A Coupled Climate System Model for Long-Term Climate Studies

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1. Introduction

We have developed a low-resolution version of the CSIRO Mk3 climate system model, suitable for long-term climate studies. The model physics has been enhanced to ensure rigorous conservation of heat and freshwater. Code has been added to calculate the Earth's orbital parameters, enabling the model to be used to simulate past climatic changes. The model source code has also been modified to maximise portability across computer platforms, facilitating its use on computational grids.

We describe here the modifications which have been made to the model, and present the results of some preliminary simulations.

2. The model

We use the CSIRO Mk3 climate system model (Gordon 2002). The model is a three-dimensional numerical representation of the Earth's climate system, consisting of components which simulate the motions of the atmosphere, sea ice and ocean. To facilitate simulations spanning many thousands of years, we have developed a version which is fast and yet realistic, by making the following modifications to the model physics:

- the horizontal resolution has been reduced to a 64 by 56 rectangular grid, with each gridbox spanning around 5.6° of longitude and 3.2° of latitude
- the vertical resolution has been left unchanged, with 18 levels in the atmosphere and 21 in the ocean
- the coupling between the atmosphere/sea ice and ocean components has been enhanced, to ensure rigorous conservation of heat and freshwater
- code has been inserted which can calculate the Earth's orbital parameters for periods up to one million years into either the past or future

3. Portability

To facilitate the use of the model on computational grids, we have sought to make it as portable across platforms as possible. This has been achieved by making the following modifications to the model source code:

- proprietary compiler directives have been replaced with their OpenMP equivalents
- the dependence on external libraries has been minimised
- all dependence on proprietary libraries has been removed
- all platform-specific source code has been removed, ensuring that identical instructions are executed on all platforms

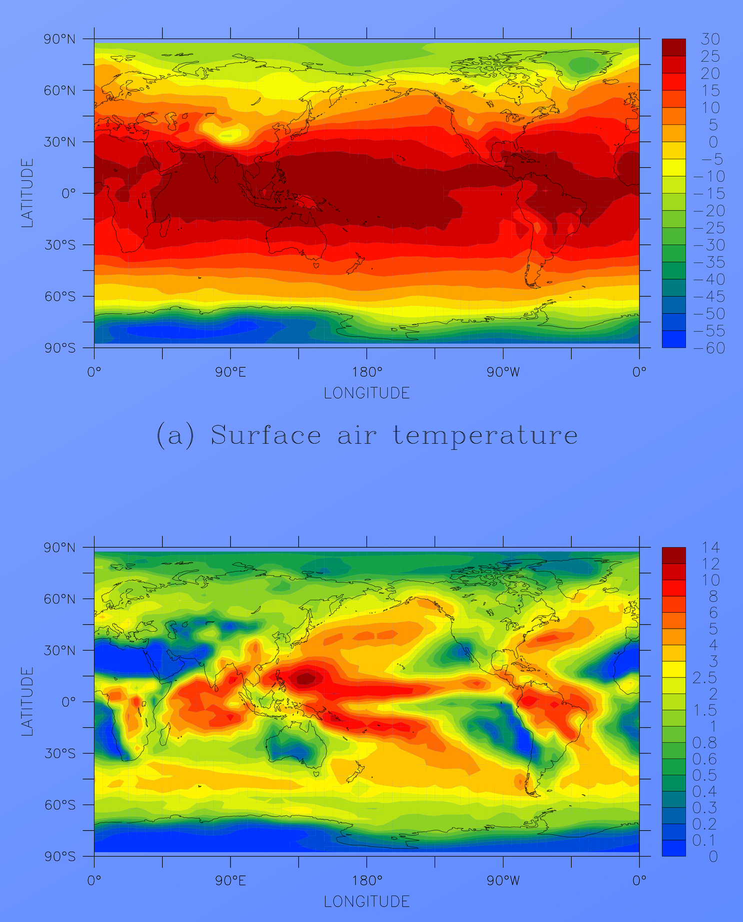
Thus the low-resolution version of the model has the following characteristics:

- it compiles and runs on any UNIX/Linux platform, without any modifications being required
- dependence on external libraries is restricted to netCDF and FFTW, both of which are freely available and open source
- loop structure is optimised for scalar architectures
- a high degree of shared-memory parallelism has been achieved

The performance of the model on APAC facilities is shown in Table 1.

Facility	Processor type	No. of processors	Elapsed time (days)
AlphaServer SC	1GHz EV68	1	244
		4	86
Linux Cluster	2.66GHz Pentium 4	1	219

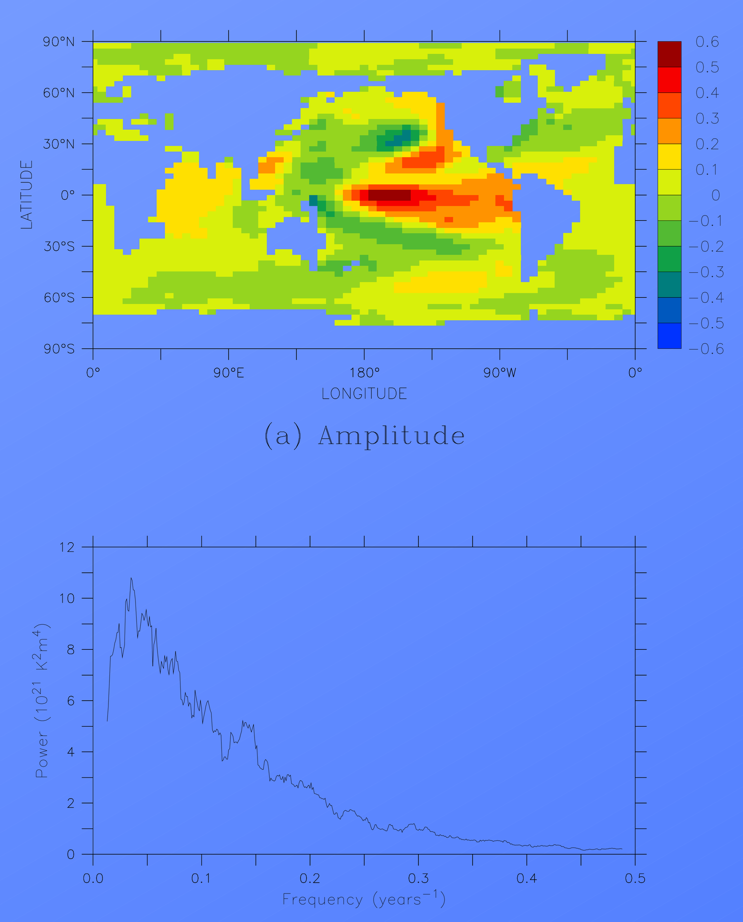
Table 1. Time taken to complete a 1000-year simulation on APAC facilities.



(a) Surface air temperature

(b) Precipitation

Figure 1. Simulated pre-industrial climate. **a** Annual-mean surface air temperature (°C) and **b** annual-mean precipitation (mm/day).



(a) Amplitude

(b) Power spectrum

Figure 2. EOF1 of annual-mean sea surface temperature. **a** Amplitude (°C) and **b** power spectrum.

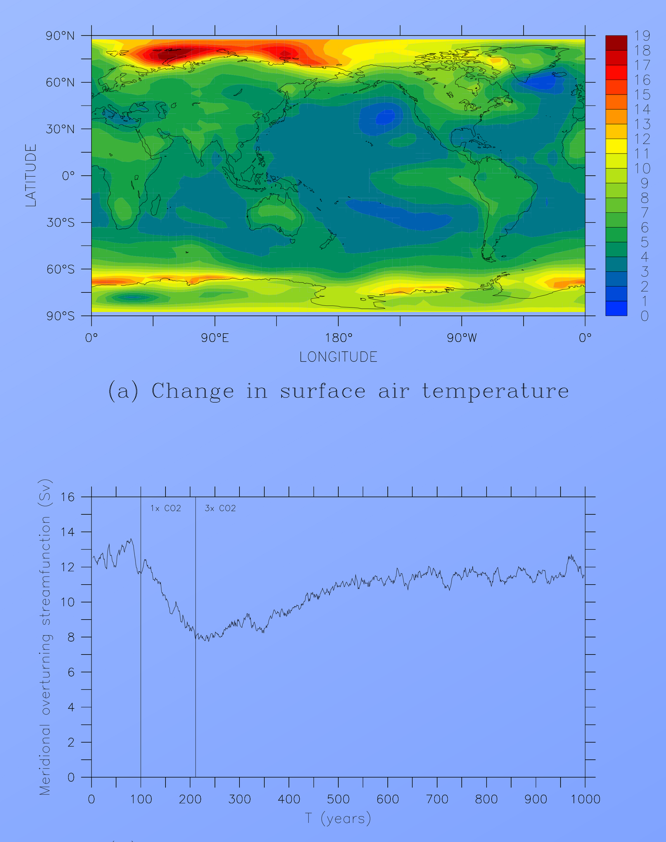
4. Validation

The model has been used to carry out a 1000-year control simulation for pre-industrial simulations. The atmospheric CO_2 concentration was held constant at 280 ppm and modern orbital parameters were used. The simulated surface air temperature and precipitation (Figure 1) agree well with observations.

The dominant mode of internal variability exhibits the same spatial structure and correlations as the observed El Niño-Southern Oscillation phenomenon. The leading EOF of annual-mean sea surface temperature (Figure 2) describes 21% of the variance. Positive anomalies in the central and eastern tropical Pacific Ocean coincide with negative anomalies to the west and at higher latitudes.

The model experiences El Niño events once every 7-8 years on average. The power spectrum of the leading EOF (Figure 2b) exhibits a secondary maximum at exactly this frequency (i.e. 0.14 years^{-1}). The power is concentrated at lower frequencies, however, indicating that the greatest variability occurs on timescales longer than El Niño.

5. Future climate change



(a) Change in surface air temperature

(b) Maximum North Atlantic overturning

Figure 3. Simulated changes for a $3xCO_2$ stabilisation scenario. **a** Surface air temperature after 750 years, relative to the control run (°C) and **b** Maximum North Atlantic meridional overturning streamfunction.

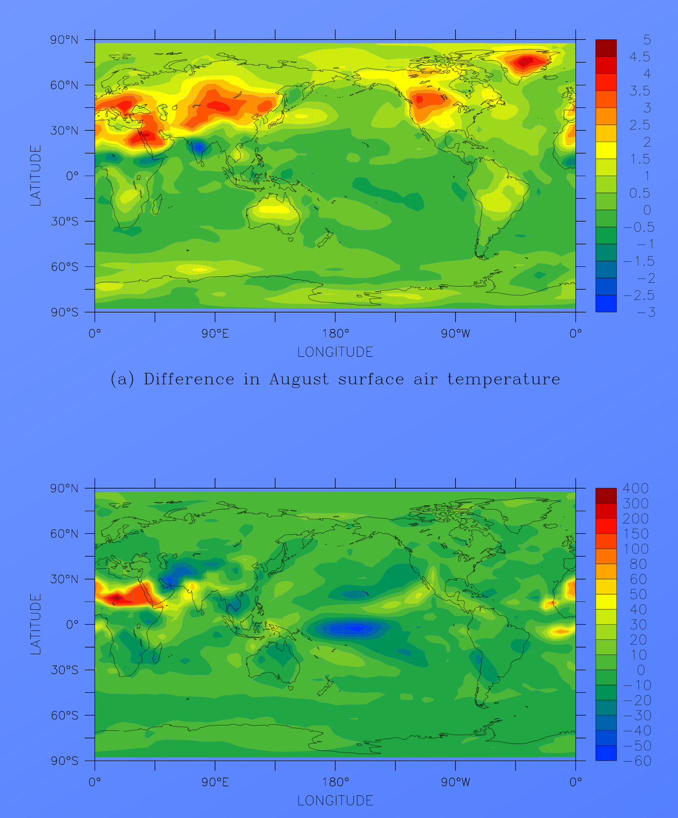
A 1000-year simulation has been carried out for a scenario in which the atmospheric CO_2 concentration is stabilised at three times the pre-industrial value. Beginning from year 100 of the control run, the CO_2 concentration was increased at 1% per year. It reached 840 ppm in year 211, and was held constant thereafter.

Global-mean surface air temperature has increased by 2.6°C at the time of CO_2 trebling, and by 5.2°C at the end of the simulation. Figure 3a shows the increase in surface air temperature 750 years after the CO_2 concentration has been stabilised. Strong warming occurs in polar regions, where the sea ice has retreated. However, the North Atlantic experiences negligible warming, which can be attributed to a weakening of the Gulf Stream. Figure 3b shows that the North Atlantic overturning weakens as the CO_2 concentration is increased. Although it exhibits a gradual recovery once the CO_2 concentration has been stabilised, it has not returned to its original strength by the end of the simulation.

6. Past climate change

A 500-year simulation has been carried out for the mid-Holocene (6,000 years ago). The atmospheric CO_2 concentration was held constant at 277 ppm, and appropriate orbital parameters were used.

The Earth's orbital geometry means that, in the mid-Holocene, the Earth was closer to the sun during the Northern Hemisphere summer than it is today. Northern summers were therefore hotter. Figure 4a shows the simulated differences in August surface air temperature between the mid-Holocene and today, with higher temperatures apparent across the northern landmasses. The hotter summers caused the Northern Hemisphere monsoons to occur at a higher latitude than today. The simulated precipitation changes (Figure 4b) indicate a dramatic shift in the African monsoon, with decreased rainfall over central Africa, but large increases across North Africa.



(a) Difference in August surface air temperature

(b) Difference in annual precipitation

Figure 4. Simulated differences between the mid-Holocene and modern climates. **a** August surface air temperature (°C) and **b** annual precipitation (%).

7. Conclusions

We have developed a low-resolution version of the CSIRO Mk3 climate system model. The reduction in resolution allows for simulations spanning many thousands of years, while the modified source code enables its use on computational grids. We have shown that the model has a realistic control climate, and that it is able to simulate both past and future climatic changes.

8. References

Gordon, H.B., L.D. Rotstayn, J.L. McGregor, M.R. Dix, E.A. Kowalczyk, S.P. O'Farrell, L.J. Waterman, A.C. Hirst, S.G. Wilson, M.A. Collier, I.G. Watterson and T.I. Elliott, The CSIRO Mk3 Climate System Model, CSIRO Atmospheric Research technical paper no. 60, 2002.

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