/l/k118.htm	
My own experience	Butterflies, beetles, etc.	Skeptical Science http://www.climatemodellingprimer.net/l/k119.htm and climate negotiations http://www.climatemodellingprimer.net/l/k120.htm LINK	
Oceans	Algae and seaweeds	Movie featuring the ocean conveyor belt 'The Day After Tomorrow' (2004). Watch carefully about 6.5 minutes in for 2 minutes (and then enjoy)	
Change behaviour	Exotic stuffed birds	Disturbance growth – butterfly effect (BBC) http://www.climatemodellingprimer.net/l/k121.htm	
Pretty things	Arrangements of sea-shells	Lorenz Attractor explanation http://www.climatemodellingprimer.net/l/k122.htm	
How it works	Artefacts	What is a cloud? (NASA) http://www.climatemodellingprimer.net/l/k123.htm	
		Testing climate model predictions http://www.climatemodellingprimer.net/l/k124.htm	

this book is to collect great climate model examples. Choose ones that you find interesting and that you can work out how to explain to someone else. In each chapter, look out for new discoveries and add to your collection any that are illustrative of points or aspects of climate modelling you find tricky or amazing (or both).

Ludicrous Ludo (we all play along)



1.6 Summary: research and review

Part 1 – Review questions

1. List the five reasons most persuasive, in your opinion, for building or using models. You do not need to restrict your list to climate modelling but, for each of your chosen reasons, give an example of how a model has contributed already and could help in the future.
2. Imagine you have to explain the incredible properties of water to a group of keen 11 year olds. What would you say? Allow yourself less than 500 words in total. What two experiments would you show them?
3. One of the longest running data collection efforts designed to assist and evaluate climate models is the International Satellite Cloud Climatology Project (ISCCP).[62] Together with other satellite data, this has been analysed to create a record of cloud amount from 1982 to date (Figure 1.25). Consider these measurements in the context of their use for climate modelling. List as many ways as you can think of how this measure of cloud amount could be exploited by climate modellers. Beside each use, give as many caveats as you can. (You may find it useful to refer back to Figure 1.12.)
4. Most people today understand that some aspects of life affect the climate (for example, plants have an important role in regulating the atmospheric burden of carbon dioxide). Review any newspaper or magazine (choose one you have not yet studied here) for as many issues as you need to find two articles about how *people* affect the climate. Summarise both articles in less than 100 words each.

Part 2 – Discussion questions

1. Human influence on climate is clear (in land-use change effects as well as greenhouse gas warming). On the other hand, climate has changed over the whole lifetime of the Earth, most of which has been without human modification. Construct a quick set of figures (back of envelope numbers) that compare the effects of people with at least two different non-human influences on climate.
2. How do you think climate modellers might better portray themselves to outsiders (aliens)? Research examples of astronomers' efforts to explain our civilisation, e.g. the Pioneer 10 plaque, the Arecibo message and the Voyager 'Golden Record', and use these as templates for sharing understanding about climate modelling. Suggest how to improve the magazine articles you read for Climate Model Communication Box 1.2.
3. Improving global governance depends upon many issues. To what extent can you make a case for international laws informed by results from climate models? Why might some people believe this is hazardous (even foolhardy) and do you agree or disagree?

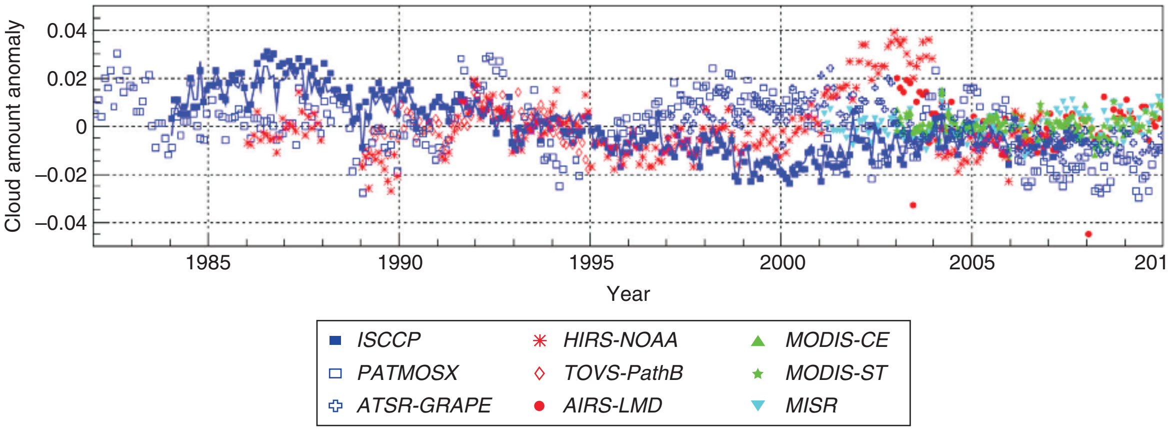


Figure 1.25 Time series of global cloud amount anomalies from the long-term mean from multiple satellites (*dots*) and International Satellite Cloud Climatology Project (ISCCP) anomalies created using the whole diurnal time statistics (*blue line*). For most of the data, the local observation time is 1.00 pm (except 3.00 pm for ISCCP, 10.00 am for ATSR-GRAPE and 10.00 am for MISR). Source: Stubenrauch et al. (2012). Reproduced with permission of the American Meteorological Society.

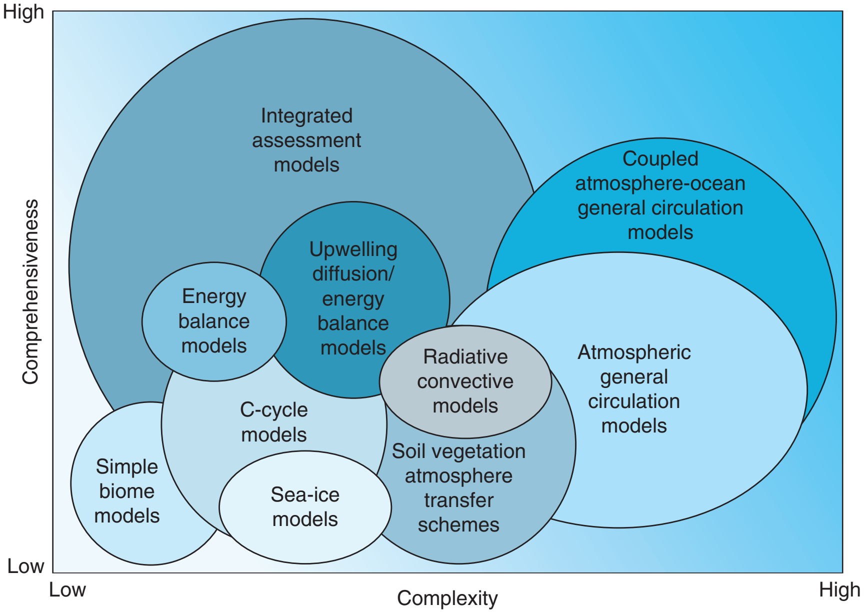


Figure 1.26 Comparison of the comprehensiveness and complexity of a variety of climate model types (C-cycle is carbon cycle). This straightforward plot can be compared with the two diagrammatic categorisations of climate models shown in Figure 1.22. Source: After Houghton et al. (1997). Reproduced with permission of the IPCC.

4. There are many different ways of arranging or classifying climate models. For example, Figure 1.22 compares two depictions and the diagram in Figure 1.26 is another. Consider these three sketches and either select the best and explain the reasons for your choice or create another, still better, method of showing how the different types of models relate to one another.

Your Climate Modelling Treasures

Begin to assemble a set of attractive visualisations of aspects of climate modelling and be sure that you are able to explain these to any interested person – say a friend or family member. Use the template in Table 1.11.

Quick historical literature review

1963: Lorenz, E.N. (1963) Deterministic, non periodic flow. J Atmos Sci 20, 130–141.

1986: Thompson, S.L., Schneider, S.H. (1986) Nuclear winter reappraised. Foreign Affairs 64(5), 981–1005.

1987: Gleick, J. (1987) *Chaos: Making a New Science*. London: Vintage.

1999: Feynman, R.P. (1999) The value of science. In: *The Pleasure of Finding Things Out*. New York: Perseus Publishing.

1999: Schellnhuber, H.J. (1999) 'Earth system' analysis and the second Copernican revolution. Nature 402(Supp. 2), C19–C23.

2003: Walker, G. (2003) *Snowball Earth: The Story of the Great Global Catastrophe That Spawned Life as We Know It*. New York: Crown.

2009: Schneider, S.H. (2009) *Science as a Contact Sport: Inside the Battle to Save the Earth's Climate*. Washington, DC: National Geographic Society.

2012: Hansen, J.E., Sato, M., Ruedy, R. (2012) Perception of climate change. Proc Natl Acad Sci USA 109, 14726–14727, E2415–E2423. doi: 10.1073/pnas.1205276109.

2012: Henderson-Sellers, A., McGuffie, K. (eds) (2012) *The Future of the World's Climate*. Amsterdam: Elsevier Scientific.

2012: Intergovernmental Panel on Climate Change (2012) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

2012: Oreskes, N., Conway, E.M. (2012) *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming*. New York: Bloomsbury Press.

2012: Shine, K., Ptashnik, I.V., Radel, G. (2012) The water vapour continuum: brief history and recent developments. Survey Geophys 33, 535–555. doi: 10.1007/s10712-011-9170-y.

2012: US National Academy of Science (2012) *A National Strategy for Advancing Climate Modeling*. Committee on a National Strategy for Advancing Climate Modeling. Board on Atmospheric Studies and Climate; Division on Earth and Life Studies. Washington, DC: National Academies Press.

2012: Victor, D.G., Kennel, C.F., Ramanathan, V. (2012) The climate threat we can beat. Foreign Affairs 91(3), 112–121.

2013: Kopparapu, K.R., Ramirez, R., Kasting, J.F., et al. (2013) Habitable zones around main-sequence stars: new estimates. Astrophys J 765 (2), 131. doi:10.1088/0004-637X/765/2/131.

2013: Winton, M., Griffies, S.M., Samuels, B.L., Sarmiento, J.L., Frölicher, T.L. (2013) Connecting changing ocean circulation with changing climate. J Climate 26, 2268–2278. doi:10.1175/JCLI-D-12-00296.1.