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The Relative Impact of Regional Scale Land Cover Change and Increasing CO_2 over China

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ABSTRACT

A series of 17-yr equilibrium simulations using the NCAR CCM3 (T42 resolution) were performed to investigate the regional scale impacts of land cover change and increasing CO_2 over China. Simulations with natural and current land cover at CO_2 levels of 280, 355, 430, and 505 ppmv were conducted. Results show statistically significant changes in major climate fields (e.g. temperature and surface wind speed) on a 15-yr average following land cover change. We also found increases in the maximum temperature and in the diurnal temperature range due to land cover change. Increases in CO_2 affect both the maximum and minimum temperature so that changes in the diurnal range are small. Both land cover change and CO_2 change also impact the frequency distribution of precipitation with increasing CO_2 tending to lead to more intense precipitation and land cover change leading to less intense precipitation—indeed, the impact of land cover change typically had the opposite effect versus the impacts of CO_2. Our results provide support for the inclusion of future land cover change scenarios in long-term transitory climate modelling experiments of the 21st Century. Our results also support the inclusion of land surface models that can represent future land cover changes resulting from an ecological response to natural climate variability or increasing CO_2. Overall, we show that land cover change can have a significant impact on the regional scale climate of China, and that regionally, this impact is of a similar magnitude to increases in CO_2 of up to about 430 ppmv. This means that that the impact of land cover change must be accounted for in detection and attribution studies over China.

Key words: land cover change, CO_2 level, surface air temperature, intensity of precipitation, return value

1. Introduction

Greenhouse gas increases and land cover change (LCC) are two significant human activities that can affect the climate (IPCC, 1995; IPCC, 2001). In a recent series of papers which focused on the impact of historical land cover change (rather than future LCC impacts), Chase et al. (2000) and Zhao et al. (2001a, b) investigated the impact of historical (from prior human activity to the present day) LCC on the global climate. They showed that the direct effect of LCC in the Tropics and S. E. (Southeastern) Asia can affect remote areas via teleconnections. Pitman and Zhao (2000) compared the relative impact of observed changes in LCC and CO_2. On the global scale, they found that the impact of LCC on averaged near surface air temperature was negligible. However, at high latitudes and at regional scales, LCC was shown to have an impact on temperature of similar magnitude as the observed CO_2 increase. Chase et al. (2001) compared surface temperature from several transient GCMs that investigated CO_2 or CO_2/aerosol forcing with simulations that examined the historical LCC impacts. They showed that the direct and remote effects of LCC were comparable to the effects of increasing CO_2, having similar amplitude and occurring in similar regions of the globe. These results mean that including the historical impact of LCC in detection and attribution studies would likely improve the capacity to identify a CO_2 signal by removing trends in climate caused by LCC.

One of the key regions of the globe which has experienced large scale human-induced LCC is China. Gao et al. (2001, 2002, 2003) explored the impact of

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climate change due to the greenhouse effect and LCC over China using a regional climate model at 60 km resolution, performing 5-yr simulations. Their thorough analyses have demonstrated the impact of increasing greenhouse gases on the Chinese climate, and, separately, the impact of LCC on climate. Wang et al. (2003) also explored the impact of historical LCC over China, again separately from change in CO_2. In this paper, we compare the relative impacts of LCC and increasing CO_2 on the regional scale over China by performing parallel experiments that allow us to directly equate the impact of LCC with the impact of increasing greenhouse gases. Our work also differs from Gao et al. (2001, 2002, 2003) because our longer simulations enable us to explore the impact of LCC and changes in CO_2 on climate extremes.

Since the climate of China is strongly influenced by the East Asian monsoon, we investigate the winter and summer wind fields, the monthly temperature series, and extreme and frequency changes in maximum temperature and convective precipitation. We also investigate whether the impacts of LCC on these quantities will change with increasing CO_2. Our methodology has an advantage over Gao et al. (2001, 2002, 2003) in that our experiments are fully coupled with the climate system and are relatively long in terms of time (17 years). This allows us to explore changes in mean quantities, but also to investigate changes in extremes. However, our methodology has a disadvantage that we are required to use a relatively coarse resolution model (approximately $2.8° \times 2.8°$) in contrast to the high resolution (60 km) simulations employed by Gao et al. (2001, 2002, 2003). Thus our results can be viewed as complementary to Gao et al. (2001, 2002, 2003) reinforcing their findings where we agree and highlighting areas of uncertainty where we disagree.

We wish to explain the rationale behind the use of historical LCC coupled with future CO_2 concentrations. Quite clearly, the changes in land cover we explore over China (see Methodology) cannot re-occur since much of China has already been converted to agricultural land. Our rationale is to compare the impacts of LCC with changes in CO_2 as a basis for future studies in detection and attribution. As CO_2 concentrations increase, so will the amount of warming (IPCC, 2001). When we performed the experiments discussed in this paper, CO_2 had increased from about 280 ppmv to 355 ppmv (hence the first two CO_2 levels selected). At the same time, very significant LCC had occurred over China. Studies that now explore the changes in climate over China are likely to infer that observed changes in temperature, rainfall etc. identified in the observational record are caused by the increasing CO_2. We want to identify the relative contribution of LCC, in comparison to changes in CO_2, in causing regional climate changes over China. If the impact of LCC is small, then detection and attribution studies can ignore it and focus on the CO_2 signal. If the impact of LCC is large and additive to the CO_2 signal then it must be removed to prevent a false-positive attribution of changes in climate to increasing CO_2. Finally, if the impact of LCC is large and opposite to the CO_2 signal then failure to account for the impact of LCC will lead to a false-negative attribution of changes in climate to increasing CO_2 and a delay in identifying CO_2-induced warming over China.

We present our methodology in section 2, followed by results in section 3 and a discussion and conclusion in section 4.

2. Methodology

We used the standard version of the NCAR (National Centre of Atmosphere Reasch) CCM3 (Kiehl et al., 1996) at T42 resolution (approximately $2.8° \times 2.8°$) coupled with the Biosphere-Atmosphere Transfer Scheme (BATS, Dickinson et al., 1993) and a mixed layer ocean model. We performed two equilibrium simulations, one using an estimate of natural land cover and another simulation using current land cover both at the 280 ppmv CO_2 level. Identical pairs of experiments at 355, 430, and 505 ppmv (each an increase of 75 ppmv) were also performed. We will use N (natural land cover) or C (current land cover) and subscript CO_2 level (e.g., N280 and C280, etc.) to present each experiment in the following text. Each simulation was integrated for 17 years with spin-up achieved after two years. Details concerning the natural and current land cover datasets can be found in Zhao et al. (2001a). The main changes in land cover change over China include the replacement of tropical forests with mainly grass and crops (but also some mixed woodland) over southern China and the replacement of deciduous and mixed woodland with crops and short grass over northern China (Fig. 1). In our experiments, the change in CO_2 only affects radiation, and no direct CO_2 affect on plants was included. Overall, the geographical extent of the LCC over China is of order half of the extent of a traditional tropical deforestation experiment. In all cases, results are presented as the current vegetation simulation minus natural vegetation simulation or high CO_2 level minus low CO_2 level (all the CO_2 experiments were conducted using natural land cover).

We applied the approach of Katz (1982) to investigate the statistical significance of simulated changes. Katz (1982) proposed a procedure based on parametric time series modelling involving the fitting of low-

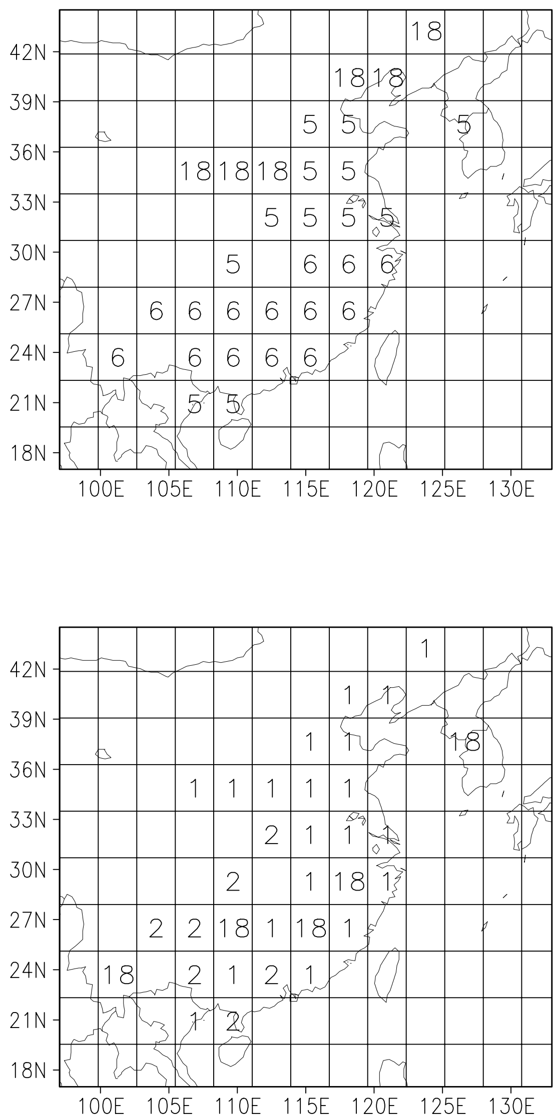

Fig. 1. The natural (top) and current (bottom) land cover over China. Shown are the BATS vegetation classification codes: 1: crop; 2: short grass; 5: deciduous broadleaf tree; 6: evergreen broadleaf tree; 18: mixed woodland.

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 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. We also used the Bayesian information criterion for selecting the appropriate order of the autoregressive processes which Katz (1982) argues improves the reliability of the methodology.

To calculate the extreme return values, we used the method of L-moments (Zwiers and Kharin, 1998). The advantage of the L-moments method is that it is computationally simpler than the method of maximum likelihood, and the L-moments method parameter estimates have better sampling properties for short samples. Dupuis and Tsao (1998) pointed out that the method of L-moments may not contain all the data from which distribution parameters are estimated (called non-feasible parameter estimates). The problem arises because the generalized extreme value distribution is bounded above when the shape parameter $\geqslant 0$ and below when $\leqslant 0$. Sampling variability may lead to parameter estimates that violate these constraints (Kharin and Zwiers, 2000). Thus, we also applied the hybrid estimators (Kharin and Zwiers, 2000) whenever the distribution obtained with the standard method of L-moments was non-feasible. When we calculated the changes in frequency of the daily data, we deleted frequencies less than 15 (once per year) for each simulation in order to clearly identify the major signal.

3. Results

3.1 *Impact on mean climatological quantities*

As a result of the changes in land cover, the surface winds change substantially. Figure 2 shows the change in the surface wind field as for December, January, and February (DJF) as a result of LCC at four CO_2 levels (Figs. 2a–d) and as a result of just a change in CO_2 (Figs. 2e–g). Figure 2a shows the impact of LCC at 280 ppmv. Our result is remarkably similar to Gao et al. (2003) (see their Fig. 4). Over the locations of LCC (Fig. 1), the surface winds increase by more than 1 m s^{-1} on the seasonal average. The impact of LCC at the higher levels of CO_2 (Figs. 2b–d) gives a similar result with small increases ($\sim$1 m s^{-1}) over the northern part of China and 2–3 m s^{-1} over southern China. The increase in the wind speed is the result of the reduction in the surface roughness that reduces the friction exerted by the surface. The greater increase in the wind speeds over southern China reflects the larger change in roughness length in this region where tropical forest (with a 2-m roughness length) has been replaced mainly by short grass and crops. Over northern China, deciduous and mixed forest (with a roughness length of 1.5 m) is replaced mainly by crops. In DJF, the impact of the change in CO_2 on surface winds over the land is very small under natural land cover (Figs. 2e–g). A similar result is found for June, July, and August (JJA) (Fig. 3). The large changes resulting from LCC suggest an impact on the monsoon circulation.

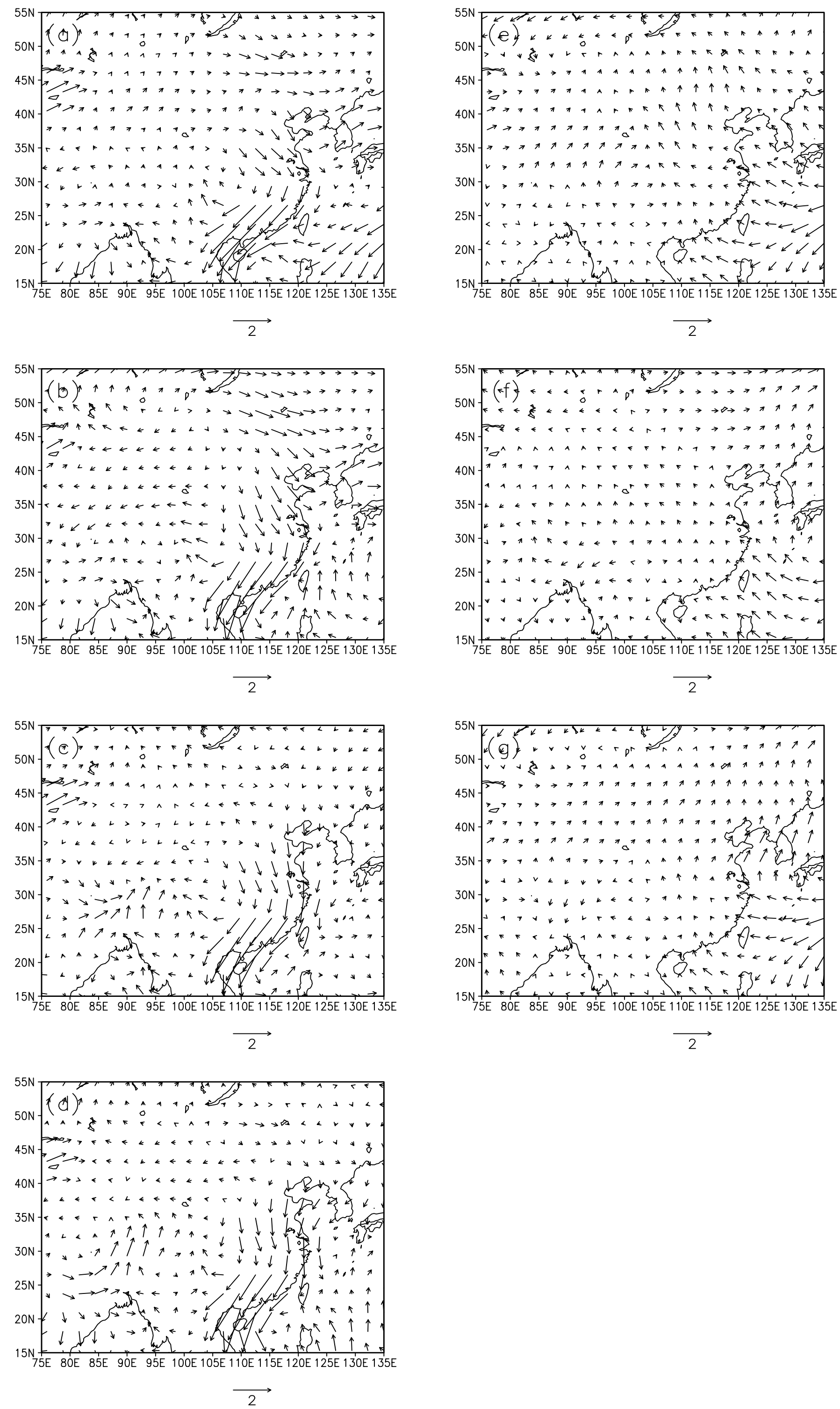

Fig. 2. The changes in the surface wind field for DJF resulting from (a) LCC at 280 ppmv; (b) LCC at 355 ppmv; (c) LCC at 430 ppmv, (d) LCC at 505 ppmv; (e) a change in CO_2 from 355 ppmv to 280 ppmv; (f) a change in CO_2 from 430 ppmv to 355 ppmv; and (g) a change in CO_2 from 505 ppmv to 430 ppmv. The CO_2 experiments were conducted using natural land cover.

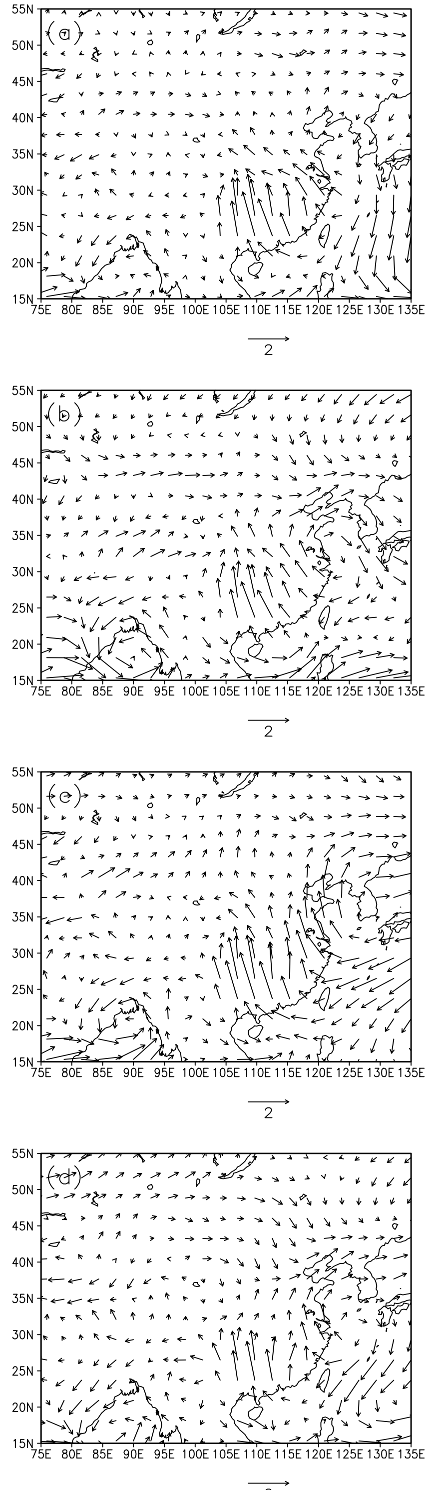

Fig. 3. As Fig. 2 but for JJA.

LCC influences both the surface momentum balance and the surface energy balance. The changes in BATS' parameters resulting from LCC affect the partitioning of available energy between sensible and latent heat and, as a consequence, affect the surface temperature. Figure 4 shows the impact of LCC and changes in CO_2 on the surface temperature, combined with statistical significance levels of the changes. The removal of forests and their replacement by crops reduces the latent heat flux in BATS and therefore tends to increase the surface temperature leading to an increase in the JJA averaged surface temperature of up to 1 K at all four CO_2 levels (Figs. 4a–d). These changes temperature are statistically significant at 98% significance levels over a large area. The impact of LCC over the south eastern part of China is consistent at all four CO_2 levels (Figs. 4a–d) indicating that LCC is likely to remain significant at higher levels of CO_2 expected in the future. Gao et al. (2003) found a similar result away from the coast with a large area of warming by up to 2 K. They also identified coastal areas where warming exceeds 4 K. Unfortunately, our coarser resolution prevents us from providing confirmation of this latter result and our smaller changes near the coast should not be interpreted as casting doubt on Gao et al.'s (2003) results. The impact of CO_2 on surface temperature is larger geographically, affecting virtually the whole domain (Figs. 4e–g) at statistically significant levels, but similar in terms of the size of the warming. Thus, overall, LCC affects surface temperature over the regions where the land cover is modified. CO_2 clearly has a more geographically extensive impact, but over regions of large scale LCC such as China, the impacts caused by LCC and increases in CO_2 (at least up to 430 ppmv, Fig. 4f) are quite similar in magnitude.

3.2 *Impact on extremes and return values*

LCC and changes in CO_2 can affect temperature extremes as well as the average surface temperature. Figure 5 shows changes in the mean, maximum, and minimum surface temperatures as well as the diurnal temperature range over the seasonal cycle (all averaged over the locations of LCC). LCC leads to a decrease in the mean, maximum, and minimum temperatures from November to February and an increase in these temperatures in the other months at all CO_2 levels (Figs. 5a–c). This result is qualitatively similar to Gao et al. (2003). The increase in the minimum temperature is very small in summer, but the maximum temperature increases by more than 2 K (Fig. 5b) irrespective of the CO_2 level. This causes a net increase in the diurnal range (Fig. 5d) in almost every month. Changes in CO_2 have a very different "signature" with warming in the mean temperature in each month (Fig. 5e) and seasonal variations in the impact of CO_2 being generally smaller than seasonal variations in the impact of LCC. Over China, the impact of changes in CO_2 on the maximum and minimum temperatures appears to be similar (Figs. 5f, 5g) in both cases, increasing the temperature in agreement with Gao et al. (2003). However, both temperatures change by similar amounts, leading to negligible changes in the diurnal range (Fig. 5h), a result that seems to conflict with Gao et al. (2002). However, a careful analysis of our Fig. 5h with Gao et al.'s (2003) Figs. 3 and 4 indicates that the differences in the actual results are small with both results showing significant increases in the maximum and minimum temperatures.

The changes in maximum temperatures can also be viewed in terms of changes in the return values of extreme temperatures. Figure 6 shows the impact of LCC and changes in CO_2 on the 20-yr return value for the annual daily maximum temperature. LCC leads to an increase in the return value of 1–3 K over southern China at all four CO_2 levels (Figs. 6a–d). Increases in CO_2 affect a larger area and larger increases in CO_2 lead to more widespread increases in the return value. However, the magnitude of the change in the return value (1–3 K) does not appear to change with larger increases in CO_2 and remains similar to the change in the return value resulting from LCC. These changes in return values can also be seen in Fig. 7 where the frequency of maximum temperature and convective precipitation are shown. There is a clear reduction in the frequency of cooler temperatures with a corresponding increase in warmer temperatures (Fig. 7a) due to LCC. A very similar signal can be seen due to increasing CO_2 (Fig. 7b), but the LCC leads to slightly higher maximums (29°C) than CO_2 (27°C). The impact of LCC on convective precipitation contrasts with the impact of changes in CO_2. The LCC leads to an increase in convective rainfall events in the lower classes (less than 1.6 mm d^{-1}, Fig. 7c) and a decrease in higher rainfall classes (6.4 mm d^{-1}) (i.e., a reduction in extreme events). The increase in CO_2 leads to a reduction in the lower rainfall classes and an increase in the more severe rainfall classes (Fig. 7d). This impact of CO_2 on rainfall was identified earlier by Hennessy et al. (1997) and McGuffie et al. (1999), but the comparative impact on convective rainfall due to LCC has not been reported before. Unfortunately, Gao et al. (2002) and Gao et al. (2003) do not report results of extreme analyses, preventing us from comparing our results.

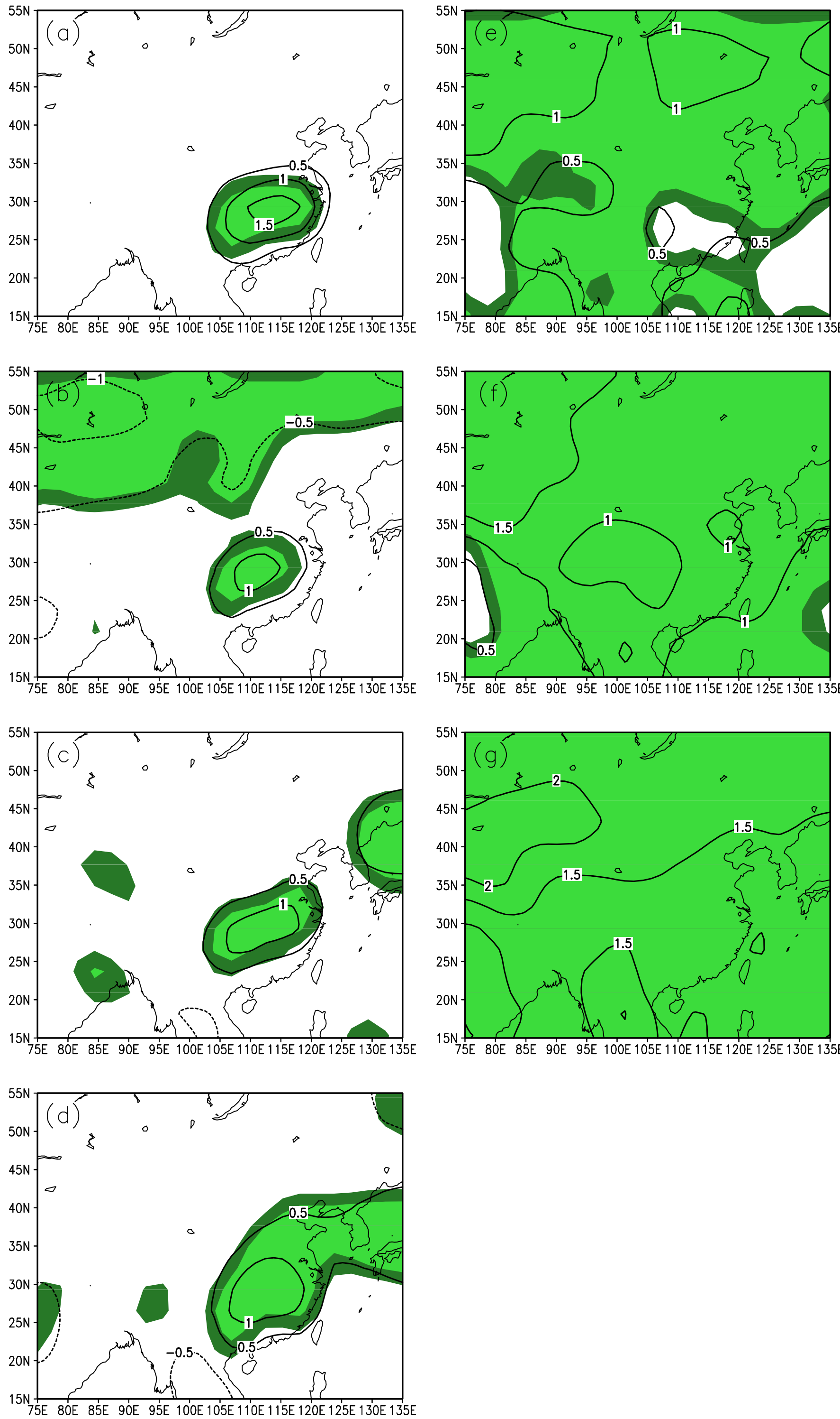

Fig. 4. The changes in JJA near surface air temperature (K, contours) together with statistically significance levels (shaded) due to LCC at (a) 280 ppmv, (b) 355 ppmv, (c) 430 ppmv, and (d) 505 ppmv; and due to increasing CO_2 under natural land cover (e) N355–N280, (f) N430–N280, and (g) N505–N280. Statistical significance levels are shaded from dark to light at 95% and 98% levels.

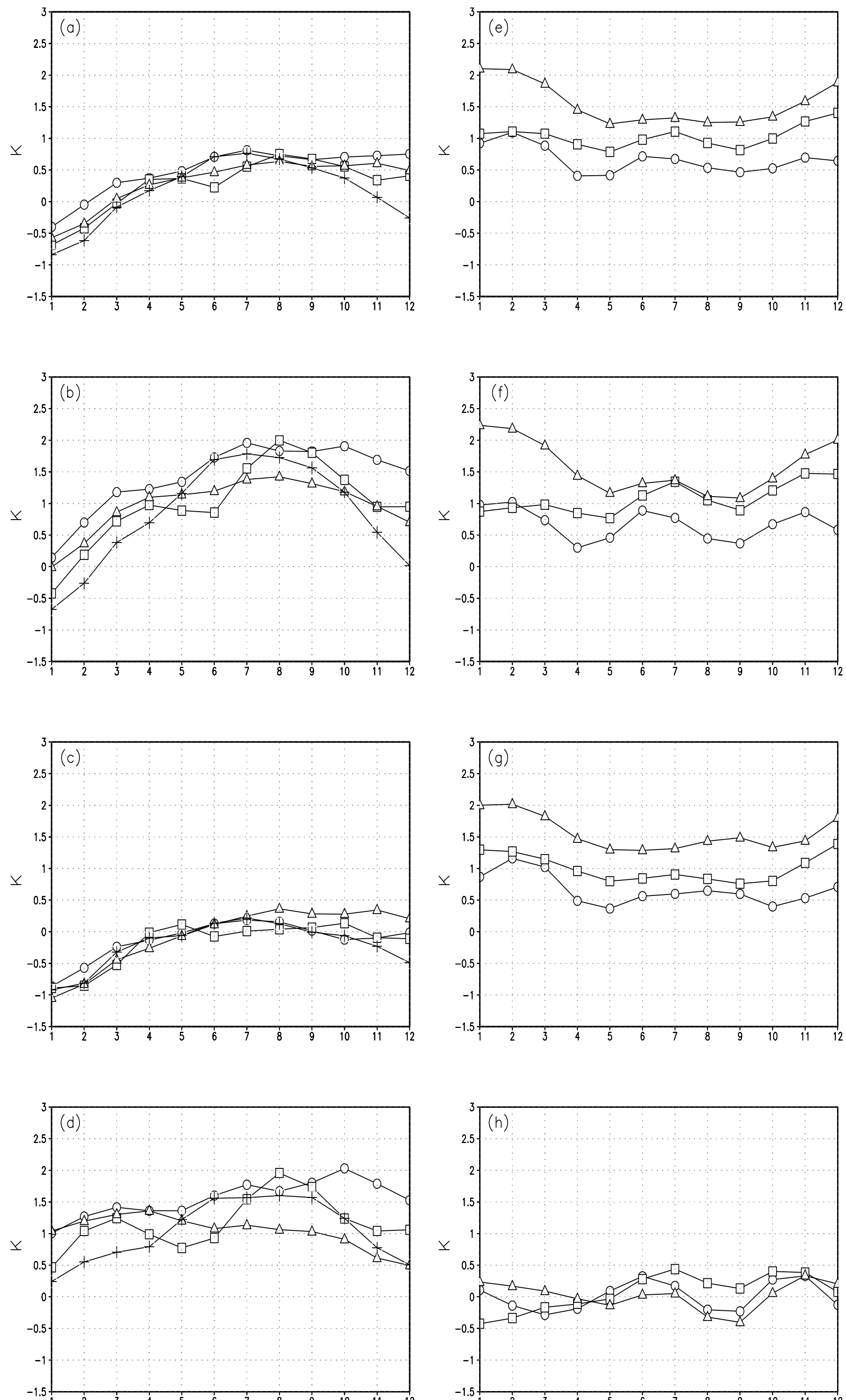

Fig. 5. The changes in (a, e) monthly mean temperature, (b, f) maximum temperature ($T_{\max}$), (c, g) minimum temperature ($T_{\min}$) and (d, h) diurnal range ($T_{\max}-T_{\min}$, from top to bottom) due to (left) LCC at four CO_2 levels (circles are for 280 ppmv; squares are for 355 ppmv; triangles are for 430 ppmv; crosses are for 505 ppmv) and (right) increasing CO_2 under natural land cover (circles are for N355–N280; squares are for N430–N280; triangles are for N505–N280).

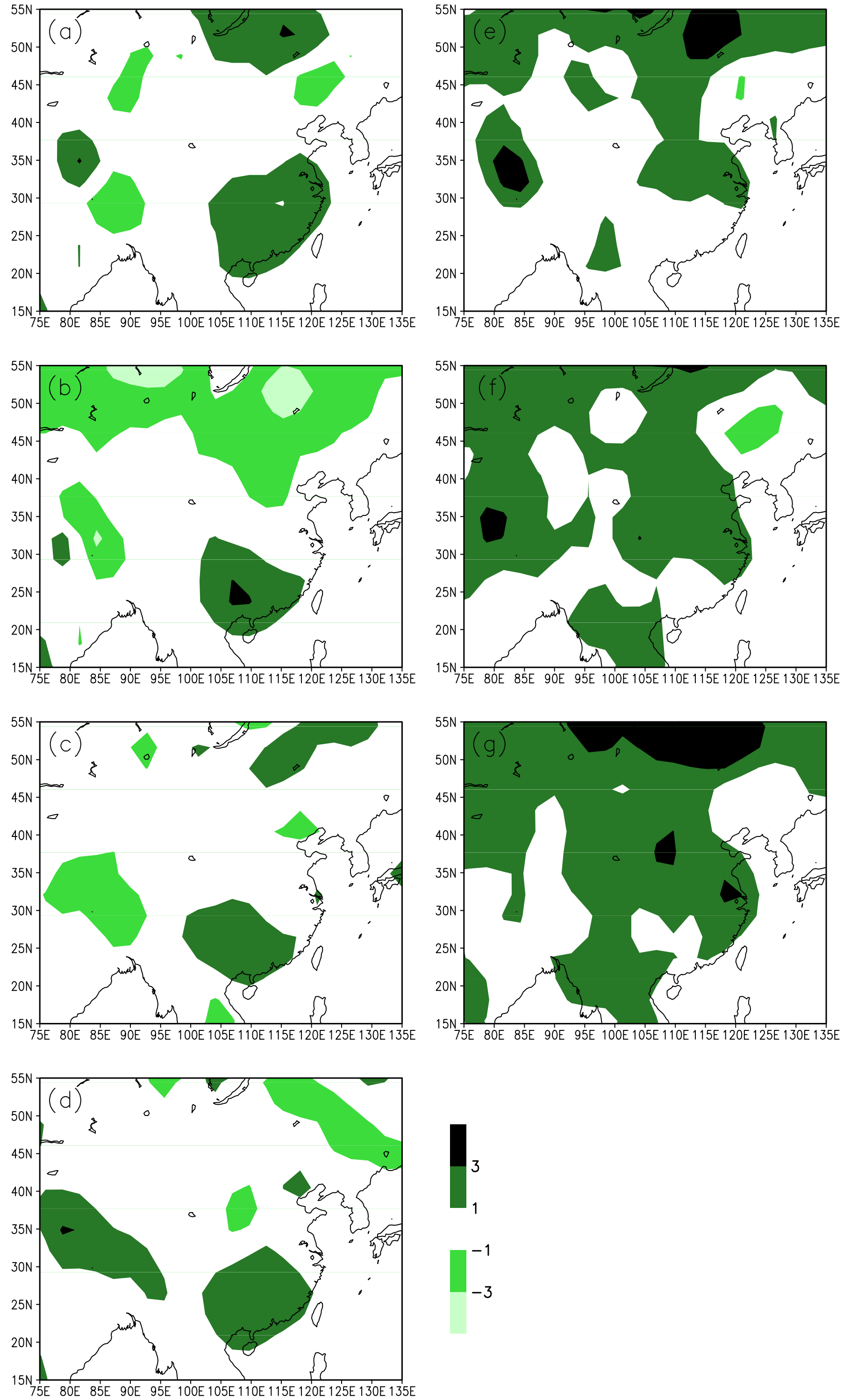

Fig. 6. The changes in the 20-yr return values for annual daily maximum temperature due to LCC at (a) 280 ppmv, (b) 355 ppmv, (c) 430 ppmv, and (d) 505 ppmv; and due to increasing CO_2 under natural land cover (e) N355–N280, (f) N430–N280, and (g) N505–N280.

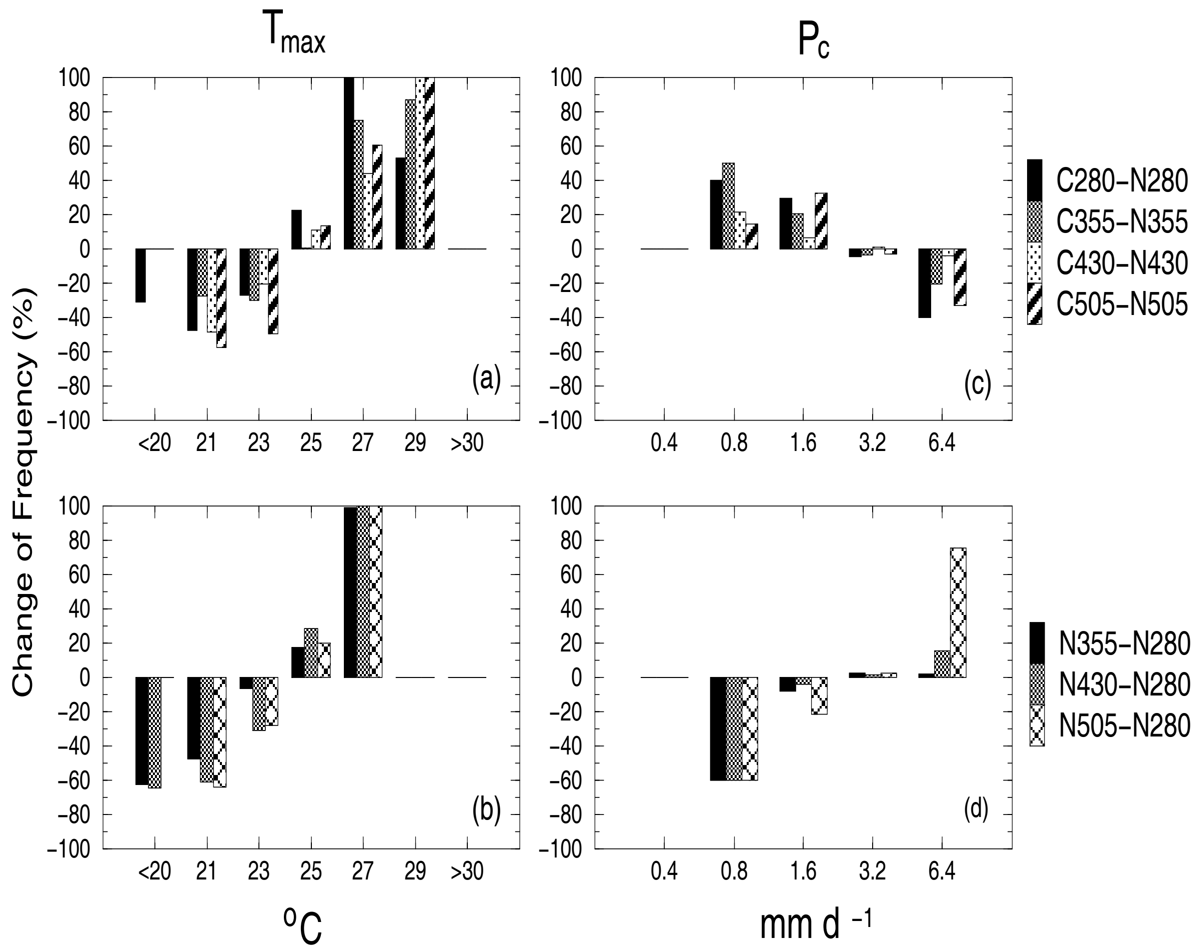

Fig. 7. The changes in frequency of maximum temperature ($T_{\max}$) and convective precipitation (P_c) due to LCC under different CO_2 levels (a, c) and increasing CO_2 under natural land cover (b, d) in JJA.

4. Discussion and conclusions

LCC over China appears to lead to statistically significant changes in average, maximum, and minimum surface temperature and surface wind fields. Gao et al. (2003) independently found compatible results in much higher resolution but shorter timescale simulations. The impact of LCC on the wind fields over land are quite large and suggest that it may have a larger affect on the monsoon flow than increases in CO_2 (at least up to levels of 505 ppmv). An impact has also been identified on the return values for maximum temperatures and the frequency of maximum temperature and convective precipitation. The impact of LCC on these quantities appears to be independent of CO_2 level. In contrast, the impact of increases in CO_2 on these quantities is sensitive to the amount of the CO_2 increase. In general, changes in CO_2 influence a larger geographical area than the impact of LCC, but the size of the changes in temperature, return values, or the frequency of extreme events is quite similar. Our results are in agreement with Gao et al. (2002, 2003) and help confirm their findings. LCC also has a large impact on the seasonal and diurnal temperature ranges. The nature of these changes is quite distinct from the changes caused by increases in CO_2. This difference in the "signature" of the changes induced by the two perturbations, seen most clearly in the changes in the diurnal range and in the changes in convective precipitation, offers the potential to identify the causes of changes within the observational record. Certainly, care needs to be taken in interpreting observed changes in convective rainfall or maximum temperatures since the results reported here indicate that LCC and CO_2 can both influence these quantities at a comparable level.

These modelling experiments were conducted using a single climate model and a single land surface scheme, linked to one LCC scenario. The significance of these limitations is reduced since our results largely agree with those of Gao et al. (2001, 2002, 2003). While our results should be interpreted with care, they do suggest that including land cover in future transitory climate modelling experiments is worthwhile if regional scale impact studies are to be conducted. They also indicate that the incorporation of land surface models that are able to interact with the evolving climate and changes in vegetation type or physiological characteristics is a priority (Pitman, 2003). Our results do not suggest that the impact of increasing CO_2 over China has been overrated, but they do suggest that the significance of LCC, either resulting from direct human intervention or indirectly via increasing CO_2, has been underestimated as a significant factor in understanding regional climate change.

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