Chapter 1

Introduction

1.1 Climate variability and change

The climate system is composed of interacting components which include, but are not restricted to, the atmosphere, the oceans, the cryosphere and the biosphere. The physical processes which govern their evolution are non-linear, with each component exhibiting different response timescales and thermodynamic properties (e.g. *Bard*, 2002). The large heat capacity and thermal isolation of the deep ocean provides the climate system with a long-term "memory", as a result of which the spectrum of internal variability extends to millennial timescales (e.g. *Bigg and Wadley*, 2001).

Natural climate variability arises both from variability within each of the components of the climate system, and also from the interactions between them. The non-linear nature of the system gives rise to modes of variability that include phenomena such as stochastic resonances and rapid transitions between regimes. A well-known example of the former is the El Niño-Southern Oscillation (e.g. *Philander*, 1990), which represents a mode of internal variability of the coupled atmosphere-ocean system. Examples of the latter include the Dansgaard-Oeschger and Heinrich events that characterise the glacial climate (e.g. *Bard*, 2002).

Climate variability can also have origins which are external to the climate system. Volcanic eruptions can result in cooling lasting several years, while changes in solar output cause decadal- to centennial-scale variability (e.g. *Ramaswamy et al.*, 2001; *Robertson et al.*, 2001). On timescales of $O(10^4\text{–}10^5)$ years, pseudo-cyclic variations in the Earth's orbital parameters give rise to the glacial cycles (e.g. *Berger and Loutre*, 2004); on timescales of $O(10^6)$ years and longer, tectonic processes become significant, as do the sun's evolution and orbital path through the galaxy (e.g. *Pavlov et al.*, 2005; *Sloan*, 2006).

Human activity is also having a discernible influence upon the global climate (e.g. *Mitchell et al.*, 2001). While this is generally attributed to the emission of carbon dioxide and other greenhouse gases during the industrial era, it has been suggested that land-use changes began to exert an influence upon global climate as long as 8,000 years ago (*Ruddiman*, 2003). There is therefore a two-way interaction between the climate system and human society: while it provides people with an environment within which to live, their activities also have a significant impact.

An understanding of the full spectrum of natural climate variability is necessary not only if recent climatic changes (e.g. *Mann and Jones*, 2003; *Jones and Mann*, 2004) are to be attributed to human influence, but also in order to anticipate the full range of climate states that might be encountered in the future. Given the potential for significant anthropogenic climate change during the coming decades (e.g. *Cubasch et al.*, 2001), the ability to anticipate future change, both natural and anthropogenic, is essential for informed decision making.

1.2 Climate models and model evaluation

Computer models of the climate system enable the numerical solution of the physical equations which govern the evolution of the climate. They therefore represent an invaluable tool in the study of the Earth's climate, enabling the degree of natural variability within the climate system to be studied, and enabling the responses to external forcing - such as an increase in the atmospheric carbon dioxide concentration - to be simulated. Different models are used to address different questions, with the models exhibiting varying degrees of complexity. The range of models which exists has variously been described as forming either a "heirarchy" (*McGuffie and Henderson-Sellers*, 1997; *McAvaney et al.*, 2001) or a "spectrum" (*Claussen et al.*, 2002).

The most complex models are coupled general circulation models (e.g. *Gordon et al.*, 2002; *Collins et al.*, 2006; *Delworth et al.*, 2006; *Johns et al.*, 2006), which include three-dimensional representations of the atmosphere and ocean. Various other sub-models are incorporated, representing components of the climate system such as sea ice, the land surface, vegetation, atmospheric chemistry and marine biogeochemistry. Earth system models of intermediate complexity (EMICs, e.g. *Weaver et al.*, 2001; *Claussen et al.*, 2002; *Goosse et al.*, 2003; *Montoya et al.*, 2005; *Wang et al.*, 2005) lie towards the middle of the spectrum. EMICs simulate the interactions between the components of the climate system but, to enable longer simulations to be conducted, are simpler in nature than coupled general circulation models. A typical EMIC consists of an oceanic general circulation model, a sea ice model and an energy-moisture balance atmosphere model; they can also incorporate ice sheet models, vegetation models and ocean biogeochemistry models. The simplest models are zero-, one- or two-dimensional models (e.g. the one-dimensional box model of *Wigley and Raper*, 1987), which can be used to study the global response to external forcing over a wide range of parameter space. A comprehensive review of the history of climate modelling, and of the recent state of the field, is provided by *McGuffie and Henderson-Sellers* (2001).

Despite their increasing sophistication, it is important to understand that numerical climate models have their limitations. They are only reliable to the extent that they correctly encapsulate the physical processes which they seek to represent, and to the extent that they are supplied with correct boundary and initial conditions. The physical realism of a model is restricted not only by understanding of the climate system, but also by computational limitations. The spatial resolution of a model, and the extent to which it incorporates representations of physical processes, are chosen in accordance with the questions which are to be addressed. They will be restricted, however, by the need to obtain answers to those questions within a particular timeframe.

The results of numerical models must therefore be analysed within an appropriate context. This context includes not only an understanding of the physical limitations of the model (specifically, the spatial resolution, and the range of physical processes which it incorporates), but also an evaluation of its ability to answer a particular question. Such an evaluation might, therefore, consider its ability to simulate the mean climate state, its ability to simulate natural variability, or its ability to simulate the climatic changes arising from external forcing (such as an increase in the atmospheric carbon dioxide concentration, or a change in insolation). It should be emphasised that, within this context, *evaluation* is a more appropriate term than the commonly-used term *validation*. Validation implies an affirmation that a model is a complete and accurate representation of the system which is being simulated; however, this is impossible in practice, given that such an affirmation requires a complete and accurate understanding of that system (*Oreskes et al.*, 1994).

As a result of limited understanding of the climate system, and given that many physical processes occur on spatial scales much finer than the spatial resolution of numerical climate models, these processes are represented within climate models via *parameterisations* (e.g. *McGuffie and Henderson-Sellers*, 1997, 2001). These schemes aim to represent physical processes on the spatial scales of the model, rather than on the spatial scales at which they occur in the real world. Examples of such parameterisations are the cloud schemes which are employed within atmospheric general circulation models, and which simulate the *average* cloud cover within a gridbox (as a function, for example, of the relative humidity of the air), rather than seeking to simulate individual clouds. However, such schemes are governed by input parameters - in the case of a cloud scheme, such a parameter might be a critical relative humidity, above which clouds begin to form. These parameters often have no physical basis, and are generally only weakly constrained by observations.

A typical coupled general circulation model contains $O(10^2–10^3)$ such parameters, and there are therefore a very large number of degrees of freedom in the possible physical configurations of the model. While incomplete understanding of the climate system precludes the possibility that a climate model can be a perfect representation of the real world, observations can be used to determine optimal values for the input parameters, a process which is often referred to as "tuning". However, to determine the optimal set of values (as determined by some pre-defined criterion), observations are required of a number of distinct climate states which equals, or exceeds, the number of degrees of freedom in the physical configuration of the model. This is essentially unachievable in practice, and the physical configuration of general circulation models can therefore contain considerable uncertainty.

Attempts to quantify the uncertainties inherent in the output of climate models have typically sought to compare and contrast the response of different models to a given scenario. The Coupled Model Intercomparion Project (e.g. *Covey et al.*, 2003; *Meehl et al.*, 2005) compared the ability of coupled general circulation models to simulate the present day climate, and the response of the models to a 1% per year increase in the atmospheric carbon dioxide concentration, while the Paleoclimate Modelling Intercomparion Project (e.g. *Joussaume et al.*, 1999; *Harrison et al.*, 2002; *Crucifix et al.*, 2005; *Paleoclimate Modelling Intercomparison Project*,

2005) aims to compare the ability of models to simulate palaeoclimate epochs. Ensembles of simulations have also been conducted, using the same model but with perturbations to the model physics; the largest example of such an ensemble is the ongoing "climate*prediction*.net" experiment (*Stainforth et al.*, 2005), which aims to systematically explore model parameter space.

1.3 Coupled models and flux adjustments

Coupled general circulation models aim to represent both the variability within the components of the climate system, and the variability which arises from the interactions between them. They are therefore the only type of climate model which is capable of simulating the full range of internal variability within the atmosphere-sea ice-ocean system.

Coupled general circulation models have been shown to be capable of simulating the present-day climate, both with regard to the mean state, and with regard to the internal variability (e.g. *McAvaney et al.*, 2001; *Lambert and Boer*, 2001; *AchutaRao and Sperber*, 2002; *Covey et al.*, 2003; *Alexander et al.*, 2006; *Collins et al.*, 2006; *Delworth et al.*, 2006; *Deser et al.*, 2006; *Gnanadesikan et al.*, 2006; *Johns et al.*, 2006; *Wittenberg et al.*, 2006). Confidence in the ability of these models to simulate climatic change is enhanced by their ability to reproduce the observed trend in the global-mean climate surface air temperature during the twentieth century (e.g. *Mitchell et al.*, 1995; *Haywood et al.*, 1997; *Boer et al.*, 2000; *Meehl et al.*, 2000; *Broccoli et al.*, 2003). Coupled general circulation models have been used to simulate both the short- and long-term response of the climate system to an increase in the atmospheric carbon dioxide concentration (e.g. *Manabe and Stouffer*, 1994; *Cubasch et al.*, 2001; *Covey et al.*, 2003; *Dixon et al.*, 2003; *Stouffer and Manabe*, 2003; *Gregory et al.*, 2005; *Bryan et al.*, 2006; *Kiehl et al.*, 2006; *Meehl et al.*, 2006; *Stouffer et al.*, 2006), and also to simulate past climate states (e.g. *Hewitt and Mitchell*, 1998; *Bush*, 1999; *Otto-Bliesner*, 1999; *Braconnot et al.*, 2000b; *Voss and Mikolajewicz*, 2001; *Liu et al.*, 2003a,b; *Mikolajewicz et al.*, 2003; *Otto-Bliesner et al.*, 2006).

However, the control climates of coupled general circulation models are generally not completely stable, and tend to exhibit ongoing drift in global statistics such as the global-mean surface air temperature (e.g. *Bell et al.*, 2000; *Lambert and Boer*, 2001). If systematic errors are present within the physics of either the atmosphere and ocean models, then drift *will* be encountered upon the coupling of the two models (*Moore and Gordon*, 1994; *Weaver and Hughes*, 1996). The errors will cause the boundary conditions on each model to change upon coupling; if the simulated sea surface temperature differs from observations, for example, then the bottom boundary condition on the atmosphere model will change when coupled. It will therefore evolve into a different state, and the coupled model will drift.

One method for reducing this drift is to apply flux adjustments (*Sausen et al.*, 1988). These adjustments are diagnosed from the differences between the surface fluxes simulated by the atmosphere and ocean models during independent spin-up, and are applied to the surface fluxes within the coupled model. Flux adjustments are intended to ensure that the coupled model operates at the equilibrium reference state for which the atmosphere and ocean models were designed, and it is therefore being assumed that the climatologies of the stand-alone atmosphere and ocean models represent the best available climatologies, given the spatial resolutions, the model physics and the boundary conditions which are imposed (*Sausen et al.*, 1988; *Weaver and Hughes*, 1996).

The application of flux adjustments is undesirable, however. The adjustments have no physical justification, and can exhibit large spatial and temporal variability; indeed, they can exceed in magnitude the fluxes which occur naturally within the climate system. It has been shown that when an ocean model is forced with a specified freshwater flux, and with the sea surface temperature relaxed towards observed values, it is capable of exhibiting self-sustaining oscillations on decadal timescales (*Weaver et al.*, 1993). It is therefore possible that, when the flux adjustments are large in magnitude, they determine the structure of the internal variability within the ocean, with this mode being excited by stochastic variability in the surface fluxes (*Weaver and Hughes*, 1996). It should also be noted that drift may still occur within a coupled model, even when flux adjustments are applied. *Power* (1995) demonstrates that the response of an ocean model to perturbations about a mean surface flux is asymmetric. If the magnitude of the variability in the surface fluxes is increased, as will happen upon the coupling to an atmosphere model, the ocean model may therefore evolve into a different state, even if the time-mean of the surface fluxes remains unchanged.

The need for flux adjustments within the coupled model suggests significant deficiencies in the physics of at least one of the constituent models. Furthermore, given that the adjustments are derived for a particular climate state, a coupled model which employs flux adjustments can only be regarded as being suitable for simulating *small* perturbations about the reference state (*Cubasch et al.*, 1992). While there is no apparent definition as to what represents a small perturbation, the glacial climate, or a large increase in the atmospheric carbon dioxide concentration, would not seem to represent small perturbations relative to the climate of the present day.

Several studies have addressed the role of flux adjustments within coupled models. *Duffy et al.* (2000) assess the variability in surface air temperatures within 17 simulations which were submitted to the Coupled Model Intercomparison Project, and find no evidence that flux adjustments *directly* influence variability in coupled general circulation models; however, they note that models with lower global-mean surface air temperatures exhibit more high-latitude variability, and that, by influencing the global-mean surface air temperature, flux adjustments may have a weak *indirect* effect upon internal variability. For a scenario in which the atmospheric carbon dioxide concentration is increased at 1% per year, *Gregory and Mitchell* (1997) find that the Hadley Centre coupled model exhibits a $\sim$30% reduction in the global-mean surface temperature response when flux adjustments are not applied, relative to an otherwise-identical configuration of the model in which flux adjustments *are* applied. The spatial patterns of the temperature changes are similar in the two runs, indicating that the flux adjustments are not causing any gross distortion. In contrast, *Fanning and Weaver* (1997), who study the response of an idealised coupled model with and without flux adjustments, find only regional differences in the model response as the atmospheric CO_2 concentration is increased; once the CO_2 concentration is stabilised, however, they find that the model which employs flux adjustments exhibits greater warming, consistent with *Gregory and Mitchell* (1997).

Based on these studies, and given uncertainty regarding the validity of using coupled general circulation models to simulate large perturbations around the control state, the role of flux adjustments within coupled GCMs appears to be worthy of further study. Both the effect of flux adjustments upon the simulated internal climate variability, and upon the response of the model to external forcing, merit investigation.

1.4 Aims

This project seeks to employ a computationally-efficient coupled atmosphere-ocean general circulation model to address some of the questions raised above. Such a model would enable multi-millennial climate simulations to be conducted, enabling the full spectrum of internal climate variability to be investigated. It would also enable the equilibrium response of the model to external forcing, such as an increase in the atmospheric carbon dioxide concentration or a change in insolation, to be determined.

The aims of this project are therefore to use such a model to address the following questions:

1. How does the spin-up procedure for the ocean model influence the degree of realism of the control climate, and the magnitude of the flux adjustments which are diagnosed for use within the coupled model?

2. Do the flux adjustments influence the nature of the internal variability within the model, and the response to external forcing?

3. Does the control climate of the ocean model influence the nature of the internal variability within the model, and the response to external forcing?

1.5 Overview

Chapter 2 describes the CSIRO Mk3L climate system model, which was developed as part of this project. The atmospheric and oceanic components are spun up for pre-industrial conditions, consistent with PMIP2 (*Paleoclimate Modelling Intercomparison Project*, 2005) experimental design, and the control climates of each model are evaluated against observations. The method used to diagnose flux adjustments is discussed, and flux adjustments are derived from the atmosphere and ocean model spin-up runs. The magnitude and spatial structure of the adjustments are then analysed.

In Chapter 3, the spin-up procedure for the ocean model is considered further, with the aim of obtaining a more realistic ocean climate. A number of spin-up procedures are considered, and it is concluded that the relaxation boundary condition is the most appropriate. The effectiveness of the relaxation boundary condition is assessed, first by studying the default response of the ocean model, and then using a simple theoretical model. The response of the ocean model to changes in the relaxation timescale is then investigated.

The spin-up procedure for the ocean model is further considered in Chapter 4, with a number of modifications to the surface boundary conditions being assessed. In the first of these, the prescribed sea surface temperatures (SSTs) and sea surface salinities (SSSs) are modified to allow for the presence of sea ice and, in particular, to allow for the effects of brine rejection. The second modification attempts to correct for the phase lag between the observed and simulated SSTs and SSSs by shifting the prescribed SSTs and SSSs forward in time by one month. Finally, an iterative technique is developed, whereby the response of the model is used to obtain a set of *effective* surface tracers. These are derived so as to minimise the errors in the simulated SSTs and SSSs.

The control climate of the Mk3L coupled model, with regard to both the drift in the mean climate, and the internal variability of the model, is presented in Chapter 5. Three configurations of the model are considered: the default configuration, and two new configurations in which the ocean model is spun up in accordance with the techniques developed in the previous chapter.

In Chapters 6 and 7, the response of each configuration of the model to changes in the external boundary conditions is studied. The ability of Mk3L to simulate the climate of the mid-Holocene (6,000 years BP) is evaluated in Chapter 6. The transient response of the model to an increase in the atmospheric carbon dioxide concentration is then studied in Chapter 7. A scenario is employed in which the CO_2 concentration is increased at 1% per year, and then stabilised at three times the pre-industrial level.

Concluding remarks, including suggestions for future work, are presented in Chapter 8.

Two appendices are also included. Appendix A provides information regarding the experimental design, while Appendix B provides some statistics for the simulations which are presented herein.