

# Sensitivity of the Australian surface hydrology and energy budgets to a doubling of CO<sub>2</sub>

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Changes in surface temperature, hydrology and energy budgets are examined over Australia for an equilibrium doubled CO<sub>2</sub> experiment using the Bureau of Meteorology Research Centre (BMRC) general circulation model (GCM). Changes in the surface hydrology budget are compared with those modelled using the Geophysical Fluid Dynamics Laboratory GCM. The continent is divided into northern and southern regions. These regions display soil moisture maxima in summer and winter respectively in both models, which essentially reflects the simulated seasonality of precipitation and evaporation. In the modelled doubled CO<sub>2</sub> climate, the BMRC GCM finds a strong increase in soil moisture in northern Australia in summer, due to a large increase in precipitation. Both models find a decrease in soil moisture in southern Australia in winter. This may be contrasted with a summer drying generally found at mid-latitudes in the northern hemisphere by GCMs. The BMRC model shows the crucial change in southern Australia to be a decrease in autumn precipitation. The findings highlight the danger of considering precipitation changes alone when assessing climate change impacts, as large increases in precipitation throughout most of the year do not result in increases in soil moisture. The soil moisture/cloud feedback mechanism proposed for northern continents appears to operate in Australia as well, although does not extend to high-level clouds. Changes in the surface heat budget involve a general increase in downwards long wave radiation except for southern Australia in autumn. The model response generally produces a close 'pairing' of long and short wave radiation changes, caused primarily by clouds and resulting in net radiative changes at the surface close to zero. This forces a similar pairing of latent and sensible heat changes to occur also.

## Introduction

Potential impacts on soil moisture as a result of climate change are of great significance due to the implications for plant growth generally, and for agriculture in particular. Because of this, analysis of soil moisture changes under a doubled CO<sub>2</sub> scenario featured prominently in the Intergovernmental Panel on Climate Change (IPCC) report (Houghton et al. 1990) and the 1992 IPCC update (Houghton et al. 1992). A range of investigators have examined changes in soil moisture, and surface hydrology in various regions in the northern hemisphere under a doubled CO<sub>2</sub> scenario.

Manabe and Wetherald (1987), Kellogg and Zhao (1988) and Meehl and Washington (1988) have looked at general circulation model (GCM) simulations over North America, Europe and Asia. They find reasonable agreement between the models on summer drying over the mid-latitude northern hemisphere continents. The IPCC report (Houghton et al. 1990) listed the temperature, precipitation and soil moisture changes in five regions, including Australia, from three GCMs. In that report, considering the Australian continent as a whole, the models roughly agreed as to the size of the temperature increase. They also agreed upon the sign, although not the magnitude, of the seasonal precipitation changes. However, there was no consensus between the models on the

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soil moisture changes, with disagreement even as to the sign of the change. This degree of disagreement is not surprising, given the fact that soil moisture changes are the sum of changes in other variables, and differences between the models may be expected to be compounded. There was not, however, any discussion of the mechanisms underlying the differences in the impact upon soil moisture found by the models. In the Australian region, Whetton and Pittock (1991) have analysed the results from two GCM doubled CO<sub>2</sub> experiments for changes in temperature and precipitation, and found some disagreement, particularly in precipitation. These differences may be expected to produce similar disagreements in the soil moisture changes.

Associated with the changes in soil moisture, responses would also be expected in the surface energy budget. On a regional scale, an analysis of the surface energy budget for the same northern hemisphere areas was presented by Manabe and Wetherald (1987) and Meehl and Washington (1988). These latter authors also discussed responses in low cloud, relating these to a feedback with the soil moisture, although some changes were small and significance levels were not cited for the differences in the cloud amount or the soil moisture. They did, however, find evidence of a positive feedback amplifying the soil moisture changes.

The present study analyses the changes in the surface hydrological budget simulated by the Bureau of Meteorology Research Centre (BMRC) and Geophysical Fluid Dynamics Laboratory (GFDL) GCMs for a doubling of atmospheric CO<sub>2</sub> for northern and southern Australia. The present study investigates in detail the response of certain other parameters in the BMRC model, including surface temperature and surface heat budget, and cloud amount. This investigation does not purport to predict actual values of these parameters in a true doubled CO<sub>2</sub> climate. As noted above, the level of agreement between models is low. Indeed, even if close agreement were found between the models the study would not, of course produce definitive results. Nevertheless, such a study may highlight the important physical interactions and feedbacks which might be expected, and extends the northern hemisphere investigations to a southern hemisphere continent. In particular, this permits an examination, for the Australian region, of the soil moisture/cloud feedback proposed for the northern hemisphere mid-latitude continents by Manabe and Wetherald (1987). The changes found in soil moisture may also be compared with the differences in precipitation to serve as a guide as to how useful precipitation changes alone may be in assessing impacts of a doubling of CO<sub>2</sub>.

In the GCMs investigated, the surface hydrology scheme (the so-called 'bucket' soil moisture

model) is, of course, extremely simple. Thus some land-surface processes (for example, interactions with the vegetation canopy) are missing or inadequately parametrised. Nevertheless, the present scheme permits an essential interaction between surface wetness and the free atmosphere to take place in the models. Indeed because of the extreme simplicity of the soil moisture model used in the present study, an understanding may be gained into the most basic physical processes and feedbacks involved. The responses of the present, simplified, system should thus serve as a benchmark for comparison with subsequent results obtained using models with more sophisticated land-surface schemes (see e.g. Henderson-Sellers 1990).

## Experiment

The present results were derived from equilibrium doubled CO<sub>2</sub> experiments performed using the BMRC and GFDL GCMs. A brief analysis of the GFDL results for the surface hydrology budget will be given, as these results were quoted in the IPCC report (Houghton et al. 1990) for the Australian region. These results are from the experiment listed in Table 3.2(a) of the IPCC report (Houghton et al. 1990). This model was run at rhomboidal wave 30 in the horizontal, with 9 levels in the vertical. A description of the GFDL GCM and its global response to a doubling of CO<sub>2</sub> is given by Wetherald and Manabe (1988).

The BMRC GCM was run at rhomboidal wave 21 in the horizontal, with 9 levels in the vertical. These levels correspond to 'sigma' values of 0.991, 0.925, 0.811, 0.664, 0.500, 0.336, 0.189, 0.074 and 0.009. Vertical diffusion follows the stability dependent form of Louis (1979). Convection is treated by a modified Kuo (1974) scheme, with moistening in the convective layer following the form specified by Anthes (1977). Shallow convection follows the treatment of Tiedtke (1984) and gravity wave drag is determined using the formulation of Palmer (Palmer et al. 1986). The radiation scheme used is a modified version of the Fels-Schwarzkopf scheme developed at GFDL (Fels and Schwarzkopf 1975). A detailed discussion of the cloud-radiation interaction is given in Rikus (1991). A vertical finite differencing scheme following Dix (personal communication 1991) has been implemented. A general description of the model, and an analysis of the effects of recently revised physical parametrisations are presented by Hart et al. (1988, 1990). A description of the ocean and sea-ice models is given by Colman et al. (1992). The simulation of the present climate by the GCM with observed sea-surface temperatures is given by McAvaney et al. (1991).

The model was run for both presently observed CO<sub>2</sub> levels (the 'control' or '1 × CO<sub>2</sub>' experiment) then to equilibrium for a doubling of CO<sub>2</sub> (the '2 × CO<sub>2</sub>' experiment).

In the surface component of the hydrological cycle the soil moisture model used in both GCMs is a simple 'bucket' model (see e.g. Manabe 1969), with a field capacity specified as 150 mm for all land points. Excess moisture over the 150 mm is deemed to be 'run-off', and is effectively lost to the hydrology cycle. The prognostic equation for soil moisture,  $\omega$ , may thus be written as:

$$\frac{\partial \omega}{\partial t} = r - e + m - f \quad \dots 1$$

where  $r$ ,  $e$ ,  $m$  and  $f$  are the rates of precipitation, evaporation, snow melt and run-off respectively.

Over land points, the surface heat budget at any particular point may be expressed by the equation:

$$SW + LW + LH + SH + S + SM = 0 \quad \dots 2$$

where  $SW$  and  $LW$  represent the net downward short and long wave fluxes at the surface respectively,  $SH$  and  $LH$  represent the sensible and latent heat fluxes respectively,  $S$  represents conduction into the soil, and  $SM$  any snow melt taking place. The expressions for  $LH$ ,  $SH$  and  $S$  for the BMRC model are given by Hart et al. (1988), with the boundary-layer parametrisations based on the formulations of Louis (1979). At each time step an iterative process is used to vary the terms on the left-hand side of Eqn 2 by varying the surface temperature, so that the equation is satisfied. In the present experiment, monthly means were calculated over 15 years, after model equilibrium, both for single CO<sub>2</sub> ('control') and doubled CO<sub>2</sub> cases. Monthly and seasonal means and monthly standard deviations were calculated for each field also.

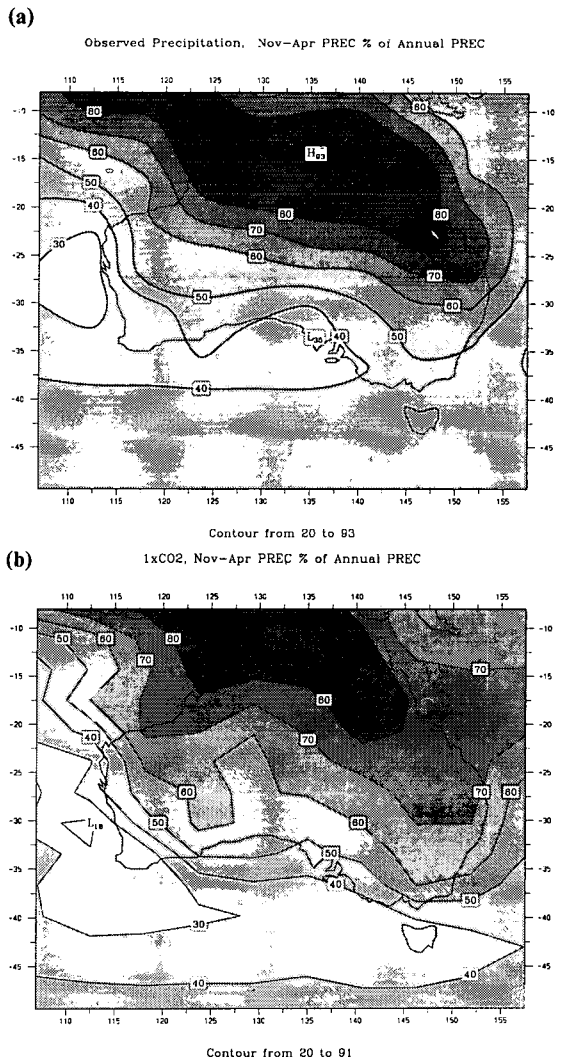
## Changes in Australian surface temperature and soil moisture

### Geographical distributions

The IPCC (Houghton et al. 1990) report quoted full Australian continental means for December–February and June–August for the three meteorological variables presented (temperature, precipitation and soil moisture). The northern and southern regions of Australia, however, are subject to contrasting climates, with northern Australia generally experiencing a summer rainfall maximum, tending towards a winter maximum in the southern parts of the continent (Whetton and

Pittock 1991). To illustrate this, Fig. 1(a) shows the rainfall occurring in Australia during the period November to April as a percentage of the annual total, from the observations of Jaeger (1976). Figure 1(b) shows the same plot for 15 years of the control experiment for the BMRC GCM. It can be seen that the pattern of rainfall seasonality found in the model agrees reasonably well with observations in this test. The contrast in seasonality across Australia is readily apparent in these plots and underlies the inappropriateness of

**Fig. 1** Rainfall occurring in the period November to April as a percentage of the annual total for the Australian continent. (a) Observations (from Jaeger (1976)), (b) as simulated by the BMRC GCM.

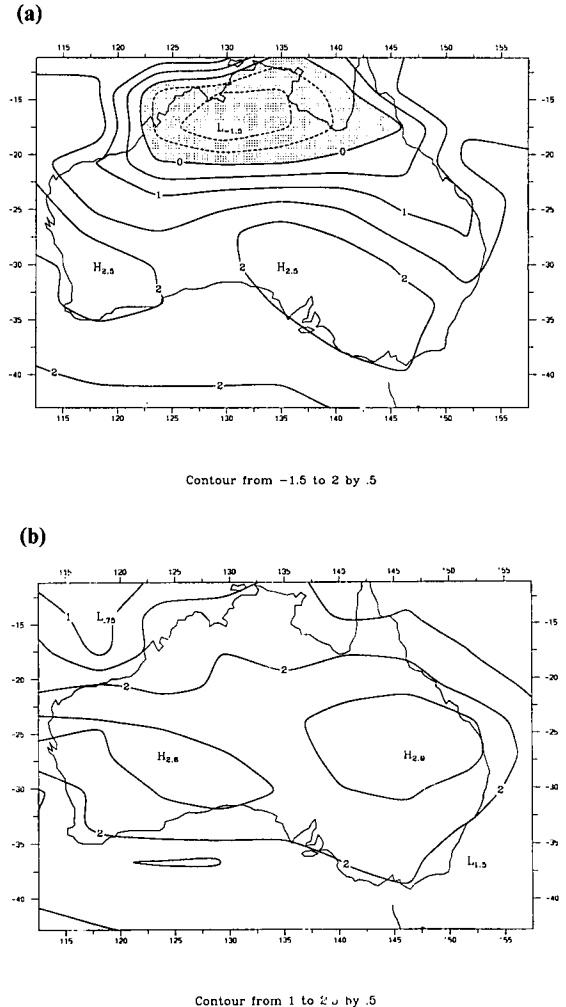


analysing a full continental mean. In the light of the results from Fig. 1, the area averages computed for Australia were divided into the region north of 25°S, denoted as 'northern Australia' (NA) and south of 25°S, denoted as 'southern Australia' (SA). Of course, a more elaborate division of the Australian continent into sub-regions could be performed (see e.g. Whetton and Pittock 1991). However, it was decided in the present analysis to divide the continent in half along a latitude, both for simplicity and also since this was found to capture the essence of the seasonal division of precipitation and soil moisture. Furthermore, the present study is not concerned with the details of finer continental sub-regions but with the broad semi-continental changes and feedbacks. Indeed, analysis of finer regions may not be justified given the resolution of the experiments and the simplicity of the important surface parametrisations used, and such analysis would certainly also reduce the statistical significance of the changes discussed (thereby necessitating much longer model integrations for significant results).

The geographical distribution of changes, due to a doubling of CO<sub>2</sub>, in surface temperature and soil moisture for the BMRC model for December–February and June–August is shown in Figs 2 and 3. Although it must be stressed that little confidence is to be placed in the details of the regional response, interesting results may be found on the semi-continental scale. The pattern of surface temperature increase shown in Fig. 2 is similar to that of other GCM results (and in particular that of the GFDL model) in June–August (JJA) (see Houghton et al. (1990), Fig. 5.4), although the BMRC increases are lower than most other models. There is a temperature increase throughout the continent, larger in the south than in the north. Notably, however, the December–February (DJF) pattern is markedly different from that of other GCM results, with a surface temperature *decrease* found in northern parts of the continent. The reasons for this temperature decrease are discussed below. It should be noted that a similar temperature decrease is found over India in JJA (not shown). However, it should also be noted that, in the annual mean, a small net temperature *increase* is found in both regions.

Soil moisture changes show a large summertime increase for the whole of Australia, particularly large in NA. In the IPCC report (Houghton et al. (1990), Fig. 5.8), this pattern is most similar to that of the Canadian Climate Center. In the winter an increase is found in the north and a general decrease in the south, again highlighting the difference in the seasonal climate change in the two regions. In the IPCC report (Houghton et al. (1990), Fig. 5.8), large disagreement is found between the three models reported. The seasonal cycle of the BMRC and GFDL soil moisture changes, as well as the other components of the surface hydrology budget are discussed below.

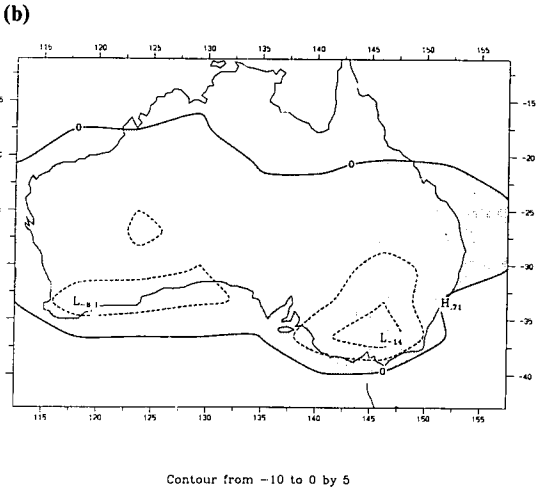
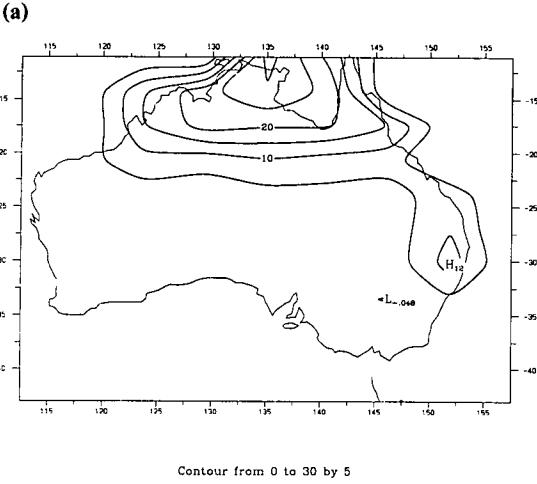
**Fig. 2** Difference in surface temperature (K) for Australia between the control and the 2×CO<sub>2</sub> climate for the BMRC model. Averages are taken over 15 years. Plots are shown for (a) December–February (DJF) and (b) June–August (JJA). Stippled areas correspond to regions of cooling.



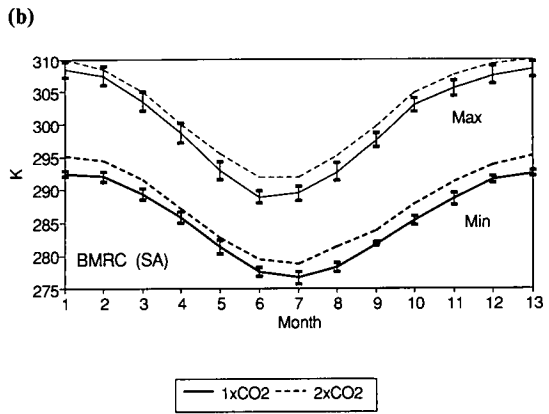
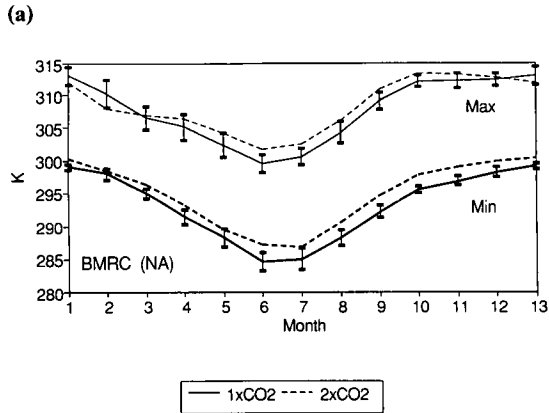
### Seasonal changes

The area average daily maximum and minimum temperatures for NA and SA from the BMRC model are shown in Fig. 4 as a function of month (January is denoted by months 1 and 13) for both the control and 2×CO<sub>2</sub> climates. In each case an error bar is shown on the control run curve, indicating the size of the change required in the variable in order that it be significant at the 99 per cent level. These error bars were calculated from the standard deviations of the monthly means over the 15-year averaging period using a two-tailed Student's t-test, and allowing for the change in variance between the control and 2×CO<sub>2</sub>

**Fig. 3** Difference in soil moisture (mm) for Australia between the control and the 2×CO<sub>2</sub> climate for the BMRC model. Averages are taken over 15 years. Plots are shown for (a) December–February (DJF) and (b) June–August (JJA). Stippled areas correspond to regions of decreased soil moisture.



**Fig. 4** Area averaged control and 2×CO<sub>2</sub> daily minimum and daily maximum surface temperatures (K) for the BMRC model as a function of month (month 1 = month 13 = January). Averages are taken over 15 years. Error bars indicate the change required for significance at the 99 per cent level, by a 2-tailed Student's t-test. Plots shown are for (a) NA and (b) SA.



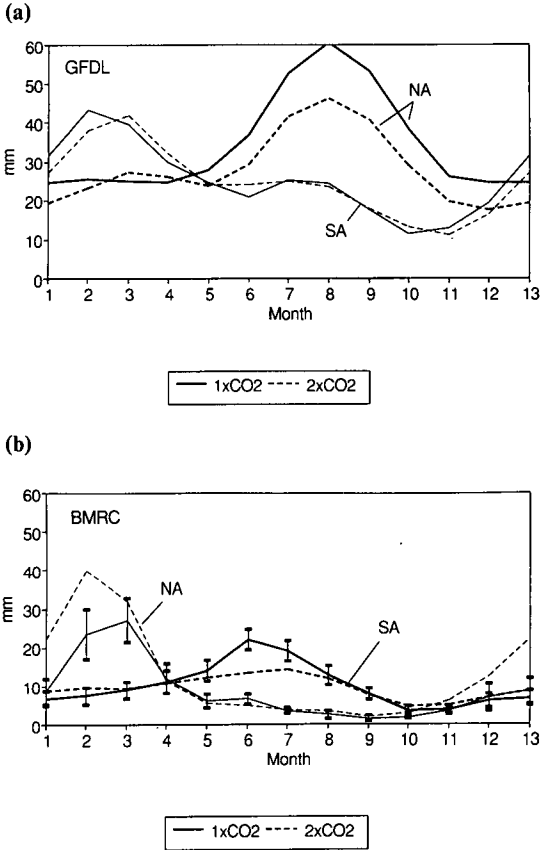
climates (Walpole and Myers 1990). From Fig. 4 it is apparent that the daily maximum and minimum temperature changes in both NA and SA are generally significant at the 99 per cent level, with slightly higher significance in SA than NA.

Two features in particular are noteworthy. Firstly, the general temperature increase which occurs in both NA and SA is found to be approximately equal in both the daily maxima and minima. In this regard there is some observational evidence that recent mean temperature increases over southeastern Australia (Houghton et al. (1990), Fig. 7.15) and over northern hemisphere

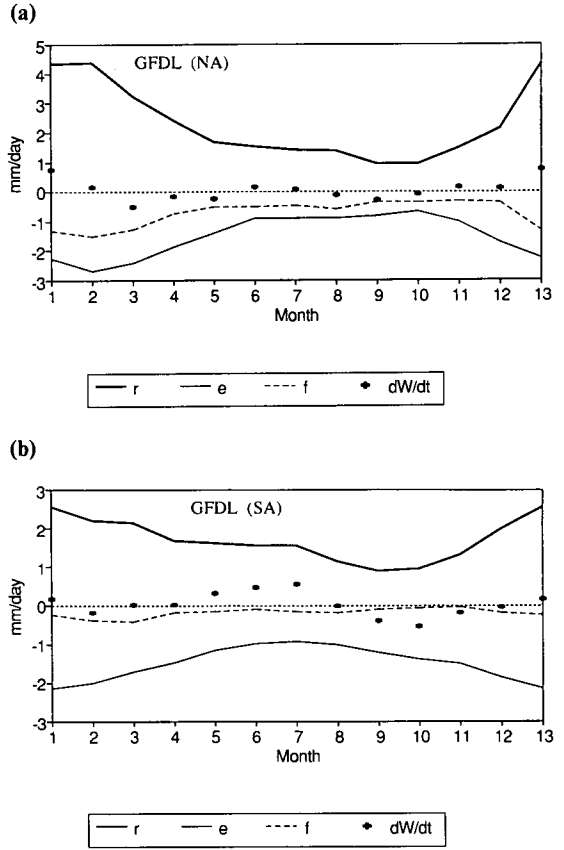
continents (Karl et al. 1991) show more of an increase in the minimum than in the maximum. Secondly, the summertime NA temperature decrease is principally the result of a daytime, maximum temperature decrease, suggesting a decrease in incoming solar radiation. As shown below, this is associated with a large increase in both low-level cloud and in the soil moisture.

The seasonal cycle of the soil moisture for the two areas (NA and SA) modelled by the GFDL GCM is shown in Fig. 5(a) and by the BMRC GCM in Fig. 5(b). These figures show results for both control and 2×CO<sub>2</sub> climates, as well as 99 per cent significance 'error' bars for the BMRC experiment. The significance levels are not available for the GFDL data. The individual components of the hydrology budget for the two areas are shown in Figs 6 and 7 for the GFDL and BMRC control experiments respectively.

**Fig. 5** Soil moisture (mm) for the control and  $2 \times \text{CO}_2$  climates for NA, and SA for (a) the GFDL model and (b) the BMRC model, as a function of month (month 1 = month 13 = January). Error bars on the BMRC control curves indicate the change required for significance at the 99 per cent level.



**Fig. 6** Components of the surface hydrological budget for the GFDL control experiment (in mm/day) for (a) NA and (b) SA. The codes correspond to those specified in Eqn 1. Positive values correspond to components contributing to an increase in soil moisture.



The patterns of annual variation in the soil moisture are markedly different for SA and NA in both of the models. However, the patterns of the seasonal cycles (i.e. of occurrence of maxima and minima) for the BMRC GCM show a reasonably similar seasonal soil moisture pattern to that of GFDL in both NA and SA (Fig. 5). The actual value of the soil moisture in the control climate and the changes, however, are different. In NA, in the control climates, both models show a maximum in soil moisture in late summer or early autumn, and a minimum in spring. In the control climate in NA, the BMRC soil moisture shows a more marked seasonal variation. The soil moisture is also substantially lower than that of the GFDL GCM throughout the year. The individual terms in the hydrological budget for the models are shown in Figs 6 and 7. Note that the sign of each term reflects whether it adds or removes from the soil moisture (hence, for example, evaporation is negative). The BMRC model control

run surface moisture budget (Fig. 7(a)) shows that precipitation and evaporation are both at their greatest in the early months of the year, with the high summer soil moisture being largely the result of the excess of precipitation over evaporation in January to March. The NA surface water budget for the BMRC model is, indeed, very simple, with  $\partial\omega/\partial t$  essentially varying with precipitation minus evaporation. Run-off is substantial only briefly, in summer. By contrast, the GFDL model shows a consistently higher soil moisture throughout the year, with a substantial run-off occurring (although significant winter run-off appears unrealistic in NA in winter). In the GFDL model, the summertime maximum in soil moisture is broader, and high values of soil moisture persist much further into the year, with a distinct minimum in late spring. In the GFDL model, Fig. 6(a) shows that the summer soil moisture maximum is principally the result of the large excess of precipitation over evaporation and run-off in December and January.

Fig. 7 As for Fig. 6, for the BMRC model.

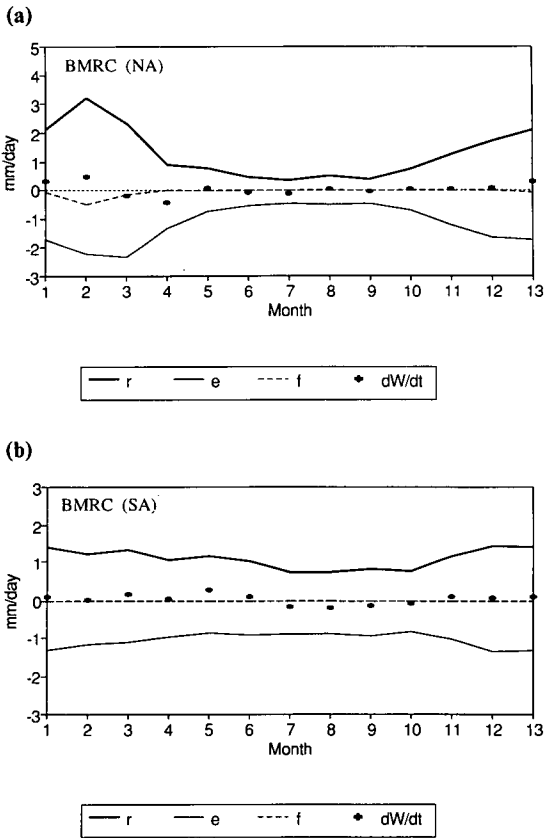


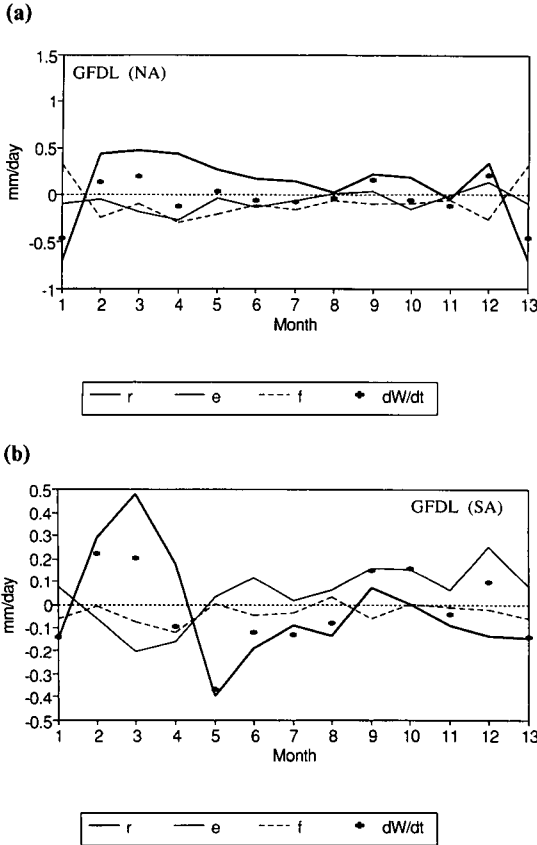
Figure 5 also shows the soil moisture annual cycle for the  $2 \times \text{CO}_2$  climate. In NA, in the  $2 \times \text{CO}_2$  climate, the BMRC model shows a very large and significant increase in summer soil moisture. Figure 5(b) shows that this increase results in approximately double the soil moisture from December to February. By contrast, the GFDL model displays relatively little change, although there is a slight drying in early summer. In both models there is very little change in autumn or winter values (and certainly no changes in the BMRC model at the 99 per cent significance level). The changes in the individual terms of the surface hydrological budget are shown in Figs 8 and 9 for the two models. Note that increases in terms *reducing* the soil moisture (such as an increase in evaporation) appear as negative. The large increase in the BMRC summer soil moisture is the result of a large increase in summer precipitation (with an increase of around 75 per cent occurring in January). Evaporation also increases, but not to the same extent. Certainly there is not the increase in evaporation which might potentially occur as a result of the doubling of the soil moisture (and hence of the potential evaporation). Run-off also increases

slightly during this time, but the changes remain smaller than the other two terms in the equation as the soil is, on average, still far from saturation. In the GFDL model there is, by contrast, a decrease in precipitation in January, and a modest increase in late summer and autumn precipitation.

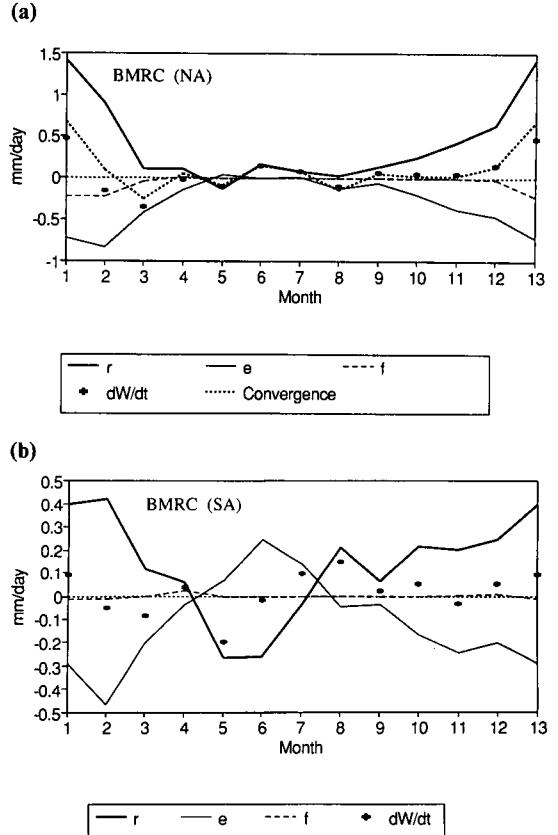
In SA, both model control climates show a prominent winter soil moisture maximum, although the peak occurs around two months later in the GFDL model than in the BMRC model. Once again, as in NA, the GFDL model has a substantially higher soil moisture than the BMRC model throughout the year. An examination of the surface moisture budgets (Figs 6(b) and 7(b)) shows the soil moisture cycle to be essentially the resultant of precipitation minus evaporation, although the GFDL model shows some run-off, due to its higher soil moisture, and hence greater number of saturated points in the averaging area. Neither model has significant snow melt. The GFDL model precipitation follows the same seasonal pattern as that of the BMRC model, but is around double the magnitude (which results in the greater soil moisture throughout the year). It is important to note that both models give a winter soil moisture maximum, despite a slight precipitation minimum in winter, because of an excess of precipitation over evaporation in late autumn and early winter.

In the  $2 \times \text{CO}_2$  climate, both models show a decrease in soil moisture. In the case of the BMRC model this drying is confined to winter, whereas in the GFDL model the decrease extends from late autumn to early summer, but is greatest in early spring. It is apparent from Fig. 5(a) that the drying noted in the IPCC report for the GFDL model (Houghton et al. (1990), Table 5.1) is dominated by changes in SA, with little signal in NA. Figures 8(b) and 9(b) show that the cause of this decrease in soil moisture in both models is a decrease in late autumn and early winter rainfall. Evaporation also decreases in both models, but not to the same extent, resulting in a slower rate of increase in soil moisture at this time of year. Changes in run-off are not found to be significant in either model at this time of year. It is interesting to note the very high sensitivity of the soil moisture in both models during the period in which soil moisture is increasing (i.e. in autumn, when precipitation generally exceeds evaporation). This also highlights the potential danger in assessing climate change impacts from changes in precipitation alone, without considering changes in evaporation (or indeed of run-off). For example, in the case of the BMRC model, there is a large and sustained increase in precipitation extending from mid-winter through to mid-autumn (i.e. during 75 per cent of the year). However, during this period, corresponding increases in evaporation ensure that there is no significant increase in soil moisture. On the other hand the relatively brief

**Fig. 8** Difference in the components of the surface hydrological budget for the GFDL experiment between the control and the  $2 \times \text{CO}_2$  climate (in mm/day) for (a) NA and (b) SA. The codes correspond to those specified in Eqn 1. Positive values correspond to components contributing to an increase in soil moisture.



**Fig. 9** As for Fig. 8, for the BMRC model.



decrease in autumn rainfall produces significant winter soil moisture decreases. In the GFDL model also, it is the brief, but large, decrease in late autumn rainfall which dominates the soil moisture changes. The large increase in late summer and early autumn rainfall, apparent in Fig. 8(b), has much less impact (partially because of increased run-off during this period).

The more sustained drying in SA found in the GFDL model compared with the BMRC model is consistent with the contention of Meehl and Washington (1988) that in a doubled  $\text{CO}_2$  scenario, drying persists longer in a wetter control climate, since very dry soil is incapable of much further drying. Of course other factors will also be important. One difference in the present case, for example, is that the drying in Australia persists through winter into spring, compared with spring into summer over the northern continents in the earlier studies.

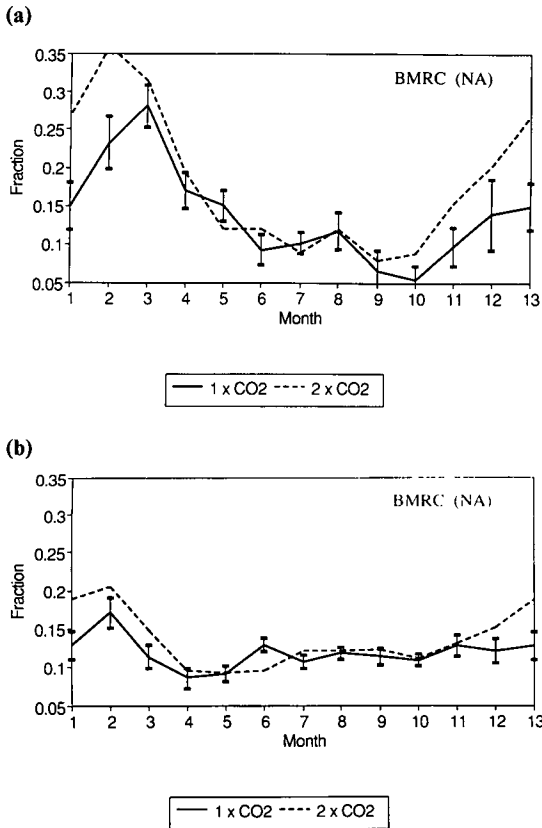
**Changes in the clouds and the surface energy budget**

Responses in the surface energy budget may be expected to be associated with changes in the soil moisture. Meehl and Washington (1988) and Manabe and Wetherald (1988) found this to be the case for the northern continents. In particular over the Great Plains of central North America, Meehl and Washington (1988) found that with a doubling of  $\text{CO}_2$  there was a general increase in downward LW radiation, roughly balanced by a corresponding decrease in downwards SW. In addition, they proposed a positive feedback whereby increased soil moisture is associated with increased evaporation, increased low cloud and increased precipitation. This may be tested in the present experiments for the Australian continent, using the results from the BMRC model.

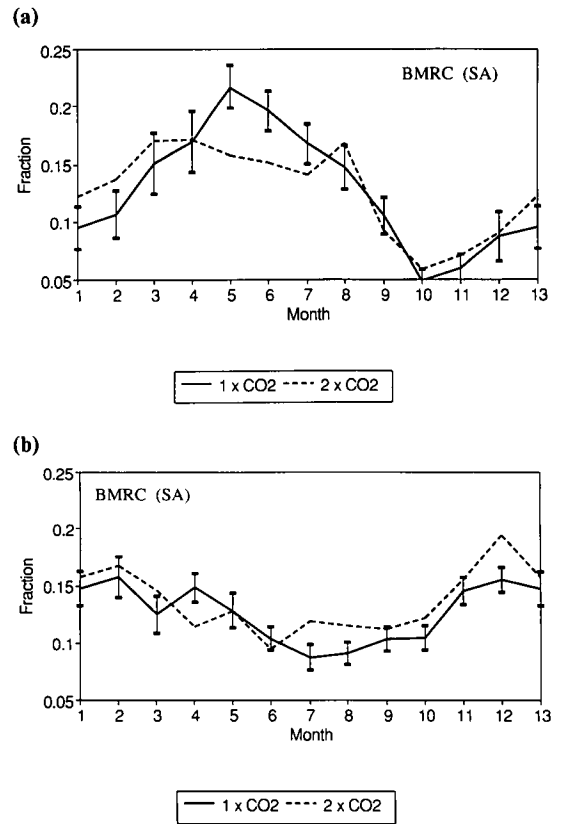
Figure 10 shows the mean seasonal cycle of low



**Fig. 10** Cloud fraction over NA in the BMRC experiment as a function of month (month 1 = month 13 = January). Averages are taken over 15 years. Error bars indicate the change required for significance at the 99 per cent level, by a 2-tailed Student's t-test. Plots shown are (a) low cloud and (b) high cloud.



**Fig. 11** As for Fig. 10, for SA.



and high cloud fraction over NA for both the control and  $2 \times \text{CO}_2$  climates for the BMRC model. These clouds occupy the sigma levels 0.925 and 0.811 (low) and 0.336 and 0.189 (high) in the model. Changes in the surface energy budget (see Eqn 2) are shown in Fig. 12. The downward LW radiation increases in almost all months (as expected from the enhanced 'greenhouse effect' (Meehl and Washington 1988)). Latent heat flux increases with the increase in soil moisture throughout most of the year, as evident in Fig. 7(a). With this evaporation increase, a large increase in low cloud occurs (see Fig. 10(a)) accompanied by a large increase in precipitation (see Fig. 9(a)). This increase in precipitation would, in turn, result in an increase in soil moisture. Thus this establishes a physical loop from soil moisture changes through again to soil moisture changes, which suggests that the soil moisture/

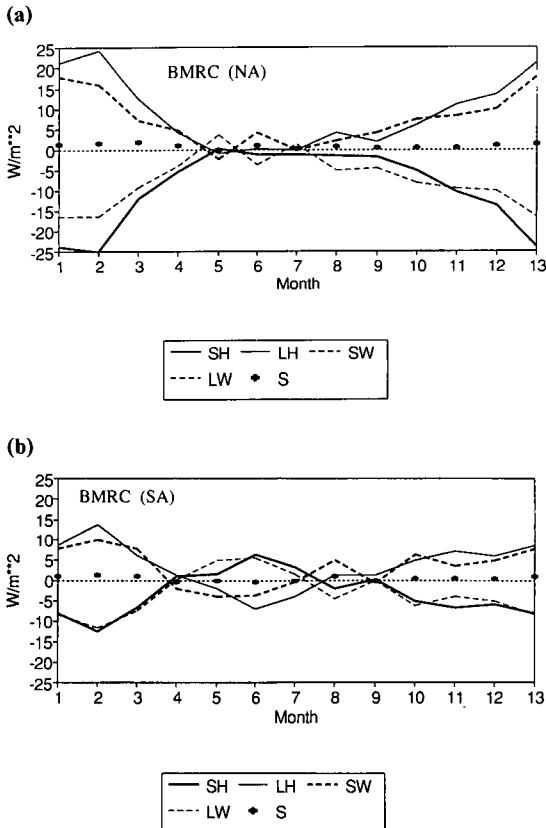
cloud feedback, suggested by Meehl and Washington (1988), is operating in NA in the model.

This is not to suggest that soil moisture changes trigger a monsoon intensification in the model, but merely that they contribute to an amplification of the changes. An examination of the total atmospheric horizontal moisture convergence over NA (shown in Fig. 9(a)) shows increased moisture convergence in January (0.6 mm/day), with almost no change in February. At the same time precipitation is found to strongly increase in both January (1.5 mm/day) and February (1.0 mm/day). Changes to the total column moisture content (not shown) are negligibly small. This indicates that the extra precipitation is the result largely of increased evaporation occurring in NA, consistent with the increased soil moisture. Indeed, the decrease in surface temperature found at this time suggests that the increase in soil moist-

ure is critical to the increase in evaporation which occurs.

Figure 12(a) shows that the decrease in downward SW is greatest in January and February, when the increase in low cloud cover is very large. Due to the large increase in soil moisture, there is also a very large increase in latent heat flux. This will tend to cool the surface. Furthermore, to maintain the surface heat balance, there must be substantial reductions in upwards sensible heat and/or LW radiation, both of which also drive the surface temperature down, in this case to *below* the temperature found in the control experiment. During this time a significant increase in high cloud is also seen (Fig. 10(b)). However, it is clear that the soil moisture/cloud feedback does not extend to the higher cloud, as a small decrease in mid-level cloud (model sigma levels 0.500 and 0.664) is also found (not shown). Furthermore, as will be shown below, consistent changes in low and high clouds are not found in SA. One additional link is seen between Figs 10(a) and 12(a).

**Fig. 12** Changes in the surface energy budget in the BMRC experiment for (a) NA, (b) SA. Positive values indicate an increase in upward energy flux.



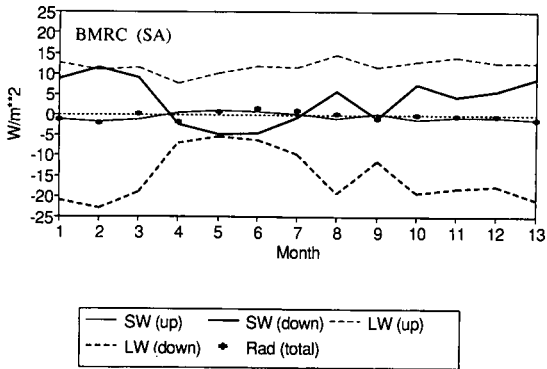
It is apparent that the model 'pairs' the changes in the heat budget, with the radiation terms varying by almost exactly opposite amounts, with a similarly sized change occurring in latent and sensible heats. This will be further discussed below.

Changes in the SA surface heat budget are given in Fig. 12(b) (note that increases in downwards fluxes are shown as negative in this figure). These are generally similar to those seen in NA, with an increase in downwards LW and a decrease in downwards SW during most of the year, although the magnitude of the changes are much smaller than the peak seen in NA. In SA, the low cloud amount changes significantly only in April to August. The increase in downwards LW and decrease in downwards SW seen between October and March are consistent with small increases in low (and also high) cloud found during this period (although the actual size of the changes is not always statistically significant at the 99 per cent level). During May to July, when substantial soil drying takes place, low cloud changes once again indicate the presence of a soil moisture/cloud feedback, but this does not appear to extend to high clouds, where no significant changes are found during this period.

The surface heat budget change shows that the increase in net downward LW radiation is accompanied by decreases in net downward SW. As in NA, the LW and SW radiation changes in the BMRC model almost exactly mirror each other. Once again too, changes in latent heat exchange are almost exactly mirrored by changes in sensible heat fluxes. The period of significant soil moisture decrease is the only one in which the signs of the changes in sensible and latent heat (and indeed in SW and LW) are reversed. It is notable that this is the only period in which the upwards sensible heat flux increases in the  $2 \times CO_2$  climate, despite the fact that the surface is warmer throughout the year.

This change in surface fluxes with increased soil moisture is similar to the findings of Manabe and Wetherald (1988) and Meehl and Washington (1988) over the Great Plains of North America, but the pairing of the components is even more marked in the present study. Furthermore, the North American results are strongly influenced by changes in snow coverage, thus producing a maximum in changes in spring and early summer. This effect is not, of course, present in Australia. In the BMRC model the pairing mechanism appears to be as follows. The change in the soil moisture alters the evaporative potential and hence the amount of evaporation (and latent heat exchange). The cloud amount responses resulting from the change in evaporation would be expected to have opposite impacts on the SW and LW radiation with, for example, an increase in low cloud decreasing downwards SW, but increasing re-radiated downwards LW radiation. The remaining surface budget terms (sensible heat and

**Fig. 13** Changes in the upwards and downwards components of the surface LW and SW radiation for SA in the BMRC experiment. Positive values indicate an increase in upward energy flux.



soil conduction) then make up any deficit. Since the soil conduction term is shown to be always small, it is the sensible heat term which changes to restore the final heat balance. Figure 13 indicates the changes in the upwards and downwards radiation components for SA for the present experiment, and illustrates this point. There is a reasonably constant increase in upwards LW radiation throughout the year from the warmer surface. Roughly balancing this is sum of the changes in the downwards LW and SW (since surface albedo is relatively small, the change in upwards SW does not contribute substantially to the total). The 'pairing' of the modulations in the downwards components of the LW and SW is apparent, and relates directly to the cloud changes seen in Fig. 11. Whereas the downwards SW roughly varies about zero, however, the downwards LW is offset, with this displacement resulting from other sources (such as downwards LW from increased atmospheric water vapour) representing the 'greenhouse effect'. The resulting balance of the radiation changes throughout the year (also shown in Fig. 13) is remarkably close to zero, and forces the pairing of the changes in latent and sensible heat. An examination of Fig. 7(a) of Meehl and Washington (1988) suggests a similar mechanism is operating in the NCAR GCM in their experiments.

## Conclusions

It must be emphasised that the preceding temperature, soil moisture and surface energy budget changes are not *predictions* for a doubled CO<sub>2</sub> climate, because of the simplicity of the model parametrisations and uncertainties in the details of the GCM simulations. They do, however, provide some insights into the surface moisture

budget, the surface heat budget and some associated feedbacks of the model.

An analysis of the impact upon soil moisture indicates that NA and SA should be treated separately in the discussion, rather than together as in the IPCC report (Houghton et al. 1990). Changes in the surface temperature in the BMRC model indicate a general temperature increase over NA and SA, but with a small decrease in average temperature in January and February. This temperature decrease was found to be due to a decrease in daytime temperatures. The BMRC GCM is the only model known by the authors to produce such a temperature decrease.

In NA, in the control simulations, the soil moisture showed a summertime maximum in both BMRC and GFDL models, although there was disagreement as to the actual magnitude of the soil moisture between the models, with the GFDL model being much wetter. In SA both models showed a winter or early spring soil moisture maximum, but with the GFDL model once again consistently wetter than the BMRC model. In both NA and SA, the models found the annual cycle of soil moisture to be largely the resultant simply of precipitation minus evaporation, although in the GFDL model there was a small amount of run-off present all year.

In a doubled CO<sub>2</sub> climate the BMRC model found strong NA summer moistening, principally due to a large increase in precipitation. In SA both models found drying, particularly in winter. This latter result highlighted the sensitivity of soil moisture in both models during that time of the year (late autumn) when soil moisture was increasing due to a surplus of precipitation over evaporation. In contrast, a sustained increase in precipitation in the BMRC model during the remainder of the year produced very little impact on soil moisture. This also underlines the caution which must be exercised when looking at precipitation responses alone in a doubled CO<sub>2</sub> climate for assessing possible climate change impact scenarios.

There is strong evidence that when soil moisture changes, a soil moisture/cloud feedback is occurring in the BMRC model of the type proposed by Meehl and Washington (1988). Responses in cloud cover then contribute to perturbations in the surface energy budget. An analysis of changes at the surface in the BMRC model showed a decrease in net upwards LW radiation at the surface throughout the year in NA and for most of the year in SA. Changes in SW radiation were found to closely 'mirror' those in the LW. In addition, perturbations in sensible and latent heat fluxes were also closely paired in this way. Snow melt and soil conduction are found to be negligibly small throughout the year. The soil moisture/cloud feedback is not found to extend to higher levels in the atmosphere, thereby including upper-level clouds.

Two vivid examples of the soil moisture/cloud feedback were noted in the BMRC model. Firstly, the large increase in soil moisture in NA in summer resulted in large increases in evaporation and low cloud, accompanied by large decreases in downwards SW radiation. The resulting surface heat flux balance forces a reduction in upwards sensible heat and LW fluxes, and drives the surface temperature down, in this case to below that of the control experiment. Secondly it was found in SA that the only period of increased downward SW radiation during the annual cycle is that during which soil moisture decreases and low cloud amount substantially decreases. This perturbs the whole surface heat budget, resulting in an increase in upward LW radiation (this being the only period during the year in which this occurs). This in turn results in an increase in sensible heat transfer at the expense of latent heat transfer, which reduces in line with the decrease in potential evaporation from the drier soil. This interaction also highlights the complexity of the models' response to the decrease in precipitation which occurs.

As more elaborate and physically based land-surface schemes are introduced it is expected that even more complex feedbacks and interactions will occur between components of the surface hydrology and other parts of the atmospheric model. In the study of such models it is hoped that studies such as the present one will form a benchmark against which such models may be compared and assessed.

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