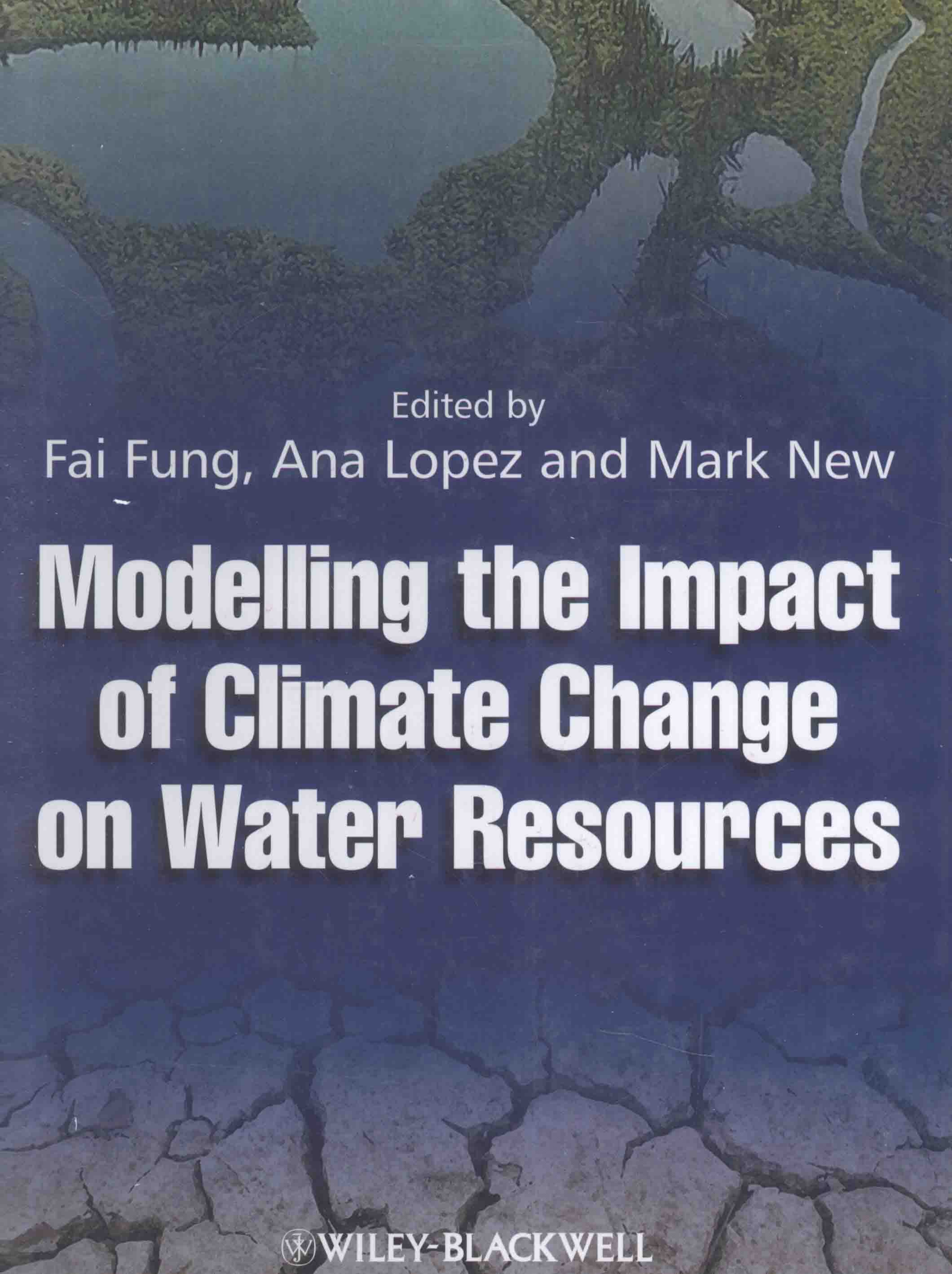

Edited by

Fai Fung, Ana Lopez and Mark New

Modelling the Impact of Climate Change on Water Resources

WILEY-BLACKWELL

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MODELLING THE IMPACT OF CLIMATE CHANGE ON WATER RESOURCES

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Preface

This is a book that many of our colleagues and collaborators have been requesting for some time, recognizing the need for a description of both the opportunities and limitations inherent in the modelling of climate change impacts on water resources. Models – be they global climate models, those used to downscale global model outputs to the scale of the catchment, or hydrological and water system models – can be powerful tools for climate change assessments. However, there is often frustration that assumptions and glitches in the models are often only privy to those directly involved in the modelling, and not transparent to those hoping to use the information. The aim of this book is provide a clear description – glitches and all – of the ways that climate change information is generated from climate models and used for modelling hydrological and water resource systems. We hope we have provided a timely book that will be a resource for students, researchers and practitioners alike.

We would like to take this opportunity to thank all the authors who have offered their contributions and also the support of the Tyndall Centre for Climate Research and School of Geography and Environment, University of Oxford, for providing the resources that enabled this book to come to fruition.

Fai Fung
Ana Lopez
Mark New

October 2010

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1 Introduction

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All member states of the United Nations have accepted that human-caused, or anthropogenic, climate change is happening and some have enshrined this explicitly in national law (e.g. the UK Climate Change Act in 2008). Now that anthropogenic climate change has been acknowledged, society will have to act to adapt to the impacts, even if mitigation is successful (New *et al.*, 2009). Adaptation requires a clear understanding of the underlying science and methods of assessing impacts, not only by climate scientists but also scientists, engineers and decision-makers in a whole host of fields, including food and agriculture, ecosystems, energy and infrastructure. Of particular concern are water resources, as these are indispensable to all forms of life and are needed in large quantities for almost all human activities (Bates *et al.*, 2008).

Numerous methodologies for assessing the potential impacts of climate change on water have been developed and reported. Nearly all these have used climate model data and water resources models. The complex climate models that are being used to produce projections of the global climate for the next 100 years generate large amounts of data, but identifying robust and reliable information within these is not a trivial task. Moreover, this is just the first step in a modelling process that goes from the climate models, to the downscaling of climate model results to the local scale and then the modelling of the water supply and demand itself. Each of these steps has to be clearly understood in order to appreciate the assumptions and caveats involved, and how these affect the interpretation of the results. The multi-disciplinary nature of the problem means that specialists tend to work in their own fields, passing information in a fairly linear process from climate modellers to water resources managers, with much of the information lost. Although scientific papers are publicly available and cited by many other scientists, often only those directly involved in the modelling are privy to the model assumptions and glitches, which are not transparent to those hoping to use the information.

So, despite the amount of work that has been ploughed into the area, how much of it has been transferred to practitioners? Indeed, how well are we informing the next generation of water managers and engineers, and those developing water policy?

Despite the multi-disciplinary nature of the problem, one does not need to be a polymath to appreciate the opportunities and limitations at each step of the modelling process: this is easily achievable and highly important. This book attempts to distil key issues in each stage of the assessment process, providing the reader with the knowledge needed to understand how their discipline may be affected by the assumptions and caveats made by modellers. The aim of this book is to provide students, practitioners and decision-makers with a critical look at recent developments in the science of impacts modelling in water

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resources systems, and develop a basis for better informed decisions on climate risks.

1.1 Key Themes

While the book attempts to discuss elements of climate and water resources modelling with the aim of providing both a brief introduction to the theory as well as current issues around the topic, some key themes cut through the whole text. These include:

- **Non-stationarity** The climate can no longer be assumed to be stationary, i.e. the observed datasets cannot necessarily characterize the future climate. Methods that have been used in the past to make decisions in water resources management based on what has happened in the recent past may not be appropriate for the study of future water resources. Indeed, this may change the way in which we approach decision-making for water resources management.
- **The uncertainty cascade** To calculate the water available at a given location in the world, a common approach is to use climate model data, which are then 'downscaled' and fed into a hydrological model. At each stage of this process, many assumptions are made and there may be large uncertainties involved; these uncertainties propagate through the process as one moves from one stage to the next. This cascade of uncertainty, and its implications on the interpretation of the results, should be assessed throughout the modelling process.
- **Evaluation of approaches** Given the limited time and resources, many practitioners are very much interested in being advised on the best approach rather than being given a suite of models and approaches to explore. Is there a way of evaluating models and approaches that will hold for a changing climate? Are certain approaches more suitable than others for a given problem? Although these answers may be pertinent and we discuss these topics in the book, we will argue that seeking one universally applicable solution is not advisable.
- **Societal–earth systems interface** The area of water resources sites squarely at the interface between human and earth systems and may be the most direct way in which humans will experience climate change. However, once human systems, in our case water resource systems and alternative adaptation options, are introduced into the modelling process, greater complexity – and also more flexibility – can arise. Developing adaptation strategies under great uncertainty requires an appreciation of both the physical mechanisms involved as well as the influence of humans on those strategies (e.g. population rise, land use changes, economics, and standards service).
- **Data resolution** The impacts community have been calling for data at much finer temporal and spatial scales than that available from global climate models. Climate data provided at scales relevant to the decision-maker, typically catchment-relevant scales, are of paramount importance for water resources managers. However, how reliable are the data at these finer scales? Indeed, one of the pressing questions is whether models are able to resolve extremes such as floods and multi-year droughts?

1.2 Structure of the Book

The book is structured to follow the methods that have been generally used in assessing climate change impacts on water. It starts with a general discussion about climate models, followed by a description of downscaling techniques used to bring climate model data to the local scale, and then the use of water resource models.

In 'Weather and Climate' by Daíthí Stone and Reto Knutti, climate models are introduced. This chapter describes different approaches to climate modelling, from simple heuristic models to general circulation models. The issues surrounding the predictability of climate, the evaluation of climate models, and uncertainties in predictions of climate change are discussed. There is a particular focus on the possibilities and limitations of using data from climate model simulations for the purpose of quantifying impacts of climate change on hydrology.

The next chapter, 'Regional Climate Downscaling' by Rob Wilby and Hayley Fowler, links climate models and hydrological/water resource models by describing approaches for downscaling the data from climate models to the temporal and spatial scales relevant for water resources planning. It includes descriptions of statistical and dynamic methodologies that have been implemented to date, and their corresponding advantages and limitations. The chapter closes with a discussion about the relevance of downscaling procedures for adaptation decision-making.

In Chapter 4, 'Water for People', Glenn Watts adresses the society–earth system interface by looking at the issues of water supply and water demand in a changing climate. He discusses the key issues with using current hydro/geological, water supply and water demand models to assess the impacts of climate change on water resources. The chapter ends with a discussion on how modelling could possibly inform decision-making under large uncertainty.

In Chapter 5, 'Emerging Approaches to Climate Risk Management', we discuss how the information obtained from the different modelling steps can be used for decision-making for adaptation to climate change. Although a complete treatment of decision theory is beyond the scope of the book, we discuss how modelling of the climate–hydrology–water-resource system can be used effectively to make decisions under deep uncertainty.

To bring together many of the ideas introduced in Chapters 2 to 4, several cases studies are presented in the final chapter; these illustrate the types of analyses and climate risk assessments that have been carried out in the past. Rodrigo Paiva, Walter Collischonn and Beatriz Schnetterling provide an example of an impacts assessment on a transnational river bordering Uruguay and Brazil. We also present two European case studies: Jean-Philippe Vidal and Frédéric Hendrickx, demonstrate the use of highly sophisticated downscaling techniques to attempt to determine the impacts of climate change on hydropower in the Pyrenees, while Ana Lopez describes the use of large ensembles of climate model data to explore adaptation options in a water resources system in the South West of England. These case studies are not necessarily models of good practice, but ways in which scientists have attempted to approach the problem at hand.

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Bates, B.C., Kundzewicz, Z.W., Wu, S. and Palutikof, J.P. (eds) (2008) *Climate Change and Water*. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

New, M., Liverman, D. and Anderson, K. (2009) Mind the gap. Nature Reports Climate Change (0912), 143–144. Available at: http://dx.doi.org/10.1038/climate.2009.126

Further Reading

While the topics that are covered in this textbook are not covered in other existing textbooks, the following texts are also useful to provide a more general reading on the subject.

Garbrecht, J.D. and Piechota, T.C. (2007) *Climate Variations, Climate Change, and Water Resources Engineering*. American Society of Civil Engineers, Reston, VA.

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2 Weather and Climate

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2.1 Introduction

2.1.1 The problem with climate change

Climate change is one of those unfortunate disciplines that cannot fit into the scientific method. It is unethical, tedious and unfeasible for scientists to conduct experiments on our planet, examining what happens when certain amounts of greenhouse gases are emitted over centuries versus when they have not been emitted, for instance. Further, it is unfeasible to construct many identical Earths so as to conduct the experiments on them. So we are stuck with observing and waiting to see if humanity's emissions cause such a large climate change that the circumstantial evidence becomes overwhelming. The situation is similar to the problem that was encountered in trying to link an increased incidence of certain diseases to cigarette smoking. It was considered unethical and rather challenging to force a random group of people to smoke for several decades and to force another random group to abstain, and then considered rather tedious to have to wait decades to see what happened. In the end, the circumstantial evidence for lung cancer and cardiac arrest was so high that it became overwhelming, but there are still other diseases for which the evidence of a link is unclear.

There is one way, though, in which the effects of anthropogenic greenhouse gas emissions and of smoking differ. The climate system is a physical system where the large-scale patterns are governed by a few well-understood laws governing the behaviour of fluids and radiation, while the human body is a biochemical system of poorly understood processes. This means that, in contrast to the human body, the climate system in theory can be modelled by constructing pseudo-Earths, consisting of a series of mathematical formulae in computer code. Thus, researchers can conduct true scientific experiments on multiple Earths after all.

Of course, in practice things are a little messier. The physical laws behind the dynamics of the climate system may be simple enough, but the sheer size of the planet makes the collection of interactions enormously complex. Add to that the fact that poorly understood biochemical processes are involved in maintaining and changing chemical components of the atmosphere that are crucial to the operation of the climate system. Squeezing an essentially infinitely complex system into a finite computing structure means that shortcuts need to be taken. In the usual modelling framework, these shortcuts involve simulating what is happening at smaller spatial and temporal scales with rather crude approximations. With today's computing power, that means anything less than a few hundred kilometres.

On the face of it, then, the prospect is not good for using climate models to elucidate the impacts of climate change on hydrology. Clouds and precipitation, two of the more obviously important aspects of weather from a hydrological perspective, are represented in climate models entirely by heuristic algorithms, not by direct simulation. Belief in any such experiment thus depends

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mainly on how much you trust the accuracy of these approximations. They may not be that bad in fact, but we simply do not know.

Nevertheless, the general outlook for hydrological studies of the impact of climate change is not necessarily so bleak. Colloquially, climate change is often known as 'global warming'. There is a reason for that. The dominant cause of current climate change is our past and current emissions of greenhouse gases, in particular carbon dioxide (Intergovernmental Panel on Climate Change 2007a). These gases make it hard for the planet to radiate energy back into space, so in effect increasing their concentrations traps the energy that the planet receives from the Sun just a little bit longer, and consequently the planet gets warmer. Changes to clouds and precipitation are thus second-order aspects of climate change, because they occur in response to the warming, not to the increase in greenhouse gas concentrations themselves (changes in aerosol concentrations can affect clouds and precipitation directly, and possibly quite strongly, but the effect is still strongest on temperature). Thus, in many regions the biggest influence of current and future climate change for hydrology is likely to arise not through relatively small changes in the noisy behaviour of clouds and precipitation, but through the direct effect of higher temperatures on the hydrological cycle. In particular, evaporation and evapotranspiration from the ground and plants will be forced to increase markedly, whilst the snowpack will be smaller and will melt earlier in the season (Barnett *et al.* 2005, 2008). Because variations in temperature tend to occur over large spatial and temporal scales, temperature is something we can argue that climate models are in fact simulating, rather than heuristically approximating. Further, because warming is the dominant response of the major factors potentially forcing our climate, we can argue that climate models are probably fairly accurate in their estimates of current and future warming. In the end then, for many regions of the world the most significant hydrological impacts of climate change concern how hydrological systems respond to something that we think climate models simulate quite well.

There are nuances to all of this of course. This chapter consists of a discussion of what climate models are, what they do and do not do, and the sort of information that can be provided from them. While we will try to keep a general overview of the field, the focus will be on aspects of particular interest to hydrological problems. First, though, we start by asking a question that should perhaps have been right at the beginning of the chapter.

2.1.2 What are climate and climate change?

When he was six years old, a now-accomplished climatologist apparently asked his mother, 'Mum, what is the difference between weather and climate?' He was off to a good start. Amazingly, given current preoccupation with climate change, there is no universally accepted definition of 'climate'. There are three main definitions commonly used, illustrated in Figure 2.1 through the simple analogy of driving on a highway. To a large extent the definition people use is determined by their profession, and the role of 'climate' in their work. Not surprisingly, this can cause quite a bit of confusion in cross-disciplinary communication. We will describe the differences here, mainly in an attempt to reduce confusion, but also to emphasize the range of interpretations of what exactly climate change is. To some degree, the choice of definition defines the uses and limitations of models of the climate system.

The traditional definition of climate is that it is the statistical properties of observed weather at some location and time of year, with these statistical properties determined from observations over some reference period of time. This definition was developed before climate change became an issue and remains favoured by daily weather forecasters. The trust in their forecasts is built through past performance, so it is convenient to define climate as the envelope of that observed historical weather. This definition runs into trouble though when we consider 'climate change', mainly because 'climate' here is ad hoc rather than describing some inherent property. If the observational period is, say, 30 years, then implicitly the climate cannot

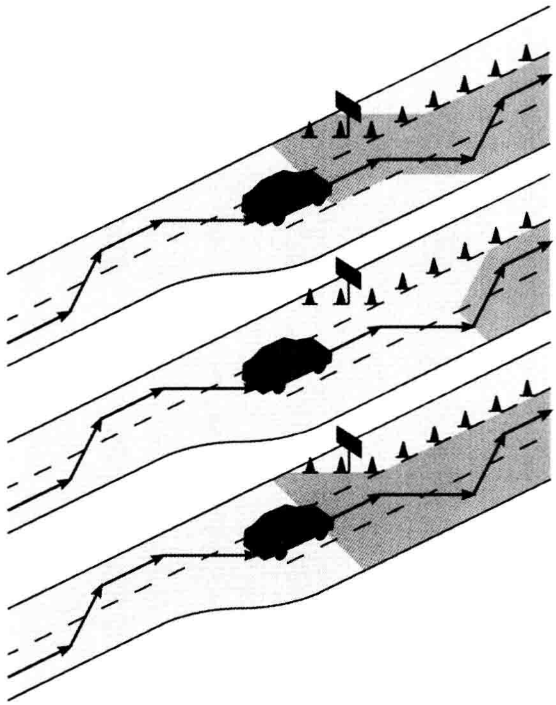

Fig. 2.1 An analogy of the different definitions of climate using the example of a car's trajectory on a highway. Top: the observational definition. The car has followed the route (weather) defined by the arrows to arrive at its current position (state), and will continue according to the arrows. The shaded area denotes the future climate successively defined by the current and two previous positions. Note that the climate can change even though nothing external has influenced it, and that it can be ignorant of the start of an additional lane and the closing of one of the original lanes. Middle: the time scale definition. With the car at its current position, the next couple of positions of the car are considered weather, while later positions are considered climate. Bottom: the external forcing definition. Anything in front of the car that is allowed by the road conditions (a new lane and the closing of a lane) is climate. Note that some of the climate, for instance the bit in the lane that is about to close, is actually inaccessible to the car because the car cannot change lanes fast enough.

change on time scales shorter than 30 years. On the other hand, if we lengthen this period, then we can get rid of climate change altogether. Further, why does the definition of climate depend on the time of year and not the time of day, given the similar (and in polar regions identical) causes?

The second common definition uses a time-scale threshold. Things that happen on a time scale of a few days, and are thus governed mainly by the 'memory' of the atmosphere, are termed 'weather', while things that happen on longer time scales are termed 'climate'. This definition comes from the seasonal forecasting field and is used to distinguish it from daily weather forecasting; indeed, seasonal forecasting is generally called 'seasonal climate forecasting'. There is a certain clarity here in the division according to important physical processes and, thus, also to forecast methodology. However, the division itself is vague: is a forecast for seven days in the future a weather forecast or climate forecast? What about eight days?

We favour climate being defined as the ensemble of all possible weather states, given conditions external to the climate (atmosphere-ocean-land-snow-ice) system. In other words, given current solar brightness, time of day, time of year, orbital eccentricity, human emissions of carbon dioxide, human emissions of sulphates, etc., a certain set of weather states is possible. Exactly which weather state we will experience depends on the exact preceding sequence of weather states. This definition arises from the discovery by Edward Lorenz that weather is chaotic, although it could just as easily be derived from assuming that weather is a slow, random process. The advantage is that 'climate' is now a well-posed property of a dynamic system and thus can change as abruptly as it wants. Some people are uncomfortable with the fact that this hypothetical climate can never be observed, because all we can observe will be the single realization of weather that we experience. However, in our opinion, this differs little from, for example, the concept of globally averaged precipitation, a quantity we will never be able to observe either but which we yet feel comfortable considering as a concrete quantity.

Of course, what is meant by 'climate' can matter when it comes to 'climate change'. Furthermore, often climate change is used to refer only to changes in climate caused by emissions of greenhouse gases from human activities, as it is for instance in the United Nations Framework Convention on Climate Change. Thus, global warming, anthropogenic climate change, and climate change are often used interchangeably, even though technically each is progressively more general.

In this chapter we will use the last definition of 'climate', the envelope of possible weather given external conditions, and will use 'climate change' to denote any change in the climate whether naturally or anthropogenically forced. This practice is by no means universal, however, even among dedicated researchers of climate change. Further, most researchers are often inconsistent, for instance considering climate to depend exclusively on external conditions yet referring to seasonal 'climate' forecasting, even though such forecasting depends explicitly on the initial state. This vagueness needs to be kept in mind when dealing with climate change and indeed climate in general, especially in an interdisciplinary setting.

2.2 Climate Models

2.2.1 Approaches to modelling

In this section we will discuss the various approaches to modelling the climate system. On the face of it this might seem straightforward but, as with hydrological modelling, practice is much messier. The physical and chemical processes of the climate system follow fixed scientific laws, so in theory there should only be one approach to modelling the climate system. In practice, though, the system is so complex that shortcuts must be taken such that the modelling approach is feasible. The choice of shortcuts creates a veritable ecosystem of models, each with their strengths and weaknesses.

There are two main approaches to process-based modelling: as simple as possible, and as complicated as possible. The simple models have the advantage of being easy to implement and easy to diagnose what is going on. The catch is two-fold: they are subject to many restrictive assumptions, and they only model certain portions of the climate system. The advantages and disadvantages of the complicated models are more or less opposite to those of the simple models: they are difficult to implement and diagnose, but they are as comprehensive as is possible given current resources. We will start this section with the simplest models, then flip to the most complicated. After, we will look at the broad middle ground.

2.2.2 Simple models

Simple models can have many different advantages. First, they are easy to implement. Either they can be solved analytically or a numerical solution can be estimated more or less instantaneously on a computer. They can also be instructive, because the progression of input through calculation to output is easy to follow.

The simplest model of time-dependent climate change due to external forcing is the simple linear relaxation model:

$$\frac{c \cdot d\Delta T(t)}{dt} = \Delta F(t) - \lambda \Delta T(t) \qquad (2.1)$$

This is usually referred to as an Energy Balance Model (EBM). The temperature of the planet changes over time t by an amount $\Delta T(t)$ in response to some anomalous energy flux $\Delta F(t)$ entering the system. $\Delta F(t)$ is usually called the 'radiative forcing', or just simply the 'forcing'. The response is delayed by the thermal inertia c of the climate system. This is dominated by the heat capacity of the mixed layer of the ocean, the surface layer that is in direct contact with the atmosphere but in little contact with the deep ocean. The amplitude of the response is governed by λ, which in a single number represents how all of the various processes in the climate system respond to the anomalous energy flux. How far the snow-ice border retreats/advances is included in this number, for instance, as is the change in behaviour of clouds. The inverse of λ is the eventual equilibrium temperature change resulting from a unit increase in the anomalous energy flux, and is often known as the climate sensitivity parameter.

This simple model uses some enormous assumptions to simplify the huge complexity of the climate system into two constant parameters. The advantage is that uncertainty in those two constants can be examined in an objective way that is not possible with a more complicated model. The complicated models make only partial approximations to the various climate processes and it is generally not clear how to sample all possible partial approximations. It is much more obvious how to sample possible values of a constant.

All of this is, of course, subject to the appropriateness of the underlying assumptions. Basically, there is a single major assumption behind this type of EBM: all aspects of the temperature response are linear, whether they be the retreat of the sea ice edge, changes in atmospheric flow, or changes in cloud properties. Perhaps a bit surprisingly, the very complicated models indicate that this is usually quite a reasonable assumption, even on relatively local scales. Of course, being a linear model, an EBM does not internally generate variability (i.e. weather noise) of its own, nor does it tell us anything about other properties of the climate system, such as rainfall and winds. Figure 2.2 shows a comparison of estimates of historical climate change from an EBM and from a simulation of a complicated state-of-the-art dynamical model (described in the next subsection). Apart from the smoothness of the EBM estimate, they look fairly similar.

Energy Balance Models do reveal interesting aspects of climate change. Let's say that the external forcing $\Delta F(t)$ keeps increasing at a constant rate. This is in fact close to how the radiative forcing from anthropogenic greenhouse gas emissions is behaving. There are two possibilities. If both c and λ are small, then the climate system is always near equilibrium, so the behaviour is dominated by λ. Otherwise, the heat capacity of the ocean mixed layer slows everything down so much that we are never close to equilibrium and c dictates the behaviour. This is the reason that the observed historical warming puts a strong lower limit of about 1.5 °C on the equilibrium climate sensitivity to a doubling of CO_2 concentrations over 1750 values, but cannot seem to impose a strong upper limit: the observed climate change is controlled by c, not λ, if the sensitivity is high (Knutti and Hegerl 2008).

Simple models also exist for other aspects of the climate system related to water resources. For instance, because precipitation is essentially a way for the atmosphere to transfer energy upwards, average precipitation depends mainly on the vertical temperature gradient. This is a competition between how hot the surface gets against how quickly the top of the atmosphere can radiate energy into space and so cool down. Thus changes in average precipitation in a changing climate can be estimated by figuring out how the external forcings are altering the vertical temperature gradient of the atmosphere. Interestingly, changes in the incident visible light from the Sun, such as produced by natural explosive volcanic eruptions, have a much stronger effect than those that affect the atmosphere's opacity to the outgoing infrared radiation, relative to their respective effects on temperature. Extremely heavy precipitation events, however, are subject to different constraints than average precipitation. How much water can fall in a heavy event is limited by how much water the atmosphere can hold. Thus according to the Clausius–Clapeyron relation, relating the saturation vapour pressure to temperature, in a warmer world a warmer atmosphere will be able to hold more water and produce more intense precipitation events.

Both these simple models of how precipitation responds to external radiative forcing seem to hold up in the very complicated climate models (see Fig. 2.2) and, indeed, in the observational measurement record. Because of their simplicity, then, they can provide a very instructive rule of thumb. There are some caveats of course, not least of which is that they assume that there is no change in atmospheric circulation patterns. In regions of the world where it seems that circulation is changing in response to enhanced greenhouse gas forcing, such as the edge of the Hadley cells in the subtropics, these simple models can fail dramatically. In that case, we need to turn to more complicated models.

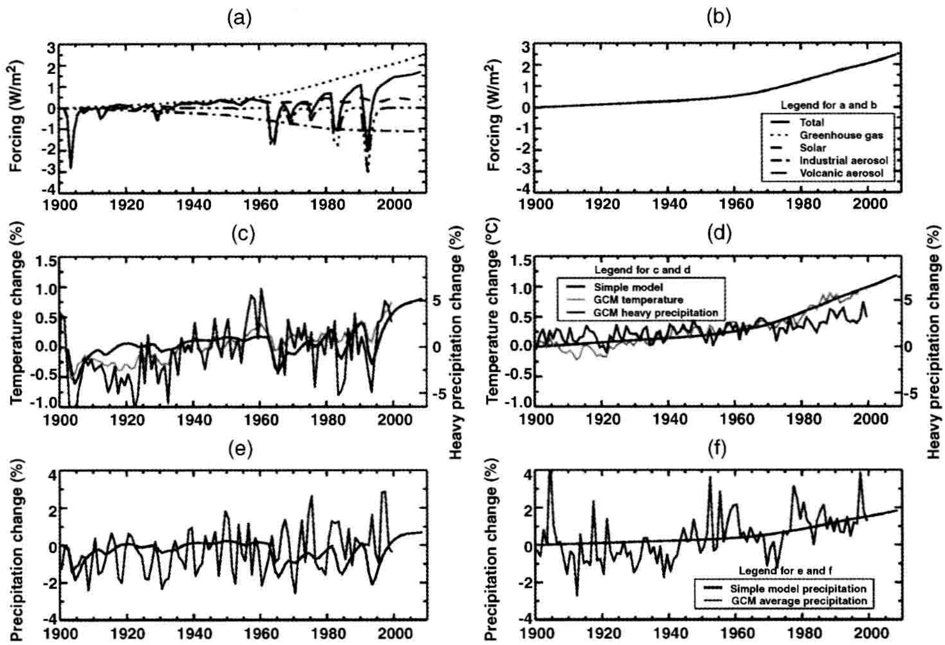

Fig. 2.2 Comparisons of output from simulations of simple and complicated climate models. Simple model values are expressed as anomalies from the year 1901 value, while values from the complicated global climate model (GCM) have been shifted to have the same average over the 1901–2000 period as the simulation from the simple model. (a, b) An expression of the external influence of changes in different factors on the climate system, expressed as the anomalous energy flux at the top of the atmosphere. In (b) only the global average forcing change due to increasing greenhouse gas concentrations is shown, while in (a) other factors are included. (c, d) Changes in global surface air temperature and heavy precipitation in simulations in which the changes in the external forcings in (a) and (b) respectively have been included. The black line is from a simulation of the simple energy balance model (EBM) described in the text, while the light grey line is from a simulation with a complicated atmosphere-ocean GCM. The dark-grey line shows changes in heavy precipitation (the annual average of the instantaneous maximum precipitation rate each month), which a simple model would have following the black line according to the right-hand axis. (e, f) As in (c) and (d) respectively but for average annual precipitation, with the black and dark-grey lines corresponding to simulations of the simple and complicated models respectively. The simple precipitation models follow Allen and Ingram (2002). GCM data courtesy of the Community Climate System Model project and the University Corporation for Atmospheric Research (UCAR).

2.2.3 Global circulation models

The models used for most purposes these days are called GCMs, which originally stood for 'General Circulation Models' but increasingly stands for 'Global Climate Models'. Headline news about what climate models say about the future, such as the projections reported in the Intergovernmental Panel on Climate Change (IPCC) assessment reports, comes from these models. They are monstrous beasts, with the most advanced examples requiring large portions of the world's largest supercomputers. It could be argued that 'climate model' is a misnomer for these models, given our chosen definition of climate and that these models in fact simulate the weather. On the other hand, these models are optimized for climate experiments, so perhaps the name is appropriate.

The first GCMs were simply retired weather forecasting models, with computing power having reached a point at which it was feasible to run them over much longer simulation periods. They