Climatic effects of land cover change at different carbon dioxide levels

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ABSTRACT: Land cover change (LCC) simulations were performed at 3 different carbon dioxide levels (280, 355 and 430 ppmv) using the standard version of the NCAR CCM3 at T42 resolution coupled with the Biosphere-Atmosphere Transfer Scheme (BATS) and a mixed-layer ocean model. We follow the evolution of the initial temperature perturbation within the horizontal and vertical structure of the atmosphere and then examine the 15 yr average of near-surface air temperature and meridional stream function differences between current and natural land cover at the 3 different CO₂ levels. Results show that LCC caused temperature perturbations which initially affected only those regions where the land cover was modified. After a short period, however, the effects of LCC propagated to remote regions. While the remote effects of LCC were generally different at each CO₂ level, 4 common remote regions of sensitivity were identified in these simulations (North Pacific, North America, northeast Asia and the Indian Ocean). The main factor in explaining the differing remote responses was the change in the zonally averaged background circulation resulting from circulation changes caused by LCC, CO₂ level, and the interaction between these 2 forcings. The 15 yr average seasonal results indicate that LCC may have impacts on surface air temperature which vary in sign between seasons, depending on the character of the initial land cover perturbation as well as local meteorological conditions. We find no evidence that the impacts of LCC decrease with increasing CO₂, rather we show that LCC does appear to affect regional climate at a statistically significant level.

KEY WORDS: Land cover change · CO₂ level · Surface air temperature · Meridional circulation · Initial perturbation propagation

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1. INTRODUCTION

The Earth's climate is a significant factor in explaining the patterns of global land cover; on the other hand, land cover has also been shown to affect climate through the exchange of heat, mass and momentum fluxes. Modifications to these fluxes may lead to changes to the regional and global climate; one way through which modifications may occur is via activity that changes the physical characteristics of the surface. Under natural conditions, land cover change (LCC) usually proceeds slowly, but human activities have caused rapid modification in more recent times (Hunt-

ley & Webb 1988). Thomas et al. (1956), Turner et al. (1990), Meyers et al. (1994) and Vitousek et al. (1997) have investigated the role of human activity in modifying land cover at regional to global scales over the past 300 yr. As the impact of human activity on land cover increases, the study of the impact of LCC on the regional and global climate has also increased (Polcher & Laval 1994, Dirmeyer & Shukla 1996, Zhang et al. 1996, Xue 1997, Nicholson et al. 1998, Betts 1999, Brovkin et al. 1999). Understanding the mechanisms that link changes in land cover with climate can aid in the understanding, modeling and prediction of global climate change.

In a series of recent papers (Chase et al. 1996, 2000, Pitman & Zhao 2000, Zhao et al. 2001), the impact of historical LCC impacts on the Earth's climate was

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investigated. Chase et al. (1996, 2000) used the NCAR Community Climate Model (CCM2) with fixed sea-surface temperatures to simulate the impacts of historical leaf area index (LAI) and LCC on the regional and global climate. They found significant global temperature and precipitation changes which were associated with changes in global-scale circulations when the patterns of observed LAI and LCC were imposed. Zhao et al. (2001) and Pitman & Zhao (2000) used the NCAR CCM3 coupled with a mixed-layer ocean model to simulate the impact of historical LCC on the global atmospheric circulation and the relative impact of historical LCC and historical CO₂ changes. Although Zhao et al. (2001) and Pitman & Zhao (2000) used a different version of the CCM and a different pattern of LCC, they also found that LCC can impact the global atmospheric circulation. In the global average, they found that the impact of LCC on near-surface air temperature was negligible compared to CO₂ impacts. A negligible impact on the global average temperature resulting from LCC was also found by Betts (1999), while Brovkin et al. (1999) found evidence of global cooling since about 1400 due to deforestation. However, at high latitudes and at regional scales, LCC was shown to have an impact on temperature of a magnitude similar to the observed CO₂ increase (Pitman & Zhao 2000). Brovkin et al. (1999) found that the biogeophysical effects of deforestation caused global scale changes of similar magnitude, but of opposite sign, to the warming caused by increasing CO₂. Chase et al. (2001) compared temperature results from several GCMs which investigated CO₂ or CO₂/aerosol forcing with simulations which examined the impact of historical LCC. They showed that the direct or remote effects of LCC were comparable to the effects of increasing CO₂, having a similar amplitude and occurring in the same regions of the globe.

Overall then, the impact of LCC on the global and regional climate remains uncertain. The aim of this paper is to investigate the impact of historical LCC on global climates and how those effects are modified by increasing levels of CO₂. Therefore, in contrast to earlier papers, we focus on the impact of LCC at 3 different levels of atmospheric CO₂ representing pre-industrial, present-day and future concentrations (280, 355 and 430 ppmv, respectively). We also test the significance of these results with greater rigor than has been done in the past. Our aim is to determine whether the impact of LCC is independent of CO₂ concentration (i.e. will the influence of LCC on regional and global climate alter as CO₂ increases further). In explaining the changes in the impact of LCC at different levels of CO₂, we will also focus on some of the mechanisms through which LCC impacts on the regional and global climate. In Section 2 we briefly outline the experimen-

tal design and statistical methods. In Section 3, we show the evolution of the initial temperature perturbation of LCC and 15 yr average results with statistical significance tests. Discussion and conclusions are presented in Sections 4 and 5.

2. EXPERIMENTAL DESIGN AND STATISTICAL METHODS

We used the standard version of the NCAR CCM3 (Kiehl et al. 1996) at T42 resolution (approximately $2.8^\circ \times 2.8^\circ$) coupled with the Biosphere-Atmosphere Transfer Scheme (BATS, Dickinson et al. 1993) and a mixed-layer ocean model. We performed 3 sets of 2 equilibrium simulations, one using an estimate of natural land cover and the other using current land cover, both at the 280 ppmv CO₂ level. Identical pairs of experiments at 355 and 430 ppmv were also performed. Our initial aim was to compare the impact of the change in CO₂ from natural (280 ppmv) to current (355 ppmv) with the impact of LCC from natural to current. However, to investigate the role of CO₂ increases into the future, we performed an extra simulation with a further 75 ppmv increment (i.e. 430 ppmv). Each simulation was integrated for 17 yr. The CO₂ change only affects radiation, and no direct CO₂ effect on plants was included. The natural land cover data set was obtained from BIOME3 (Haxeltine & Prentice 1996) and was aggregated from $0.5^\circ \times 0.5^\circ$ to T42 resolution. To determine the current land cover data set, we modified the natural land cover predicted by BIOME3 from forest or grass to a crop where LAI changed by more than 1, following Chase et al. (1996). The modified land cover imposed in our experiments leads to a change in a large number of vegetation and soil parameters within BATS. The widespread LCC over South America and Africa imposed by Chase et al. (1996, plate 1) were not included in our experiments, and we also removed some individual points which were geographically isolated. More detail on creating the natural (prior to human activity) and current land cover data can be found in Zhao et al. (2001). Overall, our LCC focussed on 4 main areas: South East Asia (mainly China), India, Europe and USA (Fig. 1), and these changes are largely constrained to 15–60° N. It is worth noting that, in contrast to a sea-surface temperature anomaly, LCC causes an essentially permanent surface anomaly, although this may vary in sign depending on many factors, including season and local meteorological conditions. In our experiments we changed approximately 7.9% of the land area, which contrasts with the findings of Vitousek et al. (1997), who suggest that around 45% of the global land area has been modified by human activity.

Fig. 1. Land cover change (LCC) between the current and natural scenarios described in the text. (a) Geographical distribution of LCC; (b) number of points changed as a function of latitude; (c) number of points changed as a function of longitude

Spin-up was achieved after about 2 yr. When average results are shown, these are averaged over the last 15 of 17 yr integration. In all cases, results are presented as the current vegetation simulation minus natural vegetation simulation.

To assess the reliability of the simulated impact of LCC on climate change, a statistically significant test is required. All differences were initially tested with Student's *t*-tests to establish significance. However, since climate variables tend to be correlated in space and time, the underlying assumption of independence in the traditional *t*- and *F*-tests may be violated. Additionally, these tests may not be sufficiently powerful to detect climate changes with the relatively small sample size typical of a LCC experiment (i.e. 10 to 15 yr integration). Therefore, we also applied the Z-test proposed by Katz (1982) to the temperature mean field. This procedure is based on parametric time series modeling involving the fitting of low-order autoregressive processes. It has 2 main advantages over the traditional *t*-test. First, it is based on a large number of daily

samples rather than limited monthly or seasonal averaged samples. Second, the Z-test does not require that the population variance in the control and experiment time series be equal or that the samples be independent. The methodology requires an appropriate model (i.e. the order of autoregressive process) to be identified; Katz (1982) suggests the use of the Bayesian information criterion (BIC) for selecting the appropriate order of the autoregressive process and showed that the maximum order was 5, but when applied to climate model results, this was concentrated on order 2 and 3. We calculated the Z-test for each order (up to 4) and found that for most of the grid points chosen, the second and the third order appeared to be satisfactory. Although applying a second order at all grid points gives the largest total area of significance, the results shown in this paper utilize the BIC procedure which Katz (1982) argues improves the reliability of the methodology. As discussed in Katz (1982), and confirmed by our own experience, the Z-tests tend to indicate larger regions of stronger statistical significance

than the t -test because of the use of daily samples. For 3-dimensional fields the daily information required by the Z -test could not be stored, and hence differences were tested only with the t -test.

As an additional test of the statistical significance of our results, we have also used the 2-way analysis of variance (ANOVA) techniques developed by Zwiers (1996) applied to the temperature variance field. ANOVA is designed for ensemble model runs and can separate signals resulting from different forcing (e.g. LCC compared to changes in CO_2) as well as separating forcing signals from model variability. We used an ensemble of six 15 yr simulations (2 types of land cover at 3 CO_2 levels), assuming that the seasonal mean time series is comprised of 4 components: a LCC-forced component, a CO_2 -forced component, an interaction of LCC and CO_2 components and an internal variability (variation between years and runs that is not accounted for by the other 3 terms). This enables separation of the variability due to the forced component (due to LCC or changes in CO_2) from that due to the model variability. Since the forced component is not sensitive to initial conditions (Zheng et al. 2000), it becomes potentially predictable. Details regarding this method can be found in Appendix 1.

3. RESULTS

3.1. Evolution of the initial perturbation of LCC

On the first day of integration (the model is initialized 1 September), the initial perturbation patterns in near-surface air temperature (Fig. 2) are isolated to locations of LCC (Fig. 1). The differences in the air temperature over Europe, India and China exceed -1.0 K at all 3 CO_2 levels. Over the USA, the impact of LCC on air temperature is less than -0.3 K. The close association of temperature change with location of LCC indicates that LCC does perturb the atmosphere locally. It will be shown later that these local perturbations propagate horizontally and vertically through the atmosphere. Fig. 2 also shows that the initial perturbation in the air temperature varies in sign between regions. This results from different changes in the parameter values used within BATS in different locations (the vegetation types vary in the natural case, and since all these are changed to crop, the net changes in parameters vary) and from variations in meteorological conditions locally. It is noteworthy that the differences between the air temperatures simulated on Day 1 between the 3 CO_2 levels are negligible, indicating the initial (Day 1) difference due to LCC is not related to CO_2 level.

Figs. 3 & 4 present the 10th and 30th day integration results respectively for near-surface air temperature. In Fig. 3, the initial perturbation has propagated across the Eurasian continent and a temperature difference of 2 K is quite common at all 3 CO_2 levels. A change in air

Fig. 2. The initial perturbations of near-surface air temperature caused by LCC (first day of integration) at 3 CO_2 levels (280, 355 and 430 ppmv from top to bottom)

temperature is also visible over the USA as well as in some high-latitude areas. The patterns of change in air temperature remain very similar at the 3 CO₂ levels. After 30 days (Fig. 4), the impact of LCC has extended

to the global scale. Large differences are visible at high latitudes in both hemispheres, remote from regions of LCC. However, these changes are also related to the large natural variability in these regions, and it

Fig. 3. The initial perturbations of near-surface air temperature caused by LCC (10th day of integration) at 3 CO₂ levels (280, 355 and 430 ppmv from top to bottom)

Fig. 4. The initial perturbations of near-surface air temperature caused by LCC (30th day of integration) at 3 CO₂ levels (280, 355 and 430 ppmv from top to bottom)

becomes increasingly difficult to attribute differences directly to LCC. By Day 30, the patterns of temperature differences caused by LCC are partially dependent on the background circulation which has, by this point, been affected both by changes in CO₂, LCC and the interaction of the two. Similarities between the simulations remain apparent over the location of the LCC as well as over central Eurasia (positive).

The changes in temperature shown in Figs. 2 to 4 remote from the location of LCC result from the propagation of the initial perturbation through the atmosphere. This can be seen clearly by viewing the changes in the vertical temperature structure of the atmosphere for CO₂ at 280 ppmv. On Day 1 (Fig. 5) the initial perturbation of low-level temperatures can be seen in those regions where LCC was imposed. The differences in vertical structure between the simulations at the 3 levels of CO₂ on Day 1 are negligible (figure not shown). The initial atmospheric perturbation in the mid-latitudes is larger than in the tropics.

Figs. 6 & 7 show the evolution of the vertical structure of temperature perturbation (5th day at 280 ppmv and 30th day integration at 3 CO₂ levels, respectively). Although the local largest perturbation is still in the low levels of the atmosphere after 5 days (Fig. 6), higher levels are also clearly affected. After 5 days, the patterns are still similar for the 3 CO₂ levels (not shown). The magnitude of the changes shown in Fig. 6 are much larger over the mid-latitudes than in the tropics. This may be related to the higher overall variability in the mid-latitudes or the geographical extent of the LCC. The vertical structure of temperature on the 30th day of integration (Fig. 7) are quite different at the 3 CO₂ levels, indicating the increasing effect of the interaction between CO₂ and LCC effects as well as inherent model variability. Despite these differences, it is still clear that the longitudinal locations of the maximum positive and negative centers remain similar, especially in the mid-latitudes.

Overall, it is clear that from the initial perturbation changes develop and propagate through time vertically and horizontally. The location and initial development of the change is tightly coupled to the location of LCC and not to model variability or CO₂ concentration. However, as the integration continues, the local perturbations propagate horizontally and vertically through the atmosphere such that the monthly averaged pattern of changes do depend on the LCC, CO₂ concentration changes and the interaction between the two. This is discussed in more detail in the following section.

Fig. 5. Vertical structure of initial perturbation of near-surface air temperature (first day of integration) caused by LCC at 280 ppmv CO₂ level, latitude is 10, 20, 40 and 50°N (top to bottom)

3.2. Fifteen year average results with statistical tests

Fig. 8 shows the 15 yr average near-surface air temperature differences between the current and natural land cover at 3 CO₂ levels in 4 seasons (DJF, MAM, JJA and SON). The 90% significance level calculated using a 2-tailed Z-test is shaded. At all 3 CO₂ levels, large responses to the LCC change can be seen particularly in the local areas where the initial perturbation in LCC occurs. Statistically significant impacts in the mid- and high latitudes over the land and over the North Pacific, North America, northeast Asia and Indian Ocean are also common. In locations directly affected by LCC, the temperature changes are quite similar at the 3 different CO₂ levels, while in areas remote from LCC, the pattern and size in the temperature changes are quite different at the 3 different levels. The similarity of the initial LCC response for each of the CO₂ levels is an indication that the differences in remote effects are, for the most part, the result of changes in the background circulation caused by the interactions between the LCC effects and CO₂ level.

At the seasonal time-scale, statistically significant LCC impacts can be seen in India and south China in all 4 seasons and at the 3 CO₂ levels (Fig. 8). In contrast, Europe has large negative impacts in JJA and some positive impacts in SON (also statistically significant). Over the USA, it is hard to find a common signal at different CO₂ levels, possibly because the initial perturbation is relatively small, but also because the propagation of the initial perturbation extends over the ocean rather than over the land, in contrast to Europe. LCC impact in the Indian region is negative in all 4 seasons. In China, LCC caused negative changes in DJF, but positive changes in other seasons. Clearly, LCC has different impacts in different locations and in different seasons.

Table 1 shows the percentage of the globe where statistically significant changes in the near-surface air temperature were found (calculated using a 2-tailed Z-test with 80, 90 and 95% significance levels). In DJF, LCC at 355 ppmv has the largest percentage of the globe affected by significant changes. In the other seasons, the percentage area of statistically significant change increases with CO₂, particularly in JJA. Compared to the *t*-test, the Z-test shows larger regions of statistical significance, which is attributable to using a large number of daily samples (see Appendix 1). The reduced area of statistically significant change found at high latitudes in the Z-test is an indication that this

Fig. 6. Vertical structure of initial perturbation of near-surface air temperature (5th day of integration) caused by LCC at 280 ppmv CO₂ level, latitude is 10, 20, 40 and 50°N (top to bottom)

Table 1. Percentage of global area showing statistically significant change in the 4 seasons at the 80, 90 and 95 % significance levels using a 2-tailed Z-test

		DJF	MAM	JJA	SON
280 ppmv	80 %	30	20	20	19
	90 %	20	11	13	10
	95 %	13	6	9	6
355 ppmv	80 %	36	22	29	23
	90 %	24	11	19	13
	95 %	17	7	13	7
430 ppmv	80 %	32	25	36	28
	90 %	21	15	25	16
	95 %	15	10	18	10

test is more able to separate signal from noise in regions of high climate variability. However, the overall regional pattern of the statistically significant areas is similar between the 2 tests (*t*-tests not show).

Fig. 9 shows the results of the ANOVA method for the changes in near-surface air temperature variance resulting from LCC (see Section 2 and Appendix 1). The shaded areas indicate common regions where all 6 simulations show statistically significant variations in the variance of near-surface air temperature due only to LCC at the 90 % significance level. LCC effects tend to be largest in MAM and JJA, with the geographical extent of statistically significant changes over land rather than over ocean. The North Pacific, North America, northeast Asia and the Indian Ocean are 4 remote areas which have a large and common response to LCC.

We have shown that LCC can have significant effects on regional near-surface air temperatures both locally and in regions remote from actual LCC. LCC also appears to affect the global-scale circulations, which is one mechanism by which LCC can affect remote regions. We now examine these changes in circulation in more depth. Fig. 10 shows the LCC impact on zonally averaged meridional circulation at 3 CO₂ levels, with shaded regions indicating 80 % significance levels in a 2-tailed *t*-test (the Z-test requires daily data, which could not be achieved for 3-dimensional fields).

The changes in the large-scale circulation due to LCC at differing CO₂ levels result from interactions between the 2 forcings. This is seen in Fig. 10a, where the Hadley cell is seen to decrease near to the equator and statistically significantly increase between 10 and

(a) C-N_280,lat=10 (30 day)

Fig. 7. (Adjacent panel and facing page.) Vertical structure of initial perturbation of near-surface air temperature (30th day of integration) caused by LCC at 280 ppmv CO₂ level, latitude is 10, 20, 40 and 50°N (top to bottom). (a) 280, (b) 355 and (c) 430 ppmv CO₂ levels

(b) C-N₃₅₅,lat=10 (30 day) (c) C-N₄₃₀,lat=10 (30 day)

Fig. 8. (Above and facing page.) Current minus natural 15 yr average near-surface air temperature at (a) 280, (b) 355 and (c) 430 ppmv CO₂ levels in DJF, MAM, JJA and SON with 2-tailed Z-test at the 90 % significance level (shaded)

Fig. 8 (continued)

Fig. 9. Regions where LCC causes statistically significant changes in the near-surface air temperature at the 90% significance level (shaded) in DJF, MAM, JJA and SON; produced using 2-way ANOVA

Fig. 10. (Above and following 2 pages.) Fifteen year average meridional stream function (current case is dark, natural case is light) and differences at (a) 280, (b) 355 and (c) 430 ppmv CO₂ levels in DJF, MAM, JJA and SON with 2-tailed *t*-test at the 80 % significance level

Fig. 10 (continued)

Fig. 10 (continued)

30° N at 280 ppmv. At 355 ppmv (Fig. 10b), the Hadley cell increases in intensity over both the equator and between 10 and 30° N, and the change in the southern hemisphere branch is statistically significant. Finally, at 430 ppmv (Fig. 10c), the Hadley cell increases over the equator but decreases between 10 and 30° N; the change is statistically significant only along the equator at low atmospheric levels. The lack of consistent changes in the Hadley cell in DJF is an indication that the interaction between LCC and CO₂ changes, combined with model variability.

In contrast, we find some common changes to the atmospheric circulation due to LCC in the other seasons at the 3 CO₂ levels. The central maximum value of the Hadley cell decreases in MAM, and the equatorial side boundary of the Hadley cell moves away from the equator in both hemispheres. In JJA, the center maximum value increases and the boundary of the Hadley cell in the northern hemisphere moves northwards. The changes in the Hadley cell are larger and more significant at the lowest CO₂ level (the maximum difference in the Hadley cell is $\sim 3.1 \times 10^{10}$ kg s⁻¹ at 280 ppmv, and $\sim 1.2 \times 10^{10}$ kg s⁻¹ at both 355 and 430 ppmv). In SON, the Ferrel cell becomes weaker in the northern hemisphere and the most statistically significant changes in this part of the atmospheric circulation occur at 430 ppmv.

The changes in the Hadley cell are consistent with changes in tropical precipitation, divergent outflow and in the 200 hPa zonally averaged jet (reported previously in Zhao et al. 2001 for 355 ppmv). These all increase and move northwards at all 3 CO₂ levels (figures not shown). In JJA the Hadley cell also shows significant changes at both the smallest and largest CO₂ concentrations.

We also investigated the impact of changes in CO₂ on the large-scale circulation of the atmosphere. Under current land cover the CO₂ impact on the zonally averaged meridional stream function (figure not shown) is statistically significant over a larger area than the impact of CO₂ (under natural land cover) in all 4 seasons. In particular, the magnitude of the impact of increasing CO₂ (from 280 to 430 ppmv) under current land cover is statistically significant over a much larger area in JJA than the equivalent change under natural land cover. Under current land cover, the change in CO₂ from 280 to 430 ppmv leads to a decrease in the Hadley cell of 1.0×10^{10} kg s⁻¹, and these changes are statistically significant between 10° S and 10° N. Under natural land cover, the Hadley cell decreased in JJA by 0.5×10^{10} kg s⁻¹ and is not generally statistically significant. Under both land cover scenarios the northern boundary of the Hadley cell moves southwards.

Overall, these results imply that the impact of LCC on the large-scale circulation is non-linear and depends on

interactions between the atmospheric circulation and CO₂. The results also suggest that the impact of LCC and CO₂ on the large-scale circulation patterns within the atmosphere are comparable in terms of size.

4. DISCUSSION OF LCC EFFECTS

The LCC imposed in these simulations caused regional thermal anomalies to develop via changes in net radiation, partitioning of surface fluxes and changes in hydrological characteristics. We have shown that these surface anomalies were quickly communicated vertically to the free atmosphere and then propagated to regions remote from direct LCC forcing. We have demonstrated that LCC resulted in changes in the mean meridional circulation at all CO₂ levels, which is one explanation for climatic effects remote from regions directly affected by LCC. Other effects expected to be at work here include changes in stationary wave climatology (Chase et al. 1996), excitation of Rossby waves (Chase et al. 2000) and Hadley-Walker circulation effects (Zhang et al. 1996), all of which will generally interact to bring about the overall response.

Four regions of common sensitivity and statistical significance in all CO₂ scenarios were found remote from the areas of LCC: North Pacific, North America, northeast Asia and Indian Ocean (e.g. Figs. 8 & 9). Hoskins & Karoly (1981) showed that Rossby wave rays respond to tropical and mid-latitude thermal forcings along a great circle route propagating to the northeast (downstream from the source region, as well as poleward). However, mid-latitude forcings have a smaller response than those in the tropics. This might explain why the North Pacific, North America and northeast Asia, all of which are northeast of LCC perturbations, appear to be most sensitive to LCC. Additionally, LCC in India and China may induce remote changes over the Indian Ocean via Walker cell propagation zonally.

The initial atmospheric perturbation due to LCC is mostly independent of CO₂ level. This is an indication that the differing response to LCC at different CO₂ concentrations is a result of interactions between changes in the basic-state circulation due to CO₂ and LCC changes. Peng et al. (1997) indicated that the basic-state is relatively important, especially when the atmosphere responds to heat anomalies at mid-latitudes. Our results suggest that we should pay attention to transient changes in CO₂ levels when investigating the climatic impacts of LCC and vegetation feedback in future modeling (e.g. Betts et al. 1997, Levis et al. 1999).

LCC has a clear and statistically significant effect in summer (JJA), especially over Europe (although this

may be the result of the pattern of LCC being substantially limited to the northern hemisphere). In part, this stronger local response in summer is likely to be due to greater available energy and therefore larger changes in sensible and latent heating following LCC. However, in addition, during summer in the mid-latitudes of the northern hemisphere, a moderately strong local temperature anomaly can develop following LCC. As the basic zonal winds lose intensity as summer is approached in the northern hemisphere, the effect of any anomaly induced by LCC is magnified as the atmospheric response changes from a strong basic-state advective state to a weak basic-state diabatic state. This encourages the anomaly to persist, which enhances the perturbation caused by LCC on the atmosphere (Webster 1982). Finally, the difference in vegetation parameters between current and natural land cover is the largest in JJA, which causes the largest temperature anomalies. This assists in the development of a relatively strong signal resulting from LCC in summer over Europe. With increasing CO₂, warming might be expected to extend the seasonal time-scale of LCC impacts at mid- and high latitudes. In contrast, seasonal changes in vegetation parameters are small at low latitudes (e.g. India and south China) and the thermal forcings are within the region of easterly zonal winds, which allows a diabatic response in either season. Thus, we see clearly the local response to LCC in India and China in all 4 seasons.

5. CONCLUSION

The effect of initial perturbations in LCC can be traced to changes in the atmosphere which propagate away from the initial perturbation vertically and horizontally. LCC generates both local and remote effects which are statistically significant. The local responses are relatively common at 3 CO₂ levels, but vary in sign between locations and seasons, depending on the character of the initial land cover perturbation as well

as local meteorological conditions. In contrast, the remote changes are more varied, depending on the CO₂ level, but the effects of LCC do not disappear with increasing CO₂ and may in some cases be amplified. Our results confirm that LCC can cause a permanent local heating anomaly source which is independent of CO₂ concentrations.

Our results indicate that the correct land-surface distribution, and the evolution of this distribution in time, is likely to be important in attempts to simulate the regional-scale impacts of perturbations such as increasing CO₂. Pitman & Zhao (2000) have already shown that LCC, observed through the 20th century can have regional-scale effects which are comparable to the observed change in CO₂. While the details of the results obtained by Brovkin et al. (1999) and Betts (1999) differ from our results in detail, all these studies have demonstrated that LCC appears to be significant in simulating climate and comparable in magnitude to the CO₂ signal. The results presented here have demonstrated that the significance of LCC does not appear to be reduced at higher CO₂ levels and suggest that LCC scenarios need to be included in transitory simulations of future climate. The impact of LCC on the large-scale circulation appears to be of similar order to the increase in CO₂ from 280 to 430 ppmv and has a larger impact on the Hadley circulation than the increase in CO₂. It should be noted that this paper has only focussed on the structural changes induced by LCC, and CO₂-induced biological feedbacks such as CO₂ fertilization were not included. These may modify the conclusions reached in this paper, and hence one significant research priority is the inclusion of land-surface schemes into climate models which can simulate the evolution of the biology within increasing CO₂. Overall, this should assist in attempts to detect and attribute warming observed during the 20th century (e.g. Santer et al. 1996). As a final caveat, the impacts of LCC reported here could be strongly dependent on the climate model (Raisanen 1999) or on the land-surface model used, and hence the role of LCC needs to be studied using different climate models.

Appendix 1. Two-way analysis of variance (ANOVA)

We select seasonal (such as DJF, MAM, JJA and SON) data for analysis. Suppose that i different treatments were used, and that these were applied in random order to i experimental units in j blocks. t is the years that experiments ran. We represent the resulting ijt outcomes of the experiment with random variables X_{ijt} , for $i = 1, \dots, 2$, $j = 1, \dots, 3$, and $t = 1, \dots, 15$, which we assume to be independent and normally distributed. If a completely randomized design is used, every treatment combination must be used more than once. If a blocked design is used, each treatment must be used within each block more than once. The

test statistics used to test for block and treatment effects are identical to the fixed effects case, but the interpretation of the tests is quite different. There are also differences in the calculation of variance proportions. For more detail about ANOVA see von Storch & Zwiers (1999), and for examples applied to GCM experiments see Zwiers (1996). Our ANOVA model form is

$$X_{ijt} = \mu + a_i + b_j + c_{ij} + d_{ijt} \quad (\text{A1})$$

where $i = 1, 2$ indicates the land cover type (natural or current), $j = 1, 2$ and 3 indicates the 3 CO₂ levels (280, 355 and

Appendix 1 (continued)

430 ppmv), and $t = 1, 2, \dots, 15$ is time (in years). The terms in the model are as follows: X_{ijt} is any seasonal mean quantity simulated in year t of the run with land cover type i and CO₂ level j ; μ is the overall mean; a_i is the effect of the i th land cover type that is common to both levels of CO₂; b_j is the effect of the j th CO₂ level that is common to both land cover types; c_{ij} represents the interaction effect between land cover and CO₂ level; and d_{ijt} represents internal variability (variation between years and runs that is not accounted for by the other 3 terms). Here we only show the null hypothesis of land cover effects H_i (i.e. whether $a_1 = a_2 = 0$). H_i is tested by comparing

$$F_i = \frac{SSS}{(i-1)} \bigg/ \frac{SSI}{(i-1)(j-1)} \quad (\text{A2})$$

with critical values from the F -distribution with $(i-1)$ and

$(i-1)(j-1)$ degrees of freedom, where

$$SSS = j \sum_{i=1}^I (X_{i00} - X_{000})^2 \quad (\text{A3})$$

is the between-simulations sum of squares that measures differences between the land cover impact of the ensemble members and

$$SSI = \sum_{i=1}^I \sum_{j=1}^J (X_{ijo} - X_{i00} - X_{0jo} + X_{000})^2 \quad (\text{A4})$$

measures the internal or natural variation which remains when the other components have been accounted for. A 'circle' replaces a subscript when an average is taken over that index.

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