Chapter 8

Concluding remarks

8.1 Conclusions

The aims of this project were to use a coupled atmosphere-ocean general circulation 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?

The success of the project in meeting each of these aims is considered in this section.

8.1.1 A coupled atmosphere-ocean general circulation model

The CSIRO Mk3L climate system model was used to address the above questions. This model consists of a low-resolution version of the atmosphere-sea ice component of the CSIRO Mk3 coupled model, coupled to the oceanic component of the CSIRO Mk2 coupled model. A horizontal spectral resolution of R21 is employed, giving zonal and meridional resolutions of 5.625° and $\sim 3.18^\circ$ respectively. There are 18 vertical levels in the atmosphere, and 21 vertical levels in the ocean.

The atmospheric and oceanic components of Mk3L were spun up for pre-industrial conditions, consistent with PMIP2 experimental design. The control climate of the atmosphere model was found to be realistic, with the simulated surface air temperature, sea ice, cloud cover and precipitation exhibiting broad agreement with observations. However, the model fails to form sea ice in Hudson Bay, resulting in surface air temperatures which are too warm in this region in winter; this discrepancy can be attributed to a warm bias in the sea surface temperatures which were prescribed as the bottom boundary condition. Other discrepancies in the simulated climate include Arctic sea ice which is generally too thin, excessive cloud cover over the tropical oceans, poor representation of marine stratocumulus, and limited success in reproducing the positions of the monsoons. These discrepancies can be attributed to deficiencies in the model physics.

The control climate of the ocean model is only moderately realistic. The rate of North Atlantic Deep Water formation is too weak, the rate of Antarctic Bottom Water formation is too strong, and the deep ocean is too fresh, too cold and too buoyant. While the simulated strength of the Antarctic Circumpolar Current agrees well with observations, the western boundary currents are too weak and diffuse. The poor representation of the boundary currents is a consequence of the coarse horizontal resolution, but the other deficiencies in the ocean model climate can be attributed, at least in part, to the relaxation boundary condition on the temperature and salinity of the upper layer of the model. The use of such a boundary condition ensures that the peak winter density and salinity of the high-latitude surface waters do not attain the maximum observed values.

Flux adjustments were diagnosed from the differences between the surface fluxes derived from the atmosphere and ocean model spin-up runs. The oceanic meridional transports of heat and salt, as simulated by the ocean model and as implied by the atmosphere model, are in good agreement, and hence the flux adjustments exhibit relatively little variability in the meridional direction. However, there is high spatial variability in the zonal direction, arising largely from the failure of the atmosphere model to adequately represent marine stratocumulus, and from the failure of the ocean model to adequately represent the western boundary currents. The flux adjustments also exhibit a large seasonal cycle, with the result that the adjustments applied at individual gridpoints and in individual months can exceed in magnitude the fluxes which occur naturally within the climate system.

The coupled model was integrated for 1400 years, with the atmospheric and oceanic components being initialised from the final states of the spin-up runs, and with flux adjustments being applied. The control climate was found to be highly stable, with the global-mean surface air temperature declining just 0.23°C over the course of the simulation. This drift arises from changes in the Northern Hemisphere sea ice cover during the first century, with the resulting decline in the temperature of North Atlantic Deep Water leading to a slight, but ongoing, cooling trend within the ocean. Otherwise, there is little change in either global or regional statistics, with the thermohaline circulation exhibiting a high degree of stability, and with negligible drift in the surface air temperature over most of the Earth's surface. The Caspian Sea, which has no connection with the world ocean within Mk3L, exhibits an upward drift in salinity, which can be attributed to changes in the simulated precipitation and evaporation. The salinity of the remainder of the world ocean increases by just 0.004 psu; however, this increase cannot be accounted for by changes in the sea ice volume or in the surface freshwater fluxes, and it therefore appears to represent a conservation error within the model.

The simulated internal variability within the model was examined, and was found to exhibit the same spatial structure and correlations as the observed El Niño-Southern Oscillation (ENSO) phenomenon. The simulated return period of $\sim$8 years for El Niño events is longer than the observed period of $\sim$3–6 years, and the simulated events are too long and too weak. The simulated ENSO also exhibits excessive modulation on interdecadal timescales.

The ability of Mk3L to simulate the climate of the mid-Holocene was evaluated. The model is capable of simulating the global-scale changes in the climate, with warmer summers at northern mid-latitudes, and slight cooling in the tropics. However, it is less successful when assessed at a regional scale, being unable to capture the cooling over southern Europe, or the increased precipitation over northern Africa. These failures can be attributed, at least in part, to the static nature of the vegetation within Mk3L. While the model also simulates a ∼13% reduction in the strength of ENSO, this is a much smaller reduction than that implied by the palaeoclimate record. This discrepancy may be a consequence of deficiencies in the model physics, as indicated by its inability to correctly simulate the characteristics of the present-day ENSO.

The response of the model to a trebling of the atmospheric carbon dioxide concentration was also assessed. The CO_2 concentration was increased at 1% per year, until it reached three times the pre-industrial level; it was held constant thereafter. The global-mean surface air temperature increases by 1.6°C upon a doubling of the CO_2 concentration, and by 2.7°C upon a trebling. There is also a 49% reduction in the rate of North Atlantic Deep Water (NADW) formation.

Upon stabilisation of the atmospheric CO_2 concentration at three times the pre-industrial level, the global-mean surface air temperature continues to increase, with a warming of 5.3°C by the end of a 1400-year simulation. The rate of NADW formation recovers, however. The sea ice cover exhibits an ongoing decline, with 90% of the sea ice in the Southern Hemisphere, and 64% in the Northern Hemisphere, disappearing by the end of the simulation. The loss of sea ice cover in the Southern Hemisphere, and the associated reduction in brine rejection, results in the cessation of Antarctic Bottom Water (AABW) formation. Ventilation of the abyssal ocean therefore becomes restricted to convection in the Southern Ocean, and the surface warming penetrates only slowly to depth. By the end of the simulation, the deep ocean is still warming at a rate of ∼0.22°C/century, indicating that it is far from equilibrium. Thermal expansion of the ocean results in a steric sea level increase of 198 cm, with the continuing warming of the deep ocean giving rise to an ongoing increase of ∼10 cm/century.

8.1.2 The ocean model spin-up procedure

The default ocean model spin-up run was found to exhibit three distinct errors in the simulated sea surface temperatures (SSTs) and sea surface salinities (SSSs): an error in the annual mean, an error in the amplitude of the annual cycle, and a phase lag between the simulated and observed fields. These errors can be attributed, at least in part, to the relaxation surface boundary condition, and account for the failure to simulate the peak winter density and salinity of the high-latitude surface waters.

A number of modifications to the ocean model spin-up procedure were evaluated, with the aim of obtaining high-latitude surface waters which have a realistic peak winter density and salinity, and hence with the aim of improving the realism of the ocean model climate. A simple theoretical model was used to study the response of an ocean model under the relaxation boundary condition, and was found to reproduce many of the features of the response of the Mk3L ocean model. The response of the theoretical model was found to be strongest when the observed annual cycle in the SST or SSS was sinusoidal, and to weaken as the annual cycle became increasingly dominated by higher frequencies. A reduction in the relaxation timescale improved the model response, but with an undesirable increase in the magnitude of the surface fluxes.

A series of spin-up runs was conducted using the Mk3L ocean model, in which the relaxation timescale was varied from 5 to 80 days. The response was found to vary in the same manner as that of the theoretical model, with a reduction in the relaxation timescale reducing the errors in the simulated SSTs and SSSs, and increasing the magnitude of the surface fluxes. A reduction in the timescale resulted in more realistic peak surface water densities, and a corresponding improvement in the properties of the deep ocean, but a cold and fresh bias remained.

Further attempts to modify the ocean model spin-up procedure concentrated upon the prescribed surface tracers. An attempt was made to modify the prescribed SSTs and SSSs at high latitudes to allow for the presence of sea ice and, in particular, to allow for the effects of brine rejection. It was possible to obtain realistic peak surface water densities and salinities, and hence to obtain realistic vertical profiles of density and salinity within the ocean, but the cold bias of the deep ocean was increased. This was found to result from increased errors in the simulated thermohaline circulation, with an increase in the rate of AABW formation, and a decrease in the rate of NADW formation.

To address the time lag between observations and the model response, the effect of shifting the observed SSTs and SSSs forward in time by one month was assessed. This was found to have negligible impact upon the annual-mean climate of the ocean model, or upon the simulated seasonal cycle, but reduced the global-mean time lags in the simulated SSTs and SSSs to close to zero. By also reducing the phase difference between the surface fluxes simulated by the ocean model, and those simulated by the atmosphere model, the amplitudes of the annual cycles in the flux adjustments were reduced. Thus a new configuration of the coupled model (designated SHF herein) was obtained, in which the annual-mean climate and the seasonal cycles were negligibly different from the default configuration of coupled model, but within which the magnitude of the flux adjustments was reduced.

A novel spin-up technique was also developed, whereby the response of the ocean model is used to derive *effective* surface tracers. The annual means of the prescribed SSTs and SSSs, and the amplitudes of the annual cycles, are modified in an iterative fashion, with the aim of minimising the errors in the model response. A uniform phase shift of one month is also applied, in order to reduce the phase lags in the simulated SSTs and SSSs. This technique was found to be highly successful, with the iterative process converging towards a solution after just 14 iterations. There was a large improvement in the ocean model climate, with realistic vertical profiles of salinity and density, and with a reduction in the cold bias of the deep ocean. The rates of NADW and AABW formation were also consistent with observations. Furthermore, there was a slight reduction in the magnitude of the flux adjustments. A third configuration of the coupled model (designated EFF herein) was therefore obtained, within which the ocean model climate was much more realistic.

8.1.3 The effect of flux adjustments

SHF was integrated for 1100 years. The rate of drift in the control climate was found to be slightly greater than for the default configuration of the model, but it is still very small. The reduction in the flux adjustments was found to have no significant effect upon the nature of the simulated internal variability. There is therefore no evidence to reject the null hypothesis that flux adjustments have no influence upon the simulated internal variability.

The response to the insolation conditions which applied at the time of the mid-Holocene, and to an increase in the atmospheric carbon dioxide concentration, was studied. While there are some statistically-significant differences between the response of SHF and that of the default configuration of the model, these are generally small in magnitude. The exception is the response over the Caspian Sea, where the differences in the response of the model were found to arise from a cooling and freshening trend within the control run.

While there is therefore little evidence to reject the null hypothesis that flux adjustments have no *direct* influence upon the response of the model to external forcing, there is evidence that flux adjustments can *indirectly* affect the response.

8.1.4 The effect of the control climate

EFF was integrated for 1100 years. The rate of drift in the control climate was found to be slightly greater than for the default configuration of the model, but it is still very small. The simulated internal variability was also found to be slightly stronger, with a ∼10% increase in the strength of the simulated El Niño-Southern Oscillation.

The response to mid-Holocene insolation was found to exhibit some significant differences relative to the default configuration of the model, most notably lower temperatures in the Southern Ocean. The response to an increase in the atmospheric carbon dioxide concentration was also studied. Relative to the default configuration, the surface warming is enhanced by ∼4%, and there is reduced penetration of this warming to depth. These differences were found to arise from the enhanced realism of the control climate, with an increased vertical density profile within the ocean. This results in reduced convection within the Southern Ocean, and hence to reduced ventilation of the abyssal ocean.

It has therefore been demonstrated that the control climate of the ocean model can influence both the nature of the internal variability within a coupled model, and the response of a coupled model to external forcing.

8.1.5 Summary

The project has been successful in achieving its aims. A number of modifications to the ocean model spin-up procedure have been assessed. Two of these have been found to result in an overall improvement in the climate of the ocean model, without increasing the magnitude of the flux adjustments. Two new configurations of the Mk3L coupled model have therefore been obtained.

These configurations have been used to assess the impact of flux adjustments, and of the control climate of the model, upon the simulated internal variability, and upon the response to external forcing. The flux adjustments have been found to have no effect upon the internal variability, and to have only an indirect effect upon the response of the model. An increase in the realism of the ocean climate has been found to lead to a slight increase in the magnitude of the internal variability, and also to influence the response to external forcing.

8.2 Future work

All of the coupled model simulations presented herein are still being integrated at the time of writing. Unless the simulations begin to exhibit significant drift, it is intended to integrate them for as long as resources permit; it should therefore be possible to extend them for many millennia. For the control simulations, this will enable the stability of the control climate of Mk3L on millennial timescales to be assessed, and will allow millennial-scale variability within the model to be investigated. The origin of the drift should be studied further, with the intention of ensuring that the control climate is stable on timescales of $O(10^4)$ years and longer. Conservation of physical quantities within the model should also be studied, as a slight salinity drift within the control simulations appears to represent a conservation error within the model.

An extension of the mid-Holocene simulations will also enable natural climate variability during this epoch to be studied. For the scenario in which the atmospheric carbon dioxide has been stabilised at three times the pre-industrial value, it will be possible to integrate the simulations towards equilibrium. This will enable the impact of the ongoing warming of the deep ocean to be evaluated, particularly with regard to the possibility that the resulting decrease in the stratification of the water column will enable the re-establishment of deep overturning in the Southern Ocean (e.g. *Bi et al.*, 2001).

Further simulations should focus upon alternative scenarios, for both the past and future. As simulations have already been conducted for two of the three standard PMIP2 experiments - the pre-industrial era and the mid-Holocene - simulations should also be conducted for the third experiment (the Last Glacial Maximum, 21,000 years BP). Simulations could also be conducted for the additional "water-hosing" experiment, in which an external source of freshwater is applied to the surface of the North Atlantic.

The computational efficiency of Mk3L makes transient palaeoclimate simulations possible. Using the equilibrium simulations for the mid-Holocene as the starting point, the Earth's orbital paramemeters could be varied dynamically, enabling a transient simulation from 6,000 years BP to the present day to be conducted. This would enable changes in the mean climate state, and in the natural climate variability, through the Holocene to be studied. Such simulations should address the role of vegetation feedbacks, either through the specification of appropriate vegetation types, as derived from biome reconstructions, or through the incorporation of a dynamic vegetation model. Comparison could also be made with similar simulations conducted using models of intermediate complexity (e.g. *Weber*, 2001; *Brovkin et al.*, 2002; *Crucifix et al.*, 2002; *Weber et al.*, 2004; *Renssen et al.*, 2005), and a study which employed a coupled atmosphere-ocean general circulation model, but which accelerated the rate of change in the Earth's orbital parameters (*Lorenz and Lohmann*, 2004).

Scenarios which consider future climate change should focus upon stabilising the atmospheric carbon dioxide concentration at different levels, enabling the relative long-term response of the climate system to be studied. Such scenarios should include stabilisation of the CO_2 concentration at two and four times the pre-industrial level, enabling comparison with other studies (e.g. *Stouffer and Manabe*, 2003).

The role of flux adjustments within Mk3L should also be investigated further. Having established that a reduction in the amplitude of the flux adjustments has no significant effect upon the internal variability, and only an indirect effect upon the response to external forcing, other methods of reducing the flux adjustments should be assessed. These should include the "minimum" flux adjustment of *Weaver and Hughes* (1996), in which the flux adjustments are zonally averaged across each ocean basin prior to being applied within the coupled model. Such adjustments are designed only to correct for the differences in the oceanic meridional transports of heat and salt, between those simulated by the ocean model and those implied by the atmosphere model, and would therefore be small in magnitude in the case of Mk3L. Alternative methods for reducing the magnitude of the flux adjustments would be to apply annual-mean adjustments only, and to derive "regional" flux adjustments through spatial averaging.