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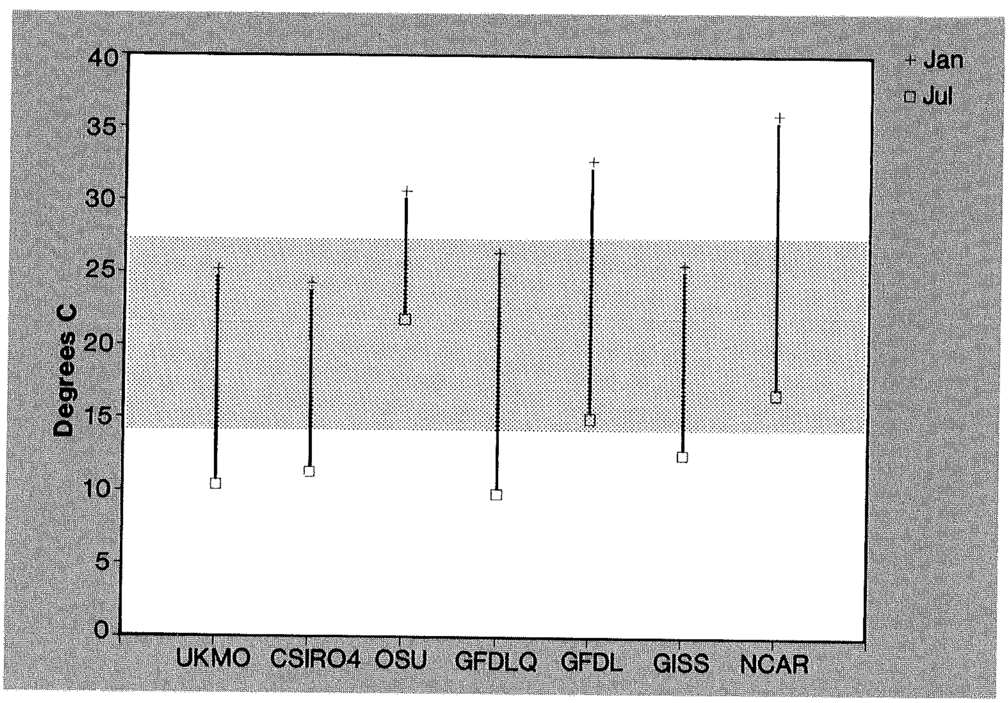
Australian Region Intercomparison of the Results of some General Circulation Models used in Enhanced Greenhouse Experiments

Peter Whetton and A. Barrie Pittock



CSIRO DIVISION OF ATMOSPHERIC RESEARCH TECHNICAL PAPER NO. 21

National Library of Australia Cataloguing-in-Publication Entry

Whetton, P.H. and Pittock, A.B.
Australian region intercomparison of the results of some general circulation models used in enhanced greenhouse experiments.
Bibliography ISBN 0-643-05113-9
1. Enhanced greenhouse warming — regional impacts
2. Climate modelling
I. Commonwealth Scientific and Industrial Research Organisation (Australia). Division of Atmospheric Research. II. Title. (Series: Division of Atmospheric Research. Technical Paper; no. 21)

Foreword

This Technical Paper is the second from the Division of Atmospheric Research arising out of the CSIRO Climate Change Research Program with funding provided by the Commonwealth Government through the Department of the Arts, Sport, the Environment, Tourism and Territories (DASETT), and research agreements with the governments of Victoria, the Northern Territory, Western Australia and New South Wales. Along with the earlier Technical Paper (No. 20) on **Envisaged Impacts of Enhanced Greenhouse Warming on Tropical Cyclones in the Australian Region** it is one of the first fruits of a systematic attempt to identify and describe the regional climate changes and impacts to be expected as a result of the increasing concentration of greenhouse gases in the atmosphere.

These Technical Papers are a means of more fully documenting the basis of conclusions which are or will be found in annual reports to DASETT and/or the relevant States, but which are too detailed or parochial to find their way into the scientific journals. The latter now frequently place severe limitations on the length and detail contained in papers which they are prepared to publish.

The philosophy of the Climate Impact Group at the Division of Atmospheric Research (DAR) is to gather together, in an eclectic but critical manner, scientific evidence pertaining to regional climate change from whatever source or discipline seems relevant. This includes original research by group members, but also the critical evaluation and detailed analysis of results from others within and outside CSIRO, including results from local and overseas general circulation modelling groups, and analyses of historical and paleoclimatic data. Where appropriate the group is carrying out its own detailed statistical analyses of the instrumental records and of model output data, as demonstrated in the present paper, and undertaking sensitivity studies with limited area models.

The group's work relies heavily on the cooperation of many individual scientists and scientific institutions both within CSIRO and outside. This is particularly notable in the case of the present paper because a critical comparison has been made between model results over Australia supplied by a number of modelling groups. Inevitably some model simulations of the present Australian climate have appeared "better" than others. This most emphatically does not imply any general ranking of some models or modelling groups as better or worse than others, since we have compared model simulations only over Australia, and these simulations were performed at different times and stages of model development. These particular results have been compared because they were the results available to us in computer-compatible form at the time of the comparison. More recent simulations by any one of the modelling groups may well reveal better performance over Australia, and indeed this is to be hoped for and expected. The ready cooperation of overseas modelling groups, and of our modelling colleagues in CSIRO, in providing detailed results from their models is thus fully and most gratefully acknowledged.

Having said that, we are particularly encouraged that the first CSIRO4 model run at DAR has stood up well in the intercomparison of control results. We approached the intercomparison with an open mind, in the full expectation that the results would highlight weaknesses in the local product. Indeed, while the locally produced results were encouraging, the comparison with observed data did reveal certain shortcomings in the model. The ready acknowledgement of this by the modelling group at DAR, and their eagerness to make improvements to the model in preparation for further simulations, is testimony to the value of having a local modelling group which is capable of responding rapidly to local needs and priorities. We are thus confident that in the not too distant future we will have improved simulations which will enable us to develop more confident scenarios or predictions of future climatic change in the Australian region.

In accordance with the general philosophy of the Climate Impact Group, this report therefore is in the nature of an interim or *pro tem* "state-of-the-art" report, and its conclusions should not be construed as giving firm predictions for future climate change in Australia. Indeed, if we do not progressively revise our predictions as new evidence comes along, we will have failed in our duty.

A. Barrie Pittock
Leader, Climate Impact Group.

Australian Region Intercomparison of the Results of some General Circulation Models used in Enhanced Greenhouse Experiments

P.H. Whetton and A.B. Pittock

CSIRO, Division of Atmospheric Research
Private Bag 1, Mordialloc, Vic 3195, Australia

Abstract

To assist in estimating likely future climate change in the Australian region, the results of seven different general circulation modelling experiments run to assess the equilibrium impact of an effective doubling of carbon dioxide are examined. They include the most recent modelling results we had available from various research centres in North America and Europe, as well as those of the CSIRO. The approach used is, firstly, to assess the quality of the control ($1 \times CO_2$) simulations from each of the models of mean sea level (MSL) pressure, temperature and precipitation in the Australian region by comparing these with the corresponding observed patterns; and, secondly, to then analyse the $2 \times CO_2$ results of only those model experiments with good control simulations. Only two model experiments of those examined provide acceptable simulations of present-day Australian region climate: these are those of the CSIRO four-level model (CSIRO4) and the model of the United Kingdom Meteorological Office (UKMO). For conditions of equivalent doubling of CO_2, both models show substantial increases in surface air temperature of around 4–6°C inland and 2–4°C in coastal regions. Both models show decreased MSL pressure over the Australian continent and increases in rainfall over northern, central and eastern Australia, particularly in the summer half of the year. The CSIRO4 model, but not the UKMO model, also shows increased pressure to the south of the continent and decreased winter rainfall in south-west and southern Australia.

1. Introduction

This report sets out findings of an intercomparison study of the results for the Australian region of seven equilibrium general circulation modelling experiments run to assess the climatic impact of doubling atmospheric CO_2. This study is being undertaken to assist the Climate Impact Group in its objective of providing the best available estimates of climate change in the Australian region due to the enhanced greenhouse effect.

For the task of estimating regional climate change due to the enhanced greenhouse effect, the regional results of general circulation models (GCMs) are a most important source of information. However, at the regional scale simulated change in important climate elements varies greatly from model to model. For example, it is not unusual for the change in precipitation given by two models for a particular region to differ in sign. Clearly these large differences make the task of estimating regional climate change very difficult. This uncertainty is greater than it need be if the researcher interested in regional climate change accepts as equally valid the results of all available GCM experiments.

In this survey of the Australian region results of various GCM greenhouse experiments (for which output data is currently available to us), we first focus on comparing the results of model control runs with observed climate. The fields we use in this comparison are mean sea level (MSL) pressure, surface air temperature and precipitation: fields directly of relevance to climate impact studies. An assessment is made of the relative performance of the models in simulating Australian region climate. We then briefly examine the global performance of the two models judged acceptable in the Australian region. Finally, an examination follows of the doubled CO_2 results of the models, in which attention focuses on the results of those models which performed well in their control run.

This approach assumes that those models which simulate well the observed regional climate in their control runs are more reliable in their simulations of regional climate under doubled CO_2 conditions. This allows some of the poor performing models to be eliminated from consideration and the range of results for doubled CO_2, and hence some of the uncertainty, to be reduced. However, it is recognised that a model performing well in the region of interest may perform poorly in other regions or globally. Indeed, assessing the performance of various models by comparing their regional control simulations with observed regional climate is only one of a number of methods that could be used (for example, GCMs are often validated on a global basis, and we have in fact added a brief global examination here). The criterion used here for selecting models should be considered a necessary, but not a sufficient, condition for placing some reliance on model doubled CO_2 results. Furthermore, it should be noted that a good control performance (however it is assessed) of a particular model is no guarantee that its doubled CO_2 simulation is reliable.

It should be emphasised that the results discussed here apply to particular GCM model simulations, the results of which are currently available to us. The comparisons therefore may well not represent the relative performance of later and possibly improved versions of the same models. Our interest is in obtaining the best current indication of the likely changes in climate in the Australian region due to the enhanced greenhouse effect, not in rating different GCMs or modelling groups for any other purposes. In this connection, we should welcome the submission of further, and hopefully improved, control and doubled CO_2 climate simulations over Australia from the same or other modelling groups.

2. GCM climate simulation output and observed data for the Australian region

2.1 Description of GCMs

The simulated climate data used come from $1 \times CO_2$ and $2 \times CO_2$ equilibrium runs using the GCMs of the Goddard Institute of Space Studies (GISS) (Hansen *et al.* 1983, 1984), the Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Wetherald 1987), Oregon State University (OSU) (Schlesinger and Zhao 1989), the National Centre for Atmospheric Research (NCAR) (Oglesby and Saltzman 1990) and the United Kingdom Meteorological Office (UKMO) (Wilson and Mitchell 1987, Mitchell *et al.* 1989). These data were obtained through Mr R. Jenne at the National Center for Atmospheric Research, Boulder, Colorado and Dr P. Rayner at CSIRO Division of Atmospheric Research. We also examine data of an equivalent experiment recently performed by Dr H. Gordon and Mr B. Hunt using the CSIRO four-level model (CSIRO4) (see Gordon and Hunt 1991). For the GFDL model, two different experiments are examined, and so, in total, the results of seven GCM experiments are used in the study.

Further details of the various GCM experiments are given in Table 1. All experiments use some form of interactive cloud scheme and include the full annual cycle of radiation. The UKMO, CSIRO4 and GISS experiments also include the diurnal cycle. There is a considerable range in both the vertical and horizontal resolution of the models, with the UKMO model having the greatest number of vertical levels (eleven) and CSIRO4 having the finest horizontal grid (3.2×5.6°). There is some variation in the CO_2 concentrations used by the models (300–330ppm in their control runs), but this variation does not matter greatly because models are tuned to some extent to match present global climate. The $1 \times CO_2$ monthly mean fields to be analysed here are constructed using data for ten model years for each experiment except for the UKMO model, where fifteen years are used. The number of model years available for the $2 \times CO_2$ runs is the same as for the control runs, except for the NCAR experiment, where the $2 \times CO_2$ results were for six years.

In each experiment, the atmospheric model interacts with a simple mixed layer ocean, and sea surface temperature (SST) is calculated. The CSIRO4, UKMO, GISS, and GFDLQ experiments use a Q-flux correction which makes allowance for the absence of currents in the model ocean. The correction is made by calculating in a special model run the additional heat flux at the ocean surface necessary to simulate present-day seasonally varying SST patterns, and using this flux correction in both the control and doubled CO_2 runs of the model. Thus, in the control run, Q-flux models are constrained to simulate closely observed SST. This favours Q-flux models in a model intercomparison study (such as the present one) in which simulation of regional SST is assessed.

Figure 1 indicates the surface topography used in each of the models studied. The CSIRO4, NCAR and GFDL models are spectral models and, accordingly, the topography for these models is represented in spectral form (note the depressions in the oceans). Other differences between models relate to differences in the horizontal resolution and location of the grid point network used and in the method used to construct the topography. All models use a very coarse representation of Australian topography in which, in particular, the climatically very important eastern highlands are poorly represented. In the CSIRO4 model this range is not resolved from the western plateau, and only in the UKMO model is there any indication of the north–south alignment of the range. These large distortions of Australian topography will have to be allowed for when considering the spatial patterns of the model output fields, particularly those of precipitation. Poorly resolved topography is a major limitation on the veracity of the model output at a regional and local scale.

2.2 Fields chosen for study

The three fields chosen for study were MSL pressure, surface air temperature and precipitation. Although other fields (e.g. those representing atmospheric conditions in the middle or upper troposphere) could be used in assessing the control performance of the models, we limited attention to fields of particular interest to us in climate impact studies. For example, surface air temperature and precipitation changes are of great relevance in estimating the climate change impact on agricultural crops, natural ecosystems, and water

Table 1: Specifications of the GCM experiments used in the intercomparison. The references given for the CSIRO4 and GFDLQ models are general references only, and do not refer to the experiments with these models examined here. Note that only six years of data were available for the 2×CO_2 run of the NCAR model.

	UKMO	CSIRO4	OSU	GFDLQ	GFDL	GISS	NCAR
resolution lat. x long. (degrees)	5.0x7.5	3.2x5.6	4.0x5.0	4.4x7.5	4.4x7.5	7.8x10.0	4.4x7.5
model levels	11	4	2	9	9	9	12
diurnal cycle	yes	yes	no	no	no	yes	no
seasonal cycle	yes	yes	yes	yes	yes	yes	yes
inter-active cloud	yes	yes	yes	yes	yes	yes	yes
oceanic Q-flux	yes	yes	no	yes	no	yes	no
no. of model yrs used in means	15	10	10	10	10	10	10
1xCO_2 conc. used (ppm)	323	326	326	300	300	315	330
main reference	Wilson& Mitchell (1987)	Gordon & Hunt (1990)	Schles-inger & Zhao (1989)	Manabe & Weth-erald (1987)	Manabe & Weth-erald (1987)	Hansen *et al.* (1984)	Oglesby & Sal-tzman (1990)

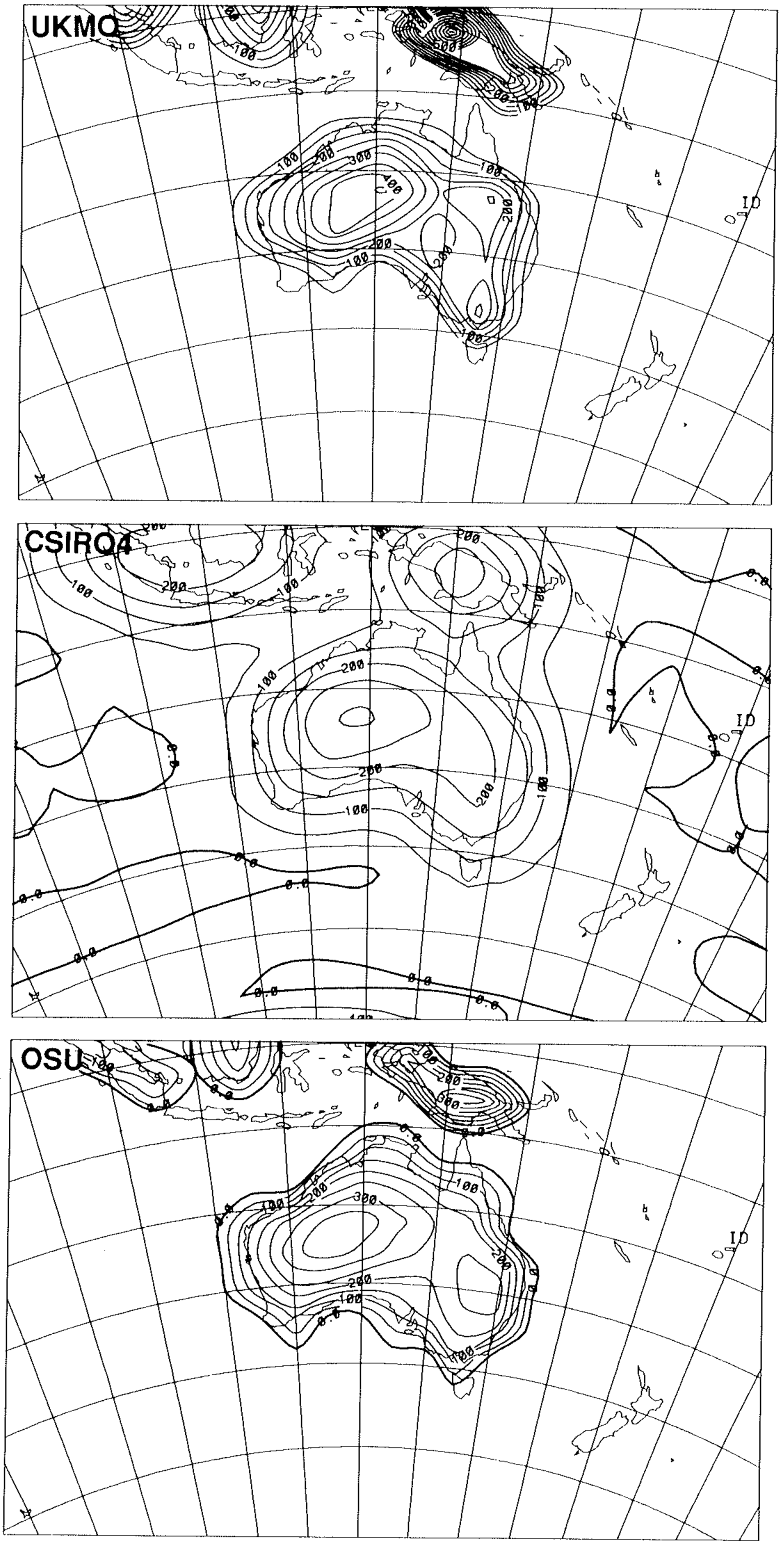


Figure 1: Surface elevation used by each model (metres).

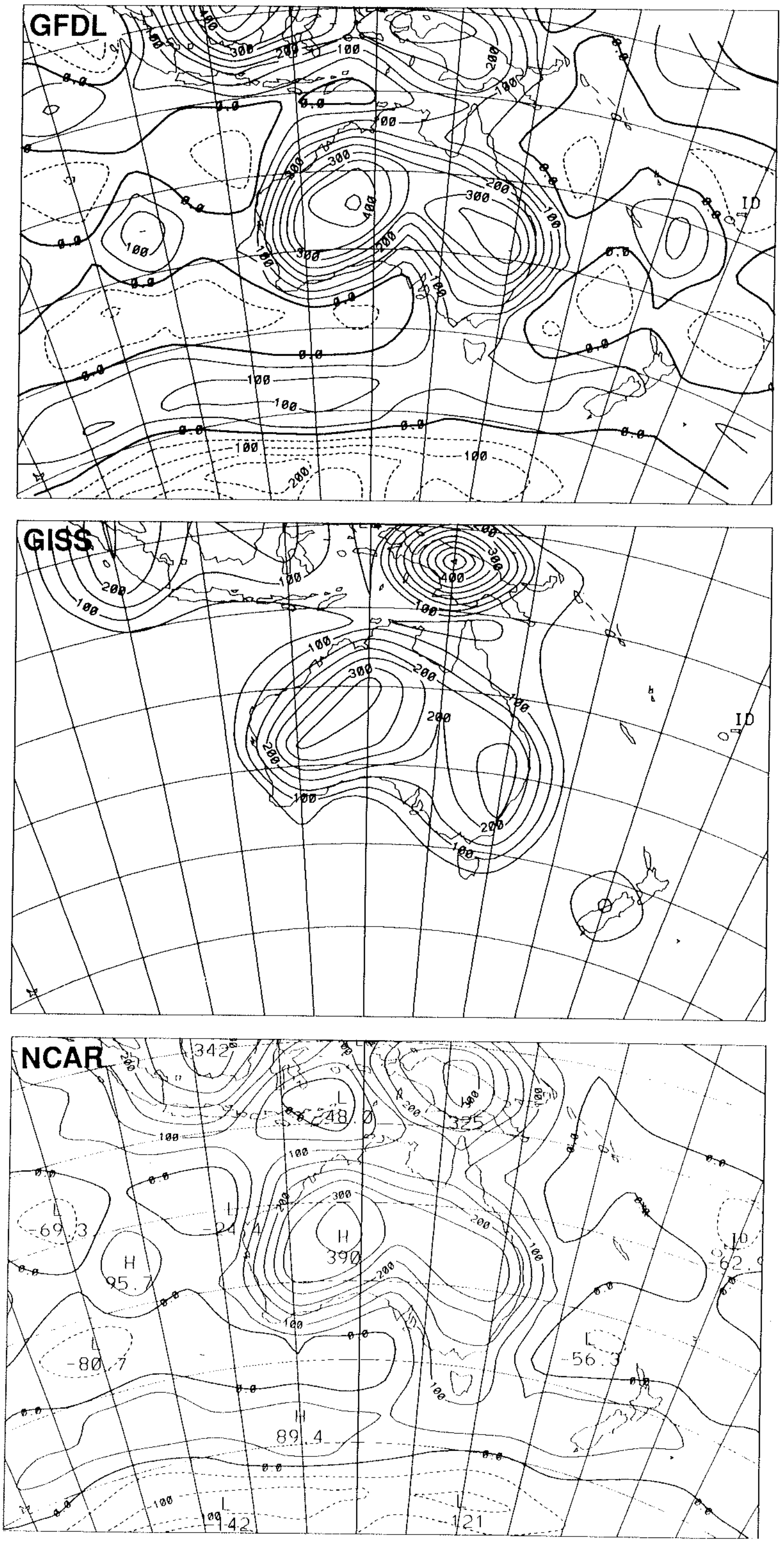


Figure 1 continued

resources. MSL pressure indicates atmospheric circulation at the surface and hence the location of important circulation features (such as the westerlies). Good simulation of MSL pressure patterns in a model is needed if the varying climatic regimes of Australia are to be well simulated. Using these three fields also gives a wide coverage of the important model components. They depend upon the dynamical formulation of the model, and physical processes represented in the model such as the radiation, convection, precipitation, surface and boundary layer schemes.

All the models studied provided comparable precipitation and MSL pressure data which, in conjunction with relevant observed data, could be readily used to assess the performance of the models. However, models generally do not give fields representing near surface air temperature which can be considered comparable. This problem is discussed further in the section 3.3 below, where the temperature data are analysed.

2.3 Observed data

To represent observed Australian region monthly mean MSL pressure the ten-year southern hemisphere climatology of Karoly *et al.* (1987) is used. This is based on the daily numerical analyses of the Australian Bureau of Meteorology for the period September 1972 to August 1982. These data were available on a 5°×5° latitude–longitude grid from 10°S to the south pole. A southern hemisphere MSL pressure data set of Jones (1990) which spanned the years 1951–1985 was examined to check the representativeness of the period 1972–82. This data set was based on data from fewer Australian region stations than that of Karoly *et al.* (1987). The Australian region MSL pressure maps for January and July from the Jones data set for the period 1972–82 differed very little (generally by less than 1 hPa) from those of the full period 1951–85.

To represent mean surface air temperature over the Australian continent we obtained long-term mean maximum and minimum screen temperature data for all available Australian stations from the National Climate Centre (NCC) at the Bureau of Meteorology. Stations with means based on less than ten years of record were not used. To represent observed mean temperature, maximum and minimum temperatures were averaged. To represent sea surface temperature in the Australian region, the historical SST data set of the UK Met. Office (MOHSST), based on the years 1854–1985, was used (Parker 1987).

To represent Australian rainfall, district monthly mean rainfall data obtained from NCC were used. These means were based on data for the period 1913–1988. An estimate was made of the area of each of the meteorological districts so that reliable rainfall averages over broader regions could be calculated.

3. Comparison of model control climate with observed data

3.1 Introduction

In this section we will examine the $1\times CO_2$ Australian region results of the models for the fields selected for study. Comparisons will be made with relevant observed data and the performance of the model assessed. As discussed above, the main purpose of this analysis is to select those models that, in the simulation data available to us, perform best in simulating

Australian region climate (if the range of performance of the models allows such a selection), so that we may then focus on the 2×CO_2 results of those models which are more likely to provide a reliable guide to climate change in the region.

When one is comparing model performance across a number of fields the problem arises of how to weigh up the relative performance of models in different areas. For example, is a good simulation of MSL pressure more important than one of precipitation? The approach used here is to identify, as each field is examined, any models which clearly fail to represent adequately that field in the Australian region. Any model so identified for any of the three fields is then excluded from consideration in section 4, where the 2×CO_2 model results are examined. As this assessment process will unavoidably involve a degree of subjectivity, the reasons behind any decision to exclude the results for a particular model will always be fully explained.

In assessing the Australian region performance of the models, simulation errors for both January and July (or, in some cases, summer and winter) are examined. In addition, some measure of the accuracy of the simulation of the annual cycle in the variable concerned (e.g. the difference between January and July) is assessed. Indeed, much emphasis is placed on obtaining realistic seasonality in fields examined, as this indicates an ability of the model to respond realistically to changes in radiative forcing associated with the annual cycle, and therefore, presumably, an ability to respond realistically to the smaller changes in radiation associated with the greenhouse effect.

3.2 MSL pressure

(a) MSL pressure maps

Figure 2 shows Australian region MSL pressure for January constructed from 10 years of observed data, and model-simulated January MSL pressure for each of the UKMO, CSIRO4, OSU, GFDLQ, GFDL, GISS and NCAR models.

The UKMO model gives a reasonable simulation of the main features of the circulation in middle to lower latitudes, such as the location of the heat low over north-western Australia and the anticyclones in the Pacific and Indian Oceans (although the anticyclones are a little weak). However, this model fails to simulate the broad region of westerly flow in the mid to high latitudes. The CSIRO4 simulation is quite good throughout the region, although the midlatitude westerlies are appreciably weaker than observed (as indicated by the pressure gradient south of the continent). The OSU simulation misplaces the heat low over the continent and has westerlies extending over much of south-eastern Australia, which is unrealistic. The GFDL and GFDLQ simulations, which are very similar, underestimate the strength and extent of the midlatitude westerlies (which all models do to a lesser or greater extent) and misplace the continental monsoonal low. The GISS and NCAR simulations are the least realistic of all the model simulations. In the GISS simulation the anticyclones in the Pacific and Indian oceans are shown much too far south and an unrealistic third centre is shown to the south of the continent, and the easterly winds over the continent are shown too far south. Also, the synoptic features in the GISS simulation show a spatial scale which is unrealistically small. In the NCAR simulation the heat low over the continent is shown as part of a high amplitude trough in the midlatitude westerly flow, with westerly winds affecting much of the continent. The circulation feature which is most prominent over the

Australian continent in summer, the easterly trade winds, are absent from the eastern half of Australia in the NCAR simulation.

Figure 3 gives maps for each model of the difference between model-simulated January MSL pressure and the observed. For this to be calculated, both model and observed data were interpolated on to a 5.0°× 7.5° latitude–longitude grid. The tendency, discussed above, for models to underestimate the strength of the midlatitude westerlies is reflected by all models showing substantial positive errors in higher latitudes; these errors are greatest in the UKMO and GISS simulations. In lower latitudes errors are clearly least in the CSIRO4 simulation. All other models show substantial errors in low to mid latitudes, although these errors are small over the continent in the UKMO simulation.

Figures 4 and 5 are the same as Figures 2 and 3 but represent July MSL pressure. As may be seen in Figure 4, the prominent features of the observed mean July MSL pressure pattern are an anticyclone centred over the continent, broad westerly flow in midlatitudes, extending further north than in January, and a distinct trough in the westerly flow in Western Australian longitudes. The UKMO simulation is reasonable, but the simulated westerlies over south-eastern Australia are too strong. CSIRO4 shows the westerlies as too far south in Western Australian longitudes but is otherwise reasonable. The OSU simulation has a generally correct pattern but seriously underestimates the amplitude of the observed pattern (it gives a weak subtropical high pressure belt and weak westerlies). The GFDL and GFDLQ simulations depict reasonably well the pattern of July MSL pressure, but generally show pressure as too high throughout the grid. The NCAR simulation similarly lacks amplitude but does better than the other models in depicting the observed trough in the westerly flow in western Australian longitudes and the split in the westerlies in the Tasman Sea. The GISS simulation appears the least realistic. It gives the anticyclone as centred south of Australia, rather than over the continent, and a blocking configuration is present in the Tasman Sea, producing south-easterly flow over south-eastern Australia rather than the observed westerly winds. Indeed, westerly winds are almost entirely absent from the Australian region in the GISS simulation.

The simulation error maps for July (Figure 5) show positive errors in high latitudes for all models, indicating the general tendency for the models to underestimate the strength of the westerlies in that region. These errors are generally largest in the GISS simulation. The CSIRO4 model has the smallest errors (around 2hPa) in lower latitudes and over the Australian continent. They are a little larger (around 4 hPa) in these regions in the UKMO, GISS, NCAR, GFDL and GFDLQ simulations. The OSU simulation shows pressure around 8 hPa too low over the Australian continent.

Figure 6 shows the difference in pressure in the Australian region between January and July in the observed data and for each of the model simulations. The most notable feature of the observed map is the region of maximum change in pressure centred over the continent. This is generally simulated well by the models, except for OSU where the annual range of pressure over the continent is considerably underestimated.

(b) Comparative Statistics

To examine in a more quantitative way the relative performance of the models in simulating regional MSL pressure, two statistical quantities were calculated for the comparisons depicted in Figures 2–5. Firstly, for each comparison of model and observed MSL pressure, an RMS error was calculated using values of the simulation error at all grid points on the common interpolated grid. This was calculated using the full Australian region and then again

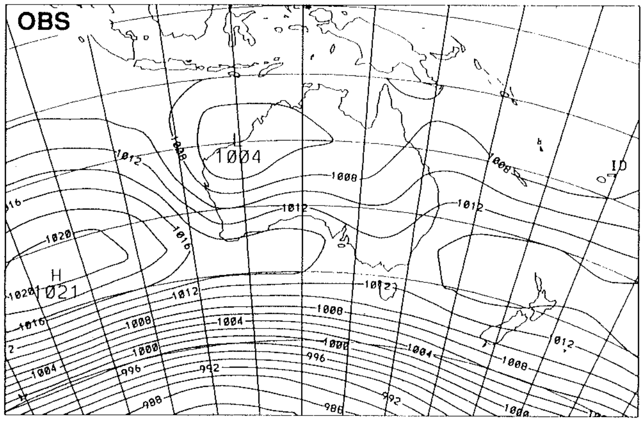


Figure 2(a): Observed January MSL pressure (hPa)

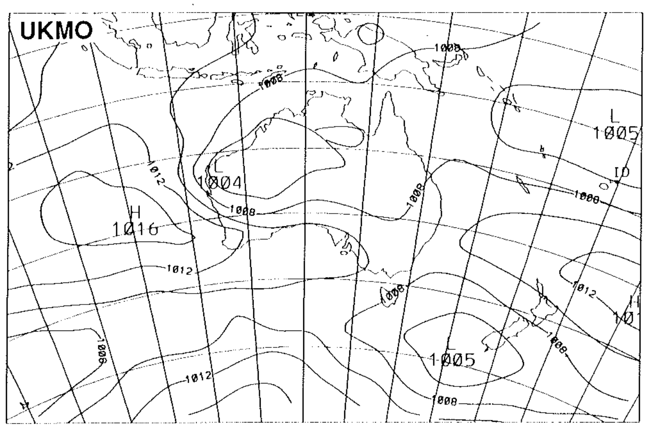


Figure 2(b): UKMO 1× CO_2 simulation of January MSL pressure (hPa)

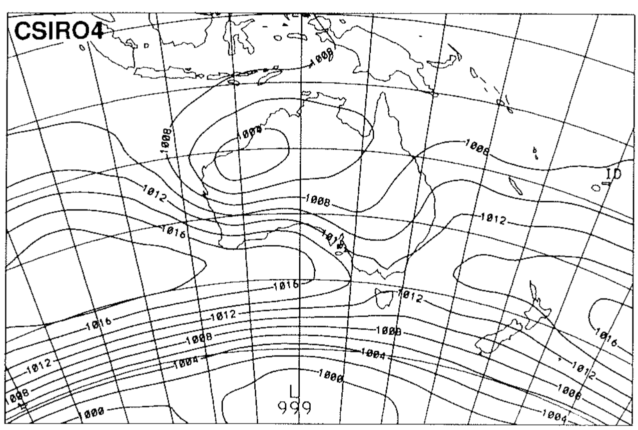


Figure 2(c): CSIRO4 1× CO_2 simulation of January MSL pressure (hPa)

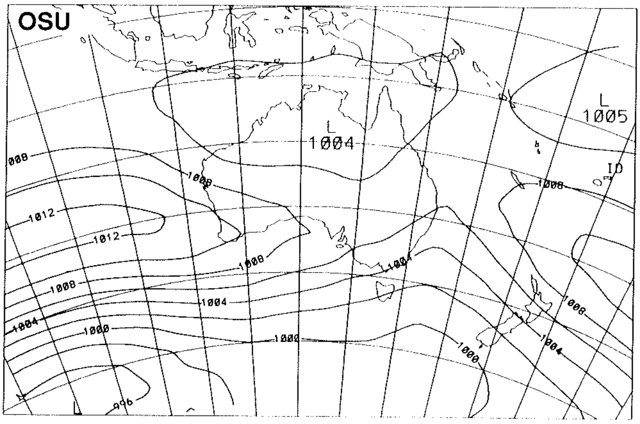


Figure 2(d): OSU 1× CO_2 simulation of January MSL pressure (hPa)

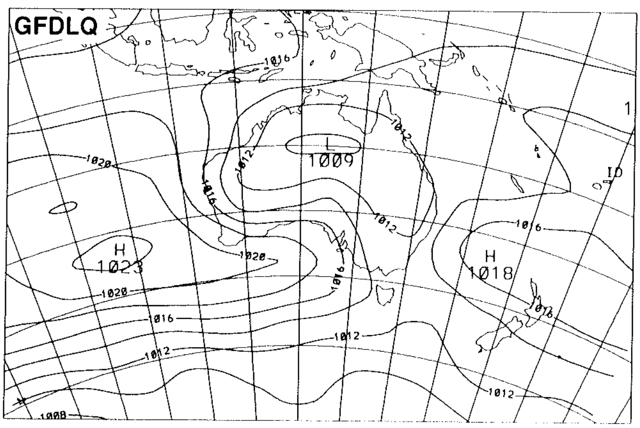


Figure 2(e): GFDLQ 1× CO_2 simulation of January MSL pressure (hPa)

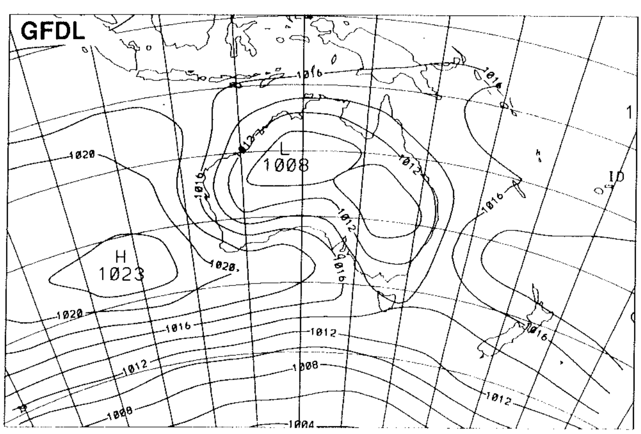


Figure 2(f): GFDL 1× CO_2 simulation of January MSL pressure (hPa)

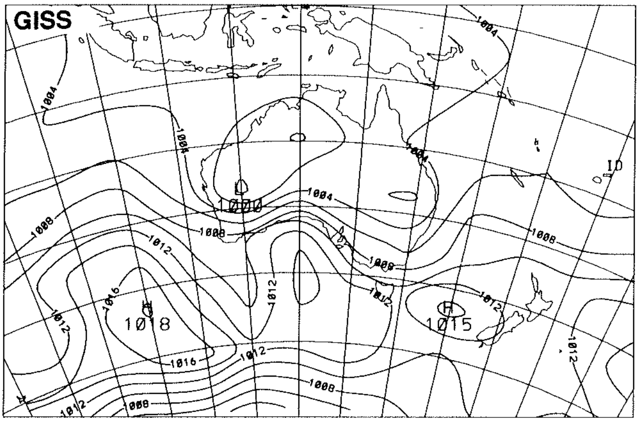


Figure 2(g): GISS 1× CO_2 simulation of January MSL pressure (hPa)

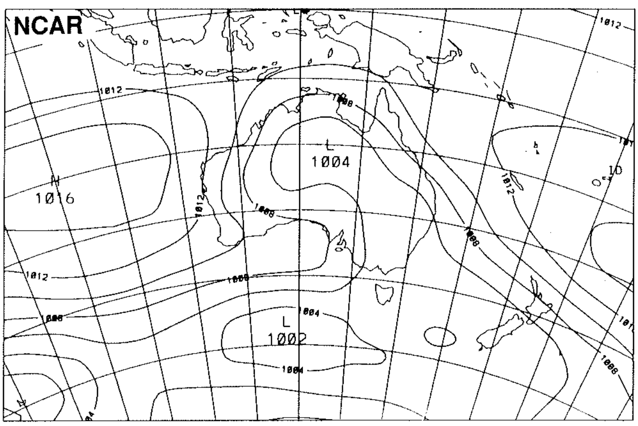


Figure 2(h): NCAR 1× CO_2 simulation of January MSL pressure (hPa)

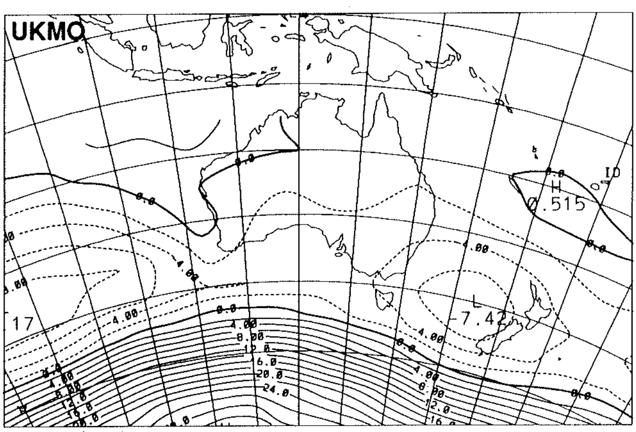


Figure 3(a): January MSL pressure: UKMO 1× CO_2 simulation minus observed (hPa)

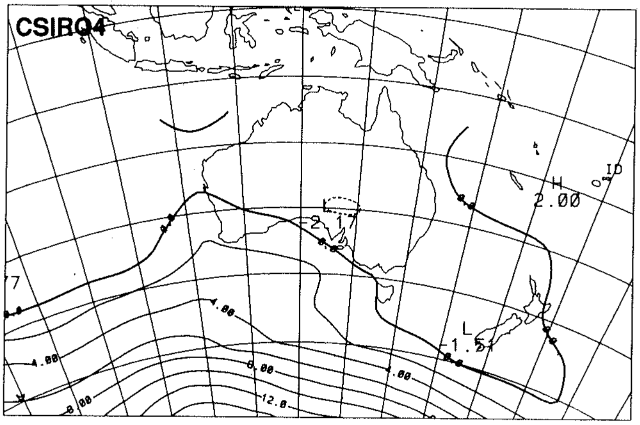


Figure 3(b): January MSL pressure: CSIRO4 1× CO_2 simulation minus observed (hPa)

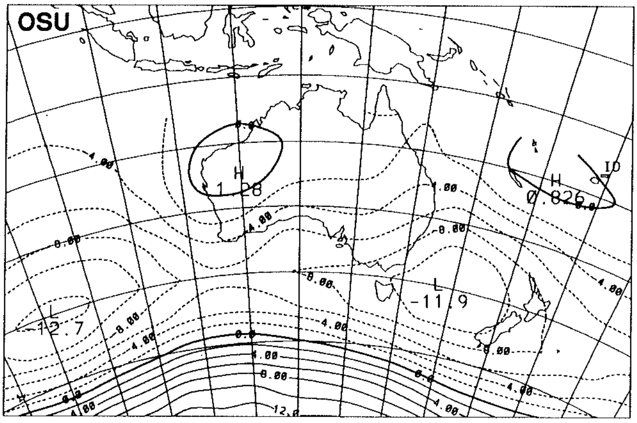


Figure 3(c): January MSL pressure: OSU 1× CO_2 simulation minus observed (hPa)

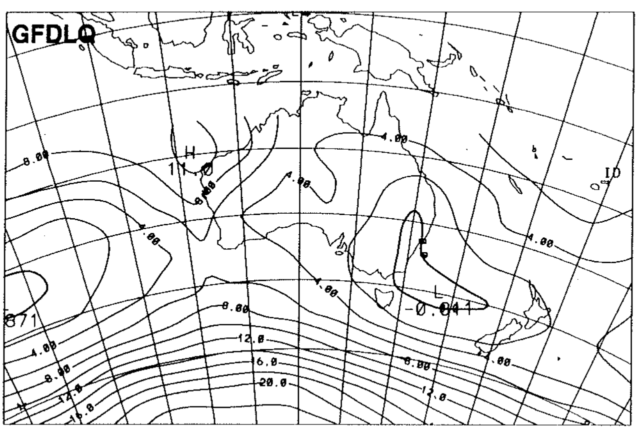


Figure 3(d): January MSL pressure: GFDLQ 1× CO_2 simulation minus observed (hPa)

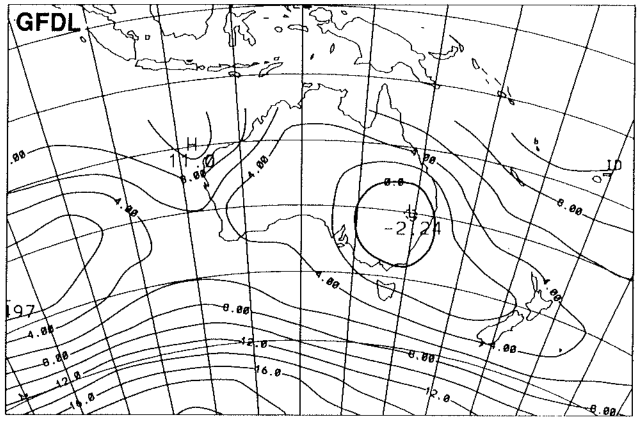


Figure 3(e): January MSL pressure: GFDL 1× CO_2 simulation minus observed (hPa)

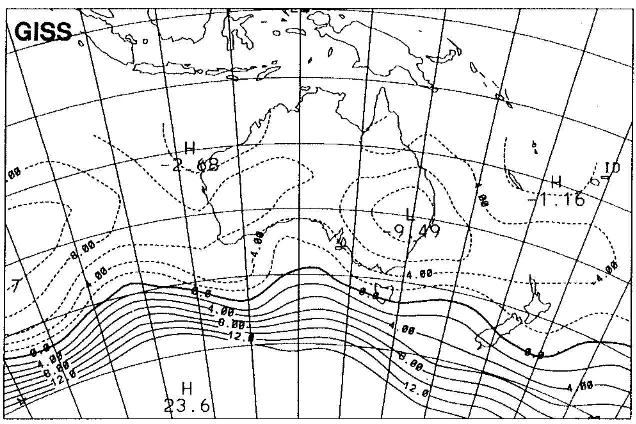


Figure 3(f): January MSL pressure: GISS 1× CO_2 simulation minus observed (hPa)

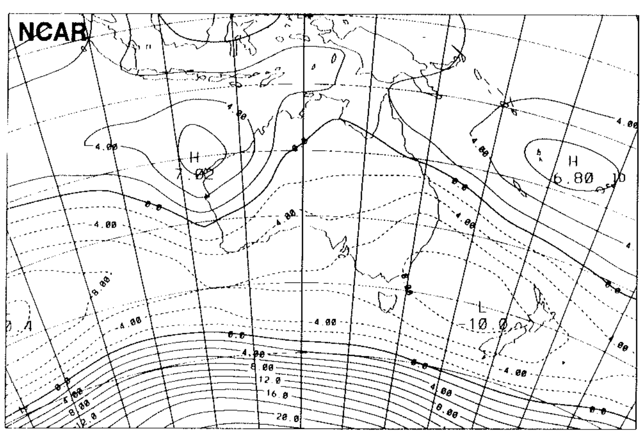


Figure 3(g): January MSL pressure: NCAR 1× CO_2 simulation minus observed (hPa)

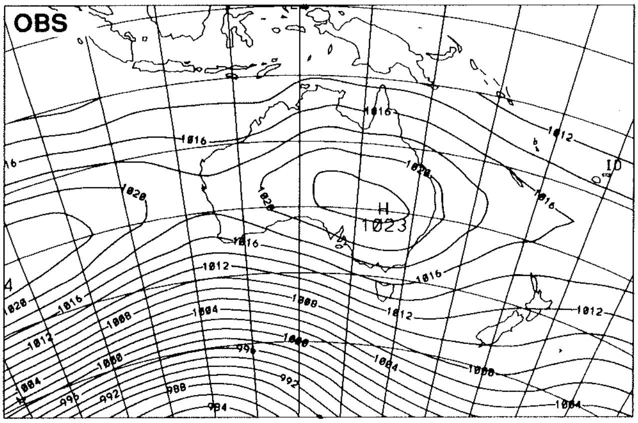


Figure 4(a): Observed July MSL pressure (hPa)

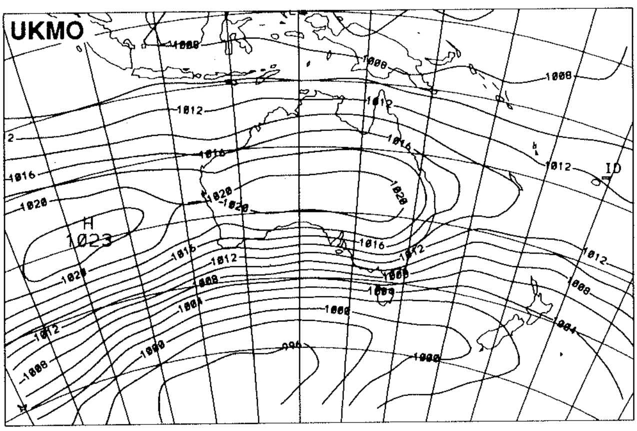


Figure 4(b): UKMO 1× CO_2 simulation of July MSL pressure (hPa)

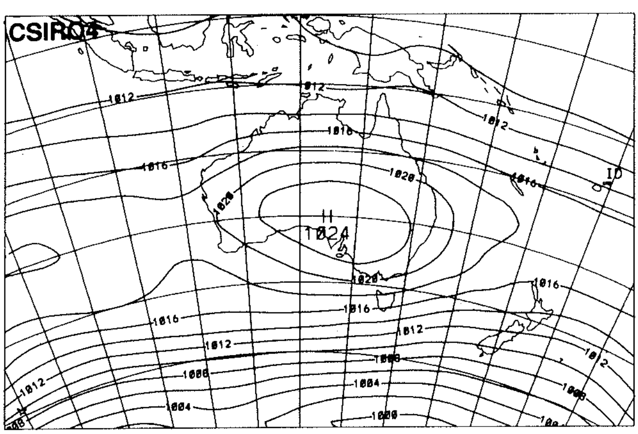


Figure 4(c): CSIRO4 1× CO_2 simulation of July MSL pressure (hPa)

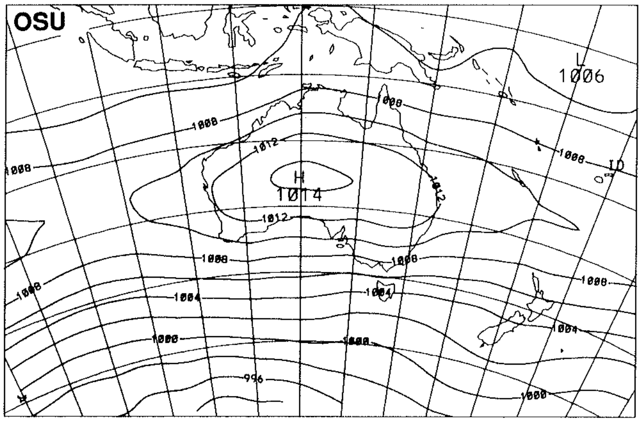


Figure 4(d): OSU 1× CO_2 simulation of July MSL pressure (hPa)

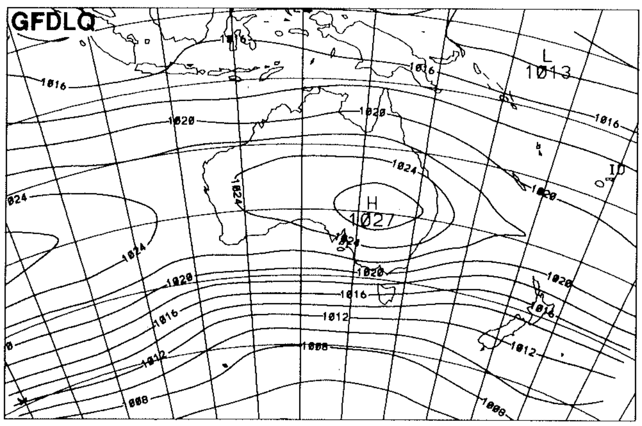


Figure 4(e): GFDLQ 1× CO_2 simulation of July MSL pressure (hPa)

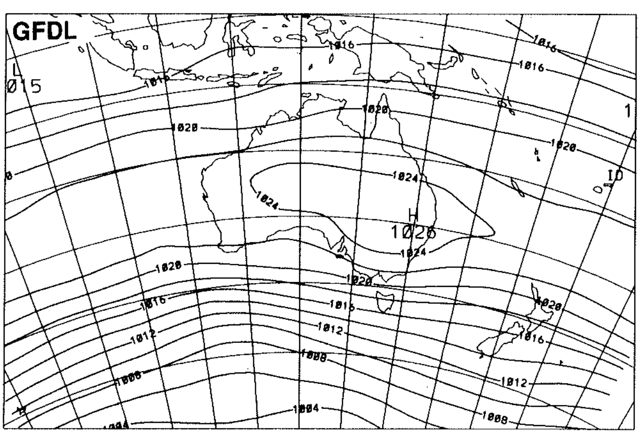


Figure 4(f): GFDL 1× CO_2 simulation of July MSL pressure (hPa)

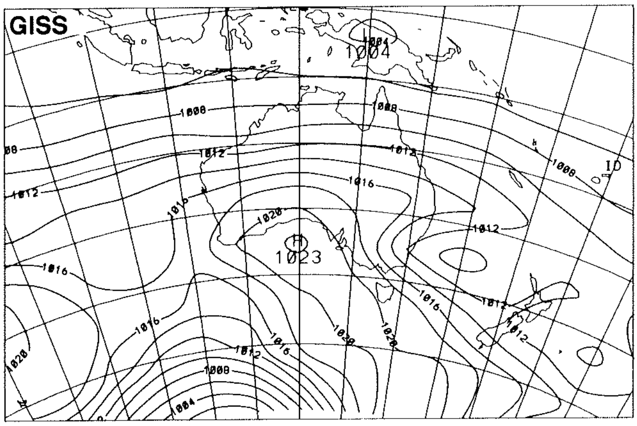


Figure 4(g): GISS 1× CO_2 simulation of July MSL pressure (hPa)

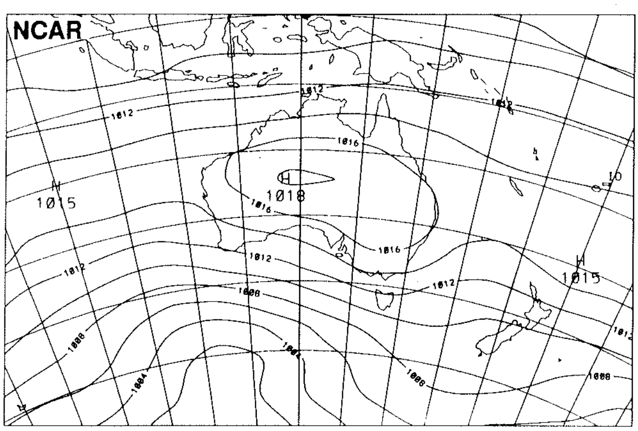


Figure 4(h): NCAR 1× CO_2 simulation of July MSL pressure (hPa)

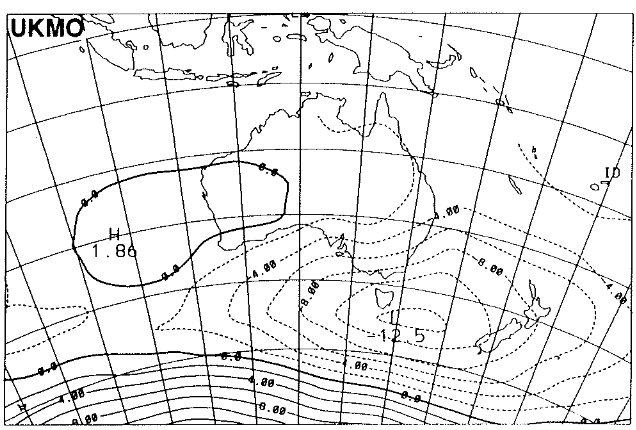


Figure 5(a): July MSL pressure: UKMO 1× CO_2 simulation minus observed (hPa)

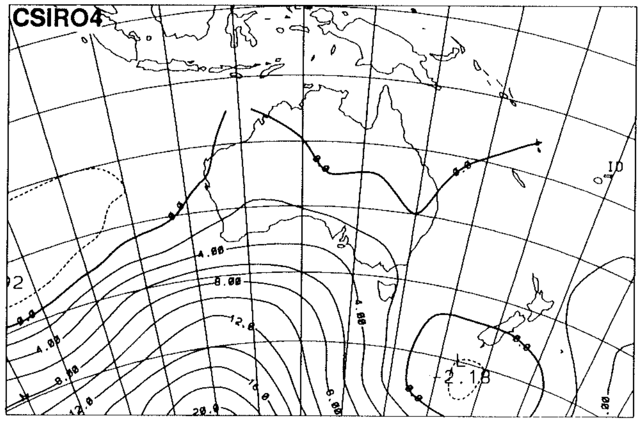


Figure 5(b): July MSL pressure: CSIRO4 1× CO_2 simulation minus observed (hPa)

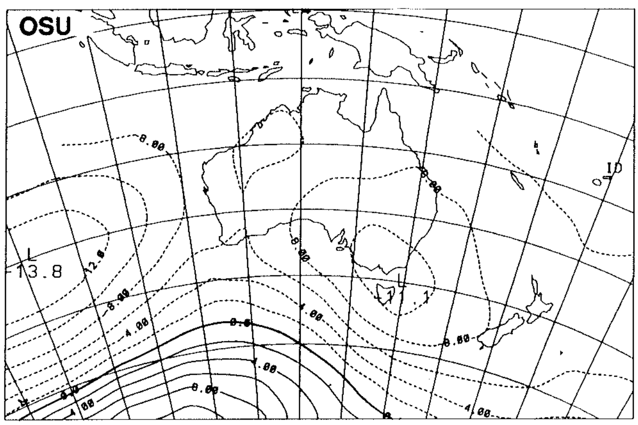


Figure 5(c): July MSL pressure: OSU 1× CO_2 simulation minus observed (hPa)

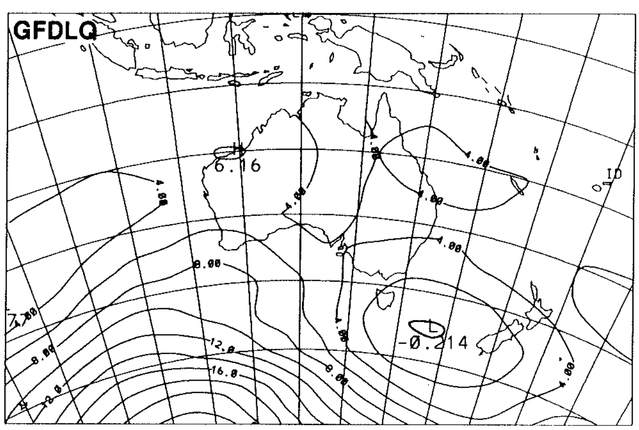


Figure 5(d): July MSL pressure: GFDLQ 1× CO_2 simulation minus observed (hPa)

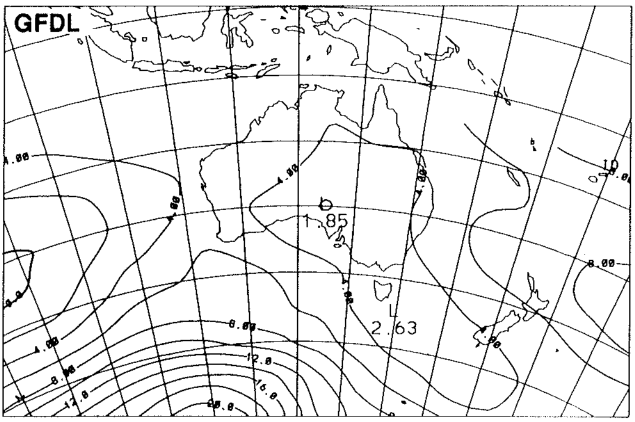


Figure 5(e): July MSL pressure: GFDL 1× CO_2 simulation minus observed (hPa)

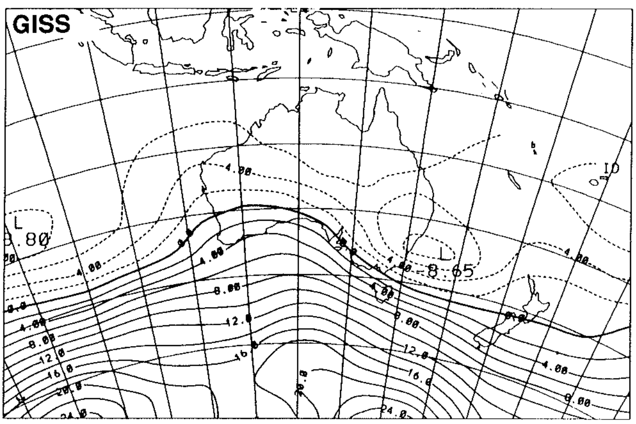


Figure 5(f): July MSL pressure: GISS 1× CO_2 simulation minus observed (hPa)

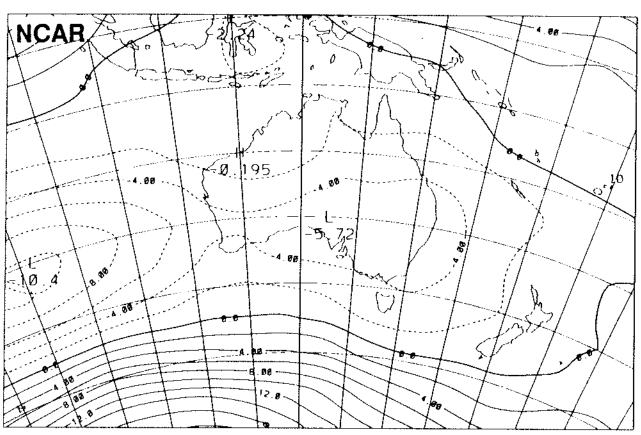


Figure 5(g): July MSL pressure: NCAR 1× CO_2 simulation minus observed (hPa)

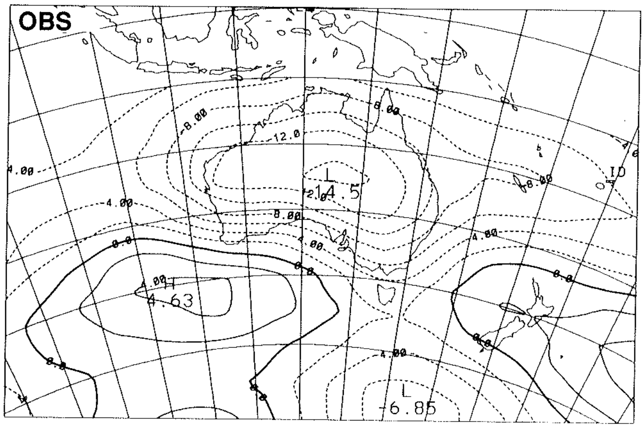


Figure 6(a): Observed MSL pressure: January minus July (hPa)

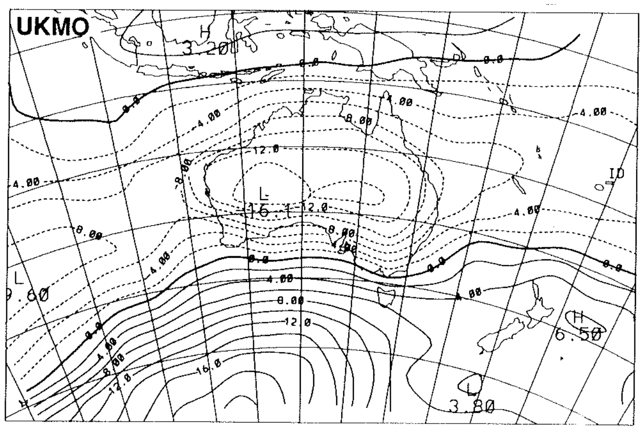


Figure 6(b): UKMO 1× CO_2 simulation of MSL pressure: January minus July (hPa)

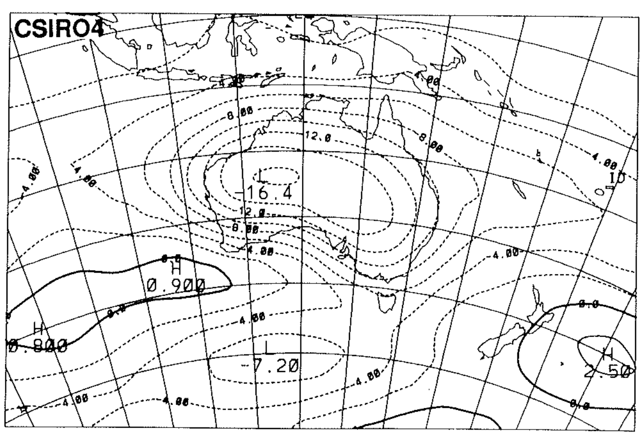


Figure 6(c): CSIRO4 1× CO_2 simulation of MSL pressure: January minus July (hPa)

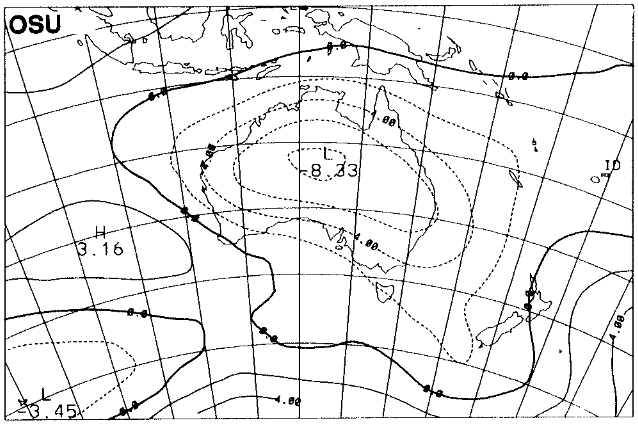


Figure 6(d): OSU 1× CO_2 simulation of MSL pressure: January minus July (hPa)

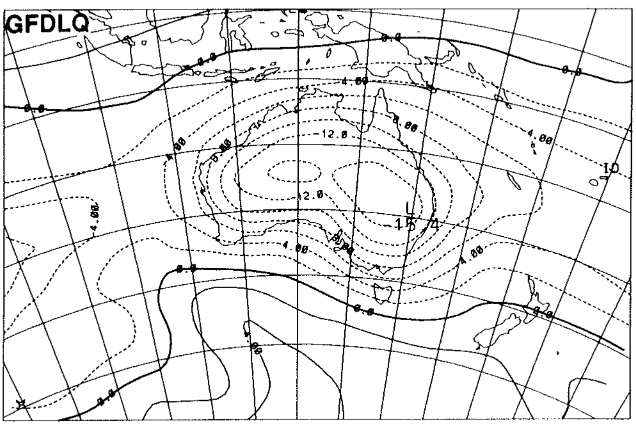


Figure 6(e): GFDLQ 1× CO_2 simulation of MSL pressure: January minus July (hPa)

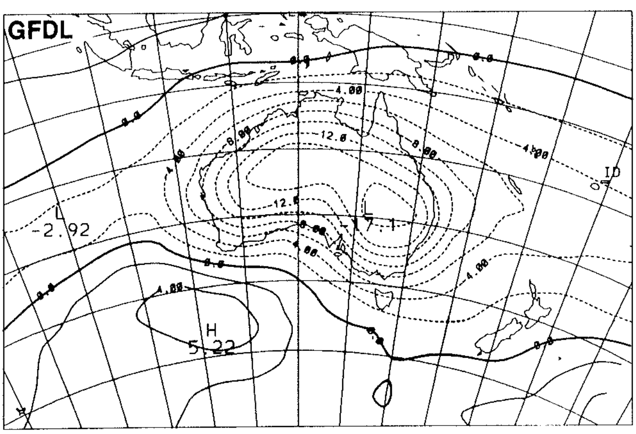


Figure 6(f): GFDL 1× CO_2 simulation of MSL pressure: January minus July (hPa)

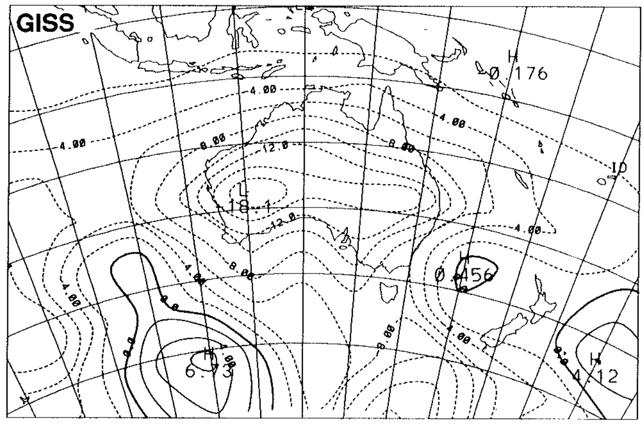


Figure 6(g): GISS 1× CO_2 simulation of MSL pressure: January minus July (hPa)

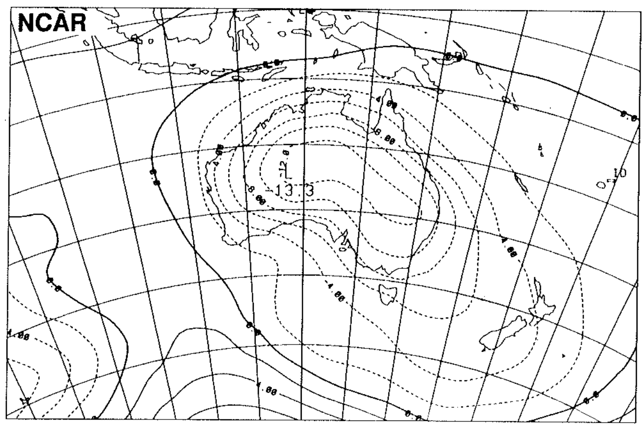


Figure 6(h): NCAR 1× CO_2 simulation of MSL pressure: January minus July (hPa)

using a sub-region covering the Australian continent and the immediate neighbouring ocean. (Figure 7 indicates the regions used). Secondly, using the same two regions, the spatial correlation between the observed and simulated patterns was calculated. The RMS error gives an overall measure of the error in simulating the absolute value of MSL pressure throughout the region. The pattern correlation coefficient gives a measure of the similarity of the pattern structure of the observed and simulated MSL pressure patterns. For a further discussion of the use of the pattern correlation statistic in model validation work see Wigley and Santer (1990). Both quantities are needed because two models may show a similar RMS error but differ greatly in their ability to represent the pattern structure of the observed field.

The RMS error and pattern correlation coefficient (r) values resulting from comparing model-simulated and observed January and July MSL pressure using the full Australian region are given in Table 2. In this table the poor performance of the GISS model is apparent with it showing both high RMS errors and near zero pattern correlation in both January and July. For the other models, although RMS errors are large, quite strong pattern correlations are obtained,

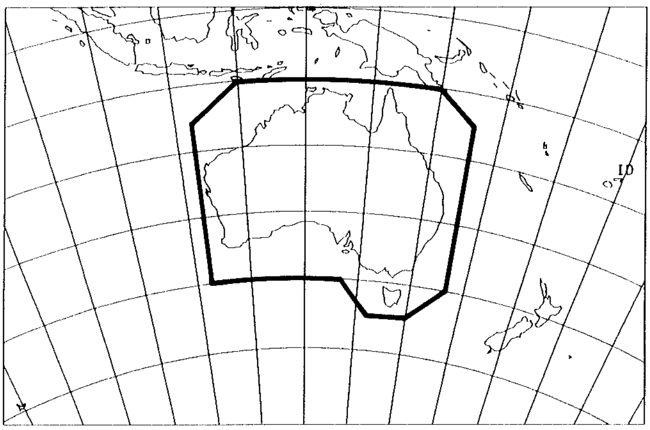


Figure 7: Boundaries of the two regions used for calculating the RMS error and pattern correlation results (see Tables 2 and 3). The outer frame encloses the full Australian region; the inner frame encloses the Australian continental sub-region.

with the exception of the UKMO and NCAR models in January. The CSIRO4 model clearly performs much better than the other models in simulating January MSL pressure.

As we noted in discussion earlier many models show large simulation errors at high latitudes, and these will clearly be affecting the results given in Table 2. The RMS errors and pattern correlation co-efficients calculated using the Australian continent sub-region (Table 3) will exclude these errors in higher latitudes and focus on the quality of the simulation in the region of greatest interest. Over the sub-region, the CSIRO4 model clearly performs best; in both January and July its RMS errors are lowest of all models and its pattern correlation co-efficients are quite strong. Amongst the other models, three stand out as performing poorly. The pattern correlation for the NCAR model in January is negative ($r = -0.19$), reflecting the failure of this model to give the observed summer easterly winds over the continent. The pattern correlation for the GISS model in July is weak ($r = 0.22$), reflecting, as we noted earlier, its simulation of south-easterly flow over south-eastern Australia where the observed flow is westerly. The pattern correlation for the OSU model in January is also weak ($r = 0.18$) which would mainly reflect its simulation of south-westerly winds over eastern Australia instead of the observed easterlies. Notably, the pattern correlation coefficient of the UKMO model in January is greatly improved over that obtained using the full region.

(c) Acceptability of the MSL pressure simulations

From the maps presented in Figures 2–5 and the summary statistics in Tables 2 and 3, it is clear that the GISS model does not produce an acceptable simulation of MSL pressure in the Australian region. In particular, this model completely fails to simulate the climatically significant westerly flow over southern Australia in July. The OSU and NCAR simulations of Australian region MSL pressure must also be considered unacceptable. The MSL pressure pattern for both of these models indicated westerlies influencing much of eastern Australia, instead of the observed easterly flow. Also, the OSU model significantly underestimated the change in pressure over the continent from January to July, whereas the other models simulated this reasonably well. The simulations of the other models are acceptable, although

Table 2: RMS error (in hPa) and pattern correlation (r) for GCM MSL pressure simulations using the full Australian region (see Figure 7).

Model	January		July	
	RMS error	r	RMS error	r
UKMO	7.7	0.02	4.5	0.88
CSIRO4	3.5	0.92	5.3	0.85
OSU	5.8	0.78	7.0	0.93
GFDLQ	8.3	0.79	7.2	0.90
GFDL	8.2	0.85	6.8	0.95
GISS	8.3	0.07	9.1	0.18
NCAR	6.6	0.43	4.9	0.91

Table 3: As Table 2 but for the Australian continent sub-region (see Figure 7).

Model	January		July	
	RMS error	r	RMS error	r
UKMO	2.7	0.76	5.1	0.83
CSIRO4	1.3	0.96	2.4	0.80
OSU	5.3	0.18	7.7	0.88
GFDLQ	5.1	0.59	4.6	0.88
GFDL	5.3	0.51	4.5	0.95
GISS	5.0	0.78	6.0	0.22
NCAR	4.8	-0.19	3.3	0.91

reservations must be expressed over the performance of the UKMO model due to its failure to simulate the westerlies south of the continent in summer (an error that did not affect its good simulation of MSL pressure over the continent itself). The simulation that was clearly the best was that of the CSIRO4 model.

3.3 Temperature

(a) Surface air temperature over land

For comparison with screen height observed temperature, the surface air temperature field of the OSU and GISS models was used. A surface air temperature field was not available for the UKMO, CSIRO4 and NCAR models, and the surface temperature (the temperature of the Earth's surface) was used instead. We received advice from the modelling groups concerned that, of the various temperature fields available for these models, model surface temperature would best represent surface air temperature. Surface air temperature was also not available for the GFDL and GFDLQ runs, but, in their case, temperature at 0.99 sigma level (around 80m above the surface), rather than surface temperature, was used in the comparison. We were advised that the formulation of the GFDL model was such that model surface temperature would poorly represent surface air temperature over land. (R. Wetherald, personal communication 1990).

The differences between models in the types of temperature fields calculated for the surface and near surface clearly greatly complicate comparisons between model and observed data. They would be most important if daily maximum and minimum temperature data from the models were to be analysed, because, under certain conditions, and for certain times of the day, differences between the temperatures at the surface, screen height and 80m above the surface can be quite large. Clearly, in such analysis, careful consideration would have to be given to which temperature data from models should be used, and what they actually represent. However, in this analysis, the temperature data used have been averaged over all weather conditions and times of day and would be expected to differ much less. As outlined above, no attempt has been made to correct temperature data to make it more comparable with screen height temperature; rather, the field deemed most relevant of those available for each model has been used in the comparison. Given the potential for differences between model and observed data to arise for the reasons given above and not due to inability of the model to simulate reality, only gross differences which cannot be otherwise explained will be considered to indicate an unacceptable climate simulation.

Figure 8 gives mean January and July "surface air temperature" for each of the models determined by averaging all land-based model grid points over the Australian continent (for the location of these grid points see Figure 13). The observed values were created by

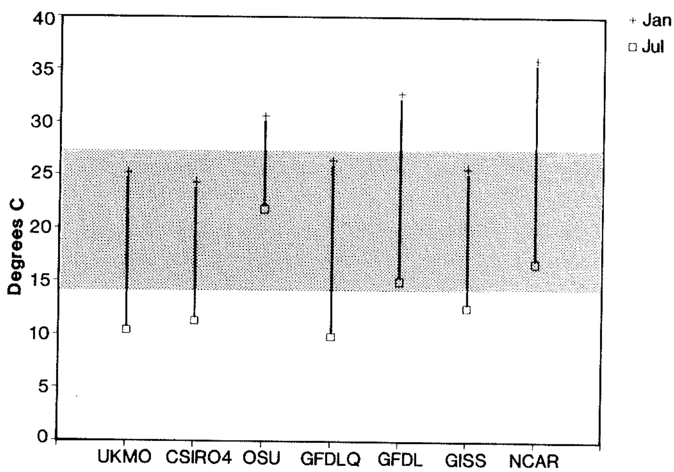


Figure 8: Observed surface air temperature and comparable model temperatures (see text) averaged over the Australian continent for both January and July (°C). The observed temperatures for January and July are represented by the upper and lower boundaries of the shaded area.

averaging mean station temperatures into 5°×5° latitude–longitude squares, and then averaging again over all of the squares with centre points falling over the Australian landmass. The area covered in this average is comparable to that covered by the model grid points. Corresponding Australian region temperature maps were also constructed. Figures 9, 10 and 11 give maps of January, July, and January minus July mean temperature over Australia (and over the surrounding ocean) as observed and for each of the models. The observed maps result from contouring the Australian station surface air temperature and grid point sea surface temperature data sets described earlier.

The results presented in Figures 8–11 show considerable variation in the temperature simulations of the models. It is particularly noticeable that the OSU model, unlike the other models, much underestimates the amplitude of the annual cycle of temperature in the Australian region (see Figures 8 and 11). In this simulation temperature in July over the continent is much too high (indeed the simulated July temperature is closer to the observed January temperature than it is to that of July). Also, the OSU simulation is the only one which fails to give a land–sea temperature difference of correct sign; in July the OSU simulation still shows northern Australia as a little warmer than the surrounding ocean. Amongst the other models, the NCAR and GFDL results show the greatest errors, with substantially higher than observed temperatures in January and a larger than observed annual cycle. Considering that 0.99 sigma level, and not surface, temperature is taken from the GFDL simulation, the GFDL errors for surface temperature would be even greater than apparent here. Generally, temperature is well simulated by the GISS model, although in the January map it gives an urealistic temperature maximum over the sea north-east of the continent. Although overall their simulated temperatures are a little too cool, the UKMO and CSIRO4 models perform notably well in their simulation of the observed temperature maximum inland of the north-west coast in January. Perhaps this reflects the higher resolution of these models and their fairly good simulation of atmospheric circulation over the Australian continent in January (see section 3.2). Comparing Figure 9 with Figure 2, it may be noted that the location of continental heat low, as simulated by each of the models, generally corresponds well with the region where temperature is simulated to be greatest.

The observed temperature fields (Figures 9(a) and 10(a)) were interpolated on to the same grid as each of the models and difference maps were constructed (not presented). RMS error and pattern correlation statistics (similar to those for MSL pressure) were also calculated. Table 4 gives the RMS error results calculated for January and July using the land-based grid points of each of the models (see Figure 13 for the location of these grid points). The pattern correlation coefficients (not presented) were all in excess of 0.8 (all models obtained the strong poleward decrease in temperature) and were not particularly useful for distinguishing model performance. The RMS error results do distinguish model performance and confirm the conclusions drawn from Figures 8–11. The largest RMS errors are for the OSU and NCAR models, and the RMS error is also high for the GFDL model in January. The RMS errors are least in the GISS simulation.

(b) Sea surface temperature

RMS errors were also calculated using the marine-based model grid-points which fall within the region 90–180°E and 10–50°S (the region over which observed temperature is contoured in Figure 9(a), excluding the land). Thus we compare observed sea-surface temperature (SST) with model surface temperature over the oceans surrounding the Australian continent. In this comparison, the model temperature fields used are the same as in the comparison of land

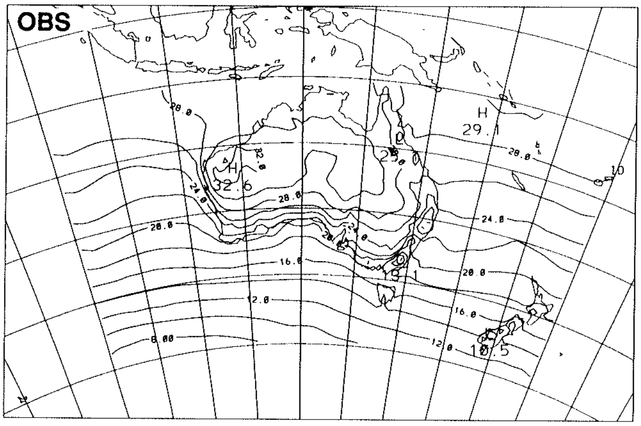


Figure 9(a): Observed January surface air temperature (°C)

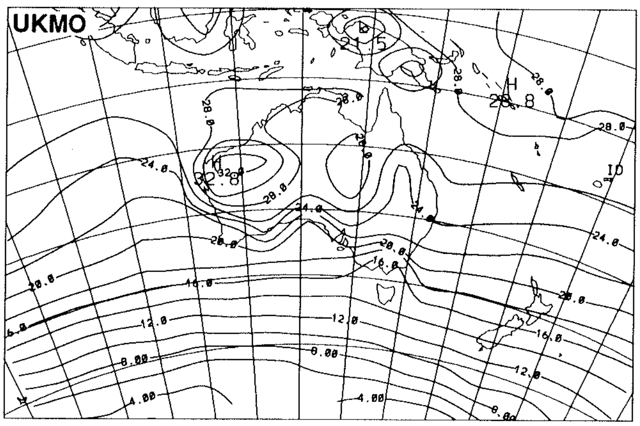


Figure 9(b): UKMO 1× CO_2 simulation of January surface air temperature (°C)

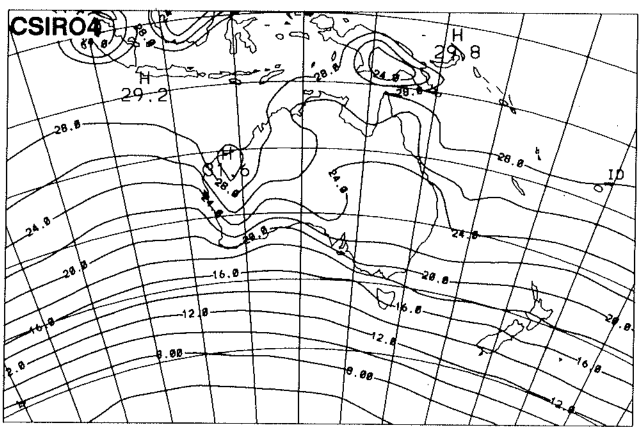


Figure 9(c): CSIRO4 1× CO_2 simulation of January surface air temperature (°C)

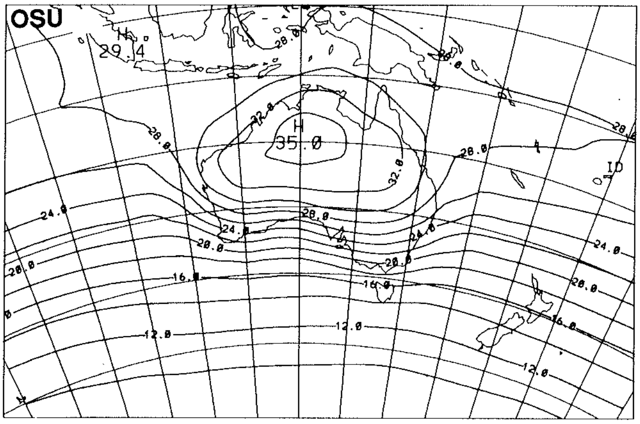


Figure 9(d): OSU 1× CO_2 simulation of January surface air temperature (°C)

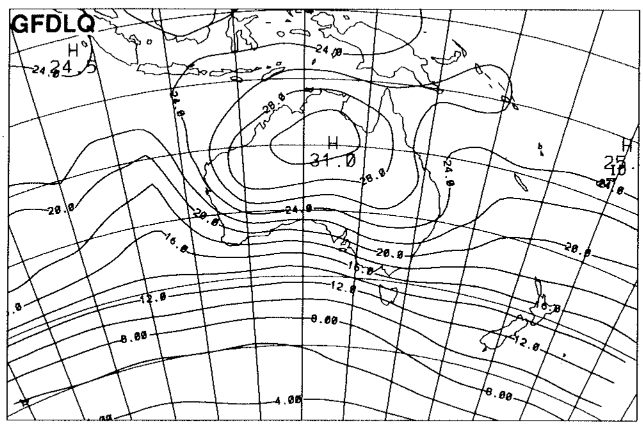


Figure 9(e): GFDLQ 1× CO_2 simulation of January surface air temperature (°C)

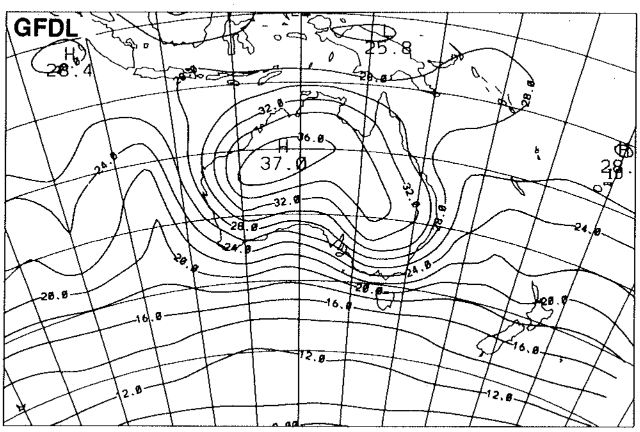


Figure 9(f): GFDL 1× CO_2 simulation of January surface air temperature (°C)

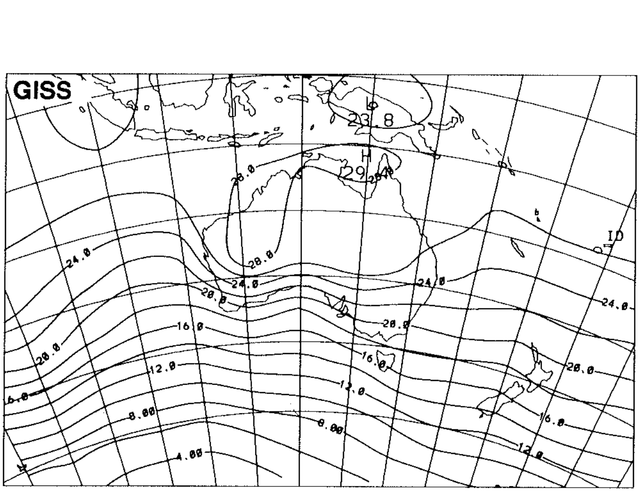


Figure 9(g): GISS 1× CO_2 simulation of January surface air temperature (°C)

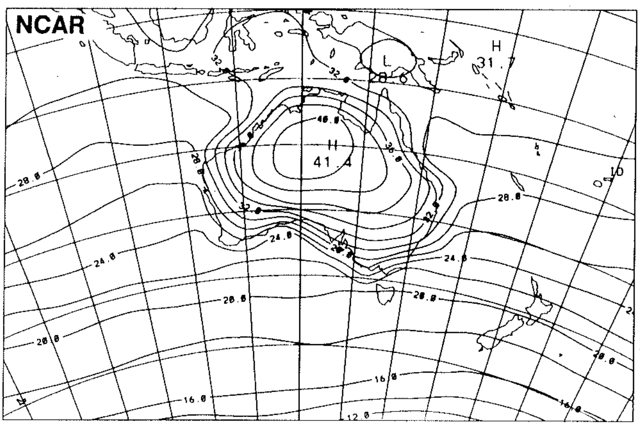


Figure 9(h): NCAR 1× CO_2 simulation of January surface air temperature (°C)

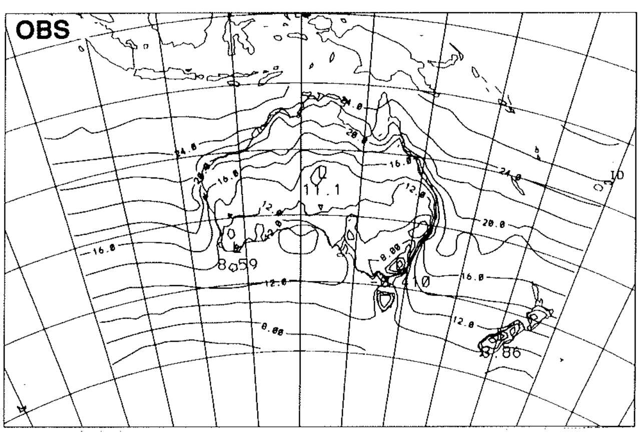


Figure 10(a): Observed July surface air temperature (°C)

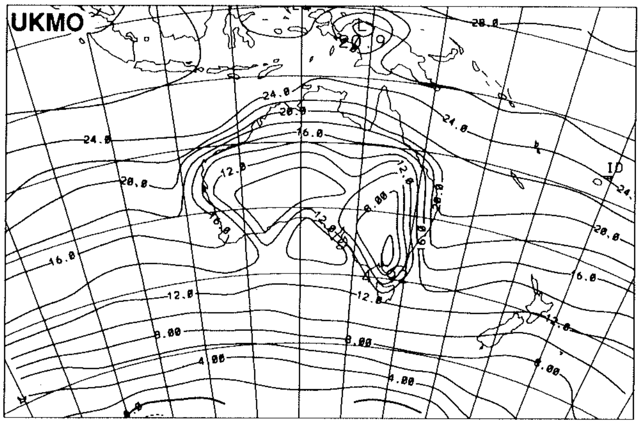


Figure 10(b): UKMO 1× CO_2 simulation of July surface air temperature (°C)

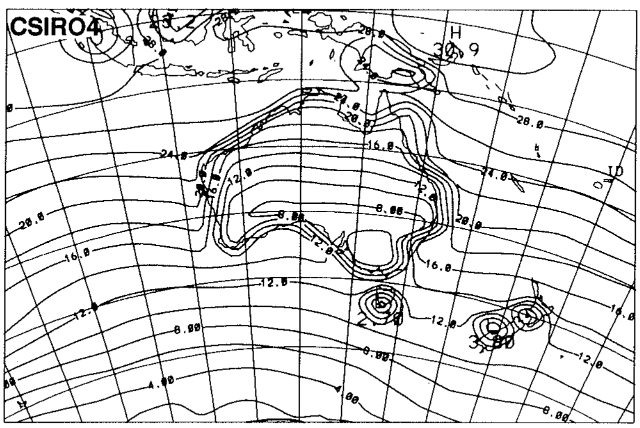


Figure 10(c): CSIRO4 1× CO_2 simulation of July surface air temperature (°C)

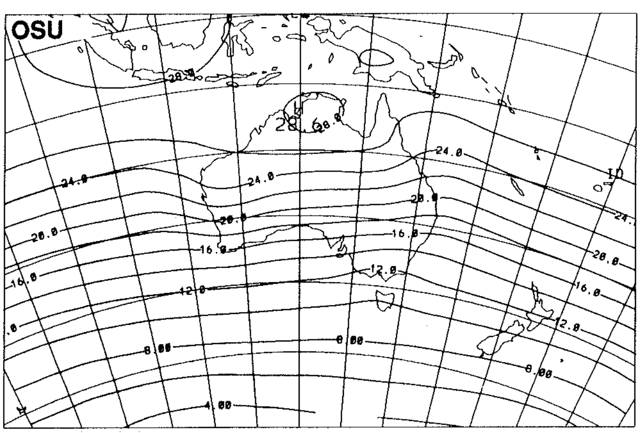


Figure 10(d): OSU 1× CO_2 simulation of July surface air temperature (°C)

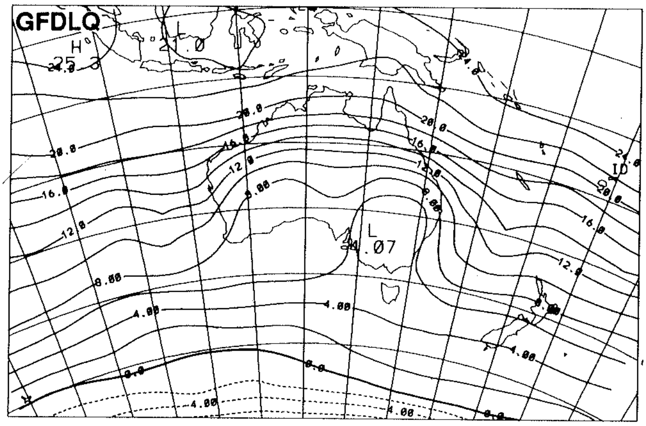


Figure 10(e): GFDLQ 1× CO_2 simulation of July surface air temperature (°C)

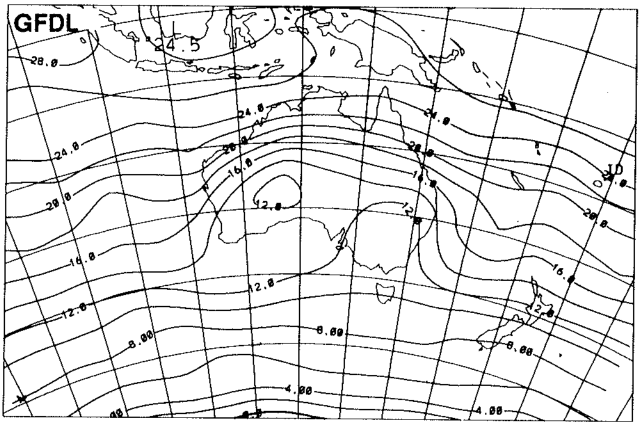


Figure 10(f): GFDL 1× CO_2 simulation of July surface air temperature (°C)

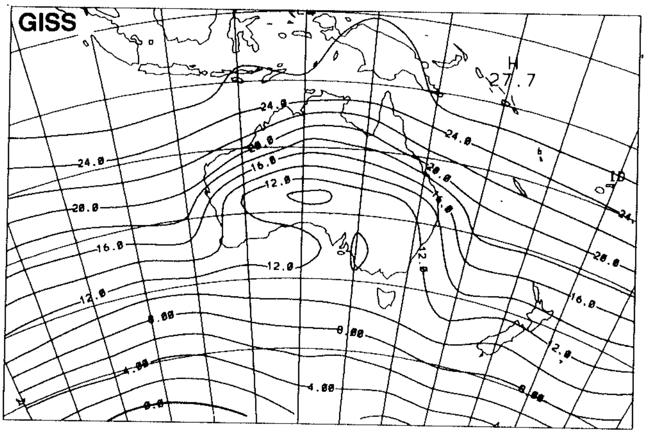


Figure 10(g): GISS 1× CO_2 simulation of July surface air temperature (°C)

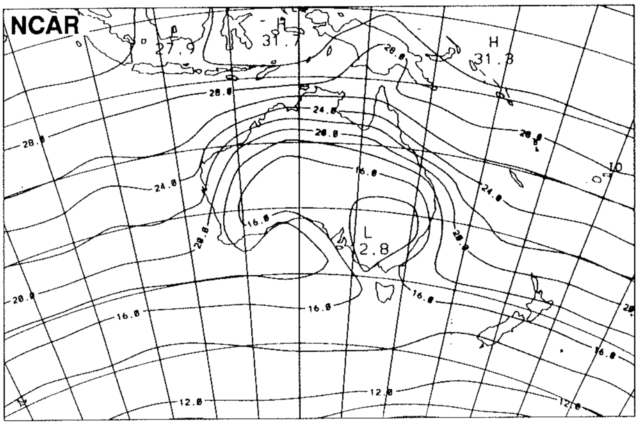


Figure 10(h): NCAR 1× CO_2 simulation of July surface air temperature (°C)

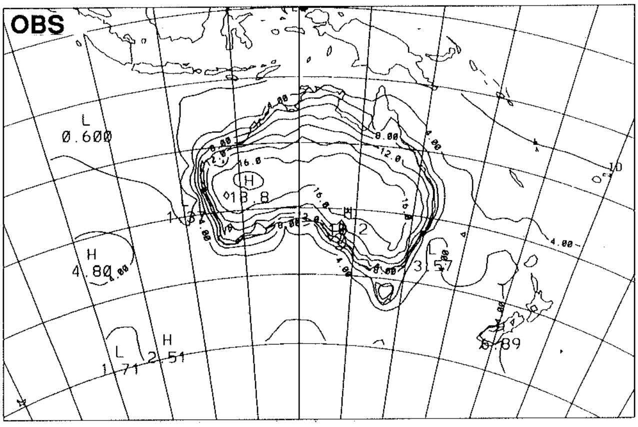


Figure 11(a): Observed surface air temperature: January minus July (°C)

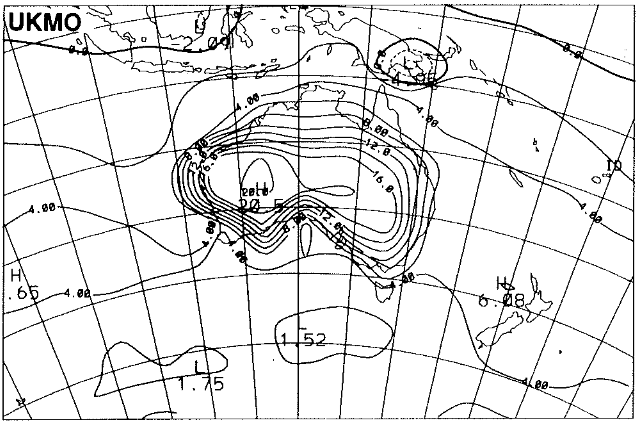


Figure 11(b): UKMO 1× CO_2 simulation of surface air temperature: January minus July (°C)

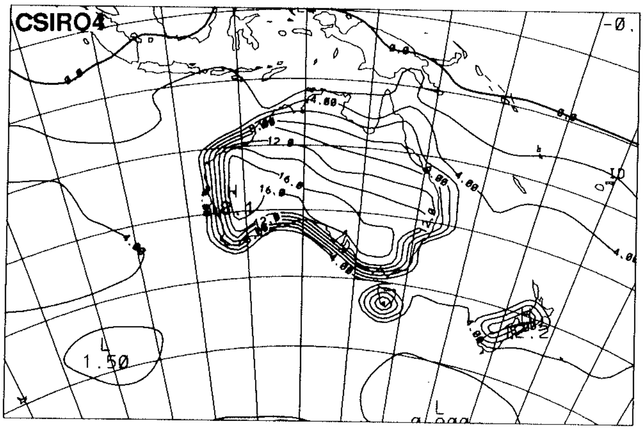


Figure 11(c): CSIRO4 1× CO_2 simulation of surface air temperature: January minus July (°C)

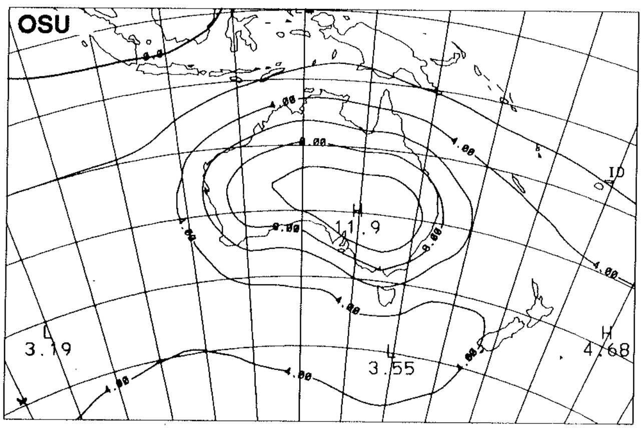


Figure 11(d): OSU 1× CO_2 simulation of surface air temperature: January minus July (°C)

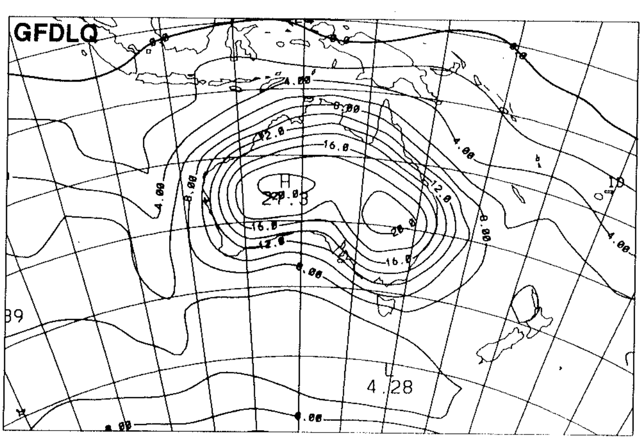


Figure 11(e): GFDLQ 1× CO_2 simulation of surface air temperature: January minus July (°C)

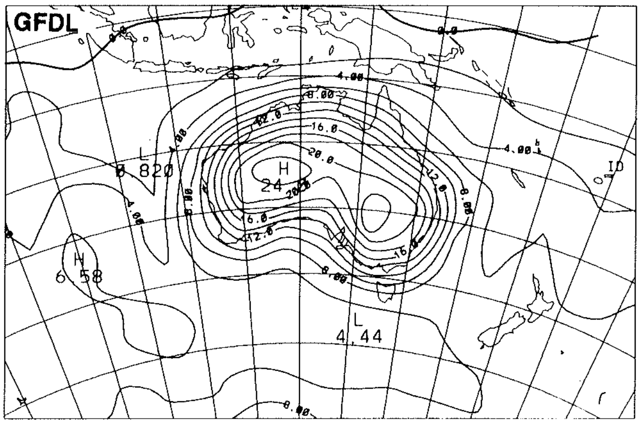


Figure 11(f): GFDL 1× CO_2 simulation of surface air temperature: January minus July (°C)

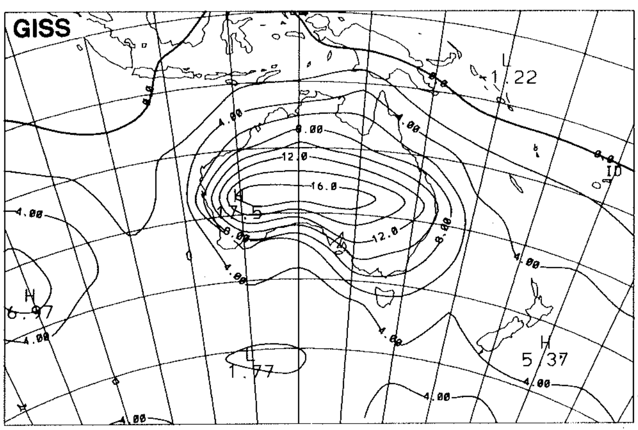


Figure 11(g): GISS 1× CO_2 simulation of surface air temperature: January minus July (°C)

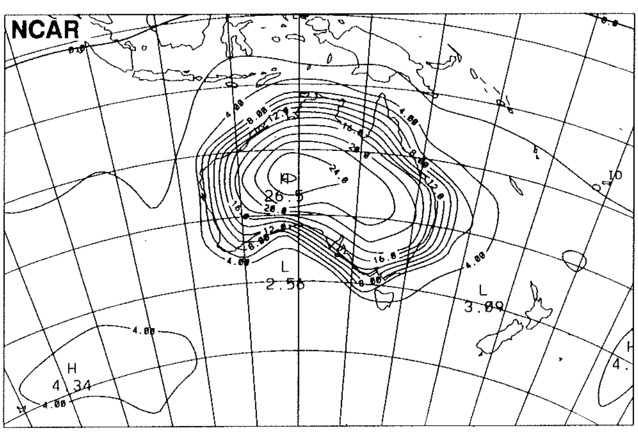


Figure 11(h): NCAR 1× CO_2 simulation of surface air temperature: January minus July (°C)

Table 4: RMS errors for GCM simulations of surface air temperature over the Australian land mass (°C).

Model	January	July
UKMO	2.6	3.4
CSIRO4	3.9	3.1
GFDL	5.3	1.8
GFDLQ	2.0	4.6
GISS	2.1	1.8
OSU	3.2	8.0
NCAR	8.5	3.1

Table 5: RMS errors for GCM simulations of Australian region sea surface temperature (°C).

Model	January	July
UKMO	1.0	1.6
CSIRO4	0.7	1.2
GFDL	3.7	4.1
GFDLQ	0.5	0.7
GISS	1.1	0.6
OSU	1.7	1.4
NCAR	4.8	4.5

temperatures, except for the GFDL and GFDLQ simulations where the surface temperature field is used. The RMS error results are presented in Table 5; corresponding difference maps were also produced and examined but these are not presented here.

One would expect that those models which use a Q-flux correction would show very small errors in SST. This is indeed generally the case. Q-flux simulations UKMO, CSIRO4, GFDLQ, and GISS give SST RMS errors of around 1°C and errors no greater than around 2°C in any individual region. The RMS errors in the non-Q-flux OSU model are not much larger, but this simulation gives SST as much as 4°C too warm south-west of Australia in January. The non-Q-flux GFDL simulation gives much larger RMS errors (3–4°C) and some individual errors of around 6°C. The non-Q-flux NCAR simulation also shows large errors in regional SST and the greatest RMS error values.

(c) Acceptability of temperature simulations

Due to its poor representation of July surface air temperature over the continent and of the annual cycle of temperature, the OSU simulation of surface air temperature in the Australian region must be considered unacceptable. The OSU model's weak seasonal cycle in temperature is clearly related to, and is probably the cause of, its weak seasonal cycle in MSL pressure noted in Section 3.2. Interestingly, when OSU temperature results are examined over the whole Southern Hemisphere or globally (Schlesinger and Zhao 1989), underestimation of the seasonal cycle is not very evident, although the annual cycle in temperature, and in sea ice, is suppressed in the high latitudes of the Southern Hemisphere.

On the basis of the large errors in the GFDL simulation of Australian region SST, this simulation must also be considered unacceptable. A considerable number of observational and modelling studies demonstrate the existence of associations between regional SST anomalies and rainfall over the Australian continent (e.g. Streten 1983, Nicholls 1989, Simmonds 1990, Gordon and Hunt 1991 and Whetton 1990). This sensitivity of both climate and climate models to anomalies in SST highlights how inappropriate it is to use climate models in climate change research which have large SST errors in their control run.

The NCAR simulation had some very large errors in surface temperature over both the land and the ocean in the Australian region, and must also be considered unacceptable.

Thus the CSIRO4, UKMO, GFDLQ and GISS simulations of temperature over the Australian continent and the surrounding ocean were considered acceptable. This conclusion is perhaps not surprising. These four simulations include a Q-flux correction, which forces the simulated SST to match the observed, which, in turn, would help to constrain land temperatures to near the observed.

3.4 Precipitation

As model-simulated mean patterns of precipitation were found to show considerable and apparently random month-to-month variability through the twelve months of the annual cycle, it was considered inappropriate to base the comparisons in this section on just the January and July maps of simulated precipitation. However, even the maps of DJF and JJA precipitation showed, for each of the models, much seemingly spurious spatial structure, reflecting the short sampling time used and, more generally, the difficulties involved in simulating precipitation processes in GCMs. In addition, the differing (and generally unrealistic) topographies of the various models affected the detailed structure of the simulated precipitation patterns. For these reasons, in intercomparing the precipitation results of the various models, we thought it best to use an approach different to that used for MSL pressure and temperature.

As our primary test of precipitation simulation performance, we looked at how well each model simulated the annual cycle of rainfall throughout the region. The failure of a model to simulate adequately the seasonality of rainfall in the Australian region represents a more serious shortcoming than errors in the annual mean precipitation amount (which may, in part, be related to poor model topography). Poor seasonality in a model represents a failure of the model to simulate the reorganisation of the pattern of rainfall in a region in response to the annual cycle of radiation, and casts doubt on the ability of the model to simulate regional rainfall changes associated with the much smaller radiation changes induced by doubling atmospheric CO_2. Here we will consider the regional precipitation simulation of a model as unacceptable if the simulation of the seasonality of rainfall in the Australian region is unacceptably poor.

In addition to this test, we also examine how well rainfall rates are simulated. However, due to failure of all models to simulate well the spatial pattern of rainfall amounts, regional averages, rather than grid point by grid point results, are intercompared.

(a) Seasonality of rainfall

To provide an overall picture of the relative abilities of the models to simulate the regional seasonality of rainfall, a map was produced for each model and the observations, giving the percentage of average annual rainfall falling in the November to April half-year (Figure 12).

In the map of observed rainfall we see that the northern half of the continent receives in excess of 70% of its rainfall in the summer half-year and the northern two-thirds of the continent more than 50%. Only southern coastal regions show a strong winter maximum

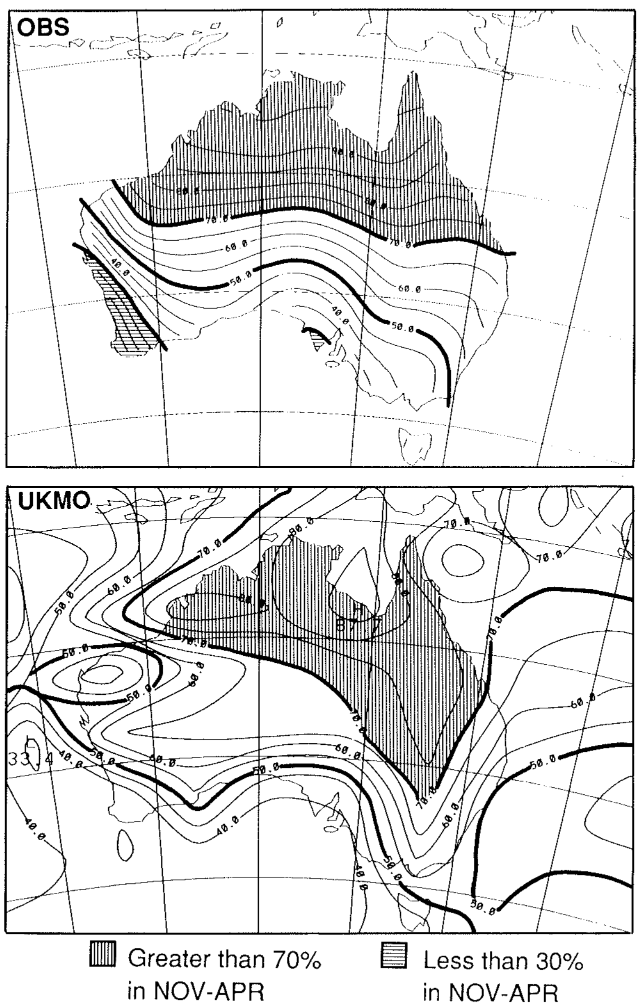


Figure 12: November to April precipitation as a percentage of annual: observed and 1×CO_2 for each model (50% contour marks boundary between winter and summer rainfall regimes).

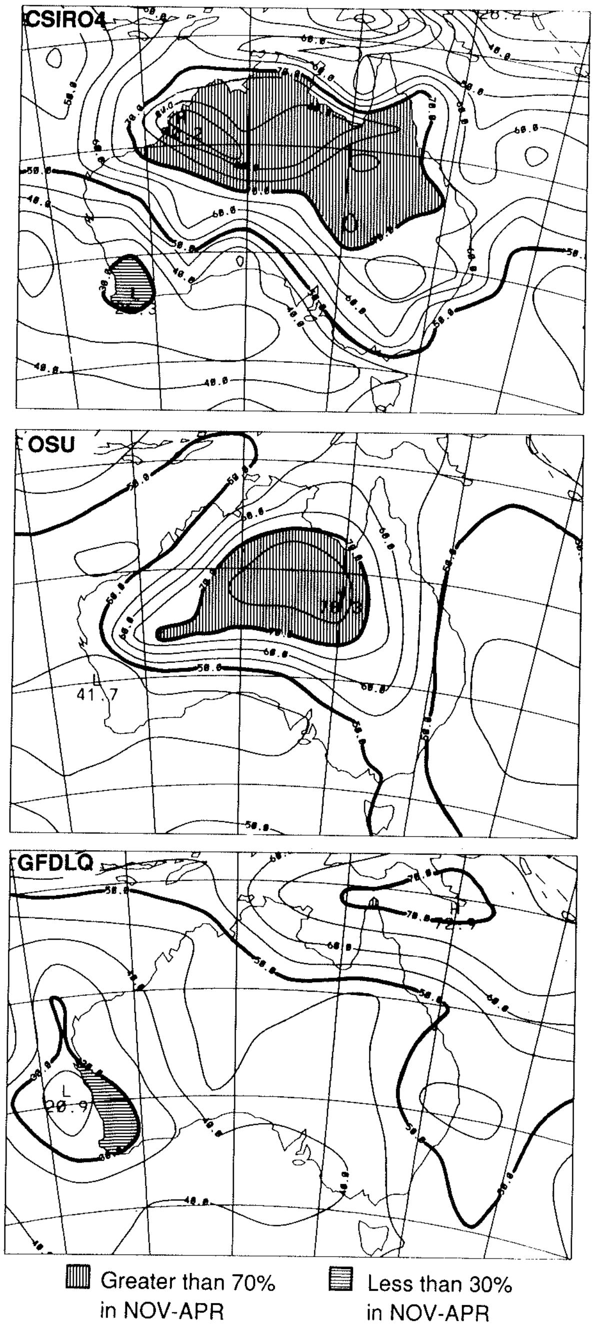


Figure 12: November to April precipitation as a percentage of annual: observed and 1×CO_2 for each model (50% contour marks boundary between winter and summer rainfall regimes).

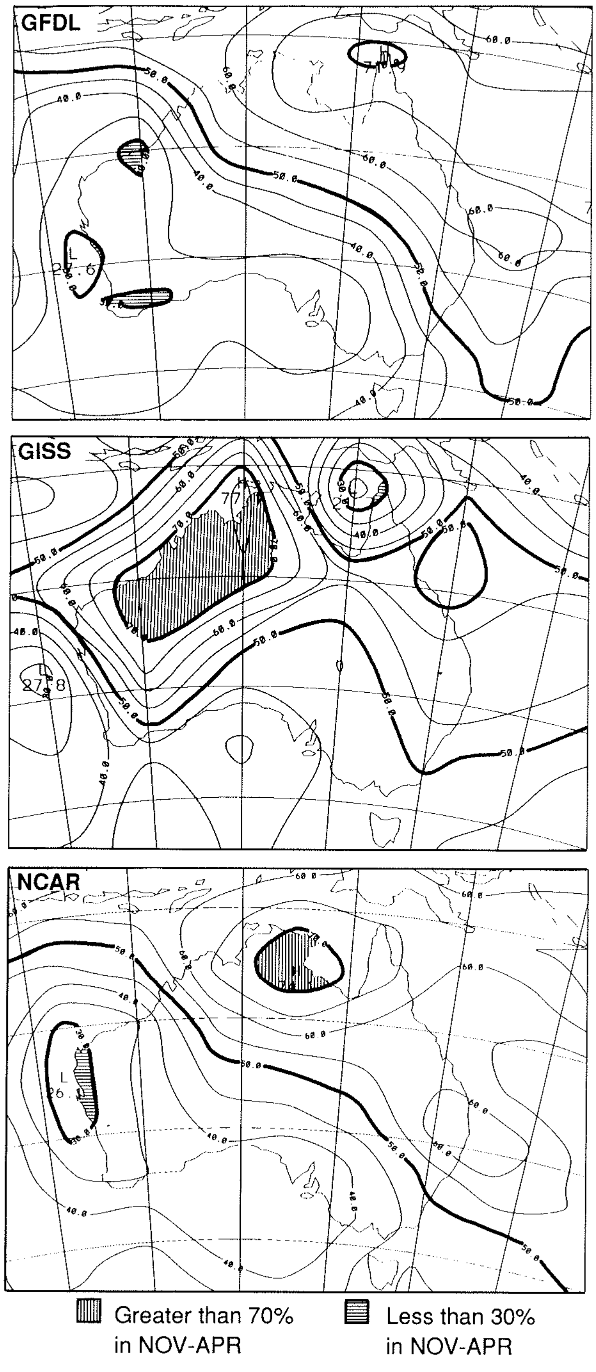


Figure 12: November to April precipitation as a percentage of annual: observed and 1×CO_2 for each model (50% contour marks boundary between winter and summer rainfall regimes).

(indicated by the 30% contour), with this regime being strongest and more equatorward in the south-west of the continent.

The simulated pattern for the UKMO model is broadly acceptable. The region of summer maximum in rainfall is well simulated, although it extends too far south over south-eastern Australia. Exposed southern regions are shown as having a winter maximum, but not as strong as in the observed. The CSIRO4 simulation is quite good, and indeed performs better than the UKMO simulation at giving the observed strong summer maximum in rainfall over the northern half of Australia in combination with the observed strong winter maximum in rainfall in the far south-west of the continent. However, like the UKMO model, it has summer rainfall too dominant over south-eastern Australia. This error over south-eastern Australia of the UKMO and CSIRO4 models may relate to the coarse topography used (see Figure 1). The poor representation of the eastern highlands used by the models would allow moist easterly winds (which predominate in the warmer months of the year) to penetrate too far inland over south-eastern Australia.

The OSU simulation is quite poor in that much of coastal northern Australia is shown as receiving nearly as much rainfall in the winter half as in the summer half of the year. This may reflect this model's poor simulation (noted earlier) of the land–sea temperature contrast over northern Australia in winter. The GFDLQ simulation fails badly in showing nearly the whole continent as receiving most rain in the winter half-year. The GFDL simulation performs better than that of GFDLQ in locating the boundary between the two rainfall regimes, but still fails in showing virtually none of northern Australia receiving more than 70% of total rainfall in the summer half of the year. The NCAR simulation is similar to that of GFDL. The GISS simulation completely fails to show the summer rainfall maximum over north-eastern Australia.

(b) Regional rainfall results

To construct regional averages for rainfall, we used only the land-based model grid points over Australia, and divided these into four regions (Figure 13). (The classification used by each model of grid points into land or sea was adopted here. However, the classification in the UKMO model of a grid point lying over land in south-west Western Australia (32.50°S, 116.25°E) as a marine grid point seemed anomalous; here it will be considered a land grid point.) Model rainfall results for each of the twelve months of the annual cycle were averaged over the grid points falling into each of the four districts. Corresponding observed values were constructed by averaging the data for the districts within each region (and applying a weighting to allow for the differing area of districts).

The results for the north-east region are shown in Figure 14. The best simulation is clearly that of the UKMO model, which gives realistic rainfall rates and the strong summer rainfall maximum observed in this region. The CSIRO4 model has rain falling at around twice the observed rate, although the seasonal cycle is well simulated. Rainfall rates are too low in the OSU simulation in summer. None of the other models show the strong summer maximum in rainfall observed in the region, and consequently give rainfall rates much too high in winter.

The results for the North-west region are shown in Figure 15. The climate of this region is similar to the North-east region, although here the dry season is even more pronounced. The models perform much as they did in the North-east region, although the GISS simulation is improved. Only the UKMO, GISS and CSIRO4 models simulate adequately the region's strong seasonality in rainfall, but the CSIRO4 simulation considerably overestimates rainfall rates.

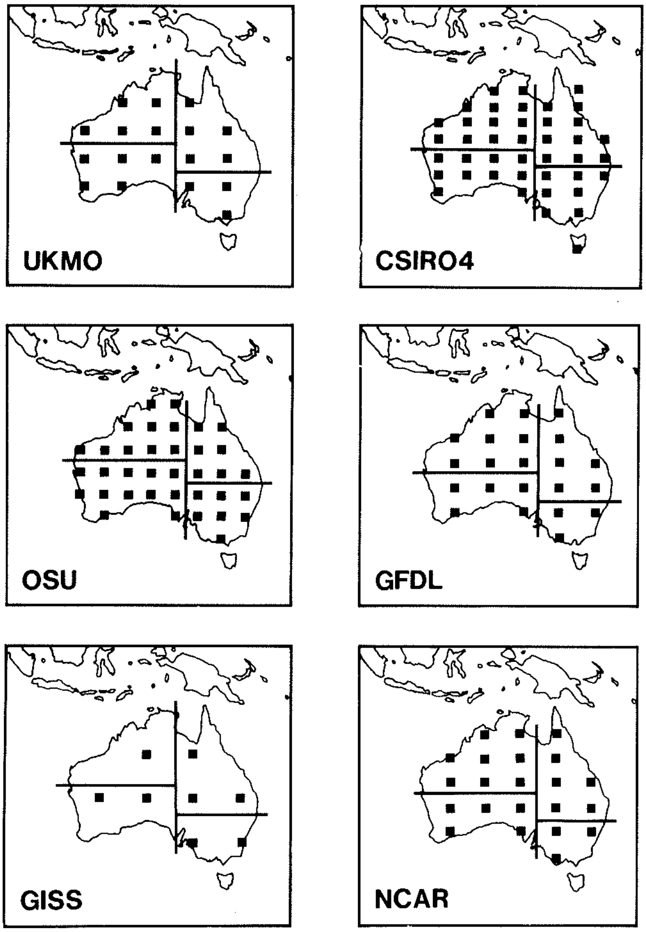


Figure 13: Map showing how model grid points were divided into the four rainfall regions used.

Rainfall in the south-east region (Figure 16) is around 1.5 mm per day, uniformly distributed through the year. This is well simulated by the OSU and GFDLQ models. The GISS model simulates well the uniform distribution of rainfall but overestimates rainfall rates. The other simulations are poorer; the UKMO and CSIRO4 models, in particular, show unrealistically high summer rainfall rates for the region.

Finally in the south-west (Figure 17), where the observed rainfall rate is low and a winter rainfall maximum is observed, no model performs particularly well. The NCAR, GFDL and GFDLQ simulations do show a winter maximum for the region, but generally overestimate rainfall rates. The CSIRO4 model shows both a winter and a summer maximum and generally has rainfall rates too high. The UKMO, GISS and OSU models fail to show a rainfall maximum in winter, although the OSU model does depict well the generally low rainfall seen in the region.

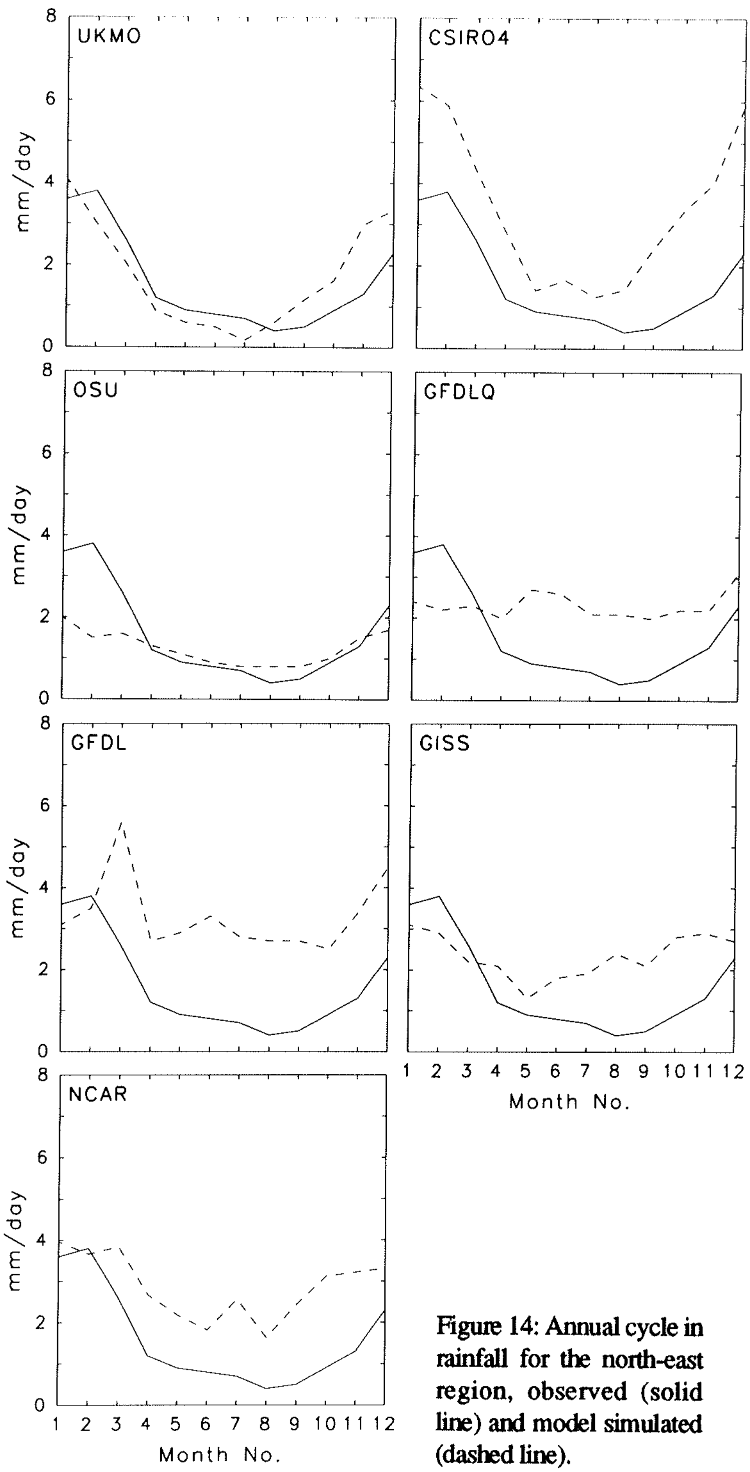


Figure 14: Annual cycle in rainfall for the north-east region, observed (solid line) and model simulated (dashed line).

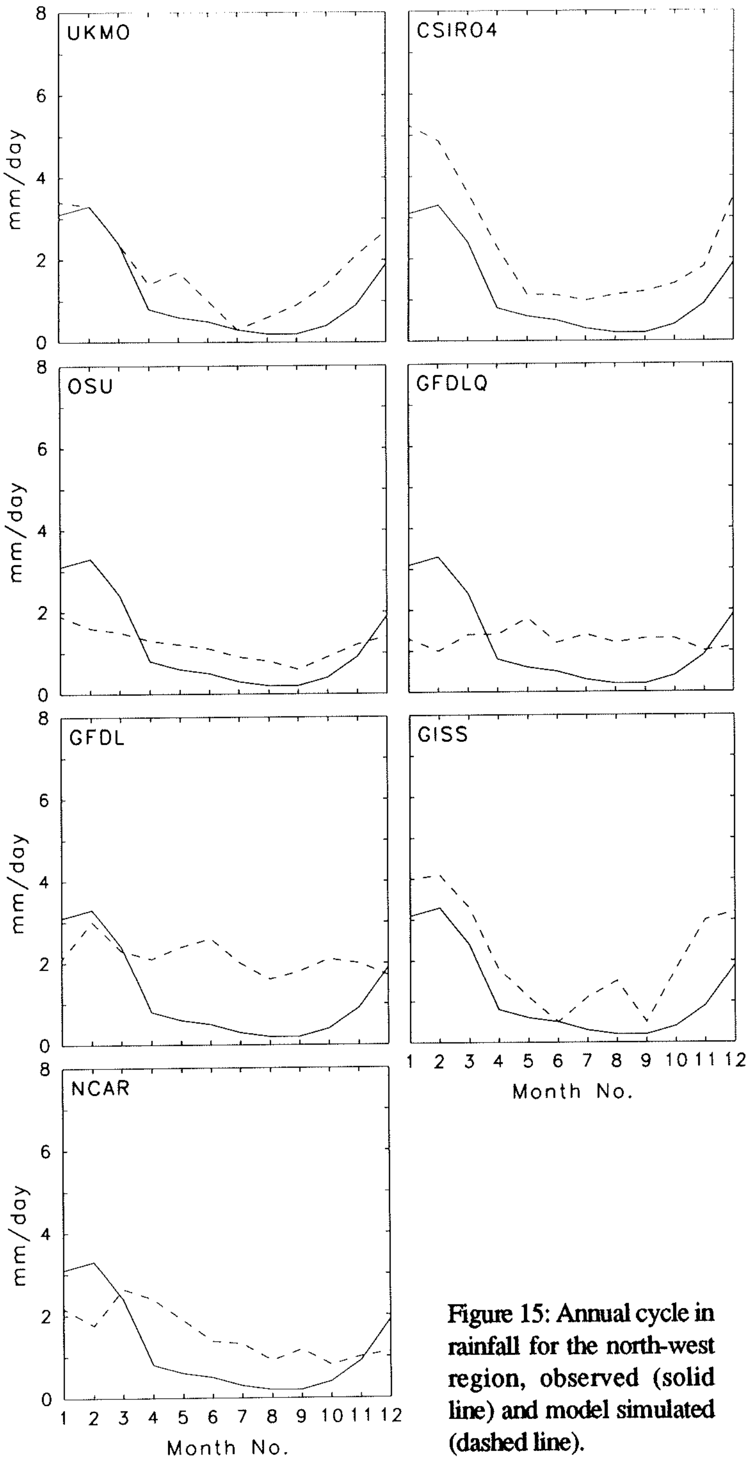


Figure 15: Annual cycle in rainfall for the north-west region, observed (solid line) and model simulated (dashed line).

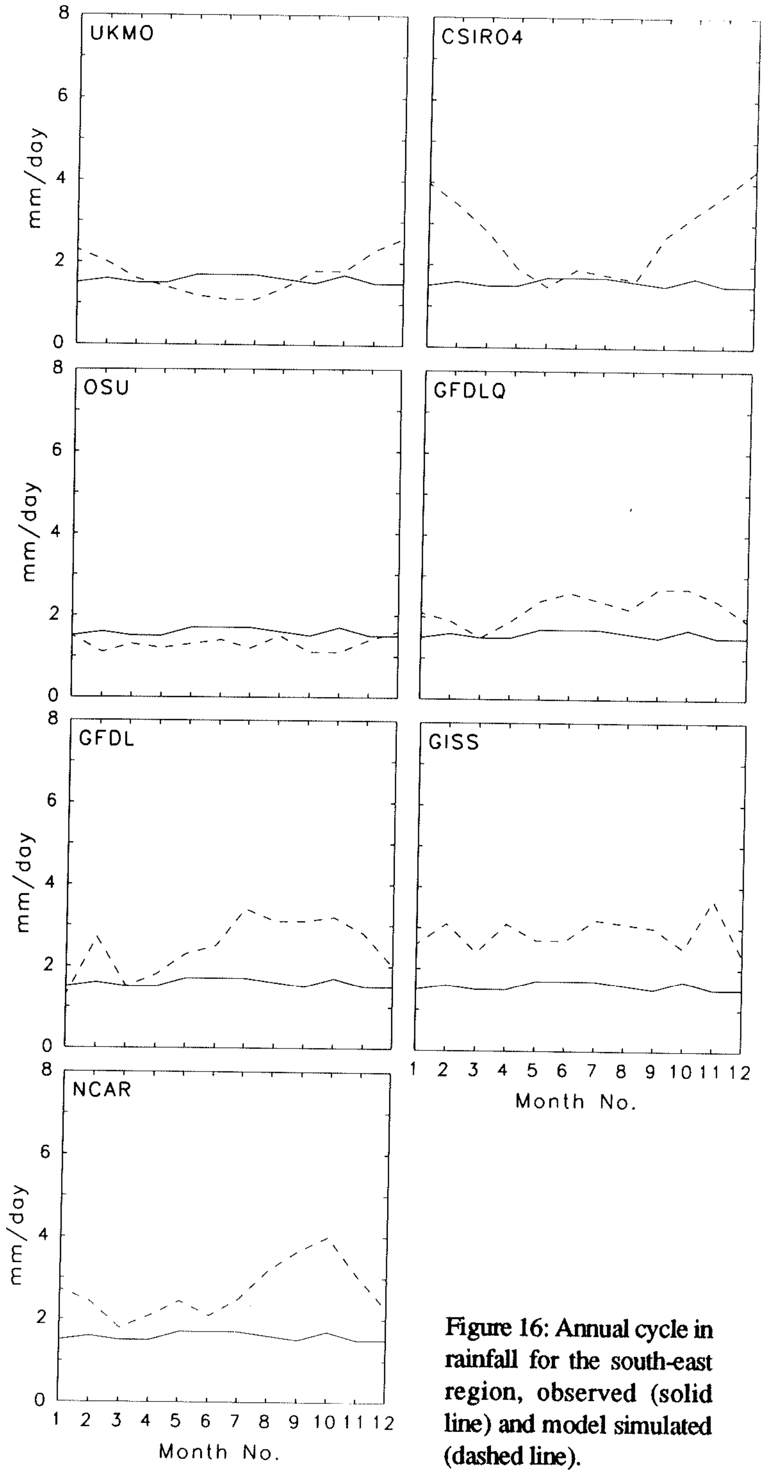


Figure 16: Annual cycle in rainfall for the south-east region, observed (solid line) and model simulated (dashed line).

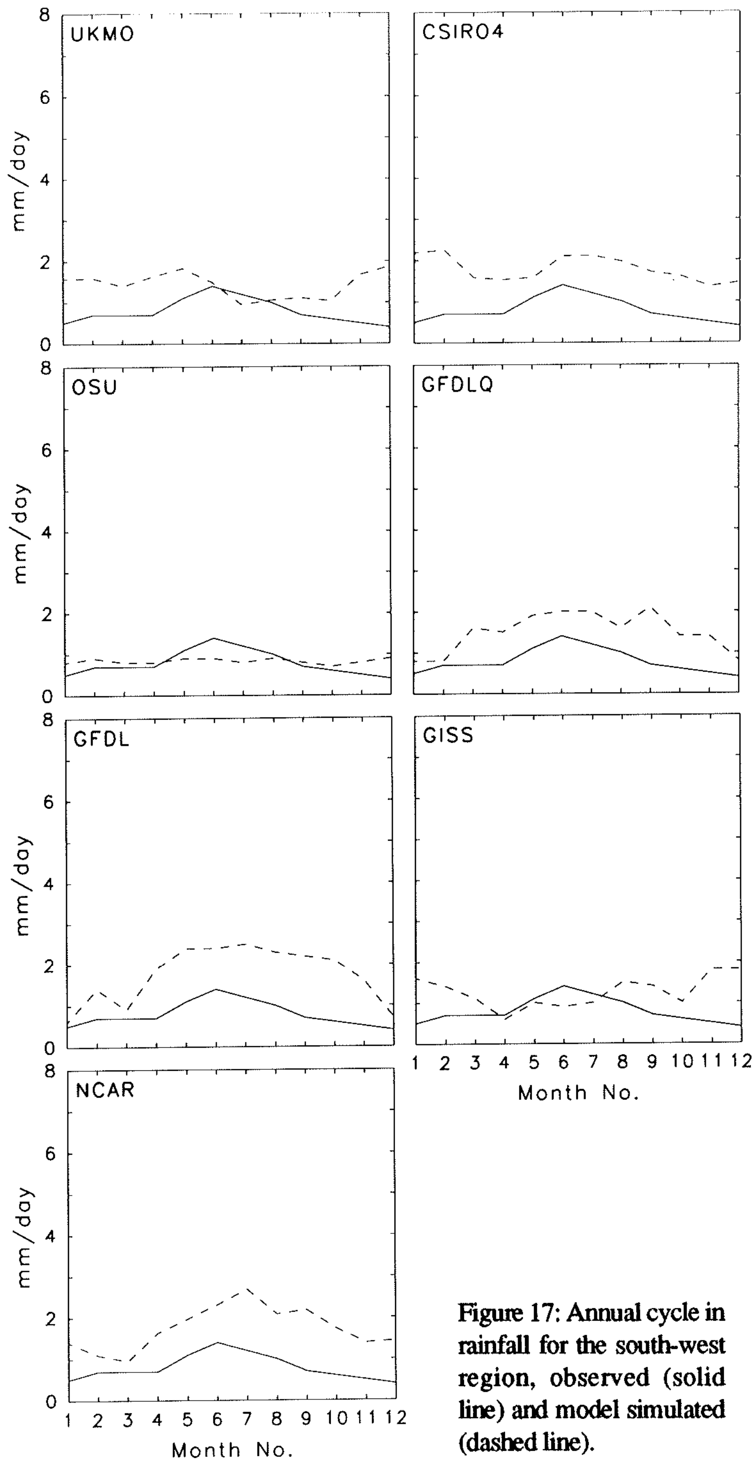


Figure 17: Annual cycle in rainfall for the south-west region, observed (solid line) and model simulated (dashed line).

The tendency for the CSIRO4 model to give the correct seasonality of rainfall over northern Australia but too high rainfall rates is explored further here. Figure 18 gives the observed DJF pattern of precipitation rate over Australia, and the corresponding simulated pattern of the CSIRO4 and UKMO models. The UKMO results are included for comparison because this model, like the CSIRO4 model, simulated well the atmospheric circulation over the continent in summer and the strong summer maximum in rainfall over northern Australia, but, unlike the CSIRO4 model, did not give unrealistically high rainfall rates. The figure shows that high rainfall rates, like those observed in coastal regions in northern Australia, occur well inland in the CSIRO4 simulation, but are more realistically confined to eastern coastal regions in the UKMO simulation. These contrasting simulated rainfall patterns need to be interpreted in light of the very different topographies (Figure 1) used by these models. The CSIRO4 model has no eastern highlands (which in the real world confine high summer rainfall rates to the coastal strip of north-eastern Australia) and, as a result, a rainfall maximum is simulated on the exposed north-east slopes of the central plateau of the model topography. By contrast, the UKMO model, which uses a topography which resolves the eastern Highlands, does a much better job of confining the highest rainfall rates to coastal regions. Model errors such as these, which can be understood, and to some extent allowed for, need not represent an unacceptable failure of the model simulation. Such errors do, however, highlight the need to use more realistic and preferably higher resolution topography, perhaps through nesting limited area models in GCMs, if rainfall patterns are to be modelled realistically.

(c) Acceptability of the rainfall simulations

As may be seen in Figure 12, both the UKMO and CSIRO4 models perform acceptably well in simulating the summer rainfall maximum over northern, central and eastern Australia and the winter rainfall maximum in southern coastal regions. Although the CSIRO4 model gave the best simulation of rainfall seasonality, we have some reservations over the CSIRO4 precipitation results because rainfall rates are generally too high. However, as this error could be partly explained by the very unrealistic topography used, the CSIRO4 simulation was still considered acceptable.

The GFDL and NCAR simulations locate the winter and summer rainfall regions reasonably well, but greatly underestimate the strength of the summer rainfall maximum. These simulations are not unacceptable, but reservations must be held on the reliability of these models with regard to northern Australian rainfall.

The OSU, GFDLQ, and GISS models fail to simulate the basic pattern of the summer and winter rainfall regions of Australia and these simulations cannot be considered acceptable.

It is perhaps not surprising that the OSU model simulates rainfall seasonality poorly, as this model was found earlier to underestimate the annual range in MSL pressure and temperature in the Australian region. The weak seasonality of the GFDL and GFDLQ simulations is more surprising, as these models, if anything, were found to overestimate the annual range in pressure and temperature in the Australian region (see Figures 6 and 8).

3.5 Conclusions on the overall acceptability of the regional control simulations of the models

Each of the preceding sections concluded with an assessment of the acceptability of the control simulation of the field concerned for each of the models. In each case the assessment made can be characterised as either "acceptable", "acceptable, but with some important

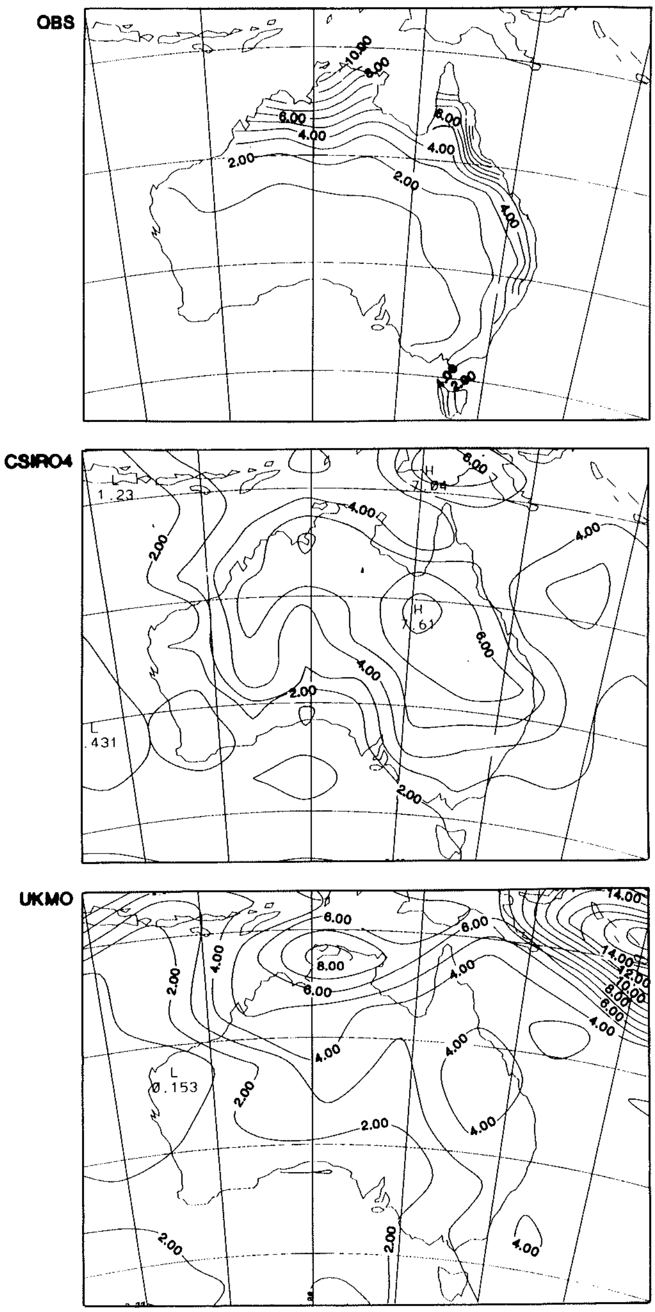


Figure 18: Maps of DJF precipitation (mm/day): observed and $1\times CO_2$ for the CSIRO4 and UKMO models.

Table 6: Summary of model performance in simulating each of Australian region MSL pressure, temperature, and precipitation. ● denotes 'acceptable' and X denotes 'not acceptable'. O indicates that the simulation was considered acceptable but with reservations (i.e. some important simulation errors were noted).

Model	MSL pressure	Temperature	Precipitation
UKMO	O	●	●
CSIRO4	●	●	O
OSU	X	X	X
GFDLQ	●	●	X
GFDL	●	X	O
GISS	X	●	X
NCAR	X	X	O

reservations" or "unacceptable". Using this categorisation, our assessment of the performance of the model simulations for each of three fields is summarised in Table 6.

The OSU model was considered to show unacceptable errors in the Australian region in all three fields, with these errors being generally related to poor simulation of the annual cycle.

The GISS model was considered unacceptable in its simulation of MSL pressure patterns, due to very large errors in its placement of the subtropical high pressure belt and consequent airflow over the Australian continent, and in its simulation of precipitation, due to failure to represent a summer maximum in rainfall over north-eastern Australia.

The NCAR model was unacceptable in its simulation of MSL pressure (due to very large errors in the January simulation) and in its simulation of Australian region temperature (there were large errors in both surface air temperature over land and in sea surface temperature).

The GFDLQ model performed acceptably on MSL pressure and temperature but failed in its simulation of the strongly seasonal rainfall of northern Australia.

The GFDL model was unacceptable only in its simulation of temperature (particularly SST) in the Australian region, although its rainfall simulation had some important deficiencies.

The simulations of the CSIRO4 and UKMO models were considered acceptable for all three fields, although reservations were expressed over the UKMO MSL pressure simulation in January (due to a poor simulation of the Southern Hemisphere westerlies), and over the CSIRO4 precipitation simulation (due to a general overestimation of rainfall rates). Thus, based on our Australian region testing of the control simulations of the various GCM experiments available to us, only two models (UKMO and CSIRO4) were considered to be performing well enough to warrant attention being focussed on their results for 2×CO_2.

Overall, we consider that errors in the UKMO simulation to be more significant than those in the CSIRO4 simulation. The CSIRO4 model performed substantially better in simulating the MSL pressure pattern and the seasonality of rainfall in the region, the UKMO simulation was superior only in that its rainfall rates were more realistic over inland Australia.

On this basis we would consider the CSIRO4 $2\times CO_2$ simulation as more likely to be a reliable guide to climate change in the Australian region.

In a study very similar to this one but focussed on the New Zealand region, Mullan and Renwick (1990) also selected the CSIRO4 model as having the best simulation of regional climate. (They examined the same collection of experiments as we do here, except that the NCAR experiment was not included.) Unlike us, Mullan and Renwick also found the GFDLQ simulation acceptable. We rejected this simulation because of poor seasonality in its rainfall simulation, whereas Mullan and Renwick did not examine the precipitation performance of the models. Due to the greater emphasis Mullan and Renwick gave to simulation of atmospheric circulation in the higher midlatitudes of the southern hemisphere, they rejected the UKMO results.

3.6 Global validation of the UKMO and CSIRO4 simulations

Even though we found the CSIRO4 and UKMO simulations acceptable for the Australian region, we should still exclude these simulations from consideration if their simulation of global climate is poor. To investigate this we examined zonally averaged MSL pressure, surface temperature and precipitation from these two models for DJF and JJA, comparing model and observed data. These variables, along with a number of others, were used in the global validation work presented in the IPCC Working Group I Report (Houghton *et al.* 1990). Our results for the UKMO and CSIRO4 models are shown in Figures 19–21. These diagrams have been constructed to be comparable to corresponding diagrams in Houghton *et al* (1990) (Figures 4.1, 4.8 and 4.10) where the results for a range of other models are presented. (The observed curves in Figures 19–21 were taken directly from these corresponding diagrams in Houghton *et al.* (1990).)

The main features of the MSL pressure profile in summer and winter (Figure 19) are simulated by the CSIRO4 model, although pressure is too high in the vicinity of the southern hemisphere circumpolar trough in both seasons and in the higher latitudes of the northern hemisphere in DJF. The first of these errors is a characteristic of low resolution GCMs (see Houghton *et al.* 1990), and amongst these models the CSIRO4 simulation is comparatively good. Excessively high pressure over the Arctic in the northern winter is not common to other models, and is an important error in the CSIRO4 MSL pressure simulation. It should be noted, however, that as the error in mainly confined to north of 60°N, the area of the globe affected is relatively small.

The performance of the UKMO model at simulating zonally averaged MSL pressure is similar to that of the CSIRO4 model in JJA but differs considerably in DJF. In the southern summer, the UKMO model shows only a very weak circumpolar trough and places this much too far north. In this aspect the UKMO simulation is much worse than the CSIRO4 simulation, and is generally worse than other GCMs (see Houghton *et al.* 1990). This result indicates that UKMO errors in simulating MSL pressure in the Australian region in January noted in the regional results are characteristic of the hemisphere. The UKMO simulation has pressure lower than the observed in the higher latitudes of the northern hemisphere in DJF, but this error is shared by a number of other models (see Houghton *et al.* 1990).

Both models simulate very well zonally averaged surface temperature (Figure 20), although there are some minor deviations in very high latitudes. To a considerable extent, this result should be expected, as both models include a Q-flux correction which ensures that substantial errors in SST do not arise.

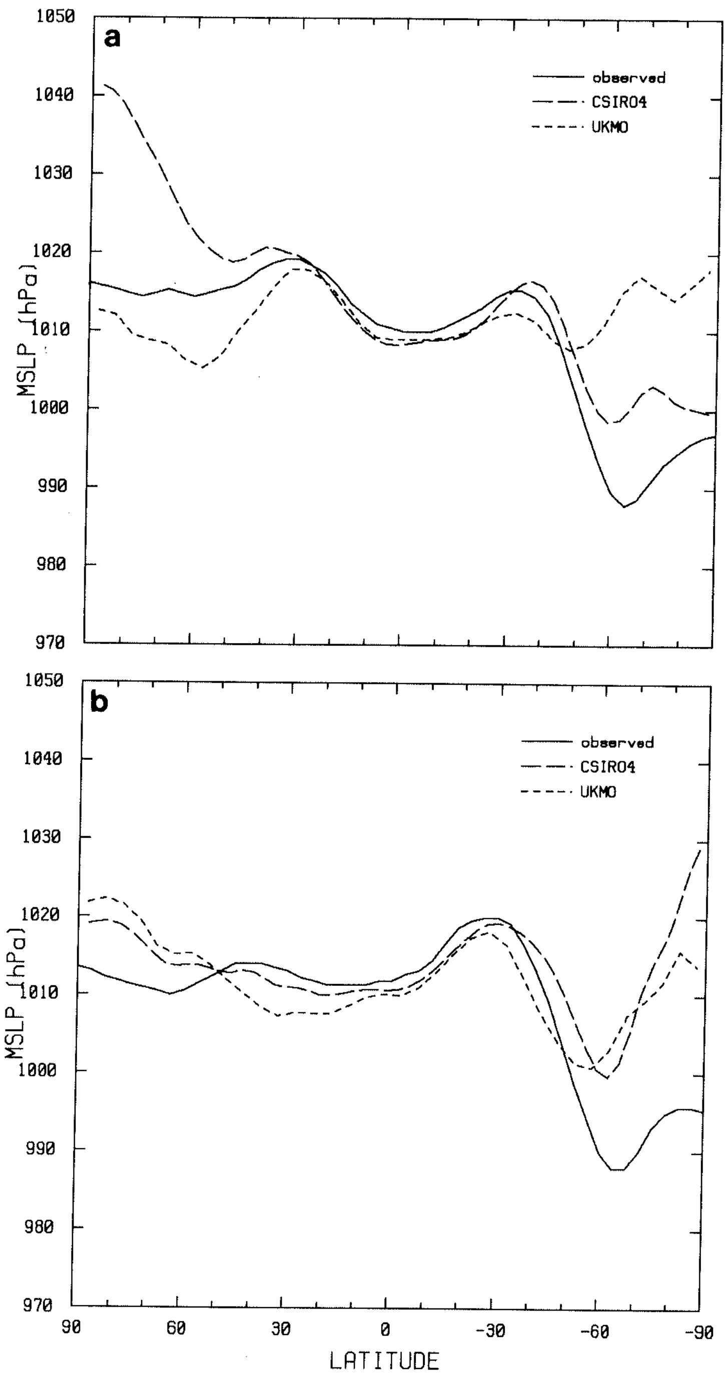


Figure 19: Zonally averaged MSL pressure for the CSIRO4 and UKMO models and as observed (Schutz and Gates 1971,1972): (a) December-January-February, (b) June-July-August.

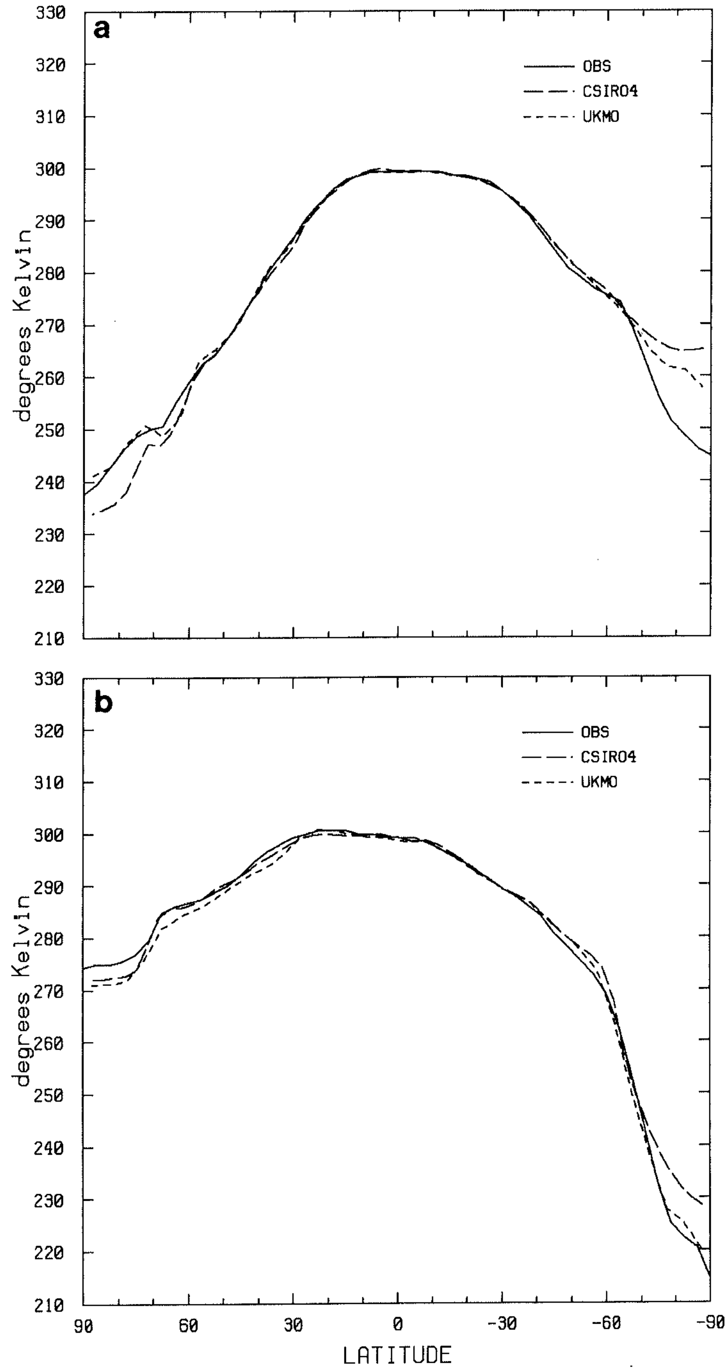


Figure 20: Zonally averaged surface temperature for the CSIRO4 and UKMO models and as observed (Schutz and Gates 1971,1972): (a) December-January-February, (b) June-July-August.

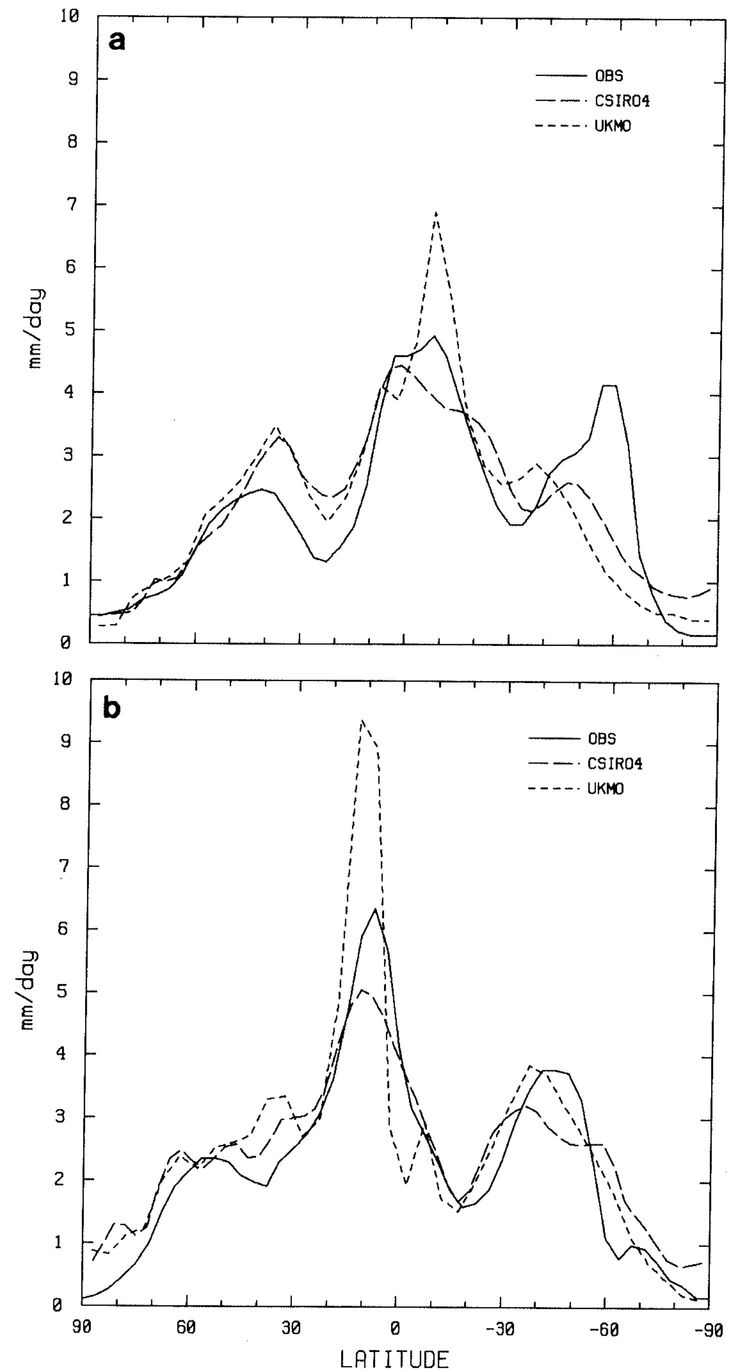


Figure 21: Zonally averaged precipitation for the CSIRO4 and UKMO models and as observed (Jaeger 1976): (a) December-January-February, (b) June-July-August.

The main features of the profile of zonally averaged precipitation, such as the rainfall maximum in the inter-tropical convergence zone, the subtropical rainfall minimum, and the shift of these from DJF to JJA, are reflected in the precipitation simulations of the two models. There are some deviations from the observed pattern (particularly in the middle and higher latitudes of the southern hemisphere), but these are not excessive compared to results from other GCMs (see Houghton *et al.* 1990). The UKMO model also significantly overestimated the rainfall maximum in the tropics.

Leaving aside errors which are common to all low resolution models, on a global basis the main simulation error of the CSIRO4 model is its anomalously high pressure in the arctic in DJF. As this error affects a relatively small area of the globe, and given that our focus is on the southern hemisphere, we did not consider that this error invalidated the CSIRO4 model results. The very weak circumpolar trough simulated by the UKMO model for the southern hemisphere in summer is, from our perspective, a more serious error. It indicates that there are some very important deficiencies in the UKMO simulation of the general circulation of the atmosphere in the southern hemisphere. We will not exclude the UKMO results on this basis, but the result strengthens our conclusion (reached on the basis of the regional results) that the CSIRO4 results are likely to be a more reliable guide to climate change in the Australian region.

4. 2×CO_2 climate simulations of the CSIRO4 and UKMO models

4.1 Interpretation of the climate changes simulated for 2×CO_2 conditions

In this section attention will focus on examining the 2×CO_2 MSL pressure, temperature and precipitation simulations of the CSIRO4 and UKMO models, and in particular the difference between these and the corresponding 1×CO_2 simulations. When examining these results, however, one must always consider the possibility that any changes in a model's simulation of a particular field as a result of doubling CO_2 may be due to chance, particularly when highly variable fields such as precipitation are being sampled. The best test of this, short of doing further modelling experiments, is to calculate the statistical significance of the differences between the 1×- and 2×CO_2 simulations.

Significance testing may be done using a simple t-test for the differences of two means. However, when applying a t-test on a grid point by grid point basis for a difference map, problems can arise. Although the results at a number of grid points may be significant, some successes would be expected simply due to chance. Further, the number of points expected to be significant by chance depends on the level of spatial inter-correlation in the data. (For MSL pressure, this correlation would be high.) To overcome these problems, the overall pattern of change can be tested for field significance using the pooled permutation procedure (see Wigley and Santer 1990, and Priesendorfer and Barnett 1983). With this method, the ten year-by-year maps (of, say, January MSL pressure) for both 1×CO_2 and 2×CO_2 conditions are pooled together and two sets of ten years chosen at random a thousand times over. For each of these trials, the number of grid points at which the difference of the two ten-year means passed a t-test is counted. The resulting distribution is compared with the number of significant grid points obtained for the difference between the 2×CO_2 and 1×CO_2 ten-year means. If, for example, the number of successes is greater than the number obtained in 98% of the random trials, then the difference map is field significant at the 98% confidence level.

In the following analysis, t-tests are used to assess significance of the results being examined, and field significance is calculated where it is deemed necessary. Unfortunately, testing by either method could only be done for the CSIRO4 results. Individual yearly data (or indeed standard deviations) were not available for the UKMO model.

Finally, it should be stressed that significance testing in this context is only a guide to the stability of the model results (i.e. it provides an indication of whether the results could be expected to alter substantially if the simulation period was extended). It is not in itself a guide to the relevance of model results to the real world.

4.2 MSL pressure

Figure 22 shows the CSIRO4 and UKMO $2\times CO_2$ simulations of mean January MSL pressure, and Figure 23 the difference between this and the $1\times CO_2$ simulation. Figures 24 and 25 are the corresponding maps for July. The shading on the CSIRO4 maps indicate regions where the change in pressure is significant at the 95% level using a t-test.

The CSIRO4 simulation shows in both seasons a decrease in pressure over the continent and neighbouring lower latitude oceans, combined with a band of increasing pressure to the south. In both January and July the decrease in pressure is significant, but only in January is the increase in pressure significant. The pattern of pressure change in January has a field significance of 97%, and that in July, 92%. (A similar pressure pattern change for winter as a whole (JJA) had field significance of 95%, lessening the concern that the July result was by chance.)

The change in pressure given by the CSIRO4 model represents a southward migration of the subtropical high pressure belt and the associated trade winds and midlatitude westerlies. On theoretical grounds Pittock and Salinger (1982) expected such a migration to accompany global warming, given that high latitudes were expected to show greater warming, thus slackening the meridional temperature gradient. The CSIRO4 model does indeed show greater warming in high latitudes (see Figures 26 and 27 below).

The UKMO simulation shows a decrease in pressure over, and to the south of, the continent in both seasons, resulting in a slightly stronger heat low in January and a slightly weaker continental anticyclone in July. The decrease in pressure to the south of the continent in January is not evident in the full summer season (see Wilson and Mitchell 1987), indicating that this result is unlikely to be significant.

As the CSIRO4 control MSL pressure simulation was superior to that of the UKMO model, particularly in its depiction of the midlatitude westerlies in summer, the CSIRO4 simulated change should be considered the more reliable of the two simulations.

4.3 Temperature

Figure 26 shows the difference in surface air temperature between the $2\times CO_2$ and $1\times CO_2$ January simulations of the CSIRO4 and UKMO models. Figure 27 shows the results for July. The CSIRO4 results, by any criteria, are highly significant (in both January and July more than 95% of grid points showed temperature increases significant at least at the 95% level) and shading to indicate significance is not used in the figure.

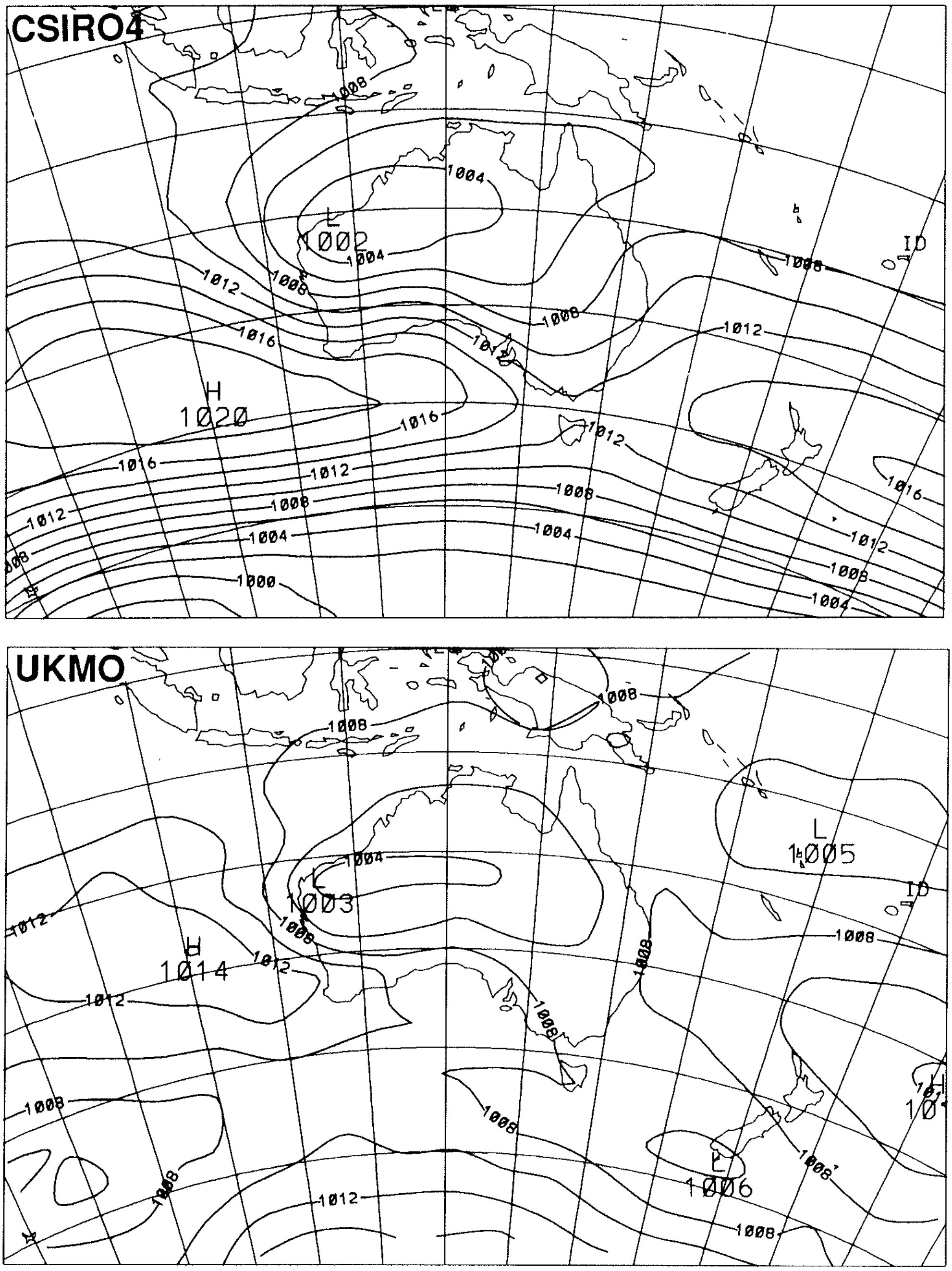


Figure 22: January MSL pressure: $2\times CO_2$ for CSIRO4 and UKMO models (hPa)

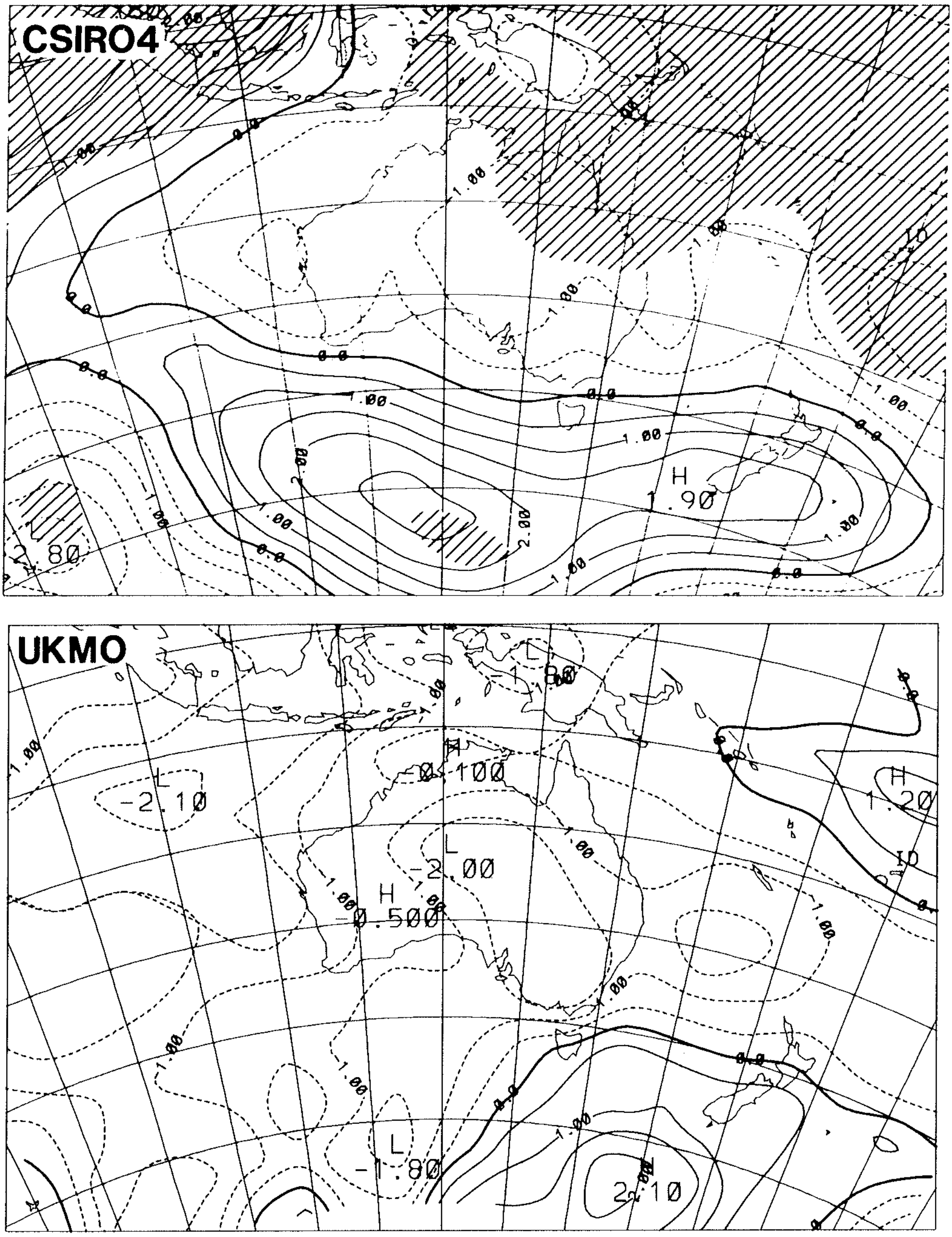


Figure 23: January MSL pressure change: $2\times CO_2$-$1\times CO_2$ for CSIRO4 and UKMO models (hPa). For the CSIRO4 model, changes significant at the 95% level are shaded.

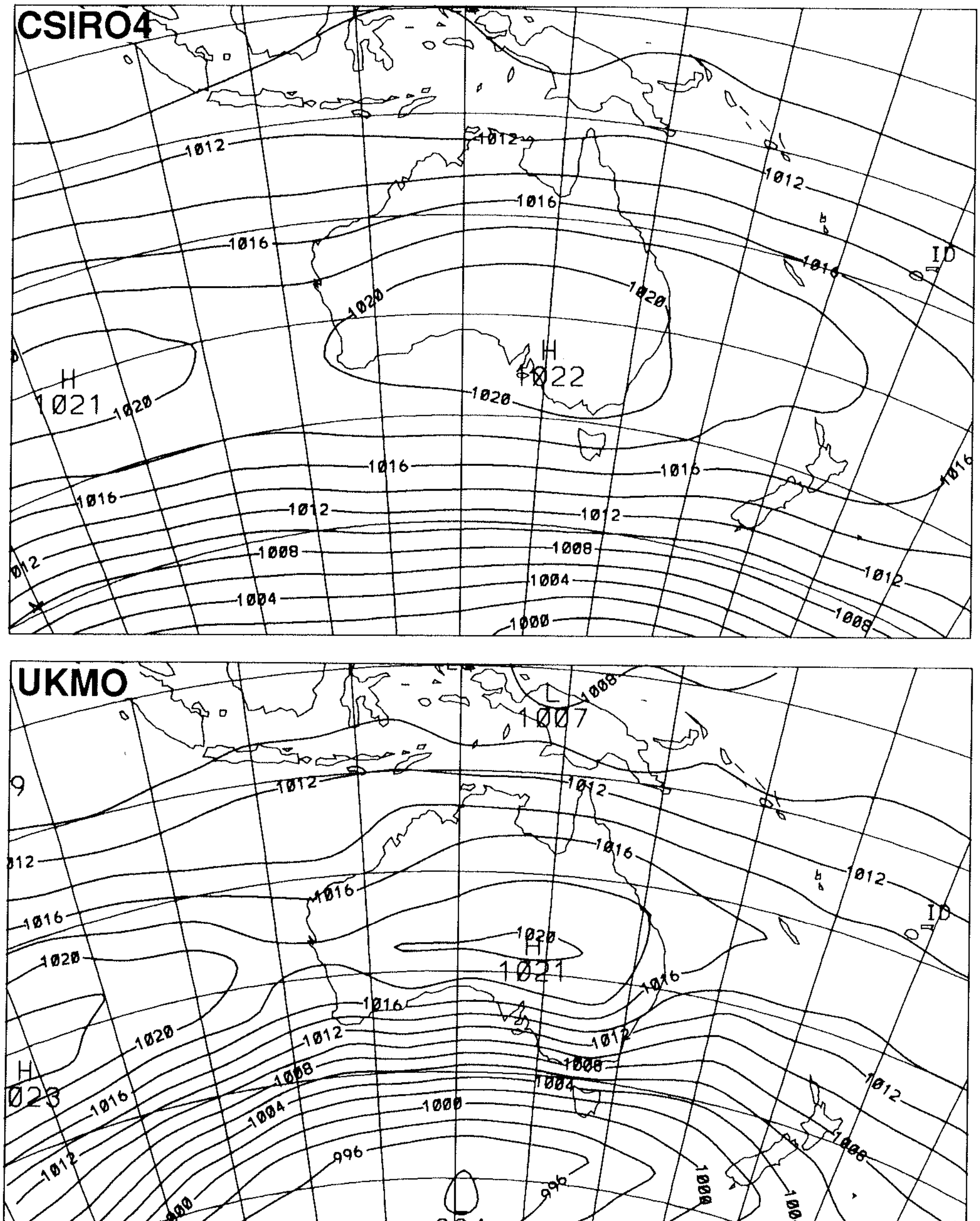


Figure 24: July MSL pressure: $2\times CO_2$ for CSIRO4 and UKMO models (hPa).

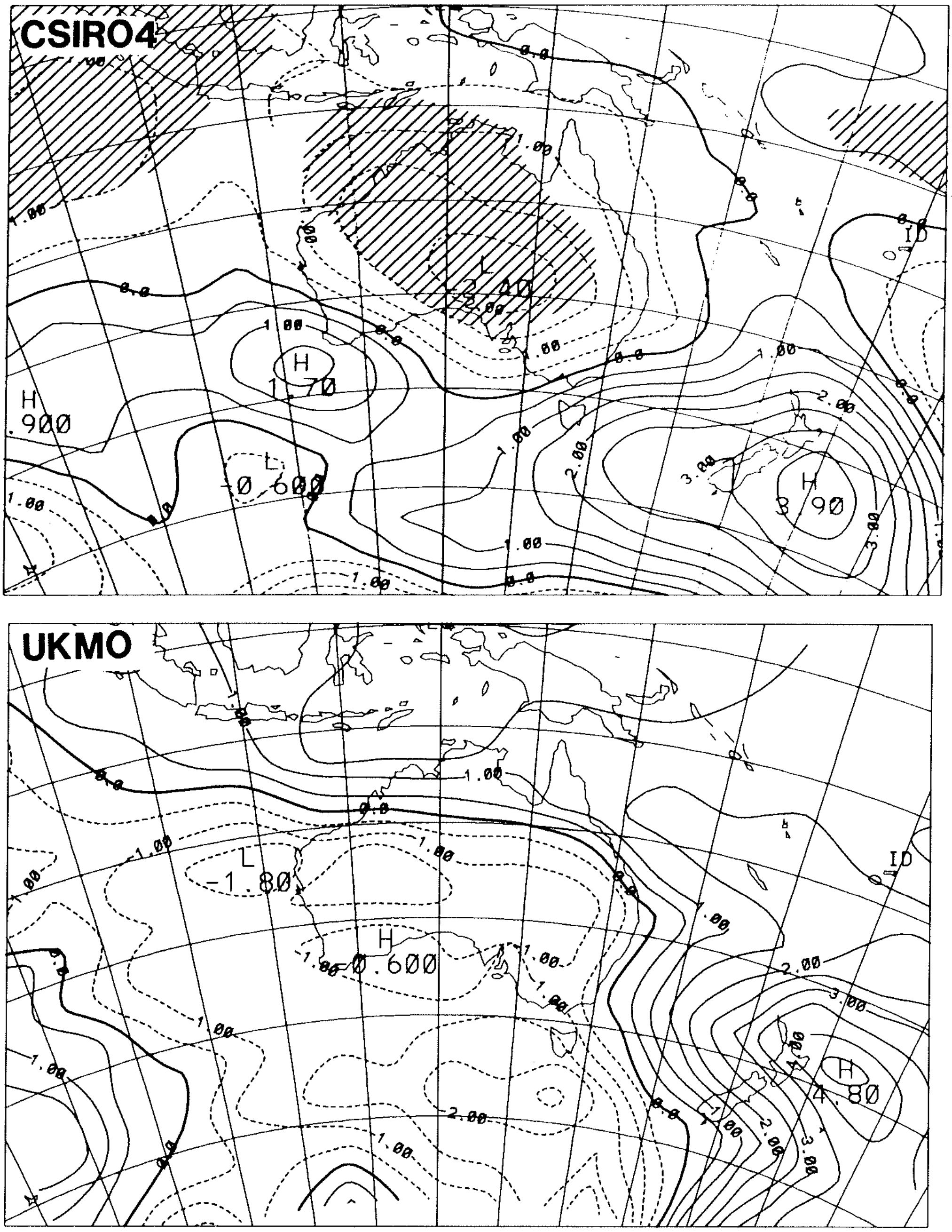


Figure 25: July MSL pressure change: $2\times CO_2$-$1\times CO_2$ for CSIRO4 and UKMO models (hPa). For the CSIRO4 model, changes significant at the 95% level are shaded.

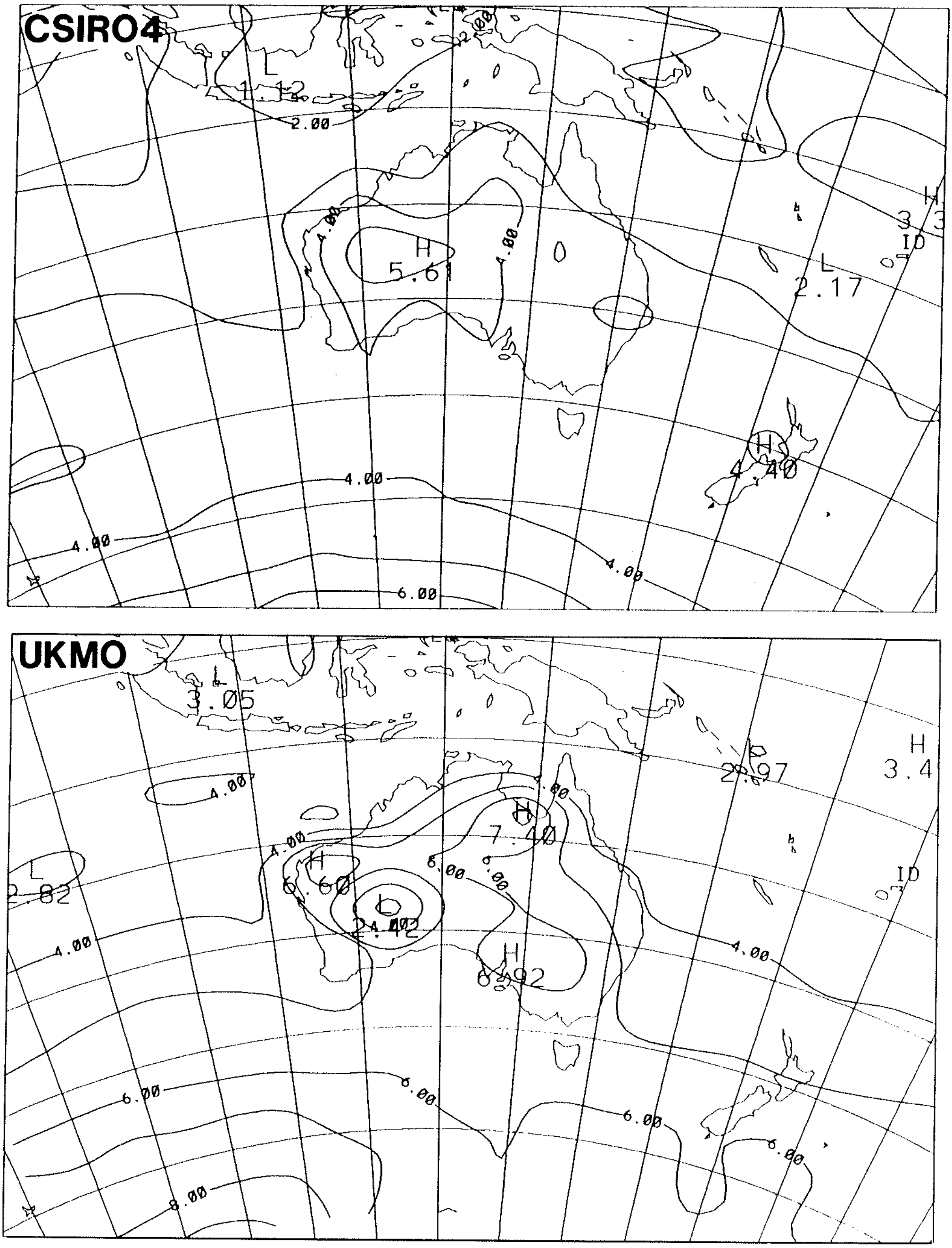


Figure 26: January surface air temperature change: $2\times CO_2$ - $1\times CO_2$ for CSIRO4 and UKMO models (°C).

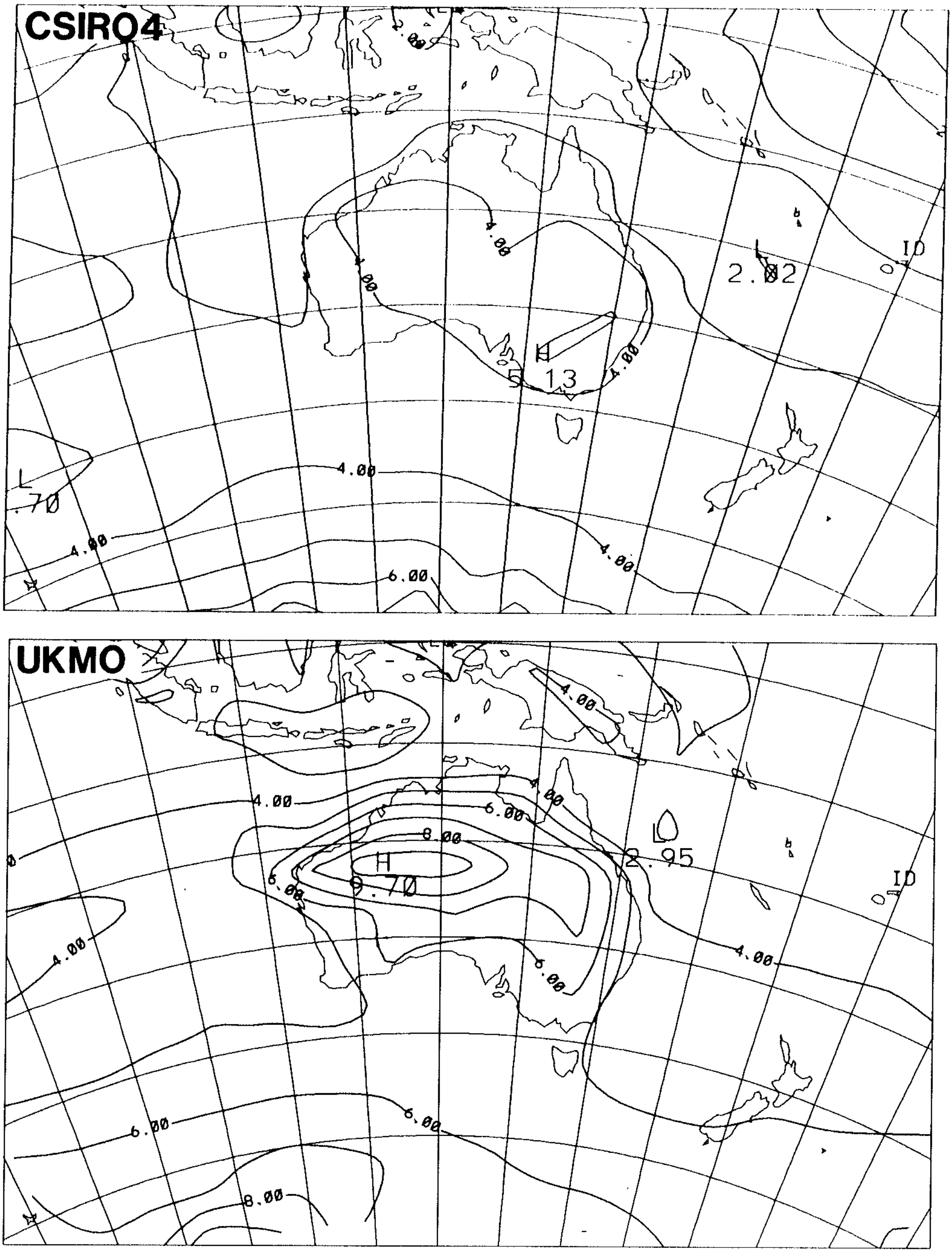


Figure 27: July surface air temperature change: $2\times CO_2$ - $1\times CO_2$ for CSIRO4 and UKMO models (°C).

Over the whole grid there is a tendency in both models and both seasons for greater temperature increases in higher latitudes, which can be attributed to the effect of sea–ice–albedo feedback and the presence, in winter, of a strong temperature inversion in high latitudes which confines any warming to a shallow near-surface layer (Mitchell 1989). This tendency is not prominent over the continent, where the pattern is generally one of greater temperature increases in inland regions. One would expect drier regions to warm more, as less heat would be diverted into increased evaporation. Some of the details of the pattern of temperature increase over the land appear unrealistic (notably that for the UKMO model in January). This patchiness appears to relate to similar patchiness in the simulated changes in precipitation (see Figures 28 and 29), with the warming being least in regions of much increased precipitation.

Overall the warming is greatest in the UKMO model (9°C in one region in July). However, it should be noted that a more recent run of the UKMO model (Mitchell *et al.* 1989), in which the cloud formulation was changed, showed a much reduced global warming which presumably reduced the warming in the Australian region as well. We have made a preliminary examination of the results of a recent high resolution experiment with the UKMO model (which also included the cloud formulation modification). This new simulation shows a reduced warming over Australia and a control temperature simulation which is still acceptable.

4.4 Precipitation

It should be stressed at this stage, that any simulated changes in precipitation are unlikely to be as reliable as those simulated for MSL pressure and temperature, and should be treated with less confidence. This is because precipitation occurrence is quite dependent on sub-grid scale processes, that are necessarily very crudely simulated in GCMs.

Figures 28 and 29 give the DJF and JJA model simulations of the change in rainfall (as a percentage) as a result of doubling CO_2, and shading indicates regions where changes are significant in the CSIRO4 model at the 95% level using a t-test. Only the broadscale structure of these patterns should be examined because averaging periods used (10 years for CSIRO4 and 15 for UKMO) are, for precipitation, very short, and much of the detailed structure is likely to be spurious.

The CSIRO4 model shows, in both seasons, a pattern of increasing rainfall through northern and eastern Australia, but decreased rainfall in the south-west. Both the increases and decreases are of the order of 10 to 20%. Only in a few patches over the continent are the changes in rainfall significant using a grid point by grid point t-test. Field significance of the rainfall changes (assessed using only the grid points over the Australian land mass) is 98% in DJF and 84% in JJA. For the UKMO model there is increased precipitation throughout the continent in both seasons (except at one grid point in summer; and in parts of northern Australia in winter, although at that time of the year there is normally little rain). The increases in rainfall are generally of the order of 10 to 30%.

The pattern of rainfall change given by the CSIRO4 model, particularly in winter, appears to be one of decreased rainfall in the region exposed to westerly winds and increased rainfall elsewhere. This pattern resembles the pattern of rainfall change determined from observational studies (Pittock 1975) to be related to a southward shift of the subtropical high pressure belt. Thus, the simulated rainfall change in the CSIRO4 model is broadly consistent with its simulated change in the pattern of atmospheric circulation (as shown in Figures 23

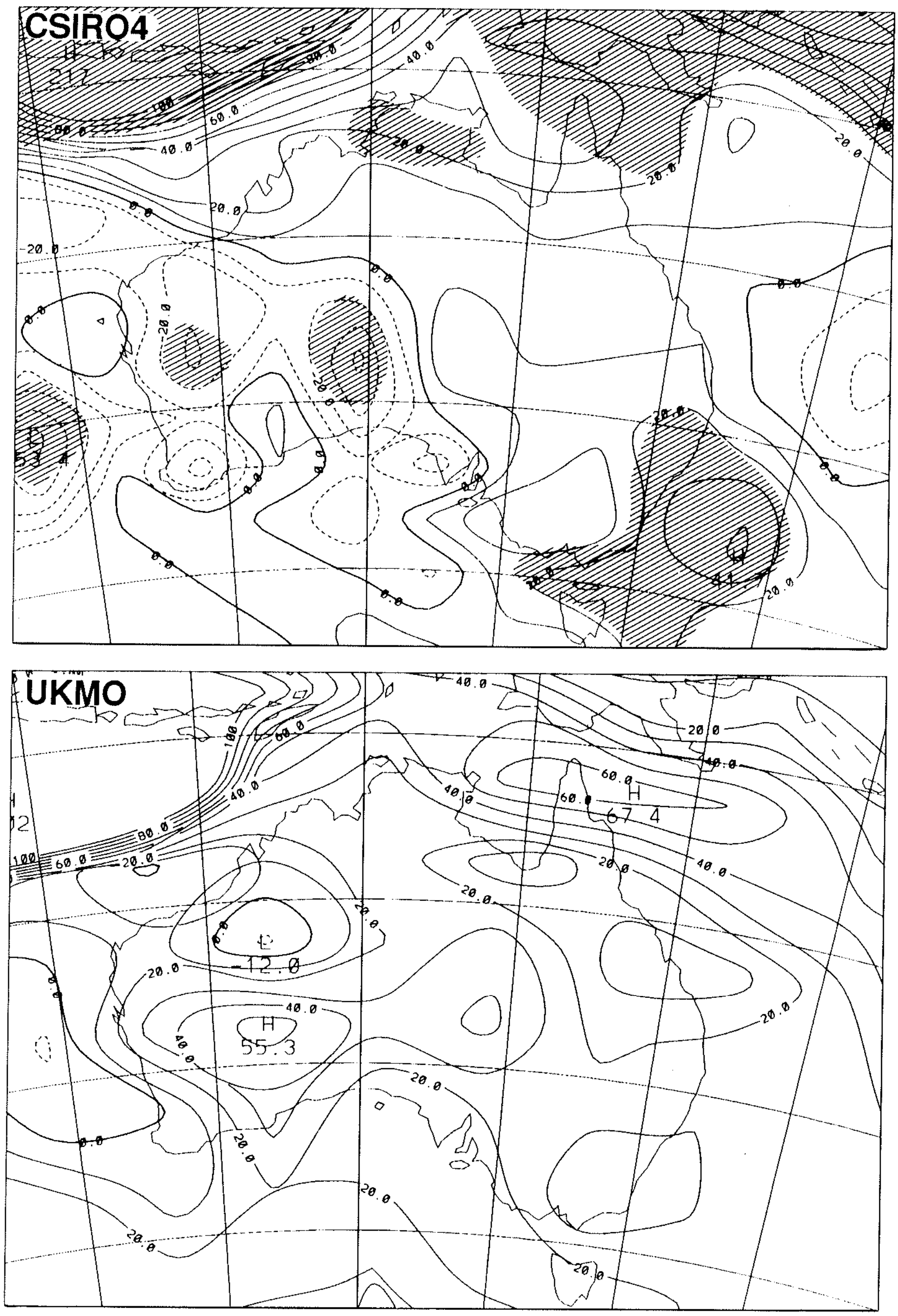


Figure 28: Percentage change in DJF rainfall (2×CO_2 simulation relative to the 1×CO_2 simulation): CSIRO4 and UKMO models. For the CSIRO4 model, changes significant at the 95% level are shaded.

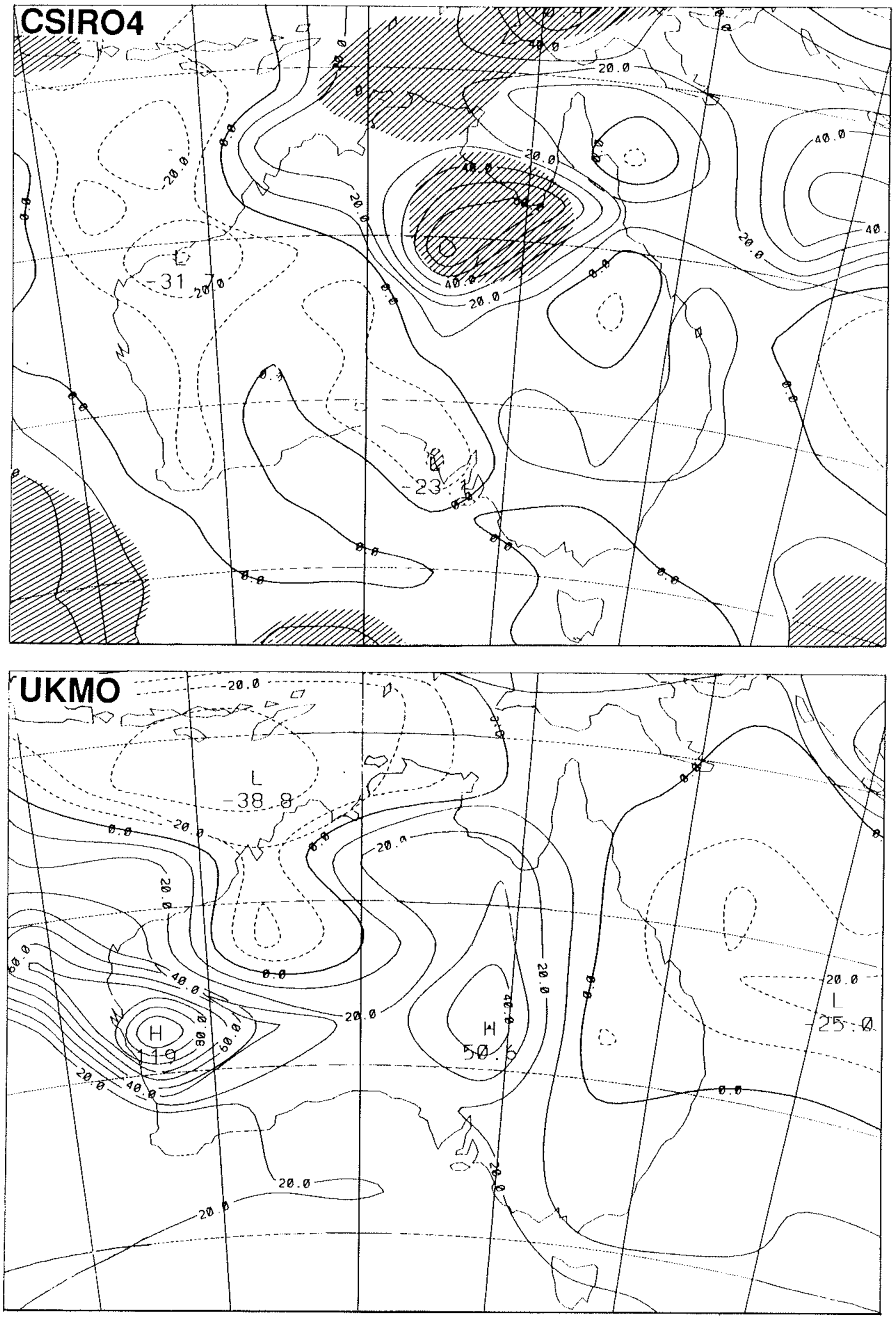


Figure 29: Percentage change in JJA rainfall ($2\times CO_2$ simulation relative to the $1\times CO_2$ simulation): CSIRO4 and UKMO models. For the CSIRO4 model, changes significant at the 95% level are shaded.

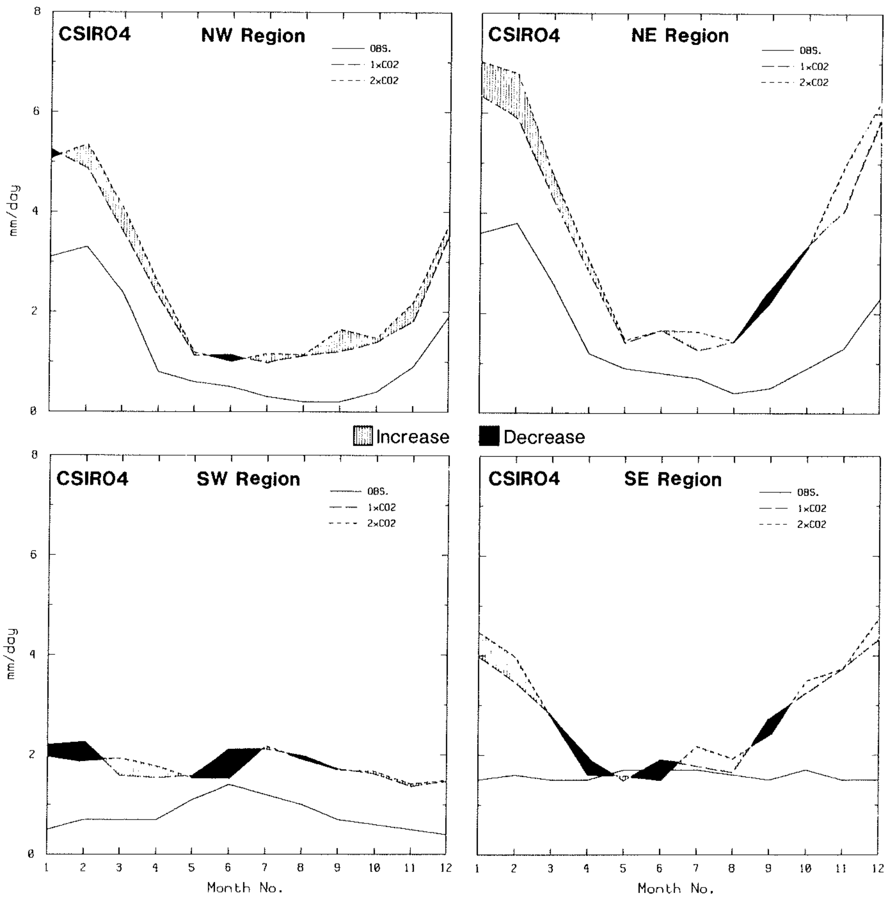


Figure 30: Change in rainfall through the twelve months of the year simulated by the CSIRO4 model for doubled CO_2 in each of the regions defined in Figure 13.

and 25), particularly when allowance is made for the poor representation of topography in the model. Although these results generally suggest a southward shift of circulation features over Australia with a doubling of CO_2, the examination by Ryan *et al.* (1991) of the CSIRO4 model results failed to find any significant southward shift of the monsoon shear line, although the monsoon winds were found to strengthen over northern Australia.

Notably, both models show, in summer, a large increase in rainfall to the north-west of the continent, which, in the CSIRO4 simulation, is statistically significant. In the CSIRO4 simulation this increase in rainfall appears to be linked to a substantial strengthening of the monsoonal westerly winds in this region. This strengthening of the wind was identified by Ryan *et al.* (1991) and Pittock (1990) when they examined tropical low level winds in the CSIRO4 model results.

Figures 30 and 31 give, for the CSIRO4 and UKMO models respectively, the rainfall changes for doubled CO_2 through the twelve months of the year, for each of the four regions

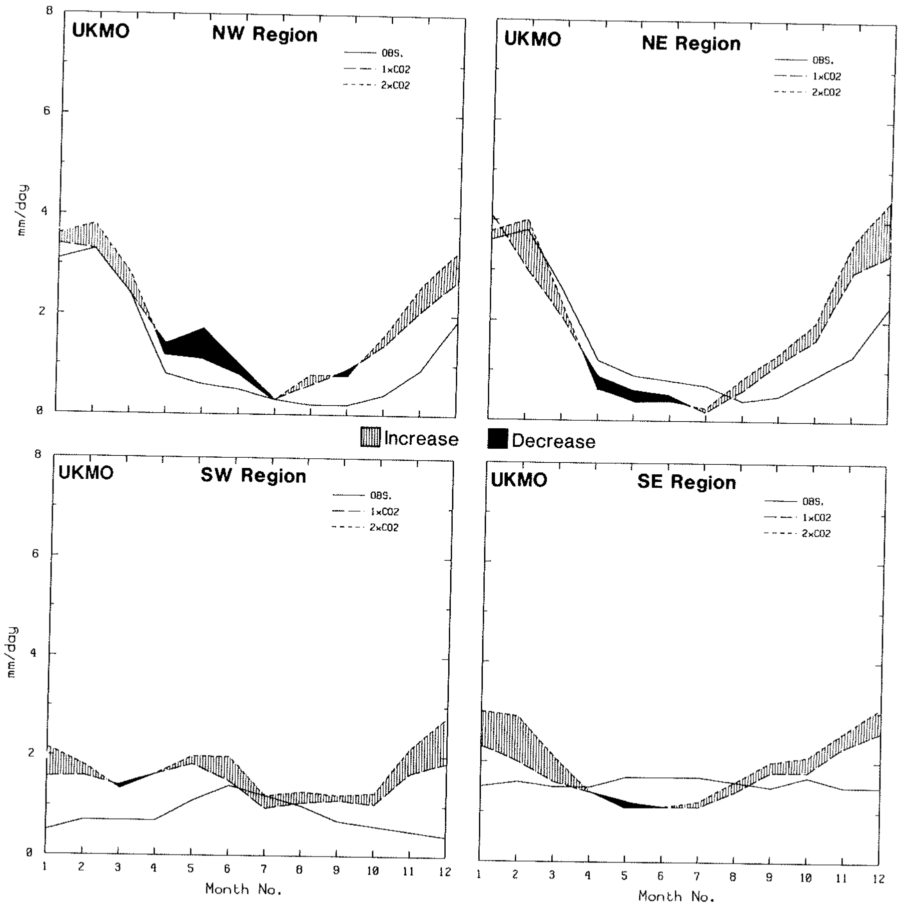


Figure 31: As Figure 30, but for the UKMO model.

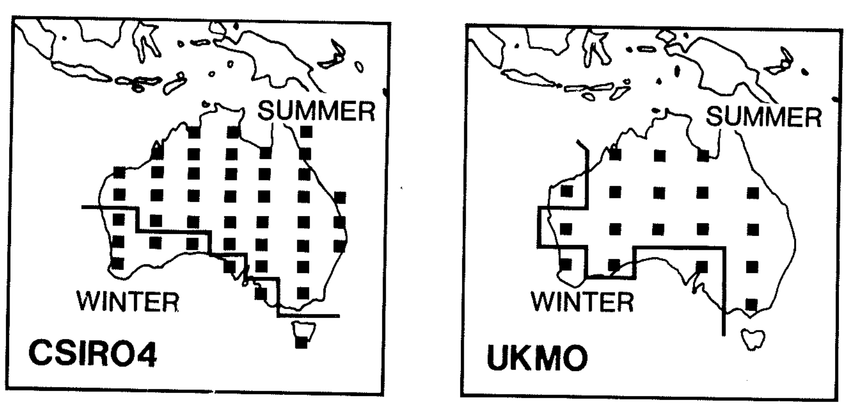


Figure 32: Winter and summer rainfall regions as defined in the control run of the CSIRO4 model, and the UKMO model. A grid point fell in the summer rainfall region if more than 50% of total annual rainfall at that grid point fell in the November to April period.

Table 7: Percentage change in rainfall given by CSIRO4 model (2×CO_2 simulation relative to the 1×CO_2 simulation) for winter and summer rainfall regions and various averaging periods. The two regions are shown in Figure 32. Two asterisks indicate changes significant at the 95% level, and one asterisk significant at the 90% level.

	Nov-Apr	May-Oct	Year
Summer rainfall region	+7.6**	+4.3	+6.6**
Winter rainfall region	-2.1	-7.6*	-5.3 *

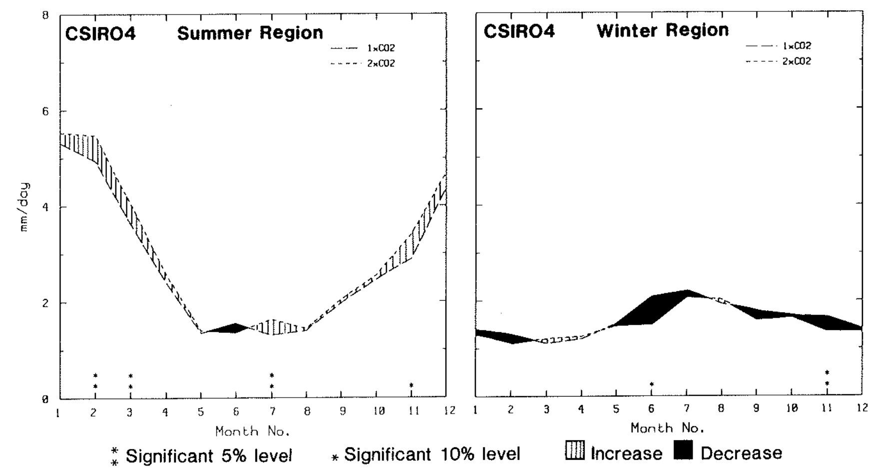


Figure 33: Change in rainfall through the twelve months of the year simulated by the CSIRO4 model for doubled CO_2 for the winter and summer rainfall regions of the model (see Figure 32(a)). Significant changes marked by asterisks, as in Table 7.

used for Figures 14–17. In all regions the CSIRO4 model shows a general increase in rainfall in the warmer months. However, in the two southern regions some rainfall decreases are apparent, particularly in the early winter. The UKMO model shows increasing rainfall in all regions throughout the year except, curiously, during the autumn months, when some decreases are apparent, particularly in the north.

The tendency for the CSIRO4 model to show decreasing winter rainfall in the winter rainfall regime of southern Australia is a result of interest, and if reliable, of some concern. Figure 32 divides the CSIRO4 grid points into those which show, in the control run, a maximum in rainfall in the winter or in the summer half of the year. The two regions so defined correspond poorly with the four regions used in the earlier figures, and hence any tendency for rainfall to change in opposite directions in winter and summer rainfall regions would not have been highlighted in the earlier regional figures. Results calculated using the two regions defined in Figure 32 are presented in Figure 33, and significance of the rainfall changes (based on a simple t-test) are shown. This figure clearly shows increasing rainfall

Table 8: Percentage change in rainfall given by UKMO model (2×CO_2 simulation relative to the 1×CO_2 simulation) for winter and summer rainfall regions and various averaging periods. Significance of changes could not be assessed.

	Nov-Apr	May-Oct	Year
Summer rainfall region	+17.7	+6.1	+14.3
Winter rainfall region	+4.9	+13.1	+10.0

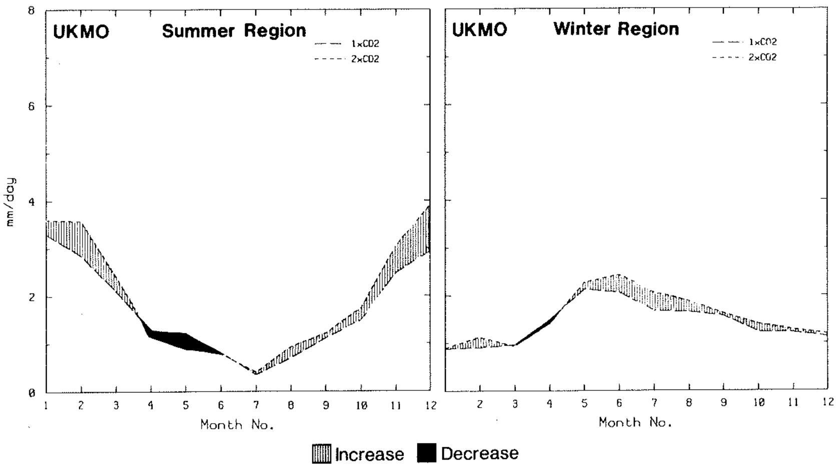


Figure 34: Change in rainfall through the twelve months of the year simulated by the UKMO model for doubled CO_2 for the winter and summer rainfall regions of the model (see Figure 32(b)). Significance of changes could not be assessed.

in the summer rainfall region (with the increase being significant at the 95% level in some months), and decreasing rainfall in the winter rainfall region. Table 7 gives the percentage change in rainfall, and significance of these changes, for the two regions for the November to April half-year, the May to October half-year, and the year as a whole. This table clearly shows that in the CSIRO4 simulation rainfall increases are strongest in the summer rainfall region in the summer half of the year, and rainfall decreases are strongest in the winter rainfall region in the winter half of the year. Based on the significance testing results, greater confidence should be placed on the simulated increase in rainfall in the summer rainfall region.

The same analysis was performed using the winter and summer rainfall regions of the UKMO model (the grid points used are also shown in Figure 32), and the corresponding results are shown in Figure 34 and Table 8. For the summer rainfall region, the pattern of change is similar to that found with the CSIRO4 model, in that the greatest percentage increase in rainfall occurs in the summer half of the year. The percentage increases in rainfall

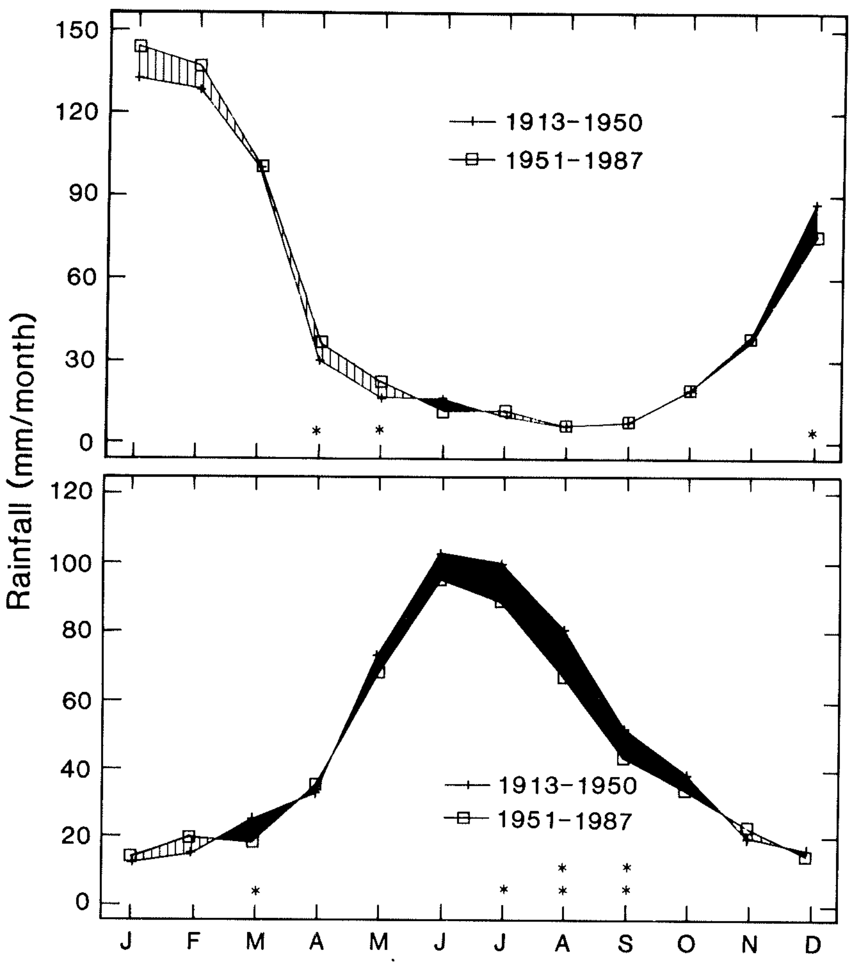


Figure 35: Annual cycle of observed average rainfall for each of two periods (1913-1945 and 1946-1978) for summer and winter rainfall regions. The summer rainfall region is where November to April rainfall exceeds 70% of the annual total, and the winter rainfall region where this is less than 30%. Increases in rainfall are hatched and decreases are fully shaded. Statistical significance if the changes at the 90% confidence level is indicated by a single asterisk, and at the 95% level by two asterisks. (From Pittock and Whetton 1990).

are considerably greater than they are in the CSIRO4 model. In contrast to the results with the CSIRO4 model, the winter rainfall region in the UKMO model shows increasing rainfall. This result, however, is based on data from just three grid points (compared with a corresponding eight grid points in the CSIRO4 model) and is unlikely to be as significant as that obtained with the CSIRO4 model.

It should be noted that Tables 7 and 8 give average changes over large areas. If these are realistic, one should expect significantly larger changes in some smaller regions where the changes in atmospheric circulation interact with the real topography. This could be brought out by the use of higher resolution GCMs or nested limited area models, or perhaps by the application of statistical relationships between broadscale and detailed local observed data (e.g. Wigley *et al.* 1990).

It is interesting to compare the CSIRO4 results, as depicted in Figure 33, with changes in rainfall observed during this century in the summer and winter rainfall regions. Figure 35 (from Pittock and Whetton 1990) compares average rainfall in the two periods 1913–1950 and 1951–1987 for summer and winter rainfall regions defined by the occurrence of 70% or greater of annual rainfall in the November–April and May–October periods respectively. Through most of the year, the observed and modelled changes are qualitatively similar. It should be noted that the agreement of results for the winter rainfall region is mainly applicable to the region of south-west Western Australia. The winter rainfall region in the model includes very few grid points from eastern Australia, due to the model's underestimation of the strength of winter rainfall in that region. The observed winter rainfall region results given in Figure 35 also include little of south-eastern Australia because the definition of the winter rainfall region used excluded the region receiving 50–70% of total rainfall in the winter half year.

Thus there is some support for the CSIRO4 results in the pattern of observed rainfall trends, and the possibility is highlighted that these trends are related to increasing greenhouse gases. Of course, opposite rainfall tendencies in the latter part of the nineteenth century (Gentilli 1971) do not readily fit into such an explanation, suggesting that observed changes this century still fit within the range of natural variability. The CSIRO4 model results for south-west Western Australia are also supported by palaeoclimatic evidence. Six thousand years ago, when global temperatures were higher than present, it appears that conditions were drier over much of south-west Western Australia (Kendrick 1977, Semeniuk 1986, and Wasson and Donnelly 1991).

5. Summary

In this study the results of seven general circulation modelling experiments run to assess the impact of doubling greenhouse gases were analysed. In particular, the model control ($1\times CO_2$) simulations of Australian region MSL pressure, surface air temperature, and precipitation were compared with the observed, to assess the overall performance of the models in simulating Australian region climate. As a result of this analysis the GISS, OSU, GFDL GFDLQ and NCAR simulations available to us were considered to be unacceptably poor in their simulation of climate in the region. The simulated MSL pressure patterns of the GISS and NCAR models were unrealistic, and the OSU and GFDLQ models poorly simulated the seasonal cycle in one or more of the three fields studied; and the GFDL and NCAR simulations had large errors in sea-surface temperature and air temperature over land.

There remained two models, CSIRO4 and UKMO, which performed acceptably in their control simulation of Australian region climate. For this reason these models were considered likely to give a more reliable simulation of the climate expected in the Australian region under conditions of equivalent doubled CO_2 concentrations. Both these models showed that, for doubled CO_2, MSL pressure would decrease a little over the continent, strengthening the heat low of summer and weakening the continental anticyclone of winter. The CSIRO4 model, which had the superior control simulation of MSL pressure, also showed a clear southward migration of the high pressure belt in both seasons. The CSIRO4 simulation gave increases in surface air temperature of around 4–6°C inland and 3–5°C in coastal regions. The temperature increases were generally one to two degrees Celsius greater in the UKMO simulation. The models agreed in showing increases in rainfall in the north and east of the continent, particularly in the summer months. The CSIRO4 model, but not the UKMO model, showed decreasing winter rainfall in south-west and southern Australia, with this being most pronounced at model grid points which show a winter maximum in rainfall. This result of the CSIRO4 model is consistent with its simulated southward migration of the high pressure belt, and is consistent with observed trends in rainfall patterns over Australia during this century.

It should be stressed, however, that the present results must be regarded as very tentative (particularly for precipitation) in terms of reliable prediction of climate change in the Australian region due to doubled CO_2. While the various model simulations are all in broad agreement about the expected warming over the continent in both summer and winter, none of the models give good regional simulations of the observed rainfall pattern, and even those which perform best are not in full agreement as to likely rainfall changes.

More confident predictions must await improved GCM simulations, particularly at higher resolution, or simulations using nested limited-area higher resolution models covering the Australian region. Rapid improvements are being made by several modelling groups, and we look forward to demonstrating improved reliability of new model simulations in the Australian region over the next few years.

Acknowledgements

We wish to thank J. Mitchell, M. Schlesinger, J. Hansen, R. Wetherald, S. Thompson, R. Oglesby, H. Gordon and B. Hunt for allowing us to use data from their modelling experiments. We also wish to thank R. Jenne of NCAR and P. Rayner of CSIRO for their assistance in obtaining some of the model data. We are also grateful for helpful discussions with P. Rayner with regard to the characteristics of the NCAR model, and of GCMs generally, and for general comments on the manuscript provided by J. McGregor and B. Ryan. The program used for assessing field significance using the pooled permutation procedure was kindly supplied to us by K. Walsh of CSIRO. M. Haylock, also of the CSIRO, undertook much of the programming work needed for this report. P. Holper prepared the layout.

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