The Impact of 200 Years of Land Cover Change on the Australian Near-Surface Climate

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ABSTRACT

The effect of land cover change on the Australian regional-scale climate is investigated using the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5). Four ensemble simulations are performed consisting of January and July experiments for eight different years with a 50-km grid spacing using natural (1788) and current (1988) vegetation cover. The statistical significance of changes that occurred following the replacement of natural vegetation with current vegetation on air temperature, rainfall, latent heat flux, and other related quantities is explored. Results show that the impact of land cover change on local air temperature is statistically significant at a 99% confidence level. Furthermore, there are indications that the observed increase in local maximum air temperatures in certain regions of Australia can be partially attributed to land cover change. The results are evidence of statistically significant changes in rainfall, and the sign of these changes over Western Australia in July, and the lack of any simulated changes in January, agree with observations. These results provide further evidence of large-scale reductions in rainfall following land cover change. Changes in wind speed are also simulated and are consistent with those expected following land cover change. The results indicate that attempts to identify greenhouse-related warming in Australian air temperature records should account for the effects of both land cover change and increasing CO_2 concentrations since both types of anthropogenic forcing exist in long-term observational records. Since further land cover change will occur in the future, directly via human impact and indirectly via CO_2 fertilization, the results support efforts to include land surface schemes that allow the vegetation to interact with changes in climate in climate models.

1. Introduction

Land cover change (LCC) has been recognized as an important anthropogenic climate forcing (Houghton et al. 2001) that can be as significant as increasing carbon dioxide (CO_2) concentrations at regional scales (Hansen et al. 1998; Couzin 1999; Pielke 2001). Climate research over the last decade has shown that a change in vegetation cover can significantly affect regional climate (e.g., Pielke et al. 1998; Pielke 2001). Regional impacts due to LCC on mean air temperature, extreme air temperature, and rainfall intensity, comparable to that of increasing CO_2, have been found (Pitman and Zhao 2000; Eastman et al. 2001; Zhao and Pitman 2002). In-depth model simulations on specific regions such as the boreal forests (Bonan et al. 1992), the United States (Bonan 1997), the Sahel (Xue 1997), and Amazonia (Henderson-Sellers et al. 1993; Polcher and Laval 1994; Costa and Foley 2000; Zhang et al. 2001a) illustrate that the effect of LCC on climate can be substantial. Further, impacts following LCC in general have been found in climate model simulations (e.g., Chase et al. 2000; Zhao et al. 2001).

The impact of LCC on the regional micrometeorology of Australia has been explored in a series of experiments (Lyons et al. 1993; Huang et al. 1995; Lyons et al. 1996; Lyons 2002) where changes in various aspects of the regional meteorology have been linked to LCC using observations and modeling. While this work has focused on short timescale impacts of LCC (usually a few days) it does hint that larger timescale impacts on weather and climate may follow LCC including large-scale reductions in rainfall. In Western Australia, this work provides one explanation for the observed reduction in rainfall (e.g., Pittock 1983). This paper explores the impact of LCC on the Australian climate, providing a continental-scale focus to global-scale (e.g., Chase et al. 2000; Zhao et al. 2001) and local-scale (Lyons 2002) studies.

Impacts following LCC are caused by modifications to the vegetation cover and soil characteristics. Converting from trees to grass, for example, reduces leaf area index (LAI), increases albedo, decreases roughness length (z_o), and alters root distribution and depth (e.g., Sellers 1992; Jackson et al. 1996). These changes affect the partitioning of available water between runoff and

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evaporation, thereby affecting soil moisture and possibly rainfall. Further, these changes affect the partitioning of available energy between sensible and latent heat, affecting local air temperature and boundary layer structure (Betts et al. 1996; Lyons 2002). Changes in roughness length may also affect wind patterns (Sud and Smith 1985). These changes may cause remote changes in air temperature, rainfall, and wind (Zhang et al. 1996; Chase et al. 2000; Zhao and Pitman 2002).

Many of the studies on the impact of LCC have used global climate models at coarse grid spacings of at least 2.5°. In this paper, we use a high-resolution regional climate model (RCM) that represents important climate forcings, such as vegetation, topography, and soil at a mesoscale resolution. Hence, impacts of LCC on mesoscale fluxes, and subsequently on air temperature and rainfall can be more accurately resolved. Climate studies in Australia (Walsh and McGregor 1995) have demonstrated that using higher-resolution models have general benefits over global climate models, especially in simulating rainfall, since they capture the influence of orography. Work has also demonstrated that RCMs are sensitive to land surface processes (Zhang et al. 2001b).

We have performed a total of 32 experiments in this study, as compared with other regional climate simulations performed over a few months in a year (Copeland et al. 1996; Wei and Fu 1999). This number of simulations was performed to permit a thorough test of the statistical robustness of our results. Our objective is to establish the statistical significance of any impact of LCC on Australian climate, independent of varying meteorological conditions. We also wished to conduct an initial examination of the effect of historical Australian LCC on observed trends in climate. From 1910 to 1988, annual mean air temperature and rainfall in Australia have generally increased by approximately 0.68°C and 55 mm, respectively (Torok and Nicholls 1996; Lavery et al. 1997) and it is possible that LCC explains some of the trends observed in these variables.

2. Methodology

We use the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) as described by Grell et al. (1994) coupled with the Pleim–Xiu (PX) land surface model (LSM) (Xiu and Pleim 2001; Pleim and Xiu 1995). MM5 is widely used in various meteorological studies including air quality research, weather simulations, and climate modeling. Recent applications of the model include simulating the evolution of convective systems (Hui et al. 1999), and the mesoscale modeling of atmospheric features such as wind and potential temperature (Bromwich et al. 2001). Coupled with the PX land surface model (MM5–PX), MM5 has been shown to simulate soil moisture conditions and evapotranspiration well, and to model seasonal trends in deep soil temperature, surface fluxes, and surface air temperature adequately (Xiu and Pleim 2001).

The MM5–PX is applied at a 50-km horizontal grid spacing, 60 × 87 grid domain, which contains almost all of Australia and covers all major areas of LCC (Fig. 1). A total of 32 simulations are performed consisting of January and July runs for 8 yr (1987, 1988, 1989, 1990, 1991, 1992, 1994, and 1995) using natural (1788, the year of European arrival in Australia) and current (1988, the bicentennial of European arrival) vegetation cover [these are the 2 yr for which the Australian Surveying and Land Information Group (AUSLIG 1990) mapped vegetation over Australia]. This large ensemble of experiments, which includes ‘‘average’’ years as well as years representative of La Niña and El Niño conditions, allows us to test whether the impact of LCC is consistent through varying meteorological conditions.

In all simulations MM5–PX is run with a 3-min time step and the following model physics configuration: simple ice microphysics (Dudhia 1989), cloud interactive radiation (Dudhia 1989), the Grell convective scheme (Grell et al. 1994), and the PX planetary boundary layer (PBL) scheme (Xiu and Pleim 2001; Pleim and Xiu 1995). Except for the PX PBL, these physics options have been used in some operational applications of MM5 and in experiments that assess the performance of the MM5 coupled to the Oregon State University–Land Surface Model (OSU–LSM) (Chen and Dudhia 2001). Although our results will be influenced by the selected model physics to some degree, we hold these options constant in all model experiments in order for us to attribute any statistically significant differences between the simulated climate using current and natural vegetation exclusively to the impact of LCC.

Vegetation data are obtained from the *Atlas of Australian Resources on Vegetation* by AUSLIG (1990). The dataset has 22 local floristic types that are mapped into the 18-category U.S. Geological Survey (USGS) descriptions used by MM5–PX. The mapping (which was performed subjectively) (given in Table 1) is based on plant physical characteristics as well as geographical location. Although we believe that an Australian vegetation classification would have little effect on our conclusions, we are currently attempting to develop a suitable classification of Australian vegetation for numerical models.

Figure 1 shows that most of the land cover over the past 200 yr has been altered from trees to grass occurring mostly in the southwestern (SW) and southeastern (SE) parts of the continent (these regions are identified in Fig. 1). This is a consequence of the European settlement in the late 1700s and early 1800s, which introduced widespread livestock grazing in Australia (AUSLIG 1990). In northeast Australia (NE), an area has been altered from sparse to shrub. In this research, we aim to determine the impact and significance of these LCCs on near-surface meteorology. In our simulations, we omit any changes in CO_2 concentration to isolate the

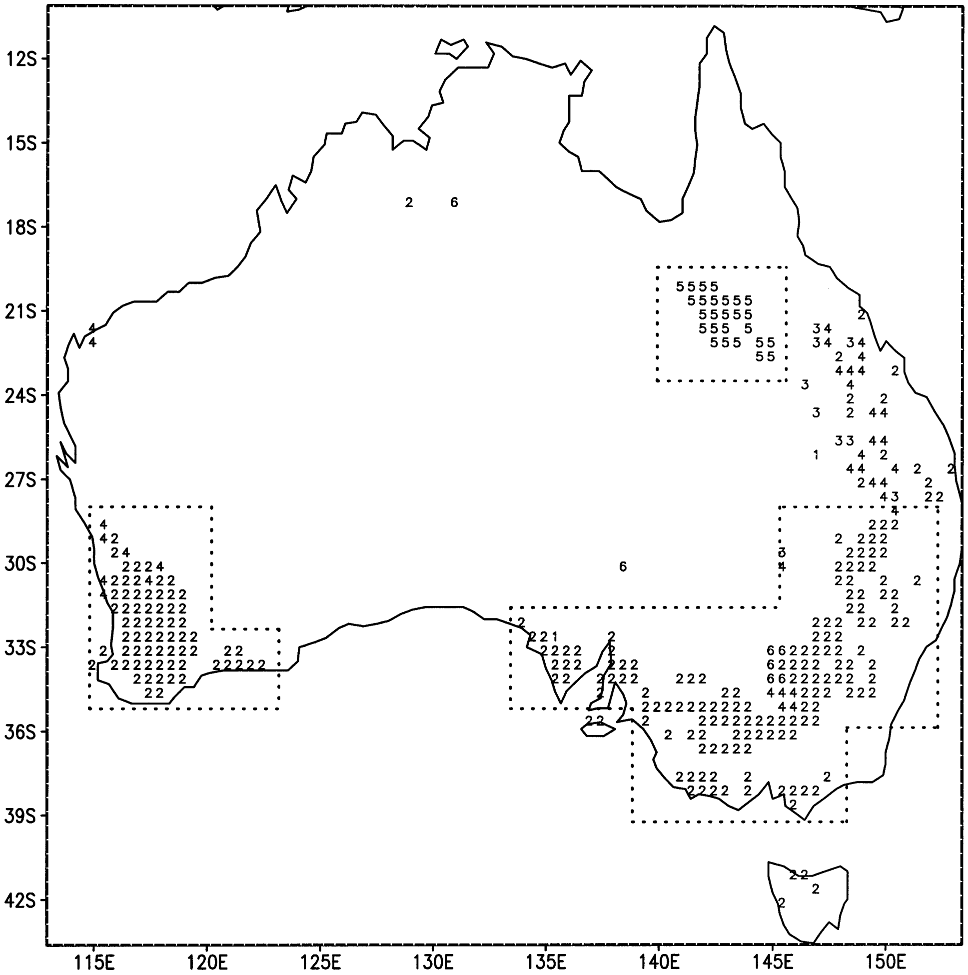

FIG. 1. Land cover change in Australia between 1788 and 1988 derived using the AUSLIG (1990) dataset. The three regions enclosed within the dotted boxes are the areas discussed in the text and are the areas tested for statistical significance. In those areas not annotated, land cover was left unchanged. The codes refer to the following changes: 1 = trees to shrub; 2 = trees to grass; 3 = shrub to trees; 4 = shrub to grass; 5 = sparse to shrub; and 6 = sparse to grass.

effect of LCC on climate. In both current (C_{veg}) and natural (N_{veg}) vegetation climate simulations, the model is initialized with the same boundary conditions taken from the National Centers for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS) analysis. Both types of LCC experiments therefore have the same background CO_2 concentrations and the 1788 simulations assume weather of the present day. This simplification allows us to attribute any impacts on climate following LCC to be the result of LCC and not increasing CO_2 levels (since 1788) or the combined effect of both.

The significance of our results is assessed by applying statistical methods for spatial field comparison described by Wigley and Santer (1990). In comparing means and variances, these methods allow us to test the likelihood that climate changes due to LCC do not occur by chance. The terminology used here is identical to Wigley and Santer (1990) to permit comparison to the detailed explanation of the statistical methodology they provide. We investigate results over Australia (the whole continent), SE, SW, and NE (see Fig. 1) in the differences between T1, two-tailed NT1, two-tailed NF1, SPRET1, and SPREX1. Here T1 is the grand mean, which is the overall averaged value calculated over space and time. NT1 is the gridpoint by gridpoint difference in time means and we test if there is a sufficient number of grid points with significantly different time means for these points not to be random. NF1 is the gridpoint by gridpoint difference in temporal variance and, similar to NT1, we test for the significance of the number of grid points with significantly different spatial means. SPRET1 is the overall difference in temporal variances and is calculated by obtaining the ratio of the spatial mean of the time variance of the two datasets. Finally, SPREX1 is the overall difference in the spatial variance, obtained by calculating the ratio of the time mean of the spatial variance of the two datasets. In all tests 1000

TABLE 1. Australian floristic types mapped to the 18-category USGS classification.

Floristic type (Australia)	USGS category	USGS code
Banksia	Shrub land	8
Casuarina including allocasuarina	Evergreen broadleaf	13
Eucalyptus	Evergreen broadleaf	13
Hakea	Shrub land	8
Chenopodiaceae (e.g., saltbush, bluebush)	Bare sparse vegetation	19
Melaleuca	Decidous broadleaf	11
Nothofagus	Evergreen broadleaf	13
Owenia (desert walnut)	Shrub land	8
Conifers	Evergreen needleaf	14
Myoporum (sugarwood)	Evergreen broadleaf	13
Heterodendrum (rosewood)	Evergreen broadleaf	13
Acacia including racosperma	Shrub land	8
Triodia and/or plectrachne	Bare sparse vegetation	19
Astrebla (mitchell grass)	Bare sparse vegetation	19
Dichanthium (bluegrass)	Grassland	7
Fabaceae (includes clovers and medics)	Shrub land	8
Graminoids	Grassland	7
Chenopodiaceae (e.g., saltbush, bluebush)	Bare sparse vegetation	19
Saccharum (sugar cane)	Crop/wood mosaic	5
Other grasses	Grassland	7
Asteraceae (daisies)	Grassland	7
Mixed or other	Mix shrub/grass	9

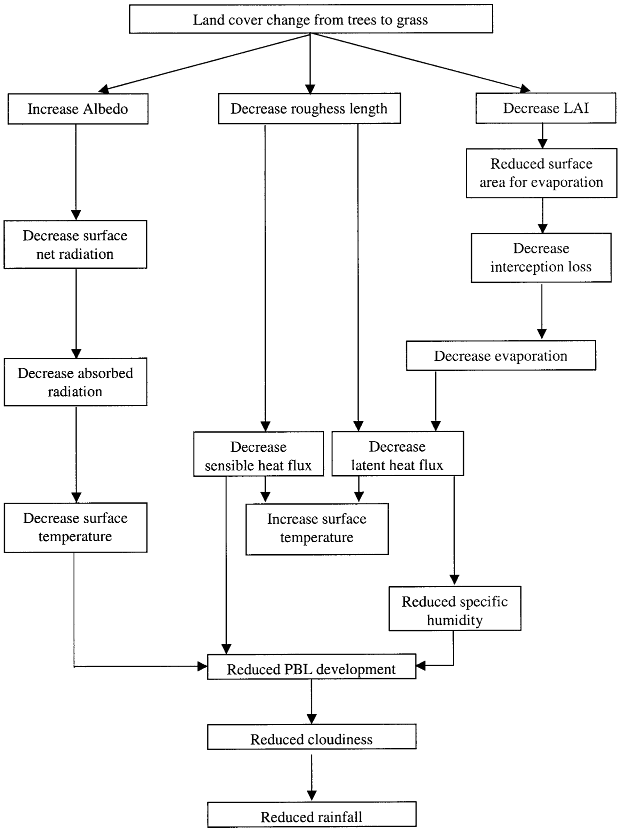

FIG. 2. Schematic diagram of the mechanisms behind the impact of land cover change, specifically from trees to grass, on temperature [adapted from Sellers (1992), Zhang et al. (1996), and Lyons (2002)].

permutations were used and we used the p values (observed significance levels) to evaluate the statistical significance of the results. A p value greater than or equal to 0.99, or equal to or less than 0.01, is statistically significant at the 1% level.

3. Results and discussion

In our results, we show the averages over the 8 yr simulated for each ensemble. The results from each simulation within the eight ensembles were very similar to each other and consistent from year to year.

Altering the vegetation cover from trees to grass modifies surface characteristics such as albedo, roughness length (z_o), and LAI, and we expect corresponding effects on the partitioning of available energy and available water as a result of these parameter changes (see Table 2 and Fig. 2). An increase in albedo, for example, should cause a decrease in surface temperature and reduced turbulent energy exchange due to decreased net radiation (R_n). This is the key mechanism found by Lyons (2002) in Western Australia that he used to explain reductions in cloud cover and rainfall. Decreasing z_o or LAI, on the other hand, should lead to surface

TABLE 2. Changes in surface characteristics when land cover is changed from trees to grass and the corresponding effect on temperature.

Surface characteristics	Southwest Australia	Southeast Australia	Expected change in temperature
Albedo	0.06	0.06	$-T$
LAI	−2.53	−2.48	$+T$
Roughness length (m)	−0.23	−0.23	$+T$

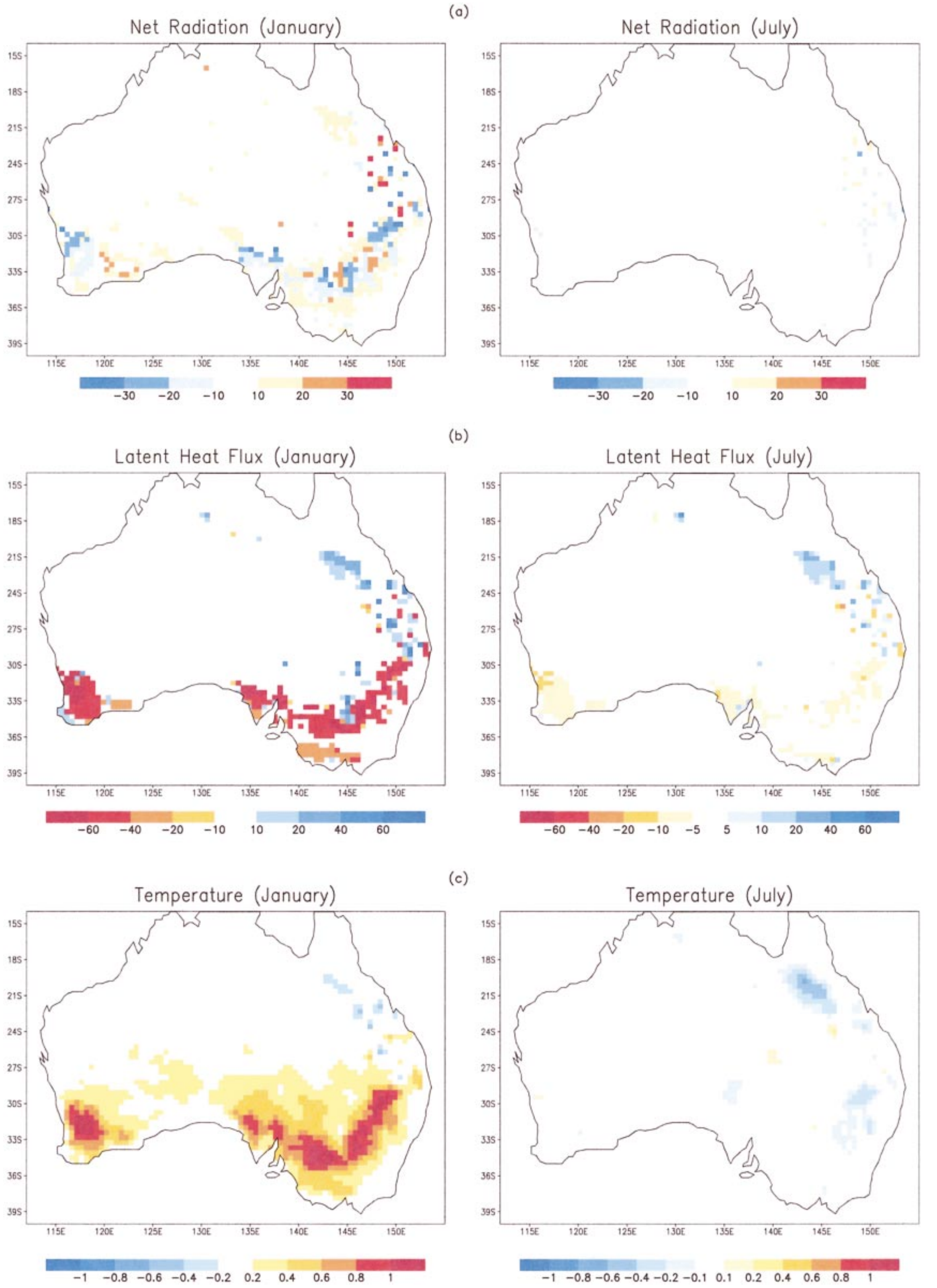

FIG. 3. Differences in (left) Jan and (right) Jul (a) net radiation (W m^{-2}), (b) latent heat flux (W m^{-2}), (c) air temperature (°C), (d) rainfall (mm day^{-1}), (e) wind direction (m s^{-1}), and (f) wind magnitude between current and natural vegetation climate.

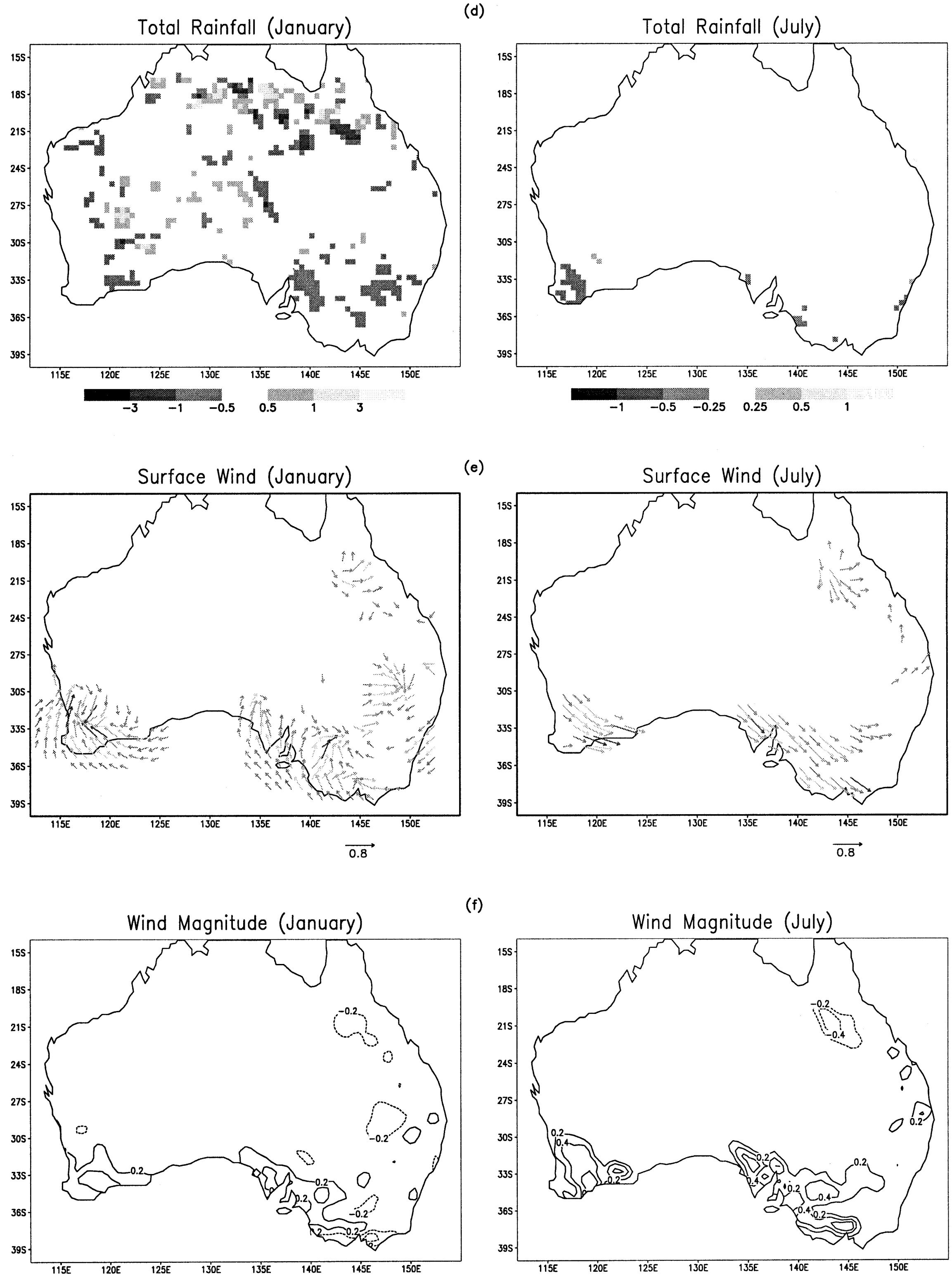

FIG. 3. (*Continued*)

warming since a lower z_o and a lower LAI limit the exchange of turbulent energy fluxes. Reducing z_o will decrease turbulent kinetic energy and consequently decrease the latent heat flux leading to warmer temperatures. Similarly, decreasing LAI will also decrease latent heat flux and tend to increase surface temperatures. Simple diagrams, derived from Sellers (1992), Zhang et al. (1996), and Lyons (2002), illustrating the mechanisms involved in surface characteristics affecting changes in temperature are shown in Fig. 2. The overall impact of these competing mechanisms depends on the precise nature of the behavior of the native and replacement vegetation. It makes a substantial difference, for example, if native vegetation is replaced by seasonal crops as distinct from grazed grasses.

In this paper we focus on the effect of modified surface characteristics on net radiation, latent heat flux, and air temperature. While these summarize the impact of LCC, these affect other quantities. We therefore also show the effect of LCC on rainfall and wind patterns. The vertical propagation of the impact of LCC on air temperature and wind are shown to illustrate the cross-sectional impact of LCC. Finally, the effect of LCC on the minimum (T_{min}) and maximum (T_{max}) air temperature extremes will be discussed.

a. *Impact of LCC on January and July mean quantities*

We first investigate changes resulting from the altered surface characteristics given in Table 2. Note that all figures in this section are obtained by calculating the difference between C_{veg} value and N_{veg} value ($C_{veg} - N_{veg}$). We focus our analyses in specific regions shown in Fig. 1, where AUSLIG (1990) indicate land cover has changed from trees to grass and where natural sparse land has been converted into shrub land.

Figure 3a shows the impact of LCC on January (summer) and July (winter) net radiation. In January, there are some small areas where net radiation changes by more than ±30 W m^{-2}, but most of the impact is restricted to less than ±20 W m^{-2}. In July, there are changes of ±10 W m^{-2} in net radiation in some isolated locations. Figure 3b shows a pronounced latent heat flux decrease of at least 20 W m^{-2} in January but exceeding 60 W m^{-2} over quite large areas. The latent heat flux increases over NE. These changes are statistically significant in the point-by-point time mean (NT1) over SW and NE, and are significant over Australia, SE, SW, and NE in the point-by-point temporal variance (NF1, Table 3). A decrease of 10 W m^{-2} in July occurs in SE and SW. This change is statistically significant in the temporal variance over SW (Table 3). In contrast, the latent heat flux over NE increases by 20–40 W m^{-2}, a change that is statistically significant in both NT1 and NF1 (Table 3). Thus far, our results are consistent with deforestation experiments (Henderson-Sellers et al. 1993; McGuffie et al. 1995; Zhang et al. 1996) showing areas of reduced net radiation and latent heat flux as a result of increased albedo and decreased z_o and LAI, respectively. The change from sparse land to shrubs in NE has increased latent heat flux due to the increase in z_o and LAI (note that the change in net radiation in NE in July is negligible, but the change in the latent heat flux is large, suggesting that albedo is not the key factor in explaining our results).

TABLE 3. Test statistic (*p* values) of the observed LCC impacts on Jan and Jul air temperature, latent heat flux, and rainfall over Australia, SW, SE, and NE. Values greater than or equal to 0.99, or equal to or less than 0.01 are statistically significant at the 1% level and are shown in bold.

Variable	NT1	NF1	SPRET1	SPREX1	T1
Jan					
Air temperature					
Australia	**1**	**1**	0.49	0.49	0.51
SE	**1**	**1**	0.26	0.33	0.29
SW	**1**	**1**	0.15	0.24	0.26
NE	**1**	**1**	0.66	0.46	0.69
Latent heat flux					
Australia	0.04	**0.01**	0.63	0.53	0.54
SE	0.03	**0**	0.79	0.59	0.64
SW	**0.01**	**0**	0.94	0.87	0.76
NE	**0.01**	**0**	0.16	0.68	0.15
Rainfall					
Australia	0.02	**0**	0.53	0.53	0.56
SE	0.02	**0.01**	**0**	**0**	0.6
SW	**0.01**	**0**	0.85	0.96	0.82
NE	**0**	0.09	0.67	0.77	0.44
Jul					
Air temperature					
Australia	**1**	**1**	0.63	0.49	0.51
SE	**1**	**1**	0.32	0.43	0.51
SW	**1**	**1**	0.38	0.47	0.50
NE	**1**	**1**	0.58	0.90	0.53
Latent heat flux					
Australia	0.08	0.53	0.5	0.46	0.51
SE	0.08	0.12	0.64	0.39	0.58
SW	0.05	**1**	0.71	0.21	0.64
NE	**0.01**	**0**	0.07	0.74	0.15
Rainfall					
Australia	0.04	0.57	0.55	0.58	0.54
SE	0.06	0.27	0.58	0.62	0.55
SW	**1**	**1**	0.55	0.58	0.54
NE	0.05	0.32	0.70	0.91	0.59

The impact of LCC on air temperature in SE and SW, shown in Fig. 3c, is a warming of about 1.0°–1.5°C in January mean air temperature, but fewer large-scale changes are simulated in July. All the changes simulated are statistically significant (at 99% confidence level) in the temporal mean and variance (Table 3) over Australia, SE, and SW. In NE, air temperatures decrease by −0.2°C in January and this cooling becomes more evident and stronger in July (−0.5°C) (in both months, the changes are statistically significant). These changes in air temperature are consistent with the changes in latent heat flux (Fig. 3b). The decrease in latent heat flux leads to

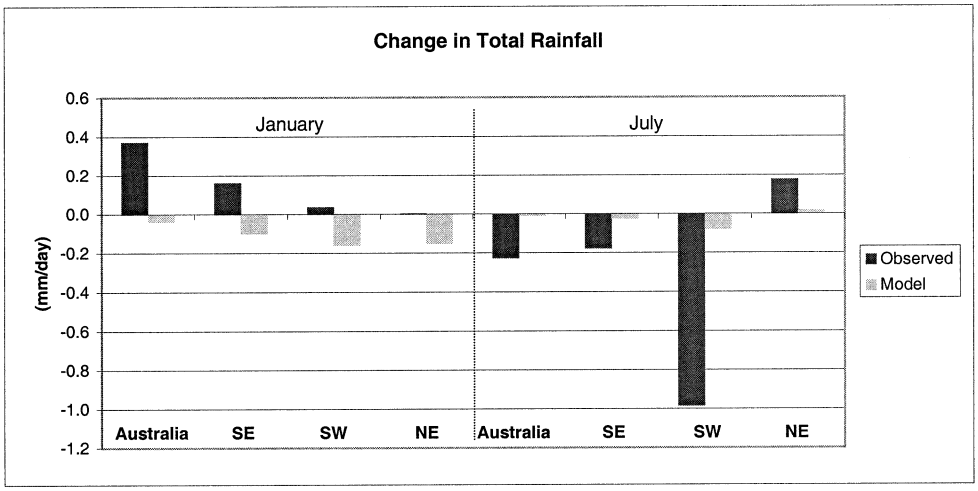

FIG. 4. A comparison between the observed change in rainfall (mm day^{-1}) from station data (1910–88) and the simulated model results (1788–1988) for (left) Jan and (right) Jul.

a repartitioning of available energy and a corresponding increase in the sensible heat flux in January over SE and SW that leads to higher air temperatures. The increase in the latent heat flux, and decrease in the sensible heat flux over NE, has resulted in slightly cooler air temperatures in the region. The reduction in latent heat flux in SW and SE has increased the sensible heat fluxes that, in turn, increase the January air temperatures, but no warming is observed in these regions in July since the change in latent heat flux is relatively small (about -5 to -10 W m^{-2}). We also note that any cooling effect that may have been caused by the increase in albedo in these areas in dominated by the large warming effect caused by the repartitioning of available energy toward sensible heat fluxes. This implies that decreasing both LAI and z_o have greater impacts than increasing albedo, a result that is similar to many deforestation experiment results.

The changes in air temperature, latent heat flux, and net radiation generate few consistent changes in the magnitude or patterns of rainfall (Fig. 3d). The simulated changes over Australia are not statistically significant in the temporal mean (Table 3) but are, in January only, in the temporal variance. The reduction in rainfall over SW in July is small and is not statistically significant. It is, however, in line with the observed reductions in rainfall in July in this region. The absence of large changes in SW in January is also in line with observations. The difference between C_{veg} and N_{veg} rainfall in January appears largely random and, for July, the figures show no other substantial changes between C_{veg} and N_{veg}. Figure 4 shows spatial averages of the impact of LCC on rainfall over the four regions compared to observations. LCC reduces simulated rainfall in January, which does not match observations. There is therefore no evidence that the observed changes in January rainfall are caused by LCC. In July, over Australia, SW and SE, both observed and simulated rainfall is reduced. Over NE, both the observed and simulated rainfall is increased. The amount of reduction, over SW for example, is only ~10% of the observed, but this is not a particular concern given that we only have eight simulations with each land cover type. The fact that, with the exception of NE, LCC leads to a simulated reduction in rainfall in January and July (where the land cover changes are generally trees to grass) is a robust and consistent result in line with earlier analyses (Pielke 2001; Lyons 2002) and strongly supports the suggestion that large-scale LCC over Australia is a factor in the observed reduction in rainfall in some regions. The NE result (a change in land cover from sparse to shrub) would be expected to increase rainfall if our results are to remain consistent and, while the model only shows a very small increase in July, the change is in the right direction.

Figure 3e shows that LCC also has an effect on wind direction near the surface in all regions but the impact is more widespread in SE and SW. The wind magnitude ($\sqrt{u^2 + v^2}$; Fig. 3f) changes by up to 0.6–0.7 m s^{-1} over the locations of LCC in SE and SW and have decreased over NE by about 0.4 m s^{-1}. These changes occur in both January and July and are the direct result of changes in roughness length following LCC (Table 2).

Figures 3a–f show few substantial changes in any quantities over regions remote from LCC. There is, however, a relationship between changes in the climate quantities and the pattern of LCC shown in Fig. 1. This, coupled with the statistical analyses, strongly supports an argument that the changes shown in Fig. 3 are not the result of model variability. Our results also indicate that the impact of LCC, specifically the change of vegetation from trees to grass, is clearer in January. We note that although there are changes simulated in July, these are generally relatively small, except in NE, compared to those simulated in January because of lower radiation levels in the southern part of the continent (note the changes in the wind pattern and magnitude are an exception to this since they are not related to seasonal variations in net radiation).

The Wigley and Santer (1990) methods also allow examination of the statistical significance of overall differences in the grand mean, the overall difference in temporal variances (SPRET1), and the overall difference in spatial variances (SPREX1). The values for T1 (Table 3) indicate that the grand mean does not change significantly in the four regions (Fig. 1). Table 3 also shows that results for SPRET1 and SPREX1 have values that are not close to one or zero and are thus not statistically significant. The one exception is over SE for the overall difference in the temporal and spatial variance for rainfall in January. It is difficult to comment on the reliability of this finding given it seems inconsistent with other results, and a larger ensemble of simulations needs to be conducted before this result is considered robust.

b. Impact of LCC on vertical profiles

We also investigated the changes in the vertical profiles of temperature and the u and v components of wind for January over specific regions of LCC. Over SE and SW, the impact of LCC on temperature propagates upward beyond the boundary layer to a height of about the 0.7-sigma level (approximately 2.6 km; Fig. 5a). There is a hint of cooling above the large area of warming at 33°S. The warming is between 0.5° and 1.0°C at 33°S (in a region bounded by 135° and 152°E) and the warming of 0.5°C extends to at least the 0.8-sigma level (approximately 1.6 km). At 36°S, similar warming occurs between 140° and 145°E. This demonstrates that the impact of LCC is not isolated to near-surface quantities and has the potential to influence the circulation patterns over Australia and the observed boundary layer temperature.

The impact of LCC on u and v are shown in Figs. 5b and 5c, respectively. These are generally changed by considerably more near the surface but do propagate vertically in a similar way to temperature. Combined with Figs. 3e and 3f, this result shows a clear impact of LCC on the local atmospheric circulation, a result in keeping with Pielke (2001) and Lyons (2002).

c. Impact of LCC on air temperature extremes

We next focus on impacts of LCC on maximum ($T_{\max}$) and minimum ($T_{\min}$) air temperatures. We obtained station data (Torok and Nicholls 1996) supplemented with data from the Australia Bureau of Meteorology (information available online at http://www.bom.gov.au/climate/change/refernce.shtml) that show trends in $T_{\min}$ and $T_{\max}$ from 1910 to 1988. In our analyses, we only use stations that are included in the Reference Climate Station Network of the Australia Bureau of Meteorology (high quality climate records located away from major urban areas). We compared these station data with the simulated change in air temperature extremes from 1788 to 1988. The comparison of the observed trend in extremes from 1910 to 1988 with a modeled estimate of the change from 1788 to 1988 is clearly a considerable approximation. However, air temperature data do not exist for 1788 over Australia, and land cover is not well known for 1910. Further, AUSLIG (1990) show that the majority of land cover change occurred in the 1900s and that prior to the 1860s land clearance was highly localized. Most land cover change therefore probably occurred largely within the period of the observational record (1910–88) as land clearance accelerated as heavy machinery became increasingly available. However, given these uncertainties, at best our results may show a common signal between the impact of LCC and observed changes, if LCC is affecting $T_{\max}$ and $T_{\min}$ and we would not expect good agreement in the modeled and observed magnitude of change.

Figure 6 shows station data and model values for $T_{\min}$ (Fig. 6a) and $T_{\max}$ (Fig. 6b) for all of Australia and for SW, SE, and NE. It clearly shows that LCC has little impact on simulated extreme air temperatures at the continental scale in January or July. The simulated change in $T_{\min}$ is negligible (0.06°C) and the change in $T_{\max}$ is only 0.17°C, about 2.5% of the observed (2.5°C). The sign of the change is consistent with the observed change, but if LCC explained the observations, the model results (1788–1988) should exceed the observed change (1910–88). Since they do not, it is very unlikely that LCC explains more than a small fraction of observed trends in continental-scale warming. The explanation for continental-scale observed warming needs to be found through other mechanisms and increasing CO_2 remains the most likely cause.

Over SE, the warming simulated by the model in January $T_{\min}$ (0.17°C) exceeds the observed trend (0.0°C). Over SW, the model does not simulate the observed change in $T_{\min}$ (0.05°C cf. observed 0.62°C) and over NE the model failed to capture the observed increase in $T_{\min}$. LCC should not have a large impact on $T_{\min}$ (which is largely driven by nighttime radiative cooling) and it is also unlikely that LCC would cause large wintertime air temperature changes since vegetative controls on evaporation would not be large enough to affect air temperatures significantly. If evaporation is low, limited by net radiation, then LCC does not have the capacity to reduce evaporation such that the partitioning of available energy affects monthly average air temperature. Thus, we should not (and do not) see relationships between the modeled and observed changes in $T_{\min}$.

However, $T_{\max}$, particularly in summer, could be strongly influenced by LCC since reduced LAI, z_o, or root depth tends to reduce the ability of the vegetation to access enough water and to maintain a high latent heat flux. These reductions in latent heat flux reduce cooling ability and tend to allow higher maximum sur-

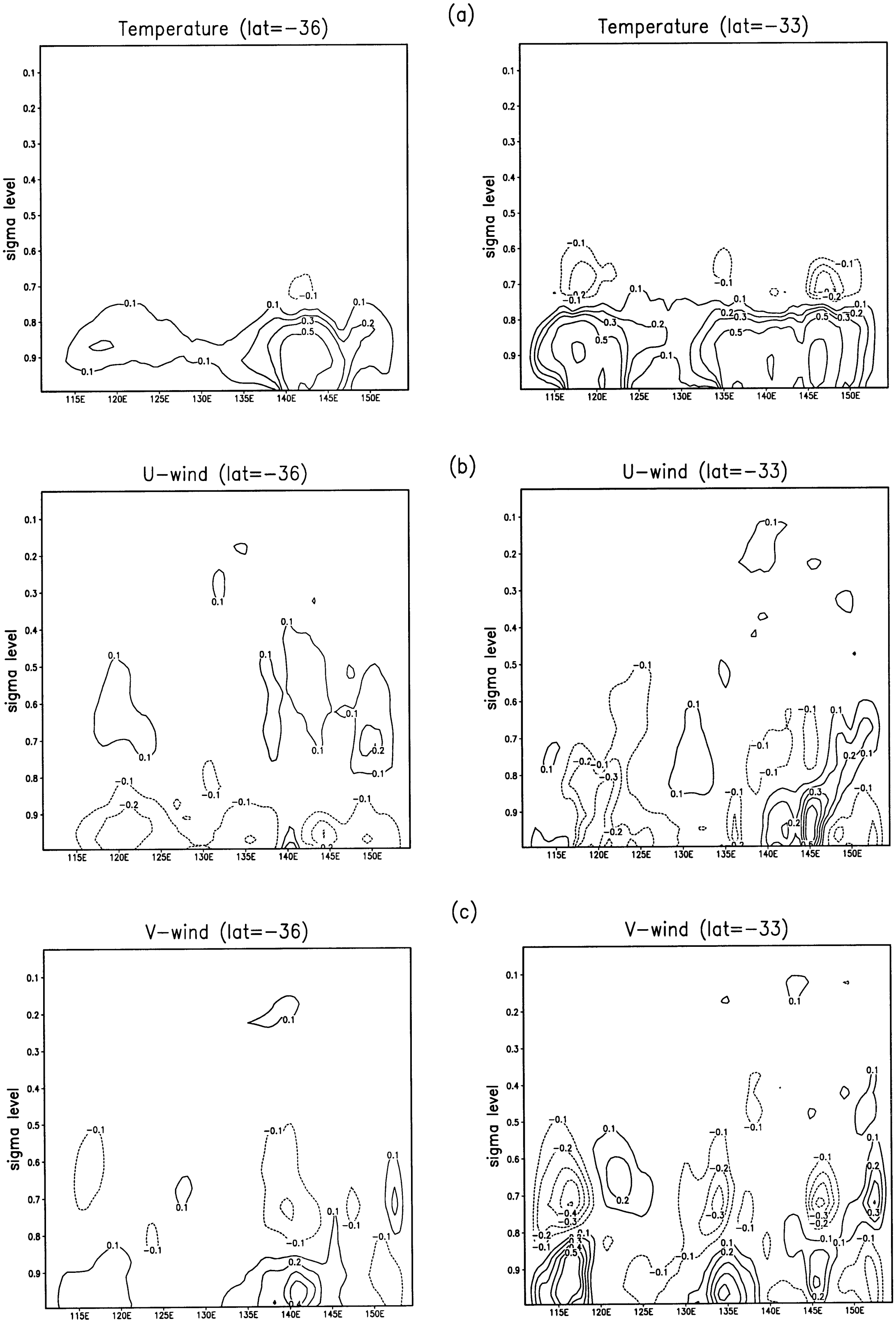

FIG. 5. Jan vertical profiles of (a) air temperature and the (b) *u* and (c) *v* wind components. (left) At 36°S (in a region bounded by 140°–145°E) and (right) at 33°S (in a region bounded by 135°–152°E).

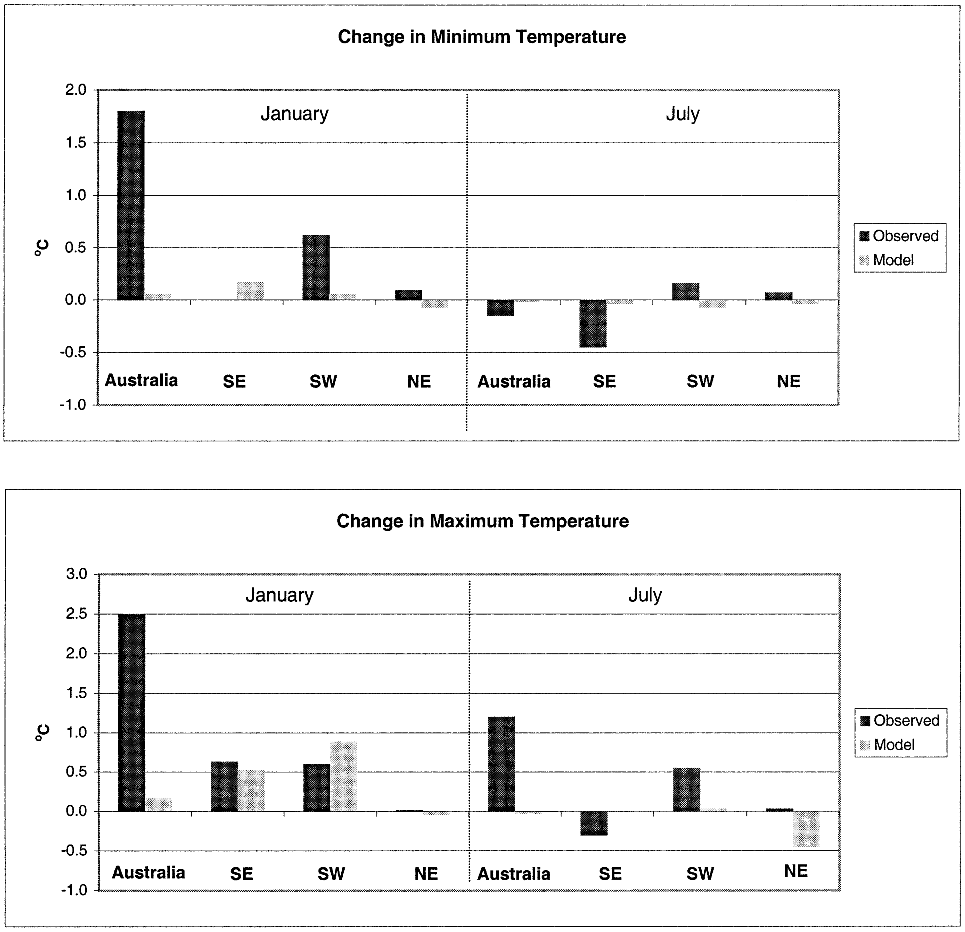

FIG. 6. A comparison between the observed change in (a) minimum air temperature and (b) maximum air temperature (°C) from station data (1910–88) and the simulated model results (1788–1988) for (left) Jan and (right) Jul.

face temperatures and thereby higher maximum air temperatures. Over SE, the model simulates warming in $T_{\max}$ (0.52°C), which is similar to the observed (0.63°C). This suggests that LCC may explain part of the observed warming trend over this region. Over SW, the model simulates an increase in $T_{\max}$ (0.89°C) similar to the observed (0.6°C). The change in NE is negligible in both the model and observed. The amount of increase in January $T_{\max}$ in SE, SW, and NE, which approximates the total observed increase, is interesting since the mechanisms that would link LCC and $T_{\max}$ are known, and such an impact is to be expected. It is thus tempting to conclude that the observed change in January $T_{\max}$ in SE and SW is likely to be due to LCC. However, since the time periods of the modeling results and observed data poorly coincide, we cannot reliably conclude that the observed increase in January $T_{\max}$ is caused by LCC. Our results do suggest however that a substantial fraction of the observed increase in $T_{\max}$ over SE and SW may be the result of LCC and highlights this issue as one for further exploration.

4. Discussion and conclusions

In this paper we have investigated the impact of LCC on the Australian climate using a high-resolution mesoscale model (MM5). Using estimated natural and current land cover obtained from AUSLIG (1990) we conducted 32 simulations to create a large enough ensemble of simulations to perform a statistical analysis of any changes in near-surface climate that may have resulted from LCC. We find that the model does not simulate continental-scale statistically significant impacts of LCC on air temperature, latent heat flux, or rainfall. However, over regions where LCC has been extensive (SE and SW) warming of 0.4°–1.0°C is simulated in January. This warming is largely the result of a change in the partitioning of available energy such that the latent heat flux (and evaporative cooling) is reduced and the sensible heat flux is increased. In July, we find fewer changes in air temperature, latent heat flux, or rainfall following LCC but some of these changes are statistically significant. Changes over NE are opposite to the changes over SE and SW because the nature of the LCC is very different. A significant impact of LCC is found on maximum air temperatures over SE and SW. These increase in the model since the changes in vegetation reduce the capacity of the land surface to support a high latent heat flux through the day and the reduced evaporative cooling permits higher surface temperatures. This increase in the simulated maximum temperatures, at least in January, is paralleled to some degree in the observational record, as is the lack of simulated changes over NE.

We do not suggest that the observed changes in Australian temperatures are the result of LCC. The increase in CO_2 concentrations is the most likely forcing mechanism at a continental scale. However, regionally the mechanisms whereby LCC can affect mean temperature and maximum temperatures are well understood and our results suggest that some of the observed changes in air temperature and rainfall over eastern and western Australia can be attributed to human-induced LCC. Further, in all simulations, LCC reduces rainfall and the mechanisms that link LCC to reduced rainfall are well understood (Pielke 2001; Lyons 2002). It seems entirely plausible that LCC has reduced rainfall over WA and EA, although this may be hidden in part by other factors including early impacts of increasing CO_2 or natural variability.

Our results, at first sight, might seem to conflict with those of Lyons et al. (1996) and Lyons (2002). They found changes in native vegetation, and its replacement by agriculture, reduced the sensible heat flux which led to weaker boundary layer development, decreased cloudiness and lowered rainfall. In our experiments, we replaced native vegetation cover largely with grassland (nonirrigated and nonharvested). This led to reduced evaporation, and this change (not a change in sensible heat) was the main influence that explained the reduced rainfall. We suspect both mechanisms operate, depending on the precise nature of the replacement vegetation cover, but irrespective of which mechanism dominates, rainfall is reduced. We argue that LCC (over large scales, where irrigation does not artificially reduce temperatures) would increase maximum and mean temperatures since the LCC would tend to reduce maximum potential evaporation fluxes through the replacement vegetation. This does not conflict with Lyons (2002), nor does it mean that the mechanisms proposed by Lyons et al. (1996) and Lyons (2002) do not also occur, rather it is simply a question of the characteristics of the replacement vegetation.

In conclusion, we argue that the role of LCC needs to be taken into account in any attempts to link regional-scale warming or regional-scale changes in rainfall to climate forcing mechanisms. We also believe that our results provide a strong rationale for efforts within climate modeling groups to develop land surface models that can adapt to changes in climate via physiological or structural changes in the vegetation. This effort will be required in order to model the future of the Australian climate where large-scale changes in the physiological and structural nature of the biosphere seems inevitable as CO_2 increases through this century. Finally, we argue that a major cost of land clearance, that of subsequent reductions in rainfall and increases in maximum temperatures should be taken into account when assessing the cost effectiveness of land clearance in Australia.

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