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The role of land surface processes in regional climate change: a case study of future land cover change over south western Australia

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With 8 Figures

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Summary

Using a high resolution regional climate model we perform multiple January simulations of the impact of land cover change over western Australia. We focus on the potential of reforestation to ameliorate the projected warming over western Australia under two emission scenarios (A2, B2) for 2050 and 2100. Our simulations include the structural and physiological responses of the biosphere to changes in climate and changes in carbon dioxide. We find that reforestation has the potential to reduce the warming caused by the enhanced greenhouse effect by as much as 30% under the A2 and B2 scenarios by 2050 but the cooling effect declines to 10% by 2100 as CO_2-induced warming intensifies. The cooling effect of reforestation over western Australia is caused primarily by the increase in leaf area index that leads to a corresponding increase in the latent heat flux. This cooling effect is localized and there were no simulated changes in temperature over regions remote from land cover change. We also show that the more extreme emission scenario (A2) appears to lead to a more intense response in photosynthesis by 2100. Overall, our results are not encouraging in terms of the potential to offset future warming by large scale reforestation. However, at regional scales the impact of land cover change is reasonably large relative to the impact of increasing carbon dioxide (up to 2050) suggesting that future projections of the Australian climate would benefit from the inclusion of projections of future land cover change. We suggest that this would add realism and regional detail to future projections and perhaps aid detection and attribution studies.

1. Introduction

This paper focusses on the role of land surface processes at regional scales, and the impact of those processes on month-long simulations of climate change. We use a case study to highlight the opportunities that regional climate modelling offers to explore phenomenon that occur at spatial scales below those that can be resolved by a global climate model. In particular, we focus on the impact of land cover change (LCC) on the January climate of western Australia in 2050 and 2100. Our case study region is of considerable importance in Australia. Over southwest western Australia, a sudden decline occurred in early winter (May–July) rainfall in the mid-20th century (IOCI, 2002). The decline in rainfall was about 15–20%, a sudden change described by the IOCI (2002) as a switch to an alternative rainfall regime. This winter rainfall reduction was coincident with warmer day-time and warmer night-time temperatures. The IOCI (2002) attributed these changes in temperature and rainfall to a combination of changes in the large scale circulation of the atmosphere and natural variability. Pitman et al (2004) explored an alternative hypothesis that the changes could be attributed to the large scale removal of natural vegetation over the region. They showed that two different mechanisms could explain the change in rainfall and temperature. The rainfall decline appeared related to a change in moisture convergence and vertical velocities over the region due to a large scale smoothing of the region following deforestation (this is not discussed in this paper). The warming in temperatures appeared to be related to a change in the surface energy balance whereby a reduced supply of moisture to support evaporation reduced cooling and allowed warmer maximum temperatures. This reduced supply of moisture was related to the reduced rainfall, but also due to the lower capacity of grasses and crops to meet the evaporative demand.

The impact of LCC on the micrometeorology of parts of western Australia has been explored before (Lyons et al, 1993; Huang et al, 1995; Lyons et al, 1996; Lyons, 2002; Ray et al, 2003) where changes in the regional meteorology have been linked to LCC using observations and modeling. While this work has usually focused on timescales of a few days it does hint that larger time-scale impacts on weather and climate may follow LCC. Ray et al (2003), for example, find observed changes in cloudiness associated with changes in sensible heat fluxes over regions of LCC in western Australia. This suggests a potential link from the surface, via clouds, to radiation and rainfall.

This paper explores the impact of future LCCs on the January temperatures over western Australia. We focus on the potential of two LCC scenarios as a means to off-set summer warming in 2050 and 2100 projected over western Australia due to the enhanced greenhouse effect (under two emission scenarios). This also gives us a guide to how much of the observed change in temperature might be offset by reforestation. This provides an opportunity to demonstrate some of the new capacity that is being developed in regional climate modelling involving the resolving of the carbon cycle at high spatial resolutions. This paper assumes the reader is reasonably familiar with both regional climate modelling (see recent reviews by Giorgi, 1995, or McGregor, 1997) *[note that if this issue contains a more recent review I would wish to refer to it here]*. It also assumes that the reader is generally familiar with the role of the land surface in regional or climate modelling (see recent reviews by Aroro, 2002, or Pitman, 2003).

2. Methodology

2.1 Model configuration

We used the regional atmospheric modeling systems (RAMS; Pielke et al, 1992; Liston and Pielke, 2001) developed by the Colorado State University coupled to the General Energy and Mass Transport Model (GEMTM; Chen and Coughenor, 1994; Eastman et al, 2001). RAMS is a flexible meteorological modeling system that has been extensively used to study the impact of LCC on weather and climate (see Pielke et al, 1998). Importantly, RAMS has been shown to simulate the Australian climate well (Peel et al, 2005). We used the Kain and Fritsch (1993) convection scheme and the Chen and Cotton (1987) shortwave and longwave radiation schemes.

Key to this paper is the representation of the terrestrial surface. We used the GEMTM dynamic plant model that simulates the interaction between the biosphere and atmosphere. At each time step, GEMTM calculates stomatal conductance as a function of relative humidity and CO_2 concentration (Chen and Coughenor, 1994). The photosynthetic rate is dependent on the atmospheric CO_2 and vegetation temperature as well as on the photosynthetically active radiation and plant water potential. Based on an estimate of the photosynthetic rate, and the respiration rate, a net carbon balance can be calculated. Net carbon uptake can then be allocated to roots, stems, branches and leaves. The coupled model, GEMRAMS, therefore allows the vegetation to respond to changes in CO_2-concentration and to any changes in climate by growing more/less leaves, roots, stems etc (a structural response) and by varying the stomatal conductance (a physiological response). The impact of these two feedbacks has been explored quite extensively separately (Henderson-Sellers et al, 1995; Pollard and Thompson, 1995; Collatz et al, 2000; van den Hurk et al, 2003) and in combination (e.g., Betts et al, 1997; Costa and Foley, 2000).

The coupling of interactive vegetation to a regional climate model presents a problem of time scales. The rationale for including an interactive vegetation scheme is to capture any feedbacks that may exist between the vegetation and the climate. Unfortunately, the two major feedbacks operate on very different time scales. A climate or CO_2-driven change in LAI occurs at longer time scales (typically days to seasons) while the change in the stomatal conductance (g_s) is almost immediate. We account for this time lag by stabilizing the LAI before each simulation to both the climate and the ambient CO_2-concentration. GEMTM is run offline (uncoupled and without dynamic interaction with RAMS) using forcing data that were previously saved in a coupled January simulation but with seasonal and geographical variations in temperature, rainfall, and radiation imposed on to these data. We stabilize LAI by running the offline GEMTM through multiple years until LAI changes by less than 0.25 (at each individual grid point) between year n and $n + 1$. Unless this is done, the change in the stomatal conductance (the physiological feedback) will appear substantially more important than the change in LAI (the structural feedback).

Using GEMRAMS, we performed 48 ensemble simulations of the western Australian January climate at 56 kilometer grid spacings. In earlier experiments we explored the sensitivity of results to model resolution and found that, at least up to 30 km grid-scales, our results were insensitive to resolution. Multiple ensemble runs are important since if single runs are performed there is a risk that results will be sensitive to the boundary forcing. For example, if the boundary conditions were reflective of a drought, and little rain falls within the domain, the land cover would not be able to reduce the rainfall, irrespective of any surface influence. Similarly, if a “wet” year was selected, then ample moisture would be available that might mask any impact of the surface on evaporation. A reasonable sample of Januaries (here we used four independent Januaries) helps to minimize the risk of reporting a boundary-condition dependent result.

We chose to simulate the January climate because Narisma and Pitman (2003) have previously shown that there is a clear response to changes in land cover for this month, and because we were interested in how much LCC might reduce summer warming. GEMRAMS was initialized and driven by boundary conditions taken from a transitory climate simulation of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Mark 2 atmosphere-ocean model (Watterson and Dix, 2003). The CSIRO model has a spatial resolution of approximately 3.28 latitude and 5.68 longitude and includes nine vertical layers for the atmosphere. Climate simulations performed using the CSIRO model included A2 (high CO_2-increase) and B2 (moderate CO_2-increase) scenarios (see Nakicenovic et al, 2000). In the B2 scenario, CO_2 reaches 456 ppmv by 2050 and 621 ppmv by 2100. In the higher emissions A2 scenario, CO_2 reaches 532 ppmv by 2050 and 856 ppmv by 2100.

We updated boundary conditions for GEMRAMS every 12-hours which were found to be acceptable for simulations at a grid spacing of around 45 km by Denis et al (2003). Note that the figures shown in this paper do not show the full domain of the model since we have omitted an area of ocean to the west and south and areas of continent to the north and east in the graphics to aid clarity.

To represent the changes in land cover we used the Australian Surveying and Land Information Group (AUSLIG, 1990) data. They reconstructed past, including pre-European, land cover in Australia and the current land cover based on Landsat satellite imagery. Based on these data, we extrapolated two land cover scenarios, a low-recovery (LCL) future and a high-recovery future (LCH). To provide baseline values, we also performed experiments with current day conditions in terms of climate, CO_2 concentration, and land cover. For the projection experiments, we simulated future climate changes under the A2 and B2 scenarios (Nakicenovic et al, 2000) with three types of land cover scenarios. The steady-state (SS) scenario retains the current (2000) land cover in both 2050 and 2100. LCL is a “low” reforestation scenario that recovers about 25% of the Eucalypt trees that were replaced by grasslands in the last 200 years over western Australia. The LCH land cover scenario is a “high” reforestation scenario that recovers at least 75% of the deforested regions in western Australia. Figure 1 shows the difference between the SS land cover and the two land cover scenarios. Table 1 outlines the experiments performed in this paper

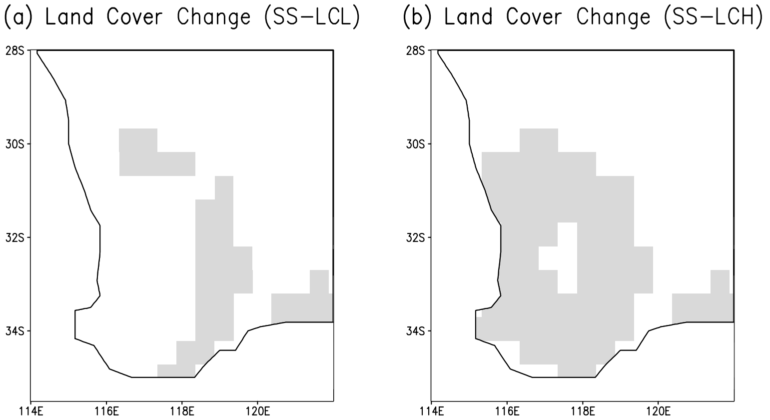


Fig. 1. Areas of land cover change between 1988 and (left) the low reforestation scenario (LCL) and (right) the high reforestation scenario (LCH)

Table 1. List of simulations used in this paper. The 1988 land cover scenario was run with only the 2000 climate and a 369 ppmv CO_2-concentration. The LCL and LCH land cover scenarios were run for both a 2050 and 2100 climate for both the A2 and B2 emission scenarios

Land cover scenario	Climate scenario	Emission scenario
1988 land cover (steady state)	2000 climate	369 ppmv
low reforestation (LCL)	2050 and 2100	A2, B2
high reforestation (LCH)	2050 and 2100	A2, B2

but we basically ran 4 January realizations for each of SS, LCL and LCH for each of the A2 and B2 scenarios for both 2050 and 2100 (so $4 \times 3 \times 2 \times 2 = 48$ simulations).

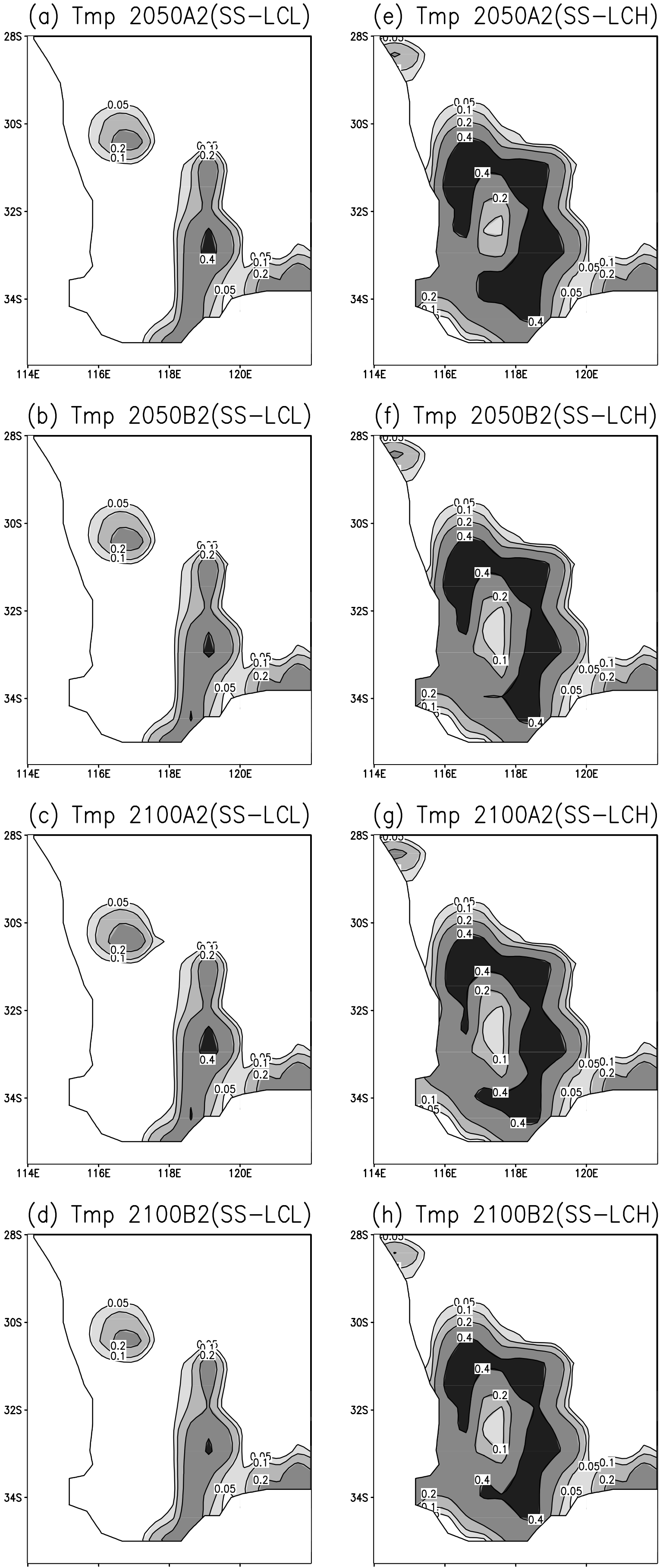
3. Results

3.1 The impact of future land cover changes on temperature

Land cover change affects surface temperature because it changes the way that available energy is partitioned between sensible and latent heat, changes the efficiency of turbulent transfer and affects the amount of available energy via a change in albedo (see Sellers, 1992, or Pitman, 2003). A change from grassland or crops to forest will tend to decrease albedo and increase the aerodynamic roughness length. The decrease in albedo should increase net radiation and warm the surface, while the increase in roughness should enhance turbulent exchange of energy and thereby tend to cool. Further, forests tend to be more deeply rooted than grasslands (Jackson et al, 1996) and can tap water more effectively to maintain transpiration through periods when the grassland becomes moisture stressed. This again tends to keep forests cooler than grasslands. We would therefore expect, given the findings of earlier work that deforestation over Australia (Narisma and Pitman, 2003) and western Australia (Pitman et al, 2004) warmed the surface that the impact of a recovery of forests over western Australia should be to cool.

We do not show results in this paper of the impact of reforestation over western Australia under present climate conditions because they can be easily inferred from the earlier work (Pitman et al, 2004) which showed the impact of deforestation. Rather, this paper focuses on the impact of LCC (reforestation) at two times in the future (2050; 2100) under two warming scenarios (A2, high emissions; B2, low emissions) given that, at least in theory, a large scale reforestation program could re-grow the forests that have been removed over western Australia on those time scales.

Figure 2a–d shows the impact of the low forest recovery (LCL) on mean January temperature (averaged over four Januaries as a difference, i.e., SS-LCL). The recovery of forest is limited to an area to the north and east of the region (Fig. 1). This leads to a cooling over the areas of reforestation of up to 0.4 °C under both the A2 (Fig. 2a, c) and B2 (Fig. 2b, d) scenarios in both 2050 and 2100, indicating that the impact of LCL is independent of the emission scenario. Figure 2e–h shows the result for the high forest recovery (LCH). The cooling effect of the forest is seen over a larger area because the scale of


(a) Tmp 2050A2(SS-LCL)

(e) Tmp 2050A2(SS-LCH)

(b) Tmp 2050B2(SS-LCL)

(f) Tmp 2050B2(SS-LCH)

(c) Tmp 2100A2(SS-LCL)

(g) Tmp 2100A2(SS-LCH)

(d) Tmp 2100B2(SS-LCL)

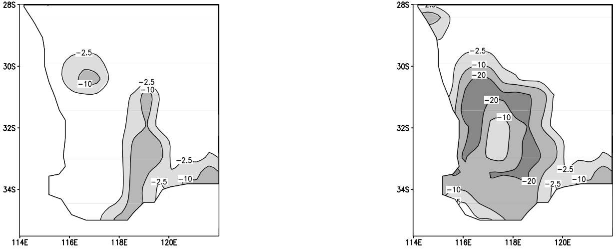
(h) Tmp 2100B2(SS-LCH)

Fig. 2. The impact of the LCL and LCH scenarios on January temperature (°C) for both A2 and B2 emission scenarios for 2050 and 2100 (this is an average over four Januaries). All changes are plotted as a difference (steady state minus the specific scenario)

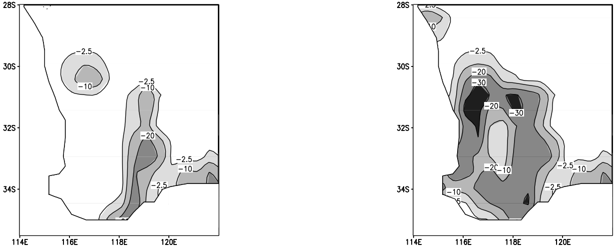
reforestation is larger (Fig. 1b). There is clearly a strong association between the pattern of temperature change and the LCC with the centre of the region showing less cooling that the periphery because of a smaller LCC. The maximum cooling effect of the reforestation is again 0.4 °C under both the A2 (Fig. 2e, g) and B2 (Fig. 2f, h) scenarios in both 2050 and 2100. These results show that reforestation has the potential to decrease the projected warming due to the enhanced greenhouse effect by up to 0.4 °C. The systematic temperature signal associated with each LCC experiment (Fig. 2) is noteworthy and gives us confidence that the result is robust.

We calculated the changes in temperature caused by LCC as a percentage of the increase in temperatures between the current (2000) and projected climate with steady state (SS) land cover. To quantify, for example, the percentage cooling effect of reforestation in land cover scenario LCL with respect to the warming for 2050A2, we have $100^{*}\Delta\mathrm{T(SS\text{-}LCL)}_{2050\mathrm{A2}}/\Delta\mathrm{T(Current\text{-}SS}_{2050\mathrm{A2}})$. This percentage would quantify the strength of the cooling effect of reforestation relative to the projected warming without reforestation (i.e., the SS land cover). Figure 3 shows that both LCL and LCH decrease the warming projected, over areas of LCC by up to 30% depending on the scenarios considered. Reforestation cools by ∼10% of the projected warming under the LCL scenario for 2050 in areas of LCC. The cooling effect is stronger in the LCH scenario in 2050, reaching 30% in the B2 scenario. However, the cooling effect of

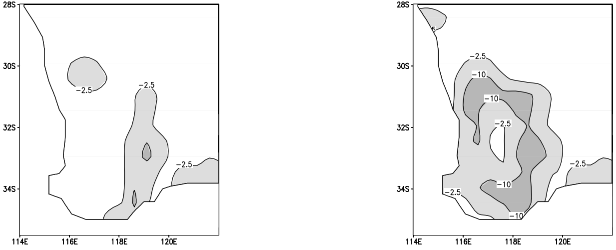
(a) Tmp 2050A2 Veg(SS−LCL)/Clim(2000−SS) (e) Tmp 2050A2 Veg(SS−LCH)/Clim(2000−SS)



(b) Tmp 2050B2 Veg(SS−LCL)/Clim(2000−SS) (f) Tmp 2050B2 Veg(SS−LCH)/Clim(2000−SS)



(c) Tmp 2100A2 Veg(SS−LCL)/Clim(2000−SS) (g) Tmp 2100A2 Veg(SS−LCH)/Clim(2000−LCH)



(d) Tmp 2100B2 Veg(SS−LCL)/Clim(2000−SS) (h) Tmp 2100B2 Veg(SS−LCH)/Clim(2000−SS)

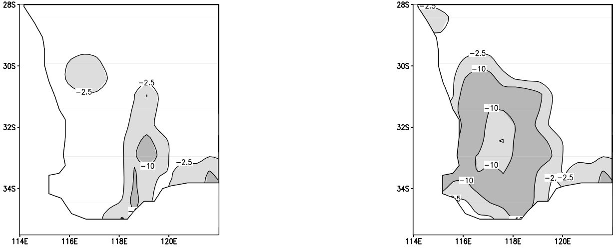


Fig. 3. The impact of land cover change on temperature (as shown in Fig. 2) as a percentage of the temperature change simulated for the particular scenario ignoring land cover change. This measures the relative importance of reforestation against the background of temperature changes driven by emission scenarios by 2050 and 2100

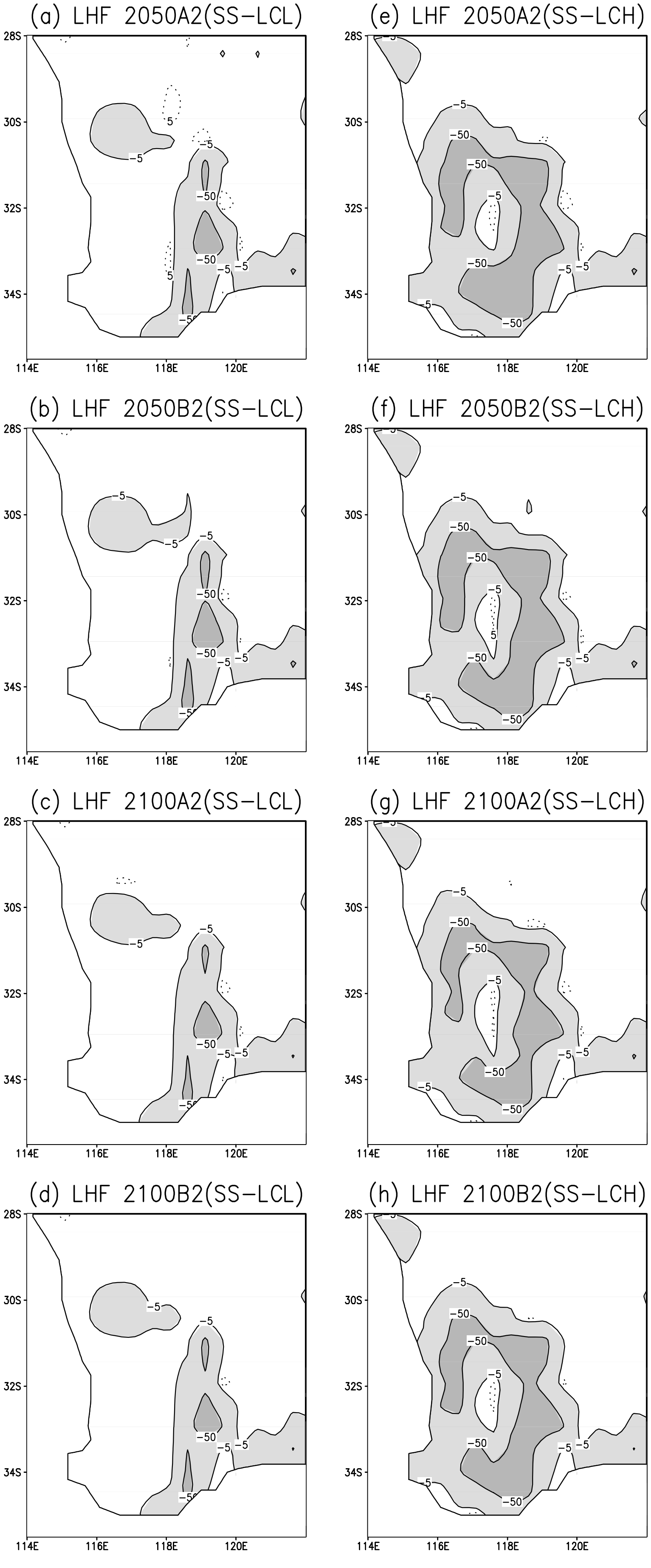


Fig. 4. As Fig. 2, but for the latent heat flux ($W\,m^{-2}$)

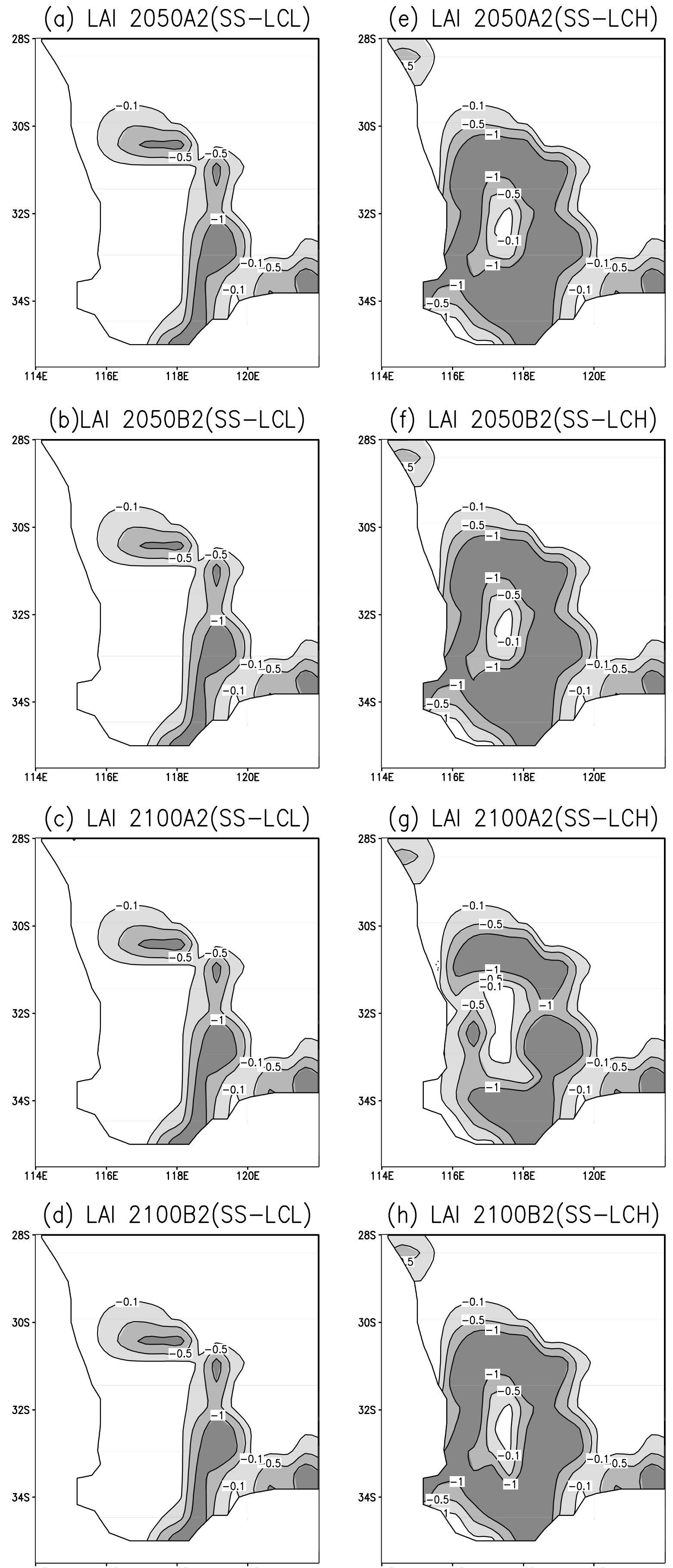


Fig. 5. As Fig. 2, but for the leaf area index ($m^2\,m^{-2}$)

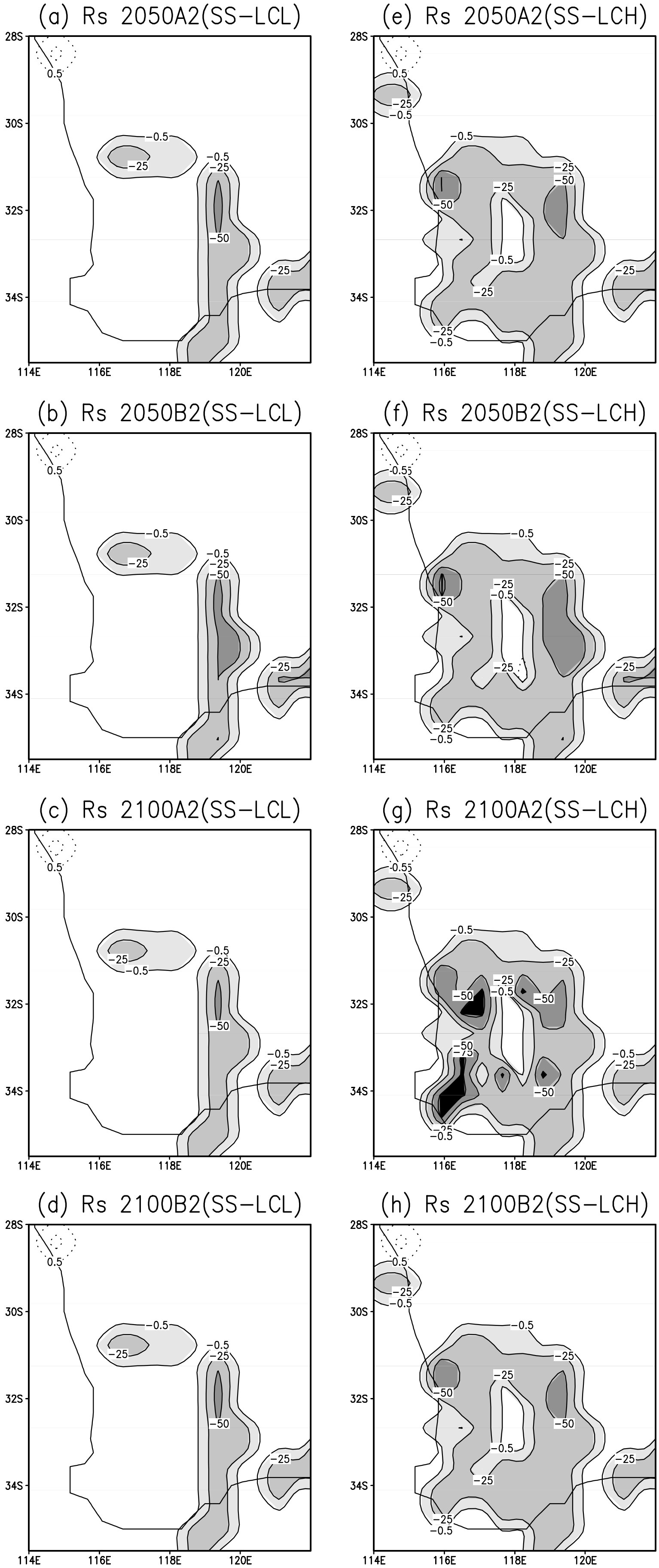


Fig. 6. As Fig. 2, but for stomatal conductance ($\mathrm{s\,m^{-1}}$)

reforestation declines in relative importance as warming intensifies such that by 2100, even the LCH scenario only offsets 10% of the projected warming.

It is important to recognize that the impacts of LCC on temperature for all scenarios are limited to the areas of LCC. The ‘‘localized’’ nature of the LCC impacts is very clear in Figs. 2 and 3 and areas remote from the LCC show no significant impacts on temperature due to LCC.

3.2 Contributions to the simulated changes in temperature

The cooling effect of reforestation in western Australia is mainly due to an increase in latent

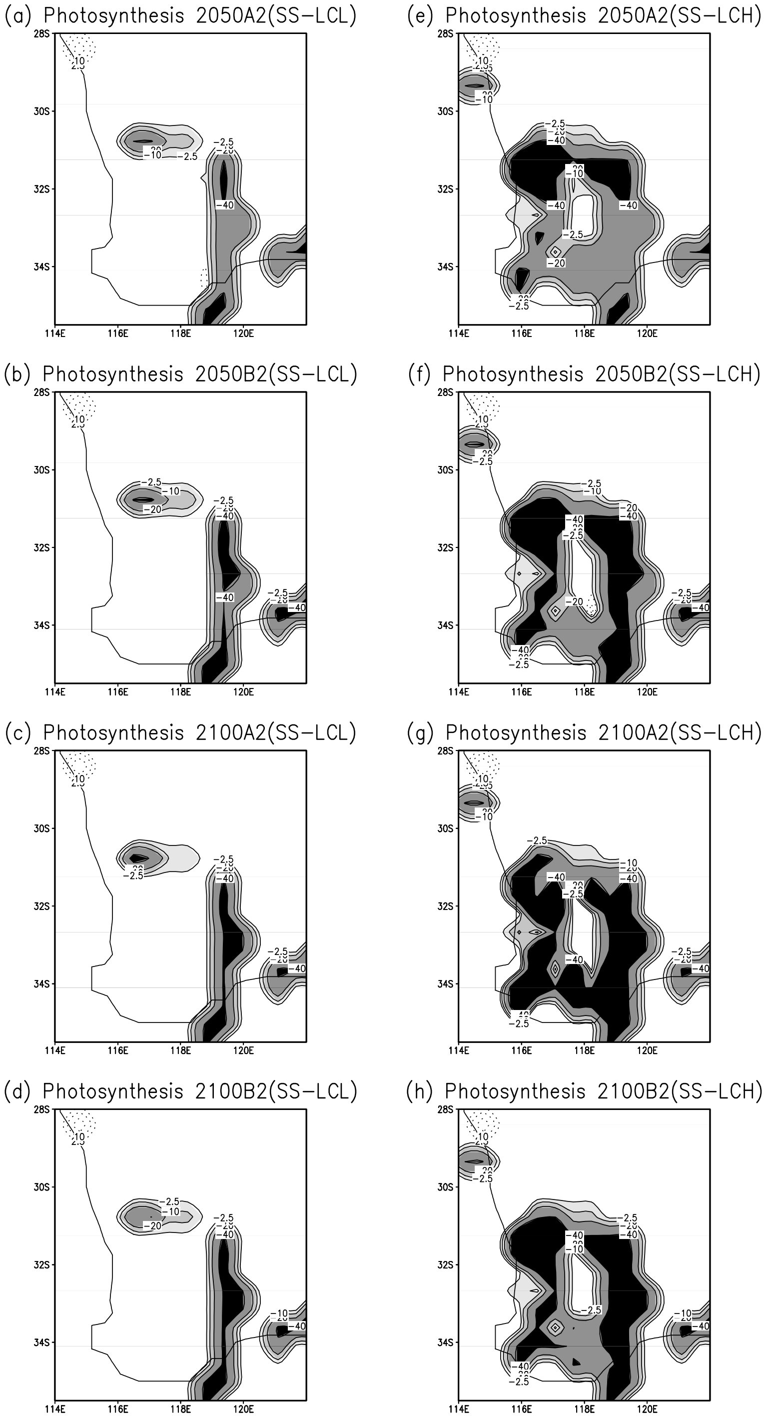


Fig. 7. As Fig. 2, but for photosynthesis

heat flux (λE). Figure 4 shows the changes in λE under each scenario and shows an increase of up to 50 W m^{-2} due to the replacement of grasses and crops with forest. While the area of increase is larger in LCH (Fig. 4e–h) the magnitude of the change is similar between LCL and LCH. Part of the increase in λE is due to the structural feedback of an increase in the leaf area index (LAI, Fig. 5). GEMTM responds to the increased CO_2 and warmer temperatures under both the A2 and B2 scenarios by growing larger leaves (LAI increases by up to 1 m^2 m^{-2}) that provide a larger surface area for transpiration and evaporation of intercepted rainfall. The physiological feedback is also significant (Fig. 6) with reforestation leading to a change in stomatal conductance. There is a significant difference in the change in g_s under LCH in 2100 depending on the emission scenario. There is a stronger response in the stomatal conductance in A2 (high emissions, Fig. 6g) compared to B2 (low emissions, Fig. 6h) which is related to the significantly higher CO_2 levels experienced by the stomates by 2100 in A2. While it is clear that, overall, the main driver of the changes seen in Figs. 4–6 is the scale of reforestation and that these changes do not systematically affect the specifics of the temperature changes (Fig. 3) there are detailed changes in the stomatal conductance that indicates a different response by the vegetation developing as CO_2-concentrations increase toward 2100.

The changes in λE, LAI and g_s should affect the exchange of CO_2 between the vegetation and the atmosphere. Figure 7 shows the impact of the scenarios on photosynthesis and demonstrates a strong coupling between the photosynthesis and the changes in λE, LAI and g_s as expected. In all our simulations, photosynthesis increases under reforestation scenarios and there is a noticeably stronger response in 2100 under the A2 scenario where the fertilization effect caused by very high CO_2-concentrations is particularly apparent.

4. Discussion

The changes in temperature simulated by GEMRAMS (Fig. 2) suggest that reforestation can cool western Australia significantly, by around 20% of the projected warming by 2050. However, as warming intensifies under both B2 and A2 emission scenarios, the cooling effect due to reforestation decreases to about 10% by 2100 (Fig. 3). This cooling is due to the impact of reforestation on λE (Fig. 4). The main vegetation relationship between the reforestation scenarios and this increase in λE is the increase in LAI. This structural feedback provides a larger surface area of leaf for transpiration and is combined with the greater ability of the trees to supply water for evaporation in comparison to grasses and crops due primarily to deeper roots.

We explored the contribution of the LAI change to the temperature change by isolating the impact of LAI from the other changes (albedo, stomatal conductance, etc). Using the LCH land cover for the A2 scenarios of 2050 and 2100, we allowed LAI to respond to the increase in CO_2 but kept the CO_2 sensed by the stomates to the current value of 369 ppmv (thereby preventing any physiological feedback). Figure 8a is therefore the change in temperature simulated for 2050 with only the structural feedback and this can be compared to Fig. 2e where both the structural and physiological feedbacks were included. Similarly, Fig. 8b can be compared to Fig. 2g (2100). Clearly, there is a very strong correspondence between the simulations with just the structural feedback (Fig. 8) and the simulations with both structural and physiological feedbacks, indicating that the major cause for the temperature changes shown in Fig. 2 were the structural changes in the vegetation. Figure 8c and d quantify the percentage of the total change simulated with just the structural feedback (Fig. 8a, b) compared to the changes where both structural and physiological feedbacks were included (Fig. 2e, g). Figure 8c and d show that 90–110% of the changes in Fig. 2e, g can be explained just by accounting for the structural feedback. This result is likely regionally specific and should not be extrapolated to other geographical or climatological regions.

Thus, over western Australia, if the aim is to simulate the impact of reforestation on January temperature, the only biospheric feedback that needs to be captured is the structural changes in LAI. Further, changes in λE are insensitive to the physiological feedback. However, while changes in temperature and λE are important, changes in other quantities should not be ignored. Ultimately, we want to be able to project

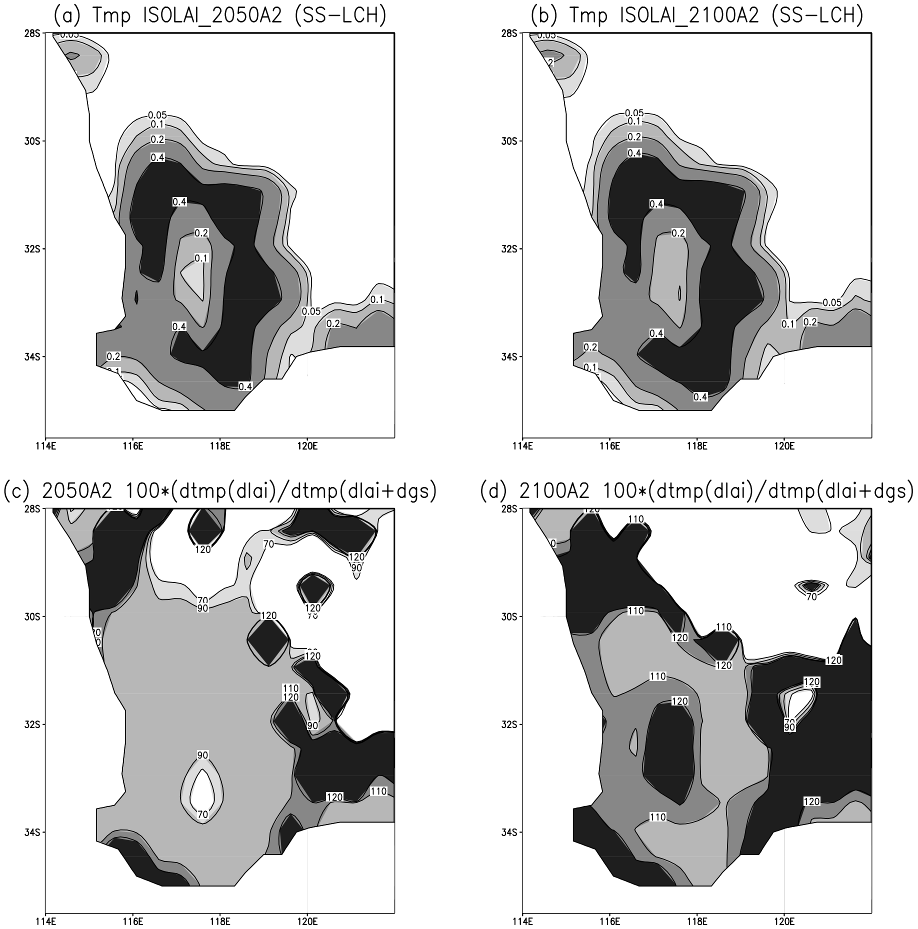


Fig. 8. The change in temperature simulated by GEMRAMS with only the structural feedback included as a percentage of the change simulated with both the structural and physiological feedbacks included (i.e., Fig. 2)

the impact of climate change on the terrestrial carbon balance, on plant function, and ultimately on the competitiveness of plants that may lead to changes in the biodiversity as new and invasive species gain advantages over native species. This requires a capacity to simulate the net carbon balance and the allocation of the carbon to leaves, stems and roots, which in turn requires the simulation of photosynthesis. While Fig. 7 showed very similar pattern of change in photosynthesis across the various experiments, there was a suggestion of a stronger response by 2100 under the A2 emission scenario. While these differences did not clearly affect λE and thereby temperature in our simulations over western Australia, this is probably regionally specific and encourages similar experiments to be conducted in other regions.

5. Conclusions

This paper has explored the role of LCC on the future temperatures over western Australia. Our results showed that reforestation has the potential to reduce the warming caused by the enhanced greenhouse effect by as much as 30% under the A2 and B2 scenarios by 2050 but this cooling effect declines to 10% by 2100. The reduction in temperature is the result of the increase in LAI which led to a corresponding increase in latent heat flux. This cooling effect of reforestation is localized and there were no simulated changes in temperature over regions without LCC. Hence, any cooling effect of LCC via reforestation would depend on the spatial scale of reforestation and, at least to first order, the cooling effect appears linearly related to the spatial scale of reforestation. This, unfortunately, significantly limits the potential to ameliorate CO_2-induced warming in the long-term in this region since the scale necessary for reforestation is unlikely to be realistic (indeed, the LCL scenario is likely overly optimistic).

There are several important limitations in our experiments. For one, we performed multiple one month-simulations for the January climate which limits a full dynamic feedback between the biosphere, climate, and carbon. Our experiments also do not involve feedbacks to a larger global atmospheric circulation. Our analyses are also limited by using only two projected land cover scenarios that are both likely overly optimistic. Other serious limitations come from model dependencies and uncertainties relating to the parameterization of land surface processes. The simulation of carbon-processes are at the cutting edge of current capacity and the outcomes are highly uncertain (compare Cox et al, 2000, and Friedlingstein et al, 2001, for example). The impact of LCC and increasing CO_2 concentrations on photosynthesis is clearly a function of a vast array of poorly represented quantities (e.g., soil moisture) and non-represented quantities (e.g., soil nutrients and changes in atmospheric deposition of nitrogen and sulfur). However, our demonstration that changes in LAI largely explained the role of LCC in moderating temperature rises over western Australia suggests that further effort to understanding how climate might affect LAI would be one way of reducing current uncertainties.

Overall, our results are therefore no more than illustrative and should be seen as an initial attempt to explore the role that reforestation might have in moderating the impact of increasing CO_2-concentrations over western Australia. With this in mind, we find that reforestation does have the potential to offset global warming but only locally where large-scale reforestation occurs. The reductions in warming caused by increasing CO_2 are quite significant ($\sim$30%) to 2050, but decline in importance to $\sim$10% as warming intensifies to 2100. The lack of remote effects caused by reforestation in our experiments substantially moderates the potential of reforestation as a means to offset greenhouse-induced warming over western Australia. Specifically, the scale of reforestation in LCL is likely overly optimistic and given the time scales required for the forests to grow, coupled with the major uncertainties in our understanding of the biophysical system, large scale reforestation does not appear to be a significant method of reducing warming due to greenhouse. It may be that seasonal simulations, or simulations over many years will show remote effects, or an impact of reforestation on rainfall remote from the regions of change and these could change this conclusion. We therefore see the extension of our work to multi-year and multi-season simulations as a priority.

Irrespective of the lack of remote impacts of LCC on temperature over western Australia, the local impacts were substantial under both A2 and B2 scenarios to 2050. Therefore, while we do not argue for a large scale reforestation project over Australia (the uncertainties are simply too large) we do conclude that LCC scenarios should be included in future projections of the Australian climate since these would add realism and regional detail to these projections and perhaps aid detection and attribution studies. We note that a very substantial model and scenario development exercise is required to build confidence in the reliability of climate projections that include all significant forcing terms on the future climate of Australia.

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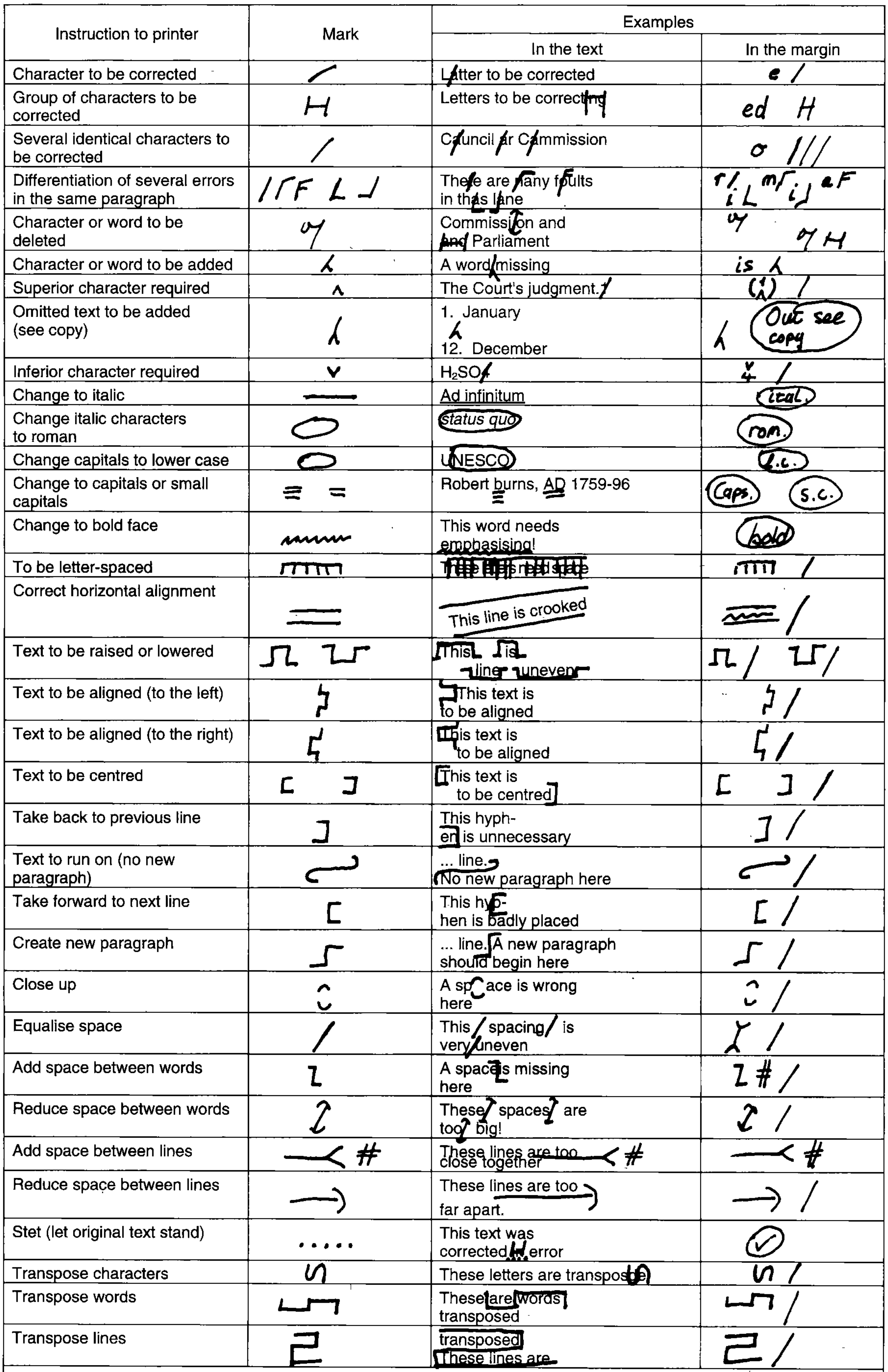

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