

# CHARACTERIZING THE IMPACTS OF INCREASING LEAF-LEVEL CARBON DIOXIDE ON THE LAND SURFACE

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## 1. INTRODUCTION

Increasing carbon dioxide (CO<sub>2</sub>) in the atmosphere directly affects the physiology of plants (Field et al. 1995; Ainsworth and Long 2005). Stomates, which regulate the fluxes of water vapour and CO<sub>2</sub> at the leaf surface, reduce their opening under an enriched CO<sub>2</sub> environment since they are able to take up CO<sub>2</sub> more efficiently. As a result, plants transpire less, which in turn affects the surface energy and water balance.

Simulations where the stomatal resistance is doubled show that the suppression of transpiration leads to a global mean increase in temperature with impacts on rainfall and soil moisture (Pollard and Thompson 1995, Henderson-Sellers et al. 1995, Martin et al. 1999). Inclusion of the physiological forcing also offsets the enhanced evapotranspiration that would have resulted if only the radiative effect of CO<sub>2</sub> was considered (Bounoua et al. 1999, Levis et al. 2000). The changes in the surface climate arising from the physiological response of vegetation may be small relative to the radiative effect of doubled atmospheric CO<sub>2</sub> at the global scale but they are significant at regional scales including the tropics (Sellers et al. 1996) and boreal forests (Pollard and Thompson 1995, Henderson-Sellers et al. 1995, Martin et al. 1999). Some studies have explored the impact of the physiological feedback on the Australian climate (e.g. Aston 1984, Narisma and Pitman 2004) but a systematic assessment of the impact of increased CO<sub>2</sub> on plant-soil-climate interactions in a climate model over Australia, where evaporation is typically water limited, has yet to be reported.

Using a coupled atmosphere-land model, this paper explores the scale of the impact of changes in leaf-level CO<sub>2</sub> via its impact on stomatal conductance only. We explore whether

changes in stomatal conductance affect transpiration, and thereby canopy energy balance, enough to affect surface temperature statistically significantly at various levels of leaf-level CO<sub>2</sub>. In particular, we aim to characterize the changes in the surface climate over Australia under differing conditions of moisture availability.

## 2. METHODOLOGY

To isolate the changes in the land surface that result *only* from the stomatal response to CO<sub>2</sub> fertilization, only the level of CO<sub>2</sub> concentration at the leaf surface is changed in the parallel simulations using the coupled Conformal-Cubic Atmosphere Model (CCAM, McGregor and Dix 2001, 2008) and Community Atmosphere Biosphere Land Exchange (CABLE, Kowalczyk et al. 2006, Wang et al. 2007, Abramowitz et al. 2008) model. Six concentration levels of CO<sub>2</sub>: 280 (pre-industrial), 375 (present-day), 500, 650, 840 and 1000 ppmv, have been specified in the land surface model for the experiment. In all simulations, a fixed atmospheric CO<sub>2</sub> concentration of 375 ppmv is specified in CCAM to remove any direct impact of the changes in CO<sub>2</sub> on the net radiation at the surface.

The mean January rainfall was obtained from a separate 26-year AMIP II-type run (1979 to 2004), from which rainfall anomalies were derived for each January over Australia. The three driest and three wettest Januarys were then selected, as determined by the rainfall over the Murray Darling Basin. These were averaged and classified as the *dry* case and the *wet* case, respectively. The wet case is analogous to La Niña conditions and the dry case is analogous to El Niño conditions over Australia. Fifty-one realizations were run, for each of the six Januarys for each CO<sub>2</sub> concentration. Members of the ensemble vary by slight perturbations to the initial deep soil temperature.

The difference in the ensemble monthly means of transpiration, canopy temperature and rainfall from the 280 ppmv simulation (control run) was obtained for each of the higher CO<sub>2</sub> levels. The statistical significance of the differences is determined with a two-sample F- and t-test at a 95% significance level. The percentage area of

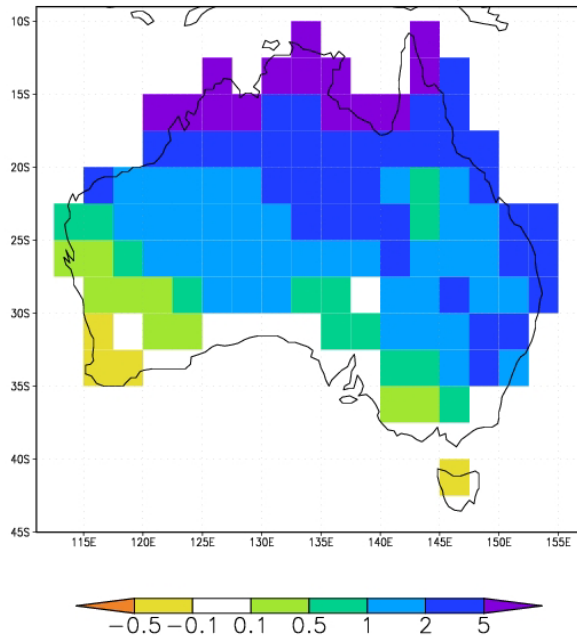
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the 95% statistically significant differences was also taken over all land points. Following Findell et al. (2006), note that more than 5% of the area of interest must pass the significance test at the 95% level locally for a field to be considered statistically significant on the whole, to account for spatial correlation within the field.

### 3. RESULTS

Based on the parameterization of the role of leaf-level  $\text{CO}_2$  in CABLE, an impact on the simulation of water and  $\text{CO}_2$  through the stomates would be anticipated. A distinction was made between the dry case and the wet case to determine the extent of impact of moisture availability on the changes in transpiration, temperature and rainfall resulting from the stomatal response to increased  $\text{CO}_2$ . While the wet case is wetter by up to  $5 \text{ mm d}^{-1}$  on average in some areas, there is less rainfall over southwest Western Australia (Fig. 1).



**Fig. 1.** Difference in the monthly mean daily rainfall rate ( $\text{mm d}^{-1}$ ) between the dry case and the wet case. Each case is an average of three Januarys.

#### 3.1 Mean Changes in the Dry Case

In the dry case, there is almost no significant change in transpiration over Australia when  $\text{CO}_2$  is initially increased from 280 ppmv to 375 ppmv, except for some areas along the east coast (Fig. 2a). However, the area of significant

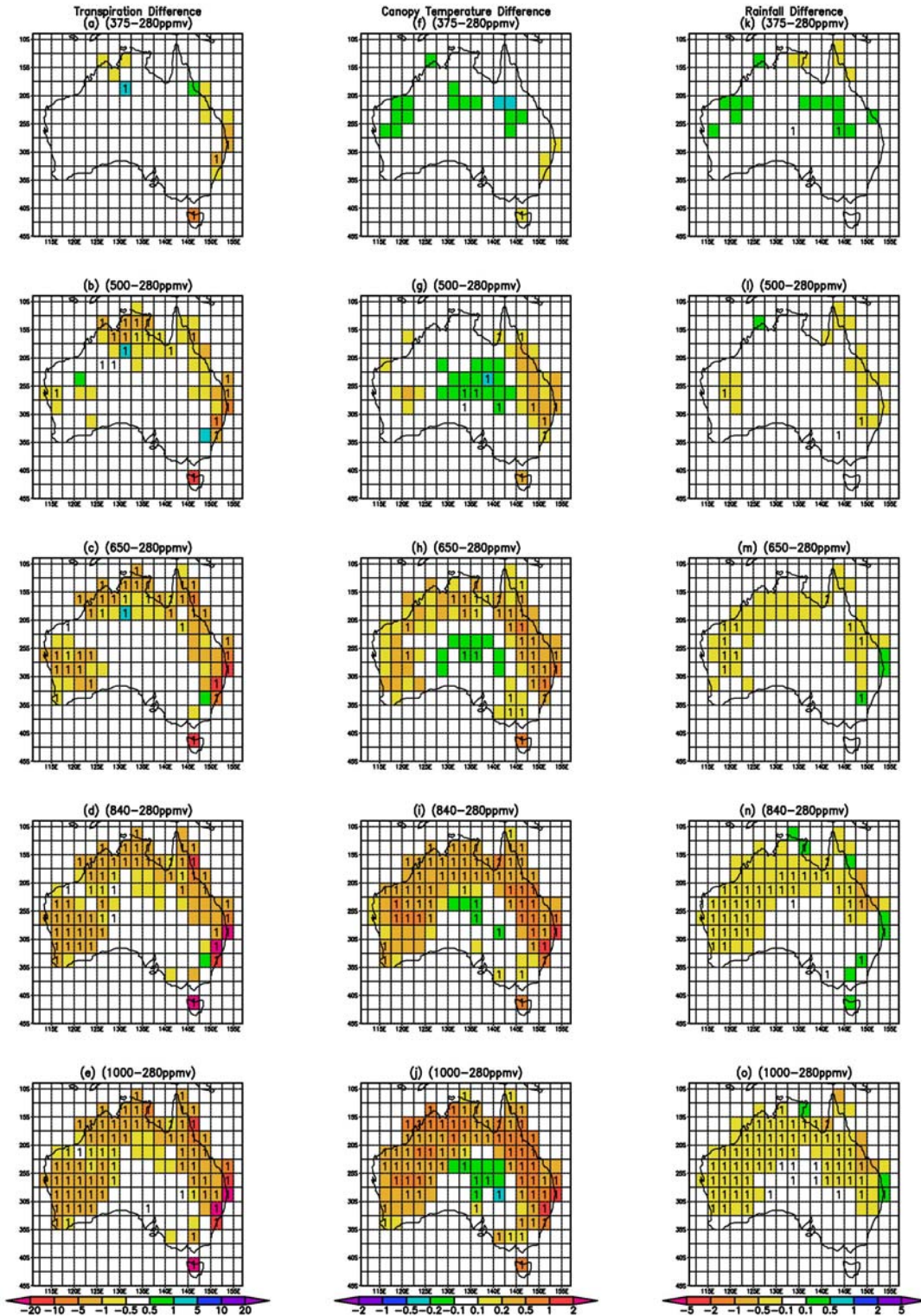
change in transpiration increases from 3.4% to 18.1% of the land area at 500 ppmv, which is larger than what we might expect by chance (Table 1). Statistically significant decreases in transpiration occur over the tropics and the east of Australia, which is expected since the stomates reduce their opening when leaf-level  $\text{CO}_2$  is increased (Fig. 2b). The area of reduced transpiration expands over Australia with further increases to  $\text{CO}_2$  (Figs. 2c to 2e). Since the patterns of change are coherent at various levels of  $\text{CO}_2$  and grow in magnitude and area as  $\text{CO}_2$  is increased, this suggests that the changes in transpiration are not due to internal model variability. This is similar to the results obtained previously for global simulations (Cruz et al. 2008).

No significant change in transpiration is simulated south of central Australia. The water stress, as well as shallow rooted vegetation, in south-central Australia limits the impact of the elevated  $\text{CO}_2$  on transpiration of this region. This can be attributed to the representation of the stomatal conductance in the land surface model, where it is limited not just by increases in  $\text{CO}_2$  but also by soil water availability.

The areas of warming are coincident with the areas of reduced transpiration as expected (Figs. 2f to 2j), due to reduced evaporative cooling at the surface. The coherent cooling observed over south-central Australia in Figs. 2g to 2j may be related to an increased divergence of surface winds caused by the enhanced warming of the surrounding area. The reduced transpiration and warming could affect rainfall because of less water vapour flux from the land surface. Figs. 2k and 2l show few significant changes in rainfall until 650 ppmv (Fig. 2m). The scale of this continental reduction in rainfall is not enormous, but it is a drying on an already dry continent. Note the clear emergence of a coherent and consistent pattern of change in the transpiration, temperature and rainfall through the various  $\text{CO}_2$  levels.

**Table 1** Percent area of regional surfaces affected at a 95% level of statistical significance by the increases in leaf-level  $\text{CO}_2$  concentration

CO <sub>2</sub> level (difference from 280 ppmv)	Transpiration		Canopy temperature		Rainfall	
	Dry	Wet	Dry	Wet	Dry	Wet
375	3.4	16.4	0.9	14.7	1.7	30.1
500	18.1	22.4	10.3	34.5	2.6	46.6
650	33.6	41.4	29.3	50.9	8.6	52.6
840	50.0	69.8	56.9	56.0	33.6	55.2
1000	64.7	76.7	70.7	58.6	51.7	49.1



**Fig. 2.** Monthly average change in the (a-e) transpiration ( $W m^{-2}$ ), (f-j) canopy temperature ( $^{\circ}C$ ) and (k-o) rainfall rate ( $mm d^{-1}$ ) for changes in leaf-level  $CO_2$ : 375-280 ppmv, 500-280 ppmv, 650-280 ppmv, 840-280 ppmv and 1000-280 ppmv. Averages are taken over 51 realizations for each of the three Januaries for the dry case. Changes that are statistically significant at a 95% confidence level are marked with “1”.

### 3.2 Mean Changes in the Wet Case

A stronger response to changes in CO<sub>2</sub> is observed on the vegetated surface in the wet case (Fig. 3), relative to the dry case (Fig. 2) due to increased moisture availability (Fig. 1). Significant changes in the transpiration occur over 16.4% of the land (Fig. 3a), compared to 3.4% in the dry case (Table 1), with the initial increase from 280 ppmv to 375 ppmv. Transpiration is increased over northeast Australia at levels of CO<sub>2</sub> below 500 ppmv (Figs. 3a and 3b), which can be attributed to increased atmospheric evaporative demand associated with reduced rainfall (Figs. 3k and 3l). However, further increases in CO<sub>2</sub> limit the stomatal conductance and results in reducing transpiration in these areas (Figs. 3c to 3e). Both the area and magnitude of the transpiration reduction increase in response to the elevated levels of CO<sub>2</sub>.

Above 650 ppmv, there is a strong similarity between the regional changes in transpiration between the wet case (Figs. 3d and 3e) and the dry case (Figs. 2d and 2e). A significantly warmer surface, particularly over eastern Australia results from the reduced evaporative cooling due to the decrease in stomatal conductance in a richer CO<sub>2</sub> environment (Figs. 3i and 3j). The area of warming grows as CO<sub>2</sub> is increased, although only minimally where the temperature change is significant (Table 1). Changes in rainfall of up to  $\pm 0.5 \text{ mm d}^{-1}$  are also simulated at these higher levels of CO<sub>2</sub> (Figs. 3n and 3o).

### 3.3 Cooling Anomaly over Western Australia

The most confronting difference between the dry case and the wet case is the contrasting response of the surface climate to the increase in CO<sub>2</sub> over Western Australia (WA). Reduced transpiration over this region indicates that the stomates have the same response to the elevated CO<sub>2</sub> levels elsewhere. However, this area is cooler (Figs. 3g to 3i) and wetter (Figs. 3l to 3n) at levels of 500 to 840 ppmv, compared to the dry case (Figs. 2g to 2i and 2l to 2n). The contrast in the canopy temperature and rainfall is even stronger between the western and eastern regions in the wet case (Figs. 3g to 3i and 3l to 3n).

The cooling over WA (Figs. 3f to 3j) can be attributed to a higher evapotranspiration, resulting from more rainfall (Figs. 3k to 3o), even when transpiration is reduced. Although the changes in rainfall are simulated at various levels of CO<sub>2</sub>, only the 650 ppmv case will be examined

as an example, where CO<sub>2</sub> is increased substantially from 280 ppmv.

In the dry case, the CO<sub>2</sub> increase from 280 ppmv to 650 ppmv results in a warming over most of the continent, except over south-central Australia (Fig. 4a). On the other hand, there is a clear contrast in the temperature change in the wet case, where the eastern region is 0.5 to 1°C warmer but cooler by 0.5°C in the west (Fig. 4b). The moist conditions in the wet case, particularly over south-central Australia, allows the vegetated surface to respond to the elevated CO<sub>2</sub> which reduce transpiration and increase both the area and magnitude of warming over central and east Australia (Fig. 4b). The enhanced temperature gradient between the land and sea surface leads to a small southward shift of the northwesterly winds in northwest Australia which brings more tropical moisture into WA. There are also onshore winds from the south that bring somewhat moister air from the Southern Ocean. The convergence with the winds from the north produces an enhancement of rainfall, which then leads to further convergence of atmospheric moisture over WA.

Fig. 5a shows a decrease in the vertically integrated moisture convergence, as well as almost no change in the vertical velocity over WA in the dry case (Fig. 5c). On the other hand, both the increased moisture convergence in the wet case (Fig. 5b) and the enhanced rising motion (Fig. 5d) enhance the convection over WA leading to more rainfall. The increased rainfall enhances evaporation and consequently lowers surface temperature.

## 4. CONCLUSIONS

Multiple realisations with a coupled atmosphere-land model have shown the clear impact of increasing leaf-level CO<sub>2</sub> on the Australian January climate. Statistically significant reductions in transpiration generally result in significant regional-scale warming with less rainfall. Increases in CO<sub>2</sub> at various levels from 280 ppmv to 1000 ppmv lead to statistically significant increases in the magnitude and area of the changes in the climate. The results also show that the availability of moisture substantially affects the impact of increases in the leaf-level CO<sub>2</sub>, where the physiological feedback can indirectly lead to more rainfall which lessens the warming effect of reduced transpiration, such as the anomalous cooling simulated over WA. The influence of moisture availability suggests that the potential of the physiological feedback to affect the

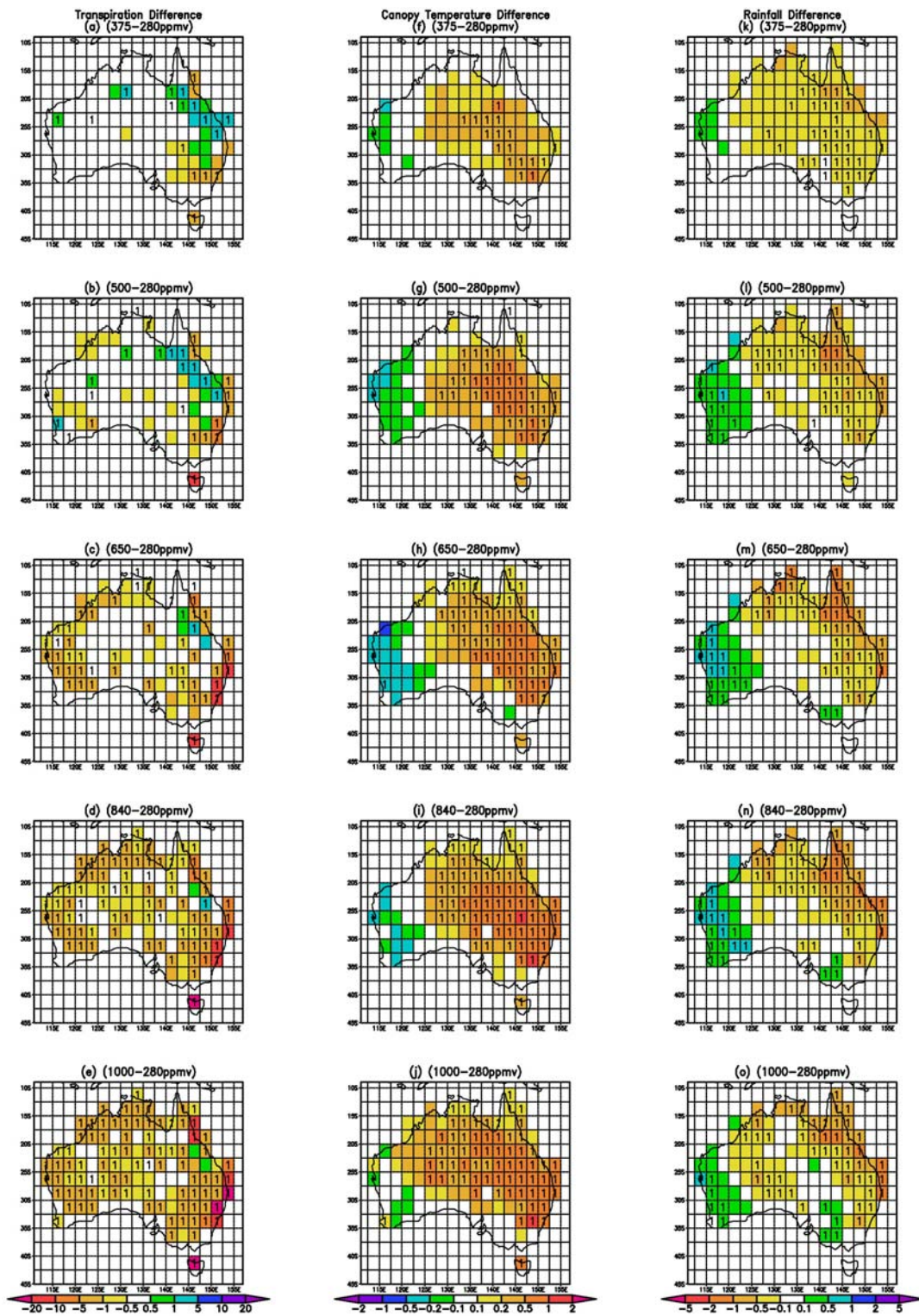
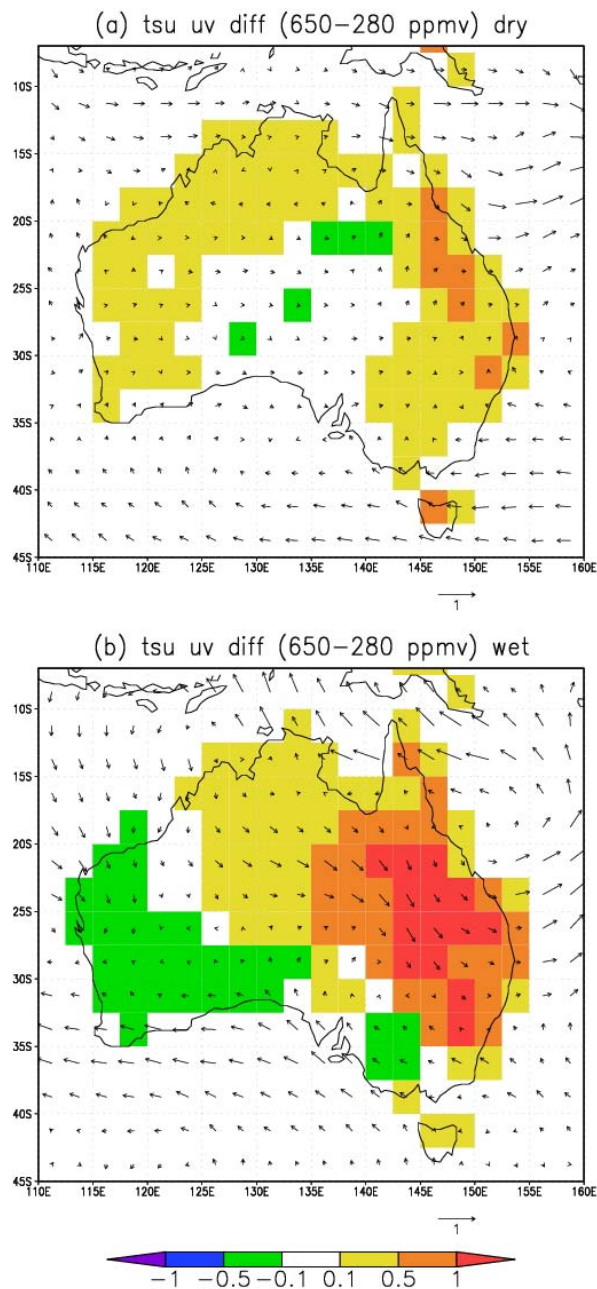
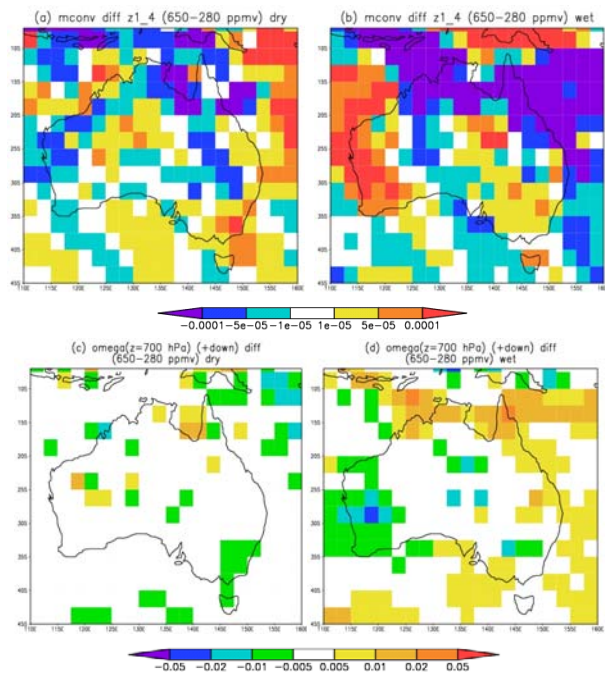


Fig. 3. As in Fig. 2, but for the wet case



**Fig. 4.** Maps of the difference in the surface temperature ( $^{\circ}\text{C}$ ) and lowest-model level winds ( $\text{m s}^{-1}$ ) between 650 ppmv and 280 ppmv for the (a) dry case and (b) wet case.

future climate may be affected by uncertainties in rainfall projections, particularly for water-stressed regions. Although we have not been able to examine changes in the annual cycle, the large sample size generated from the multiple realisations gives us confidence that the patterns



**Fig. 5.** Maps of the differences between 650 ppmv and 280 ppmv for the moisture convergence (vertically integrated over 700, 850, 925 and 1000 hPa) for the (a) dry case and (b) wet case, and for the vertical velocity ( $\text{Pa/s}$ ) at 700 hPa (positive downwards) for the (c) dry case and (d) wet case

of changes in transpiration, temperature and rainfall in January are coherent with the increases in  $\text{CO}_2$  and are not a result of internal model variability. Changes in the vegetation structure and dynamics have not been considered in the experiments. We expect that the impact of the physiological feedbacks may be moderated when the structural feedback to the increasing  $\text{CO}_2$  is also accounted for. Our results are also dependent on the parameterization of the stomatal response to elevated leaf-level  $\text{CO}_2$  in the land surface model we have used. Systematic field experiments exploring this response over Australian native ecosystems will therefore be necessary to improve our confidence in the results.

The changes in the surface climate presented suggest that the exclusion of the physiological feedbacks to increased  $\text{CO}_2$  risks inadequately quantifying the impact of global warming and human-induced land cover changes on the Australian summer climate. It is therefore important to incorporate these feedbacks in future climate assessments and projections for Australia.

## References

- Abramowitz, G., Leuning, R., Clark, M., and Pitman, A., 2008: Evaluating the performance of land surface models. *J. Clim.*, 21, 5468-5481.
- Ainsworth, E. A., and Long, S. P., 2005: What have we learned from 15 years of free-air CO<sub>2</sub> enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO<sub>2</sub>. *New Phytol.*, 165(2), 351-372.
- Aston, A. R., 1984: The effect of doubling atmospheric CO<sub>2</sub> on streamflow: A simulation. *J. Hydrol.*, 67, 273-280.
- Bounoua, L., Collatz, G. J., Sellers, P. J., Randall, D. A., Dazlich, D. A., Los, S. O., Berry, J. A., Fung, I., Tucker, C. J., Field, C. B., and Jensen, T. G., 1999: Interactions between vegetation and climate: Radiative and physiological effects of doubled atmospheric CO<sub>2</sub>. *J. Clim.*, 12, 309-324.
- Cruz, F. T., Pitman, A. J., and McGregor, J. L., 2008: Probabilistic simulations of the impact of increasing leaf-level atmospheric carbon dioxide on the global land surface. *Clim. Dyn.*, in press.
- Field, C., Jackson, R., and Mooney, H., 1995: Stomatal responses to increased CO<sub>2</sub>: implications from the plant to the global scale. *Plant Cell Environ.*, 18, 1214-1225.
- Findell, K. L., Knutson, T. R., and Milly, P. C. D., 2006: Weak simulated extratropical responses to complete tropical deforestation. *J. Clim.*, 19, 2835-2850.
- Henderson-Sellers, A., McGuffie, K., and Gross, C., 1995: Sensitivity of global climate model simulations to increased stomatal resistance and CO<sub>2</sub> increases. *J. Clim.*, 8, 1738-1756.
- Kowalczyk E. A., Wang, Y. P., Law, R. M., Davies, H. L., McGregor, J. L., and Abramowitz, G., 2006: The CSIRO Atmosphere Biosphere Land Exchange (CABLE) model for use in climate models and as an offline model. CSIRO Marine and Atmospheric Research, Paper 013. Available from [www.cmar.csiro.au](http://www.cmar.csiro.au).
- Levis, S., Foley, J. A., and Pollard, D., 2000: Large-scale vegetation feedbacks on a doubled CO<sub>2</sub> climate. *J. Clim.*, 13, 1313-1325.
- Martin, M., Dickinson, R. E., and Yang, Z.-L., 1999: Use of a coupled land surface general circulation model to examine the impacts of doubled stomatal resistance on the water resources of the American Southwest. *J. Clim.*, 12, 3359-3375.
- McGregor, J. L., and Dix, M. R., 2001: The CSIRO conformal-cubic atmospheric GCM. In: Hodnett PF (ed) IUTAM Symposium on Advances in Mathematical Modelling of Atmosphere and Ocean Dynamics, Kluwer, pp 197-202.
- McGregor, J. L., and Dix, M. R., 2008: An updated description of the Conformal-Cubic Atmospheric Model. In: Hamilton K, Ohfuchi W (eds) High Resolution Simulation of the Atmosphere and Ocean, Springer, pp 51-76.
- Narisma, G., and Pitman, A., 2004: The effect of including biospheric responses to CO<sub>2</sub> on the impact of land-cover change over Australia. *Earth Interactions*, 8, 1-28.
- Pollard, D., and Thompson, S., 1995: Use of a land-surface-transfer scheme (LSX) in a global climate model: The response to doubling stomatal resistance. *Glob. Planet. Change*, 10, 129-161.
- Sellers, P. J., Bounoua, L., Collatz, G. J., Randall, D. A., Dazlich, D. A., Los, S. O., Berry, J. A., Fung, I., Tucker, C. J., Field, C. B., Jensen, T. G., 1996: Comparison of radiative and physiological effects of doubled atmospheric CO<sub>2</sub> on climate. *Science*, 271, 1402-1406.
- Wang, Y.-P., Baldocchi, D., Leuning, R., Falge, E., and Vesala, T., 2007: Estimating parameters in a land surface model by applying nonlinear inversion to eddy covariance flux measurements from eight FLUXNET sites. *Global Change Biol* 13:652-670. doi:10.1111/j.1365-2486.2006.01225.x