The impact of land cover change on the atmospheric circulation

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Abstract The NCAR Community Climate Model (version 3), coupled to the Biosphere Atmosphere Transfer scheme and a mixed layer ocean model is used to investigate the impact on the climate of a conservative change from natural to present land cover. Natural vegetation cover was obtained from an ecophysiologically constrained biome model. The current vegetation cover was obtained by perturbing the natural cover from forest to grass over areas where land cover has been observed to change. Simulations were performed for 17 years for each case (results from the last 15 years are presented here). We find that land cover changes, largely constrained to the tropics, SE Asia, North America and Europe, cause statistically significant changes in regional temperature and precipitation but cause no impact on the globally averaged temperature or precipitation. The perturbation in land cover in the tropics and SE Asia teleconnect to higher latitudes by changing the position and strength of key elements of the general circulation (the Hadley and Walker circulations). Many of the areas where statistically significant changes occur are remote from the location of land cover change. Historical land cover change is not typically included in transitory climate simulations, and it may be that the simulation of the patterns of temperature change over the twentieth century by climate models will be further improved by taking it into account.

1 Introduction

Land cover change (LCC) can affect the regional climate simulated by climate models by changing the partitioning of available energy between sensible and latent heat, and by changing the partitioning of precipitation between evapotranspiration and runoff. These changes, caused by modifications to land surface parameters (surface albedo, roughness length, leaf area index, etc.), can cause changes in the atmosphere which feedback on the surface water and energy fluxes. Most previous studies using climate models, focussing on desertification (e.g. Rowell et al. 1995; Xue 1997; Nicholson et al. 1998) or deforestation (e.g. Bonan et al. 1992; Polcher and Laval 1994; Lean and Rowntree 1997), have concentrated on regional climate change, although McGuffie et al. (1995) did investigate whether a global signal could be identified and found evidence of middle and high latitude effects due to tropical deforestation.

In contrast to studies which focus on future changes (e.g. deforestation), Chase et al. (1996, 2000) used a climate model to simulate the impacts of historical leaf area index (LAI) and vegetation cover changes on the regional and global climate. They found significant global temperature and precipitation changes, especially at higher latitudes, when a reasonable pattern of observed LAI or vegetation change was imposed. They explained the influence of changes in the tropics on the high-latitude Northern Hemisphere winter climate by showing that anomalous Rossby wave propagation developed, causing tropical to high-latitude teleconnections. Chase et al.'s (1996, 2000) results were surprising in that most other large-scale experiments changing land use (e.g. deforestation experiments) did not obviously cause a global impact. The relatively small perturbation imposed by Chase et al. (1996, 2000), in contrast, appeared to teleconnect to cause large changes in temperature at higher latitudes and rainfall in the tropics. However, Chase et al. (1996) used an old version of the Community Climate Model (CCM2) with fixed sea surface temperatures while Chase et al. (2000) used CCM3, but again with fixed sea surface temperatures. In both cases, they ran for only ten years. While their results are self-consistent and have been explained in terms of key mechanisms operating within the climate system,

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there is a need to simulate the impacts of LCC using different climate models, with alternative patterns of LCC, coupled to a full ocean model. In this work, we aim to determine whether a more conservative change in LCC, coupled with the use of a different land surface scheme and a mixed layer ocean model lead to a different conclusion to those of Chase et al. (2000). The use of a mixed layer ocean model represents an intermediate step between the fixed sea surface temperatures used by Chase et al. (1996, 2000) and a fully coupled ocean model. In the next section, our experimental design is presented, followed by results, discussion and finally conclusions.

2 Experimental design and statistical significance testing

We used the standard version of the NCAR CCM3 (Kiehl et al. 1996) at T42 resolution coupled with the Biosphere-Atmosphere Transfer Scheme (BATS, Dickinson et al. 1993) and a mixed layer ocean model. Spin-up was achieved after about two years and all the results shown in this paper are averaged over the last 15 years of a 17-year integration. Our aim is to simulate the climatic impact of a realistic but conservative change in the geographical extent of global land cover from a natural state (prior to human activity) to present-day conditions. To obtain the natural vegetation cover, we used BIOME3 (Haxeltine and Prentice 1996) which uses ecophysiological constraints, resource availability and competition to select those plant functional types potentially present at any 0.5° × 0.5° grid point. These data were then aggregated to CCM3 T42 resolution based on the most common vegetation type within each CCM3 grid square.

To determine the current vegetation cover, we used the approach of Chase et al. (1996) to identify those grid points where LAI changed and we modified the natural vegetation cover predicted by BIOME3 from forest or grass to crop at these locations by changing the parameter values in BATS. However, we chose to only change vegetation type where Chase et al. (1996) show LAI to change by more than 1 and we removed some individual points which were geographically isolated. In total, LCC was largely isolated to SE Asia (mainly China), India, Europe and North America with only occasional pixels changed elsewhere (Fig. 1). We do not argue that these changes are entirely realistic, but they are more conservative that used by Chase et al. (1996, 2000) which should identify whether their conclusions required a substantial and geographically widespread LCC. In particular, the widespread

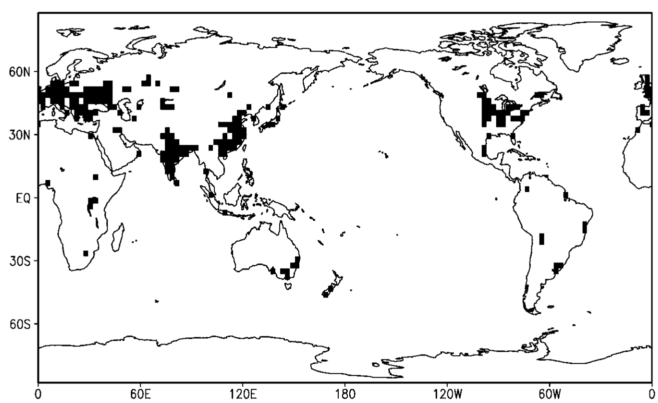


Fig. 1 The location of grid points where land cover change was imposed

LCCs over South America and Africa imposed by Chase et al. (1996, plate 2) are not included in our experiments.

The use of a mixed layer ocean model was a compromise between the lack of realism represented by the use of fixed sea surface temperatures and the extremely expensive fully coupled ocean model. Figure 2 shows a comparison of temperature standard deviation obtained using the mixed layer ocean model and obtained by Chase et al. (2000) using fixed sea surface temperatures. Temperature standard deviation from the NCEP reanalysis (Kalnay et al. 1996) are included as pseudo-observations. The simulation of temperature standard deviation is superior in the NCAR CCM3 coupled to the mixed layer model (Fig. 2) in January and July at most latitudes. The use of fixed sea surface temperatures provides a better simulation north of 45°N (in January) and over Antarctica in July (suggesting that the sea-ice distribution is better in the fixed SST simulations). Overall the improved simulations obtained using the mixed layer model, and therefore the results reported here, are likely to provide a more reliable indication of the impact of land cover change, particularly in the case of temperature.

In all cases, results are presented as current vegetation simulation minus natural vegetation simulation. Where we present statistical tests, we generally used two-tailed t-test and F-test and present 80%, 90% and 95% statistical significant levels shaded from light to dark. However, where daily data were available, we used the approach of Katz (1982) who proposed a procedure based on parametric time series modelling involving the fitting of low-order autoregressive processes to the data. This method has two main advantages over the traditional t-test. First, it is based on a large number of daily samples. Even though these samples are

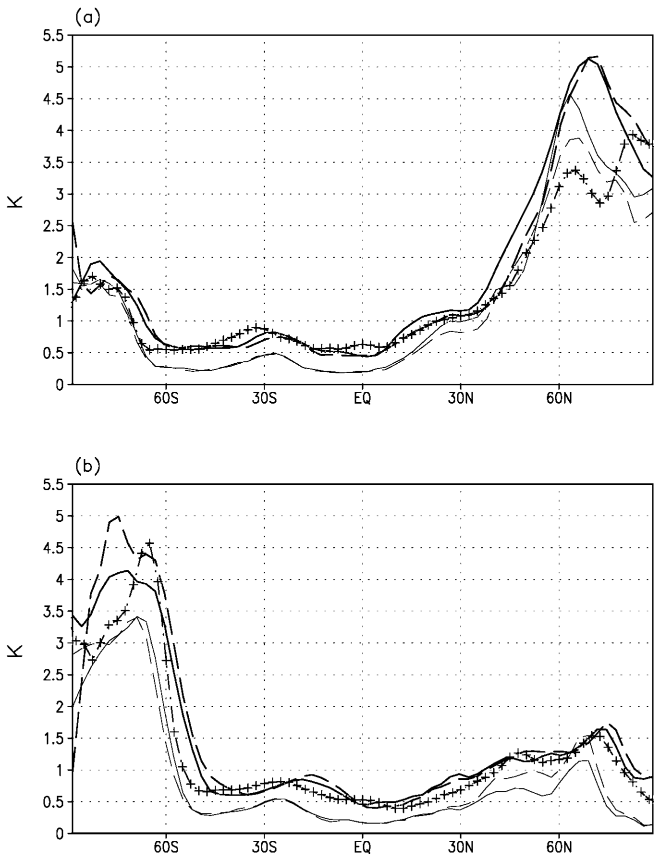


Fig. 2a, b The zonally averaged near surface air temperature standard deviation for the simulation using current land use (*solid line*), natural land use (*dashed line*) and the NCEP reanalysis (*dashed line* with *plus signs*). The *thick lines* are for our results the *thin lines* are using data from Chase et al. (2000)

dependent, the test statistic (a Z-test) approximates a Gaussian distribution unlike the t-test which requires degrees of freedom based on the length of the model simulations. Second, the test does not require that the population variances in the control and experiment time series are equal.

The Katz (1982) 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 five 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) but results showed that for most of the grid points chosen, the third and the second order appeared to be satisfactory. Although the second order indicates larger areas of significance, the results shown utilize the BIC procedure which Katz (1982) argues improves the reliability of the methodology.

3 Land surface parameter changes

In these experiments, the LCC modifies a series of vegetation parameters within BATS. Figure 1 shows that we changed the vegetation cover in four main areas (North America, Europe, India, and China) and Table 1 summarizes the overall change in each parameter in BATS. Of those parameters which are likely to be important (e.g. Henderson-Sellers 1993; Pitman 1994) the fractional vegetation cover increases in most regions but the roughness length decreases. The root distribution becomes more concentrated into the top soil layer, and the total soil depth is decreased. Albedo is changed very little. In general, the changes in access to water (the changes in root distribution and depth will reduce water storage) coupled to the reduced roughness length should reduce evaporation and lead to warmer temperatures. However, the minimum stomatal resistance is reduced which should permit higher evaporation. Over southern China, some of the parameter changes are of the opposite sign (or of smaller magnitude) than in the other regions (e.g. the changes in root distribution, LAI and minimum stomatal resistance are quite different to the changes in other regions) due to the natural land cover simulated by BIOME3 in these regions.

4 Description of results

In this section, we first present changes in near surface air temperature, total precipitation and latent heat flux and then focus on explaining our results in terms of changes in the general circulation simulated by CCM3.

Table 1 BATS parameters and the average regional change in these parameters imposed by the prescribed land use change. The coordinates of the regions are: America: 33°N to 51°N, 103°W to 71°W; Europe: 36°N to 58°N, 8°W to 45°E; India: 6°N to 33.5°N, 71.5°E to 94.5°E; China: 19.5°N to 42°N, 100°E to120°E

Parameter	America	Europe	India	China
Fractional vegetation cover	0.03	0.13	0.06	−0.01
Roughness length (m)	−0.39	−0.49	−2.23	−1.14
Fraction of roots in top 0.1 m of soil	−0.22	−0.31	−0.37	−0.19
Albedo	0.01	0.02	0.01	0.04
Maximum LAI	0.12	0.27	−0.13	−0.88
Minimum LAI	−0.29	−0.94	−0.25	−2.53
Stem area index	−1.07	−1.55	−1.18	−0.50
Light sensitivity factor (m^{-2} W^{-1})	−0.02	−0.02	−0.01	−0.03
Minimum stomatal resistance (s m^{-1})	−53	−74	−65	−28
Depth of root zone (mm)	−426	−575	−216	−625
Seasonality factor	0.20	0.34	0.25	0.06
Inverse square root of leaf dimension ($m^{-1/2}$)	3.38	4.73	4.17	3.13
Displacement height (m)	−1.06	−0.99	−0.60	−7.88

At the global scale, statistically significant changes in temperature are simulated by CCM3 due to the prescribed change in land cover. These changes are mainly in the mean and vary seasonally. Table 2 shows that the change in land cover leads to statistically significant changes in temperature over 36% of the globe (at a confidence level of 80%) in DJF and 29% in JJA. The changes in temperature variance accessed with an F-test (Table 2) occur over only about 20% of the globe (at a confidence level of 80%) which indicates that they may be random and not related to the change in land cover.

Figure 3 shows the patterns of change in the mean near surface air temperature for all four seasons. The largest changes in temperature occurred in regions remote from the location of the perturbation to land cover, in particular, over high and middle latitudes in

Table 2 Global and regional seasonally and annually averaged change in temperature, rainfall and latent heat flux. The area of regional averages are the same as Table 1. Those values underlined are statistically significant at 80%, those italicized are statistically significant at 90% and those in bold a statistically significant at 95% using a two-tailed t-test. The final two rows give the percentage of the global area showing statistically significant change using a Z-test for temperature, t-tests for rainfall and latent heat flux, and F-tests for all three quantities at an 80% confidence level

	Temperature (K)					Total rainfall (mm d^{-1})					Latent heat flux (W m^{-2})				
	Annual	DJF	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON
North America	−0.19	−0.48	−0.79	−0.28	*0.80*	−0.01	−0.05	0.13	−0.10	−0.02	−0.38	−0.43	−0.57	0.10	−0.63
Europe	−0.24	−0.20	−0.17	**−0.72**	0.13	0.02	−0.10	0.07	**0.25**	−0.13	0.72	**−2.32**	0.70	**7.83**	**−3.35**
India	−*0.22*	**−0.61**	0.00	−0.20	−0.05	**−0.21**	−0.13	−0.22	−0.21	−*0.26*	0.48	**2.31**	−3.11	0.48	**2.23**
China	0.19	−0.25	0.31	**0.31**	**0.41**	**−0.20**	−0.04	−0.11	**−0.42**	−0.25	**−4.22**	**−2.22**	**−3.76**	**−3.39**	**−7.50**
Global	0.01	0.08	0.01	**−0.20**	*0.15*	0.01	0.01	0.04	−0.02	0.01	**0.36**	0.34	**0.59**	0.34	0.18
% of globe showing statistically significant change	t-test/ Z-test	36	22	29	23		21	18	20	23		22	18	20	22
	F-test	18	19	19	21		25	29	22	24		20	24	23	23

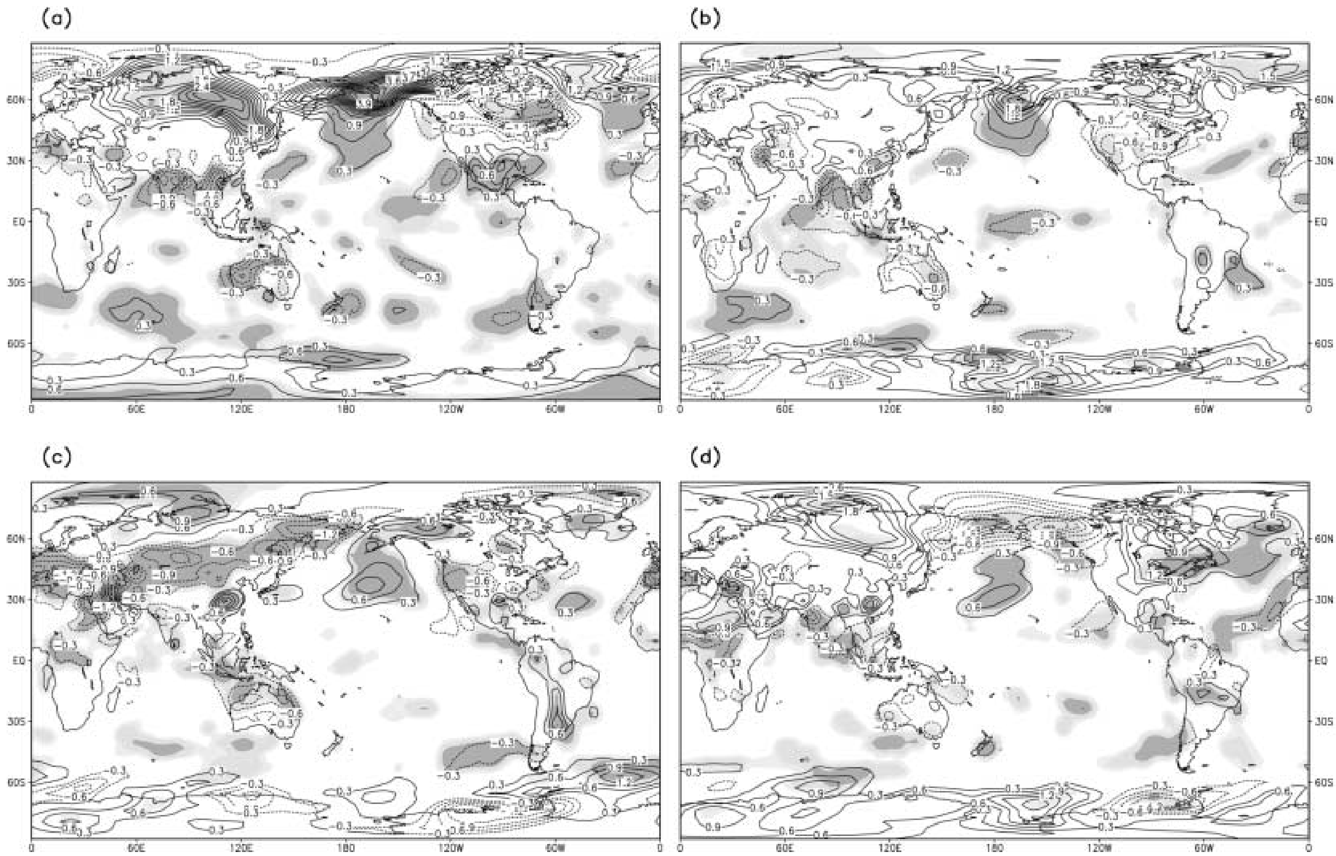


Fig. 3a–d The change (current − natural) in the mean seasonal near surface air temperature (K) for **a** DJF; **b** MAM; **c** JJA; **d** SON. Areas of statistical significance at confidence levels of 80%, 90% and 95% were calculated using a two-tailed Z-test, are plotted as *shaded areas* (from *light* to *dark*)

every season. Large changes also occurred over the North Pacific (as found by Chase et al. 2000), over northern Asia and over North America, although the changes here were only statistically significant in isolated regions. We also calculated statistical significance using t-tests rather than Z-tests and found that the patterns were similar to those shown in Fig. 3. In general, t-tests gave a smaller area of statistically significant change except at high latitudes in the Northen Hemisphere (not shown). Systematic and statistically significant changes in temperature were also simulated in SE Asia and the Asian monsoon region in all seasons. Statistically significant temperature changes do occur over areas where land cover was changed (mainly over China and India in all seasons). Over Europe, (where extensive modifications to land cover occur), statistically significant temperature changes only occurred in JJA while over North America (also a region of extensive modification), they only occur in SON (Table 2). Relatively few changes occurred in the Southern Hemisphere in DJF which contrasts with the results obtained by Chase et al. (1996) using CCM2. In their study, the change of just LAI caused changes in temperature in the Southern Hemisphere. We performed additional experiments changing just LAI using CCM3 (but with a mixed layer model) and found similar results to Chase et al. (1996), but these were reduced when vegetation type, rather than just LAI, was altered. The changes in temperature variance show statistically significant changes (not shown) in over smaller fractions of the globe than changes in the mean (Table 2). The only regions where the changes in variance are consistently statistically significant are over parts of SE Asia and China.

At the global scale, the statistically significant changes in mean total precipitation occur over about 20% of globe (at an 80% confidence level). Statistically significant changes in the precipitation variance (assessed using an F-test) are more widespread reaching 29% of the global area in MAM (Table 2). The patterns of total precipitation change for each season (Fig. 4) and indicate few systematic, statistically significant changes in large-scale precipitation. However, some key changes occur in the west Pacific and Indian Oceans and some east-west and north-south shifts in precipitation patterns appear to occur in the tropics. These changes are evidence of complex atmospheric adjustment to the change in vegetation distribution (see Sect. 5). Chase et al. (2000) found a northerly shift and a weakening of (zonally averaged) tropical precipitation in January (results for other months were not provided). We find a smaller north-south shift in the precipitation patterns, but stronger tropical precipitation in the summer hemi-

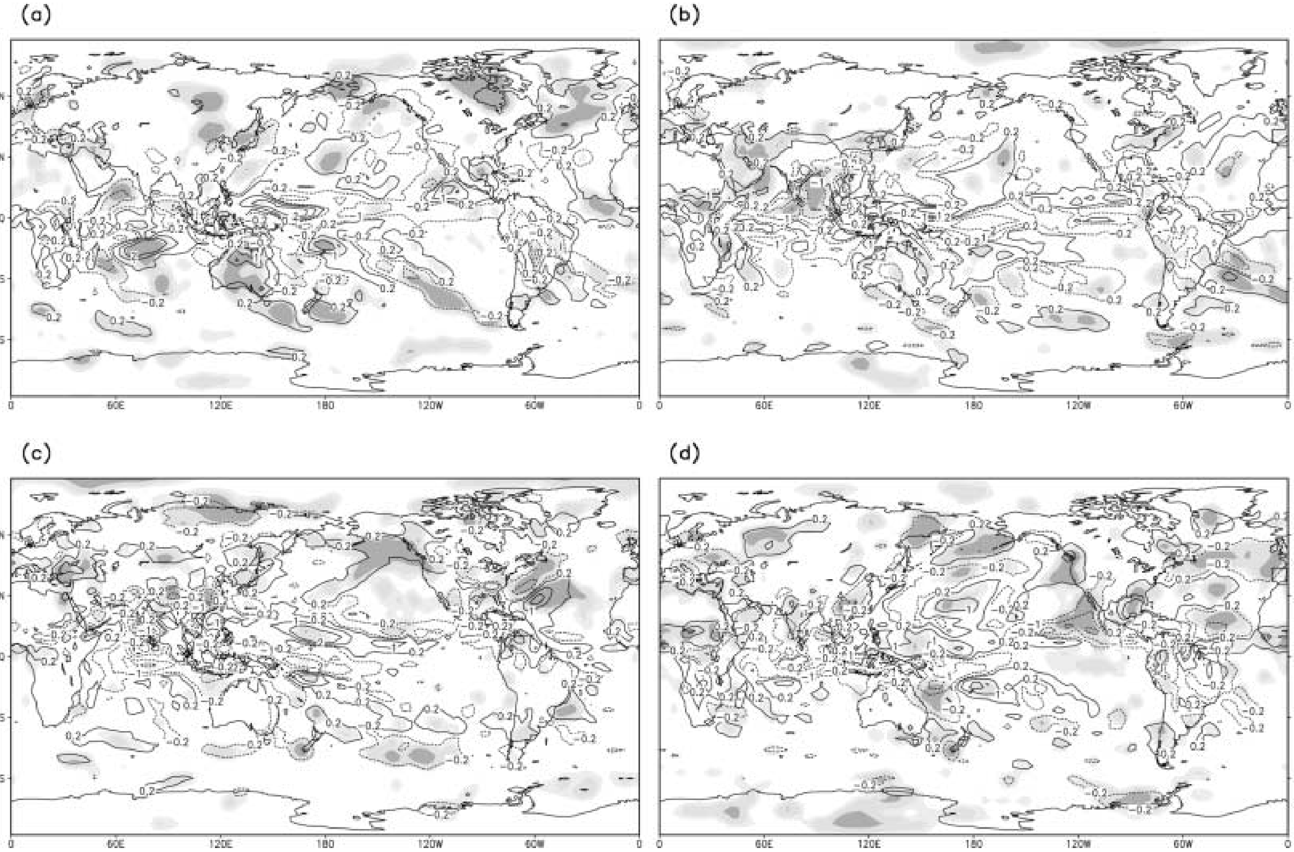


Fig. 4a–d As for Fig. 3 but for total precipitation (mm d^{-1}). The statistical significance was calculated using a two-tailed *t*-test and confidence levels of 80%, 90% and 95% are *shaded* (from *light* to *dark*)

sphere. In general, this illustrates that the sign of the change in tropical precipitation varies with both season and hemisphere. The different results obtained by Chase et al. (2000) may be due to the use of fixed sea surface temperatures rather than a mixed layer model or the differences in the patterns of LCC (see Sect. 5).

Statistically significant changes in precipitation variance occur over isolated areas especially in the tropics and parts of the Northern Hemisphere including North Africa (not shown). These changes are remote from the location of land cover change. The zonal average difference in the precipitation variance shows an increase in summer and a decrease in winter in the Northern Hemisphere (not shown). There is a change in the variance such that in DJF (JJA) there is a substantial increase (decrease) in the Southern Hemisphere and a substantial decrease (increase) in the Northern Hemisphere (not shown). We also calculated the zonal average total precipitation from 60°S–60°N (Fig. 5). We did not find a clear northerly shift in total precipitation (see Chase et al. 2000) in DJF, but there was a clear shift from south to north in the other seasons.

Finally, at the global scale, statistically significant changes in the latent heat flux occur over similar percentages of the global area to the changes in precipitation with two-tailed *t*-test (Table 2). Regionally, changes in the latent heat flux shows statistically significant changes over areas actually perturbed by the LCC (Fig. 6). Both the modification in land cover and the changes in precipitation (Fig. 4) would be expected to change evaporation. The statistically significant changes over China and India (in all seasons) hint at a systematic change resulting from LCC, but there are a lack of similar changes in the evaporation field over North America and Europe. Large changes in evaporation occur in the Sahel region indicating that some regions are particularly sensitive to small changes in precipitation due to strong moisture limitation on evaporation. Statistically significant changes were found in North Pacific (30°N–60°N) in all seasons except in MAM.

Evidence that the atmospheric circulation adjusts to changes in the land surface is shown by differences in the 500 hPa stream field (Fig. 7). Over the high latitudes of the Northern Hemisphere, the position and intensities of main ridges and troughs change. This is particularly clear in JJA where the changes in the magnitude of the 500 hPa stream field are statistically significant over a large area. In DJF the Iceland low moves to the southeast, while in SON, the Aleutian low moves to the east (these changes are both statistically significant). Finally, statistically significant changes occur in the position of the sub-tropical high in both the Northern and Southern Hemispheres. The statistically significant changes described in the Southern Hemisphere are caused by

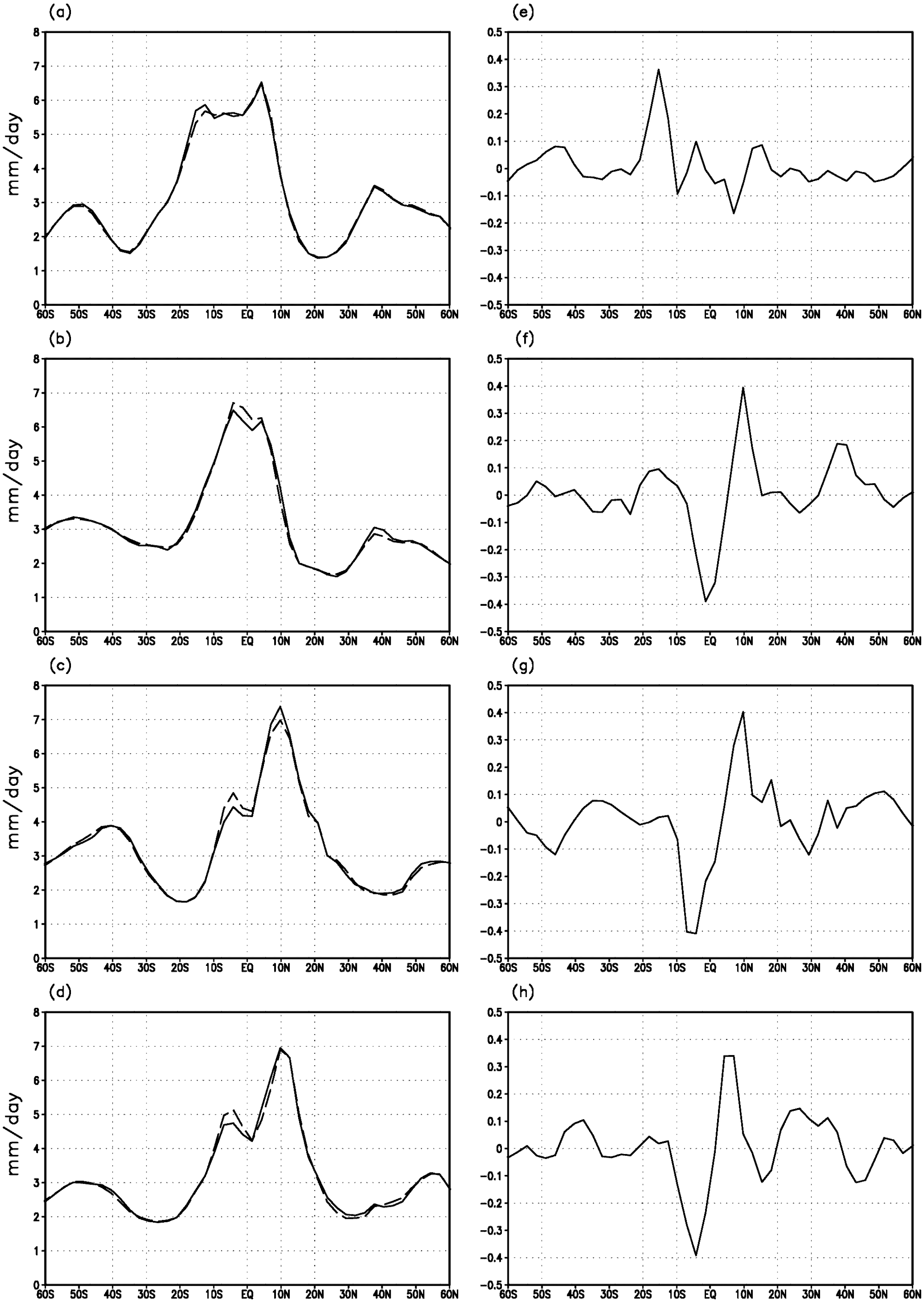


Fig. 5a–h The zonally averaged precipitation (60°N to 60°S) for the current land use (*solid line*) and natural land use (*dashed line*) experiments and the difference (current − natural) for **a, e** DJF; **b, f** MAM; **c, g** JJA; **d, h** SON (all in mm d^{-1})

teleconnections because the LCCs were almost entirely contained within the Northern Hemisphere. This implies substantial changes in the global circulation (see Sect. 5).

The meridional circulation patterns simulated in DJF and JJA (Fig. 8) show that large changes occur in the meridional stream function including changes in the intensity and location of the key features of the general circulation. In DJF the Hadley Cell strengthens while the Ferrel Cell moves northwards in the Northern Hemisphere (the former change is statistically significant). In JJA the Hadley cell in the Southern Hemisphere strengthens and deepens increasing from 16×10^{10} kg s^{-1} to 20×10^{10} kg s^{-1} but this change is not statistically significant. There is also a clear move of the Ferrel cell to the south. Chase et al. (2000) found a weakening in the intensity of the Hadley Cell in the Northern Hemisphere. While their results are different in detail, we both find systematic changes in large-scale movement of mass resulting from LCC. This change in the meridional stream function provides a mechanism to connect the changes in the tropics with higher latitudes.

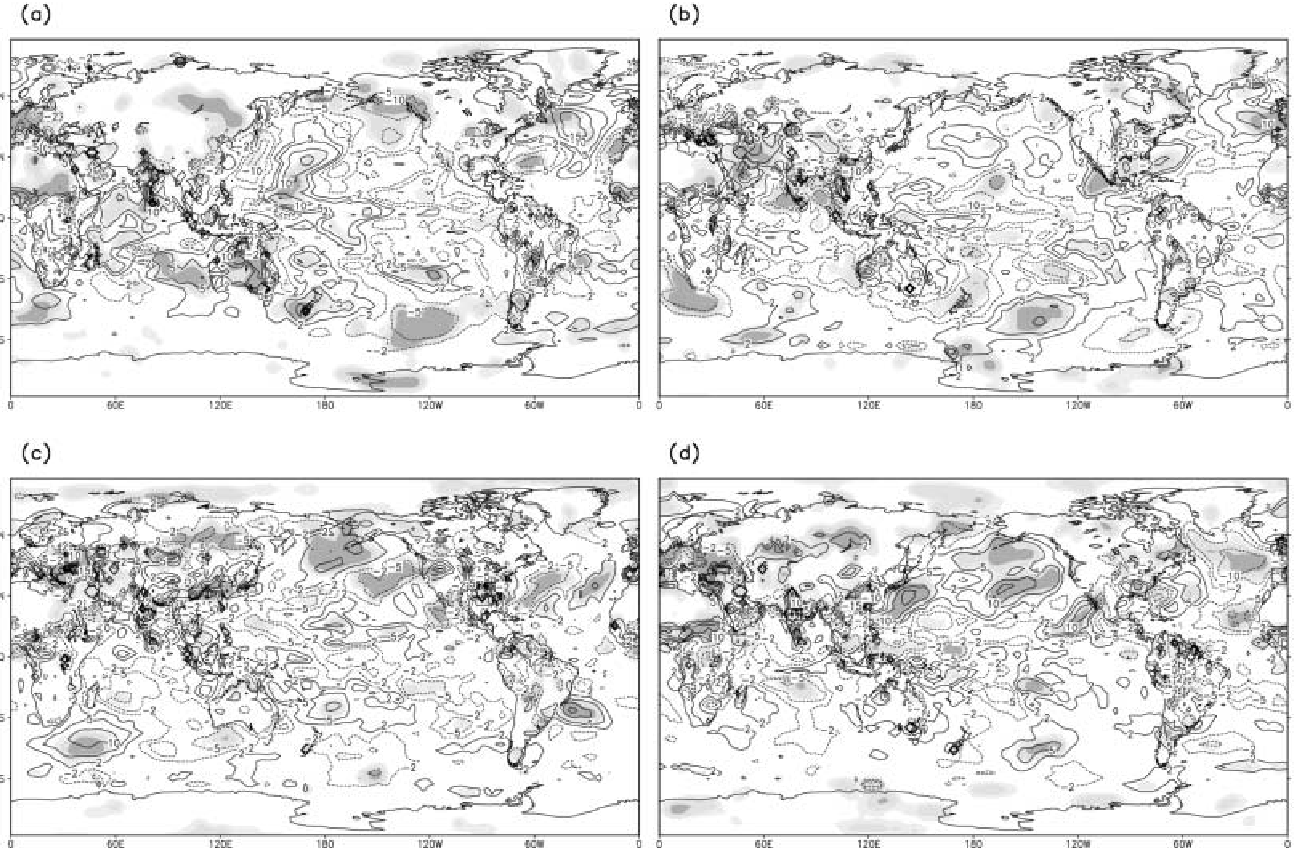
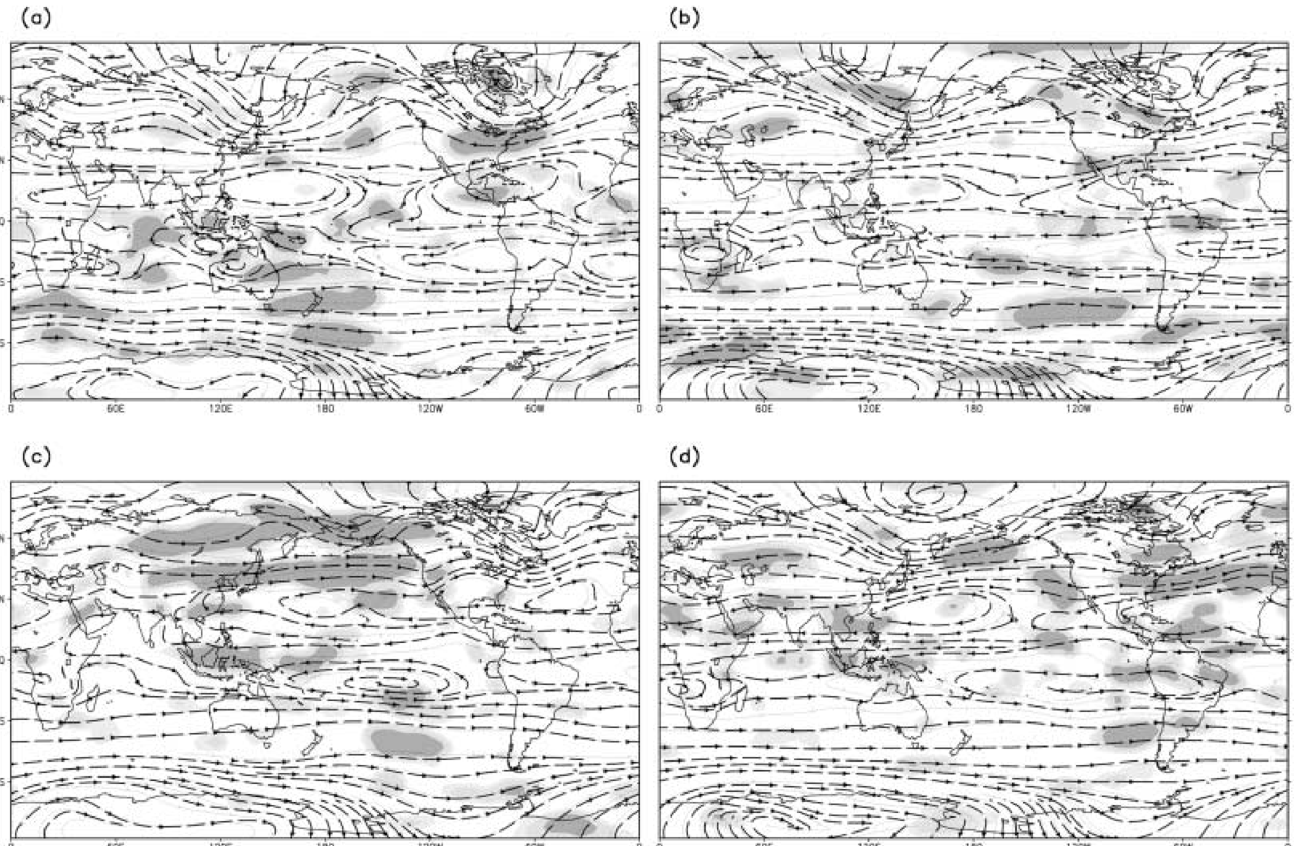


Fig. 6a–d As Fig. 4 but for the latent heat flux (W m^{-2})

Fig. 7a–d As for Fig 3. but for the 500 hPa stream field



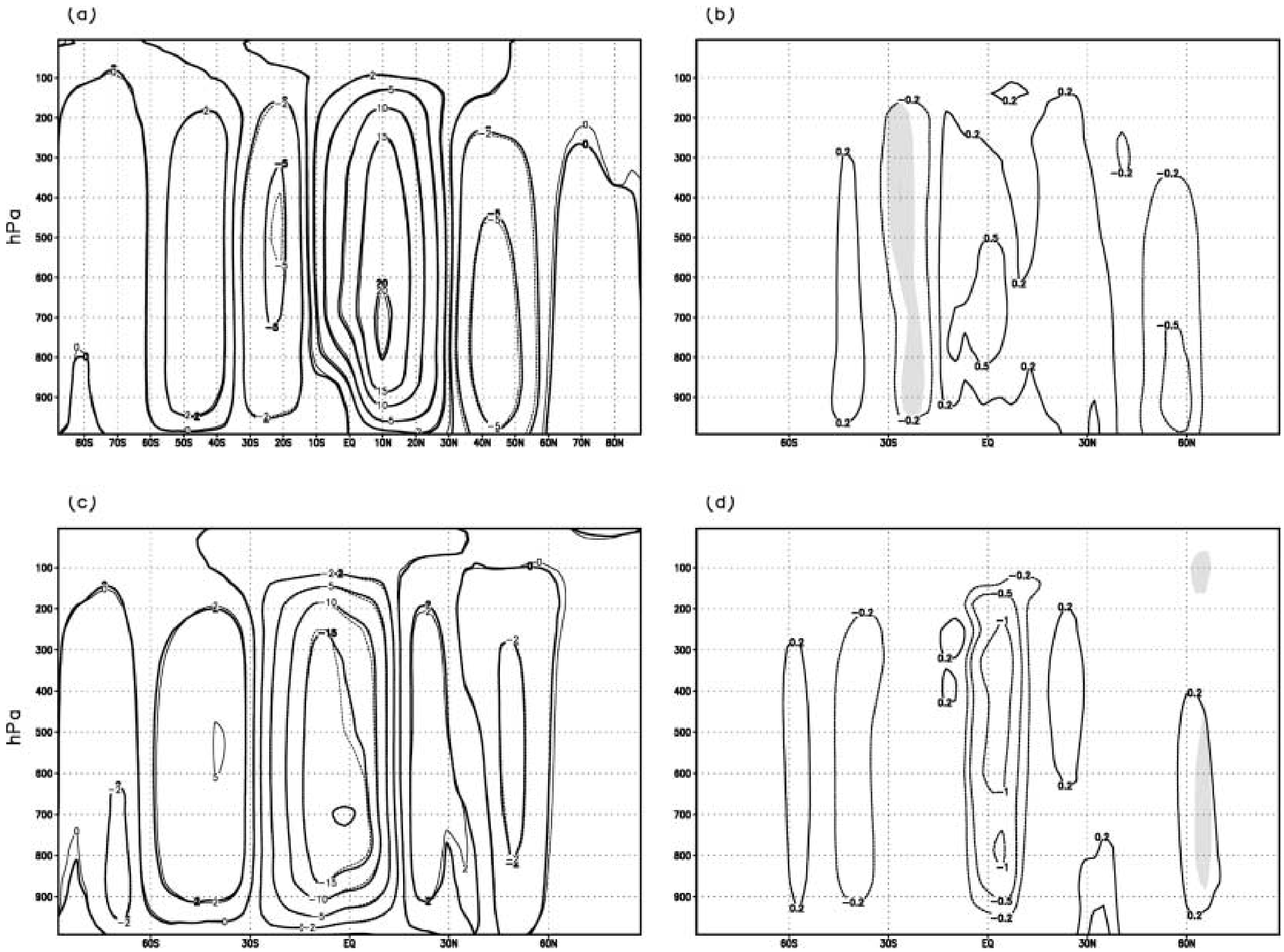


Fig. 8a–d The meridional stream function (10^{10} kg s^{-1}) for the current (*solid line*) and natural (*dashed line*) land cover. **a** DJF; **b** current minus natural, DJF; **c** JJA; **d** current minus natural, JJA. Statistical significance in the difference plots were calculated using a two-tailed *t*-test and shaded at 80% significance level

The tightening of the east-west gradient in the 200 hPa velocity potential is characteristic of a change in the Walker Cell, while the tightening of the gradient north-south is characteristic of a change in the Hadley Cell. Changes in both gradients in DJF and JJA (Fig. 9) illustrate large-scale statistically significant changes in both the Walker cell and the Hadley cell resulting from LCC (the changes are particularly large over the Asian monsoon region). In both seasons, the size of the outflow centre in the western Pacific increases and large changes occur over the Indian Ocean indicating changes in wind divergence. This indicates that this region is central to the explanation of the larger scale results. In addition, changes in the east-west gradient lead to changes in the monsoon in this region.

The increase in the Walker circulation lead to damping of precipitation in the Indian Ocean while both these changes and the changes in the Hadley circulation provide mechanisms to influence the large-scale redistribution of mass and energy. Chase et al. (1996) found a weakening in both the Walker cell and the Hadley cell when just LAI was changed, results later confirmed by Chase et al. (2000). We obtain the opposite changes to Chase et al. (1996, 2000) which is probably due to the use of a mixed layer model, although the differences in the patterns of LCC may be significant. The latter is being investigated by varying the patterns of LCC in additional experiments.

Figure 10 shows the divergent kinetic energy (at 200 hPa) for DJF and JJA and shows increased outflow in DJF over SE Asia. Changes in the branch of Walker circulation over west Pacific and India Ocean lead to changes over South America with enhanced outflow but these changes are not statistically significant using a *t*-test (the *Z*-test requires daily data which were not available). In JJA, however, there is a clear increase in outflow over SE Asia towards the Southern Hemisphere which again seems to effect South America. These results represent high-altitude outflow from both the Walker cell and Hadley cells. The largest changes occur in the west Pacific and India Ocean. These changes provide one mechanism to explain the teleconnections to higher lat-

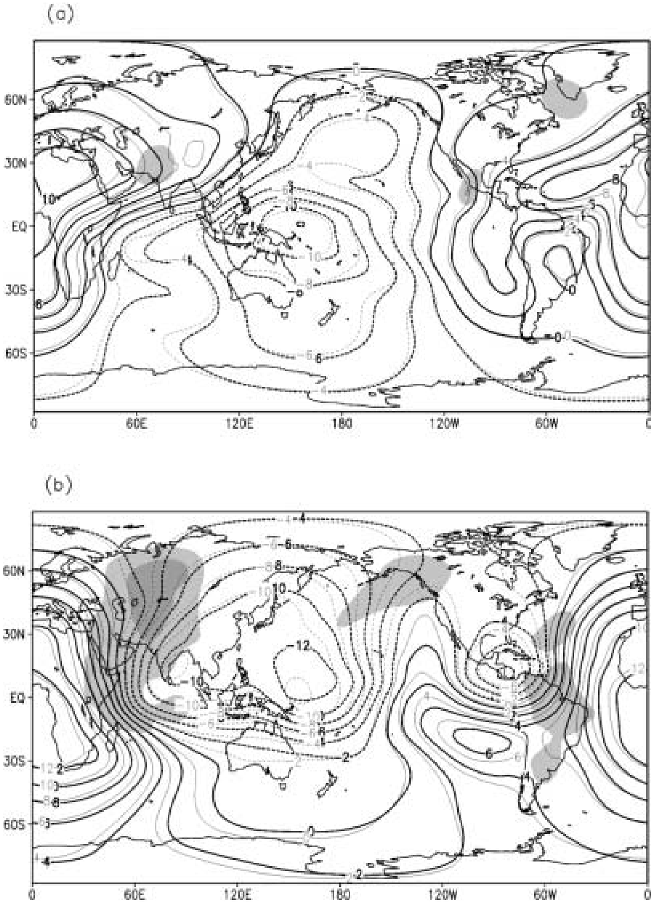


Fig. 9a, b The 200 hPa velocity potential for **a** DJF and **b** JJA (10^6 m^2 s^{-1}). Statistical significance was calculated using a two-tailed *t*-test and regions of 80%, 90% and 95% statistical significance *shaded* (from *light* to *dark*)

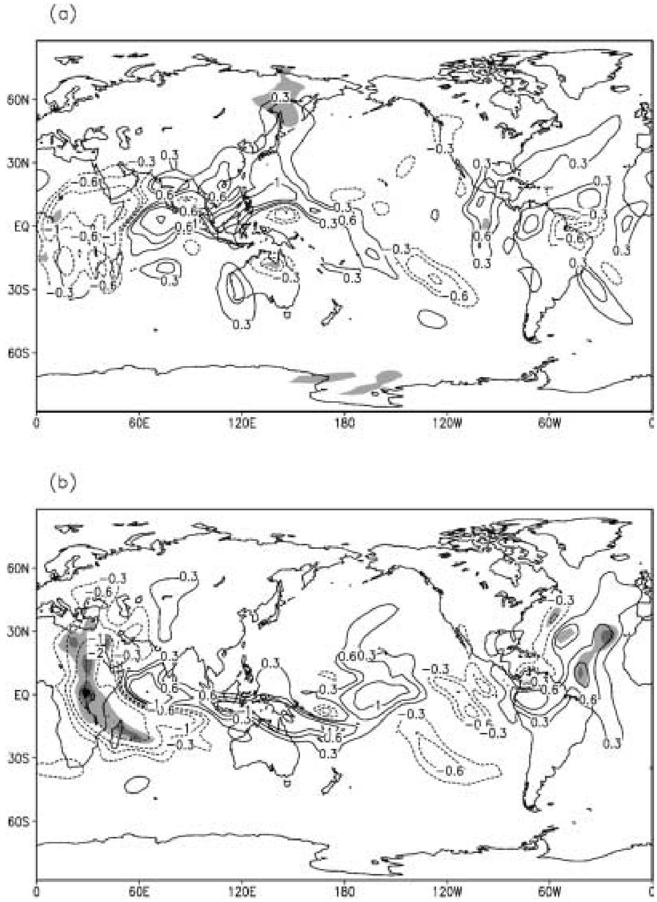


Fig. 10a, b As for Fig. 9 but for the divergent kinetic energy (at 200 hPa) for **a** DJF and **b** JJA (J)

itudes, away from the location of the LCC. The 200 hPa u-component of the wind (Fig. 11, for DJF and JJA) also shows large-scale impacts of LCC with the three Northern Hemisphere jets changing. We were able to calculate Z-tests on this field and Fig. 11 shows large regions of statistically significant changes. The three jets, over 60°E, eastern Asia and North America all strengthen (the latter two are statistically significant). While the 60°E jet remains in the same position, the eastern Asia jet does not extend so far into the Pacific, and the North American jet moves northeast. In JJA large statistically significant changes again occur in the Northern Hemisphere and in the Southern Hemisphere, the Australian jet strengths and becomes larger. These strengthening jets change the standing wave and Rossby wave climatologies. The changes simulated with CCM3 are consistent with those expected as a result of the increase in the outflow from the Hadley circulation.

5 Discussion

These results demonstrate that LCC has a statistically significant effect on regional temperature, total precipitation and latent heat flux. Statistically significant changes also occur within the atmosphere, where changes occur in the position and strength of key elements of the general circulation. The statistically significant changes in regional temperature and precipitation are more widespread in the mean than in the variance. Many of the regions of significant changes are remote from the LCC. These results provide support for the results obtained by Chase et al. (2000) and indicate that their general results are not dependent on the specific land surface model, pattern of LCC or due the use of fixed sea surface temperatures. Our results show negligible impacts on global averaged temperature or rainfall (Table 2) indicating that LCC is not likely to be a factor in (for example) the global average temperature rise. It is also worth noting that we found negligible change in snow depth or snow cover indicating that the high-latitude changes are not obviously related to snow-albedo feedbacks.

Our results generally agree with those of Chase et al. (2000). Both groups found statistically significant warming in high latitudes and cooling in the tropics, in parts of Asia and central Europe. Both groups also identified that the region close to SE Asia, and the tropical west Pacific was central to the explanation of results suggesting that LCC in this region may be

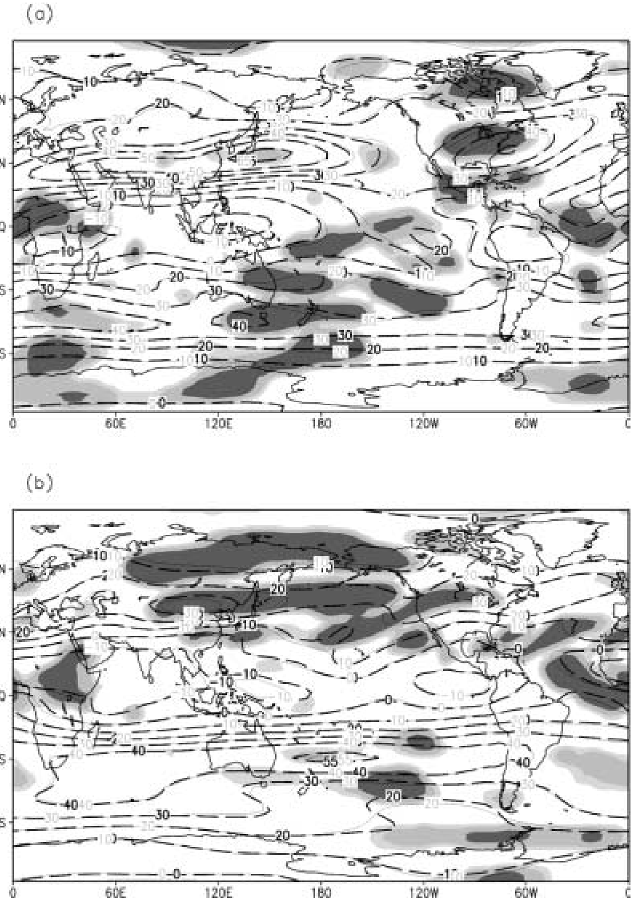


Fig. 11a, b As for Fig. 9 but for the 200 hPa u-component of the wind (m s^{-1}) for DJF and JJA. Statistical significance was calculated using a *Z*-test and regions of 80%, 90% and 95% statistical significance *shaded* (from *light* to *dark*)

particularly important. The mechanisms used to explain these differences are also the same. However, we find that the Hadley cell and Walker cell strengthen and move to the north. Subtropical high jets strengthen and the subtropical high over the southeast Asian monsoon region moves eastwards. In contrast, Chase et al. (2000) found that the Hadley cell and Walker cells weaken but still move to the north in the Northern Hemisphere. The differences in detail between our results and Chase et al.'s (2000) are most likely related to the pattern of LCC and our use of a mixed layer ocean model. In terms of the pattern of LCC, we did not change land cover over South America or Africa and it is possible that LCCs in SE Asia and India cause opposite effects to those in South America. LCC in SE Asia appears to increase the Walker circulation whereas we speculate that changes in South America may decrease the Walker circulation. Polcher (1995) found an opposite sign in the LCC in SE Asia compared to South America which provides some evidence for this suggestion. Our results may also differ from Chase et al. (2000) because we did not remove vegetation as extensively over South America or Africa. Therefore, the different sign in the change in tropical precipitation, and ultimately a series of other differences, may result from the differences in the patterns of LCC imposed. We are investigating the nature of the relationship between the precise patterns of LCC and the resulting changes in the general circulation in experiments currently underway. In the case of the use of a mixed layer model, the improved simulation of temperature standard deviation resulting from the use of a mixed layer model (Fig. 2) suggests that where changes result from the model configuration, the results obtained using the mixed layer model are likely to be more reliable.

Confirmation of our results by a climate model which does not contain the basic dynamics and physical processes included within the NCAR CCM hierarchy will have several implications. Since our results show a link between LCC in the tropics and higher latitude temperature changes, they imply that LCC may need to be included in transitory runs investigating global change, especially if the attribution problem is being considered via an analysis of regional scale patterns of change. These results also imply that the regional scale patterns of change may be sensitive to the location of LCC in that perturbations in SE Asia appear likely to have an opposing effect to changes in South America. Further, some areas which consistently appear most sensitive to LCC (North Africa and North Pacific) are geographically remote from any surface perturbation. Crossley et al. (2000) have recently reported that land surface processes in the tropical regions provides the greatest contribution to uncertainty in simulating climate change. If this is confirmed, it indicates that it will be particularly important to represent tropical LCC in future simulations.

6 Conclusions

We used the CCM3 coupled to BATS and a mixed layer ocean model to investigate the impact on the climate of a conservative change from natural to present land cover. We demonstrate that LCC has a statistically significant effect on regional temperature and precipitation, and has an impact on the atmosphere by changing the position and strength of key elements of the general circulation. The statistically significant changes in regional temperature are more widespread in the mean than in the variance. Most of the significant change areas are remote from the LCC and therefore point to large-scale climate sensitivity to LCC in agreement with results obtained by Chase et al. (1996, 2000). The differences in the detail between our results and those of Chase et al. (2000) may be important, but the underlying mechanisms proposed by Chase et al. (2000) appear to be confirmed in our results despite the use of a different model configuration including a mixed layer ocean model. The role of LCC is not typically included in transitory simulations, and it may be that the simulation of the twentieth century by climate models will be further improved if LCC is taken into account.

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