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Impact of historical land cover change on daily indices of climate extremes including droughts in eastern Australia

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[1] There is growing scientific evidence that anthropogenic land cover change (LCC) can produce a significant impact on regional climate. However, few studies have quantified this impact on climate extremes and droughts. In this study, we analysed daily data from a pair of ensemble simulations using the CSIRO AGCM for the period 1951–2003 to quantify the impact of LCC on selected daily indices of climate extremes in eastern Australia. The results showed: an increase in the number of dry and hot days, a decrease in daily rainfall intensity and wet day rainfall, and an increase in the decile-based drought duration index for modified land cover conditions. These changes were statistically significant for all years, and especially pronounced during strong El Niño events. Therefore it appears that LCC has exacerbated climate extremes in eastern Australia, thus resulting in longer-lasting and more severe droughts. **Citation:** Deo, R. C., J. I. Syktus, C. A. McAlpine, P. J. Lawrence, H. A. McGowan, and S. R. Phinn (2009), Impact of historical land cover change on daily indices of climate extremes including droughts in eastern Australia, *Geophys. Res. Lett.*, *36*, L08705, doi:10.1029/2009GL037666.

1. Introduction

[2] An important climatic consequence of elevated concentrations of anthropogenic greenhouse gases is an increase in the frequency of extremes such as droughts, severe storms and heatwaves [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007]. According to the IPCC, droughts have become more common, especially in the tropics and subtropics since 1970, while increases have occurred in the frequency of heavy precipitation events [*IPCC*, 2007]. A more extreme, drought prone climate has important consequences for the environment and society [*Hennessy et al.*, 2008].

[3] The *IPCC* [2007] recognized land use and land cover change as an important radiative forcing that can have a significant impact on regional climate [*Pielke et al.*, 2002; *Paeth and Thamm*, 2006; *Pongratz et al.*, 2009]. Studies have shown that deforestation in the Amazon Basin and land use change in the Sahel have decreased evaporation rates, reduced precipitation and have altered atmospheric circulation beyond the region of disturbance [*Baidya Roy and Avissar*, 2000; *Werth and Avissar*, 2002; *Los et al.*, 2006]. *Voldoire and Royer* [2004] showed that extensive deforestation in the Amazon resulted in a decrease in minimum temperature, an increase in maximum temperature, and an increase in proportion of days with $\leq$0.5 mm rainfall by more than 10%.

[4] There is growing evidence that the Australian climate is sensitive to LCC [*Narisma and Pitman*, 2003; *Pitman et al.*, 2004; *McAlpine et al.*, 2007]. Two centuries of European land use has left a legacy of widespread transformation and degradation of native ecosystems, especially in southeast and southwest Australia. *Nair et al.* [2007] showed that conversion of 50% native vegetation cover into croplands in southwest Australia reduced the net radiative forcing by 7 Wm^{-2}. *McAlpine et al.* [2007] found a statistically significant warming of mean temperature (0.1–0.6°C) and a decrease of 4–12% in mean rainfall in southeast Australia associated with historical LCC. Their experiment also demonstrated that LCC contributed to a higher mean summer surface temperature during the 2002/03 El Niño drought.

[5] The observed Australian climate record shows an increase in climate extremes, but with considerable regional variations [*Gallant et al.*, 2007; *Alexander and Arblaster*, 2008]. Since 1950, the number of hot days ($\geq$35°C) rose by 0.10 days yr^{-1} and hot nights ($\geq$20°C) by 0.18 nights yr^{-1}, while there was a decrease of 0.14 days yr^{-1} in the number of cold days ($\leq$15°C) and 0.15 nights yr^{-1} in the number of cold nights ($\leq$5°C) [*Nicholls and Collins*, 2006]. In southeast Australia, droughts have become hotter since 1973, with maximum temperatures during the 2002/03 El Niño drought in southeast Australia >1°C hotter than during any previous major drought [*Nicholls*, 2004]. Hotter droughts are reducing surface runoff and stream flows in the Murray Darling Basin [*Cai and Cowan*, 2008], and represent a significant economic cost to the nation [*Adams et al.*, 2002].

[6] In this paper, we addressed the question "*what is the potential impact of LCC on daily indices of climate extremes and droughts in eastern Australia?*" by analysing data derived from experiments described in the work of *McAlpine et al.* [2007]. That study assessed the impact of LCC on mean climate for Australian continent, while we specifically focus on daily indices of climate extremes and duration and severity of droughts in eastern Australia.

2. Experimental Design and Methodology

2.1. Experimental Design

[7] We used the data from a pair of ensemble (10 members each) simulations using the CSIRO Mark 3 AGCM forced with observed SST and sea ice for the period 1951–

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Table 1. A Summary of Daily Indices of Climate Extremes Used in the Analysis

Extreme Index	Definition	Units
daily rainfall intensity	Total annual rainfall divided by number of days with rainfall ≥1 mm.	%
wet day rainfall	Annual rainfall on wet days for daily rainfall ≥1 mm.	mm yr^{-1}
number of dry days	Annual count of days with rainfall <1 mm.	days yr^{-1}
Rainfall-Decile-based Drought Index (RDDI)	Derived from benchmark criterion for onset & withdrawal of a drought: *Onset of a drought*: is when 3-monthly rainfall accumulation ≤1st decile derived from a base period 1971–2000 and *withdrawal* is when 3-monthly rainfall ≥7th decile of the same base period.	months yr^{-1}
number of hot days	Annual count of days with maximum surface temperature ≥35°C.	days yr^{-1}

2003. The only difference in the ensemble experiments was a change in land cover characteristics from pre-European (1788) to modern day (1990) conditions. Satellite-based Australian and global vegetation characteristics were converted to the vegetation classification used in the AGCM, which was based on the SiB approach [*Sellers et al.*, 1996]. Pre-European parameters (vegetation fraction, surface albedo, leaf area index, surface roughness, stomatal resistance) were generated by extrapolating modern-day remnant native vegetation to pre-European extents. Details of the experimental design and land surface scheme of the model are available from *Gordon et al.* [2002] and *Lawrence* [2004].

2.2. Daily Indices of Climate Extremes and Statistical Testing

[8] The daily surface temperature and rainfall data at T63 model resolution (~1.8° × 1.8°) was extracted for eastern Australia and converted to daily indices of climate extremes according to *Frich et al.* [2002] (Table 1). We then computed the Rainfall-Decile-based Drought Index (RDDI) following *Mpelasoka et al.* [2007]. We tested whether the probability distribution functions (PDF) of climate variables for pre-European and modern-day land cover experiments were significantly different for at least 50% of the simulations by applying a two-tailed Kolmogorov-Smirnov (ks) test. The difference between pairs of extreme indices (Table 1) was tested for statistical significance. Since the distribution of indices was non-Gaussian, a parametric test such as the Student's t-test was inappropriate [*Wigley and Santer*, 1990]. We therefore applied a nonparametric bootstrapping procedure following *Efron and Tibshirani* [1993]. *Kysely* [2008] reported that for sample sizes <60, nonparametric bootstrap can overestimate the confidence intervals in analysis of extreme climate. We did not violate this condition as we used all 10 members of the ensemble, each having a sample of 52, resulting in a total sample size n = 520.

[9] The nonparametric bootstrap procedure was applied as follows: suppose $X = \{X_1, X_2, \ldots, X_n\}$ was a sample of an extreme index derived from pre-European and $Y = \{Y_1, Y_2, \ldots, Y_n\}$ the corresponding index for the same year for the modern-day experiment. The null hypothesis (H_o) stated that the difference $|\overline{X} - \overline{Y}|$ was not significant while the alternative hypothesis (H_1) stated that LCC has a significant influence. We generated N = 10,000 bootstrap samples of (X^*, Y^*) aligned pairs, where X^* and Y^* pairs were the bootstrapped samples drawn randomly from the pairs (X, Y) with replacement. The bootstrap statistic (t_{bs}) was computed as: $t_{bs} = \frac{\overline{X}^* - \overline{Y}^*}{\sqrt{\overline{\sigma}_1^{*2}/n + \overline{\sigma}_2^{*2}/n}}$, where $(\overline{X}^*, \overline{\sigma}_1^*)$ and $(\overline{Y}^*, \overline{\sigma}_2^*)$ were the mean and standard deviations of bootstrapped samples respectively. We computed the observed t-statistic (t_{obs}) using the original (X and Y) aligned pairs for the full dataset. Since the sign of differences in indices is important, we applied a two-tailed test following *Reiczigel et al.* [2005], whereby the Achieved Significance Level (ASL) was computed as: $ASL_{bs\text{-}two\text{-}tailed} = 2 \times [\text{minimum of} (\# \{(t_{bs}) \geq t_{obs}\}/N, \# \{(t_{obs}) \geq t_{bs}\}/N)]$. The bootstrapped p-values were computed using $p_{bs\text{-}two\text{-}tailed}$ = (100- $ASL_{bs\text{-}two\text{-}tailed}$)/100 and tested for significance against α = 0.01. The standard deviation (σ), standard error ($SE = \sigma/\sqrt{n}$) and differences in standard error (ΔSE) between the two experiments are shown in Figure S2 of the auxiliary material (n = number of ensembles).[1]

3. Results

[10] In this section, we describe the changes in daily indices of climate extremes and the drought duration index. The changes are shown for modern day land cover conditions relative to pre-European conditions. First, we show results for the mean response during the 1951–2003 period. We then present the response during strong ENSO events, which are associated with strong climate anomalies in eastern Australia. However, the model results only showed statistically significant differences for El Niño events associated with drought conditions.

3.1. Daily Indices of Climate Extremes and Duration of Droughts

[11] Using a two-tailed Kolmogorov-Smirnov test, we determined a statistically significant difference in the PDF of daily rainfall in eastern New South Wales and parts of south-east Queensland and Victoria (Figure 1a). Similarly, the difference in the PDF for two populations of daily maximum surface temperature was statistically significant over most of eastern Australia (Figure 1b). This indicates that historical LCC has contributed to a change in the PDF of rainfall and surface temperature. These changes are illustrated in the analysis of daily indices of climate extremes and the drought duration index, and are represented in Figures 1c–1f as red (increase) and blue (decrease) symbols; closed symbols are statistically significant.

[12] The analysis of daily rainfall intensity showed a spatially coherent decrease of ~15% in central New South Wales and northern Victoria for modern day conditions, and was statistically significant as determined by the bootstrap procedure (Figure 1c). This region corresponds to the Murray Darling Basin, Australia's most productive agricultural zone. The index of wet day rainfall showed a statistically significant decrease for modern day conditions (~10–30 mm yr^{-1}) concentrated over southern New South Wales and northern Victoria (Figure 1d). The analysis of the index for the number of dry days showed a statistically significant increase by 3–5 days yr^{-1} over coastal New South Wales, and a weak non-significant increase for inland New South Wales (Figure 1e).

[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL037666.

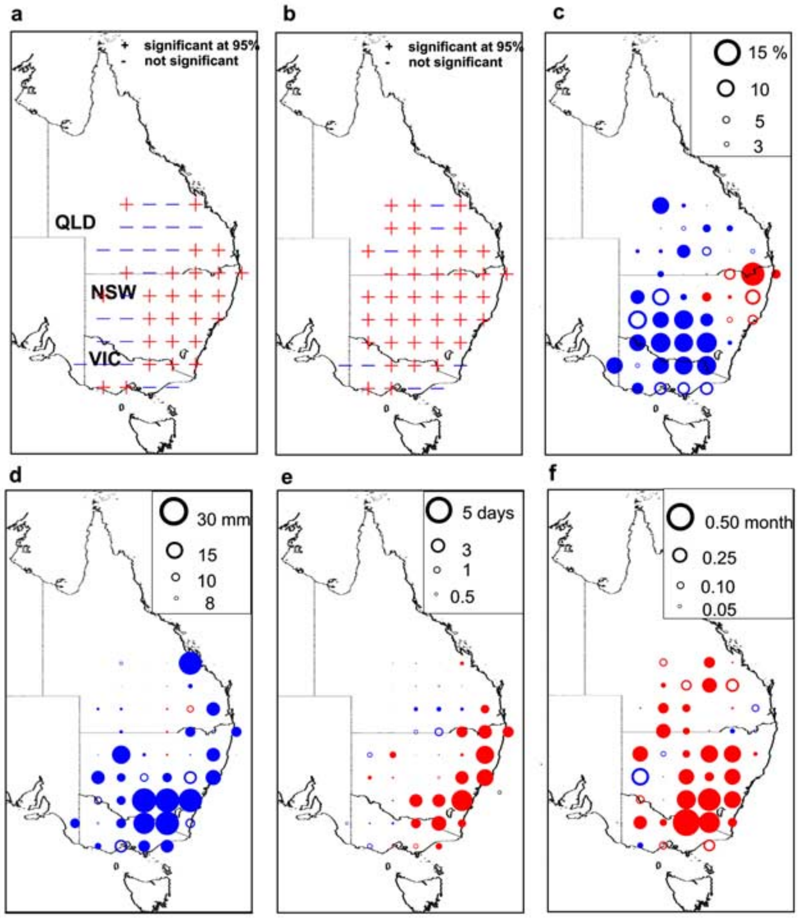

Figure 1. Statistical significance of the differences in daily PDFs of (a) rainfall, (b) maximum surface temperature over (1951–2003) of pre-European and modern day vegetation cover conditions using two tailed Kolmogorov-Simonov test (α = 0.05). Symbols: red (+) statistically significant, blue (-) not significant; and differences in annual ensemble average (1951–2003) of (c) daily rainfall intensity (% change), (d) wet day rainfall (mm yr^{-1}), (e) number of dry days (days yr^{-1}), and (f) Rainfall-Decile-based Drought Index (months yr^{-1}). Symbols: red for increase, blue for decrease, closed symbols are statistically significant, open symbols are not statistically significant at $\alpha = 0.01$; QLD, Queensland; NSW, New South Wales; VIC, Victoria.

[13] The increase in the number of dry days and decrease in wet day rainfall has direct consequences for the duration of droughts in the region, as indicated by the RDDI, which is a measure of the average number of drought months yr^{-1}. The analysis of RDDI showed a statistically significant increase by 0.25–0.5 months yr^{-1} in central New South Wales and northern Victoria for modern land cover conditions (Figure 1f). The largest changes in the tails of the PDF occurred at the extremes of surface temperature increase and rainfall decrease, indicating that LCC may be reinforcing El Niño-related droughts in eastern Australia.

3.2. Impacts on 1982/83 and 2002/03 Drought Conditions

[14] The analysis of the daily maximum surface temperature and rainfall data during November-March for the 1982/83 and 2002/03 El Niño events showed a statistically significant increase in the number of hot and dry days in eastern Australia (Figure 2). The number of hot days increased over New South Wales, Victoria and Queensland, with the largest increase of up to six days in inland New South Wales and Queensland for the 1982/83 event (Figure 2a). However, during the 2002/03 event, there was an increase of up to 18 days concentrated in northern New South Wales and southern Queensland (Figure 2c). The number of dry days increased over most of eastern Australia for both events (Figures 2b and 2d); however, for the 1982/83 event, the increase was much larger and concentrated in Victoria, northern New South Wales and inland Queensland (Figure 2b). While the magnitude of increase in the number of dry days was larger during 1982/83 event, the magnitude of increase in the number of hot days was larger during the 2002/03 event due to different characteristics of the two given El Niño events [*Nicholls*, 2004]. These results show that daily indices of climate extremes are enhanced for modified vegetation conditions, particularly during El Niño conditions as compared to the average response analysed for the 1951–2003 period.

[15] It is well-established that during strong El Niño events, eastern Australia has experienced substantial anomalies in both surface temperature and rainfall [*Nicholls*, 2006]. Figure S3 shows the observed anomalies in temperature and rainfall for the summer period during the 1982/83 and 2002/03 El Niño events. In eastern Australia, both events had a strong impact on surface temperatures, with anomalies of 2–2.5°C; however, the rainfall deficit during the 2002/03

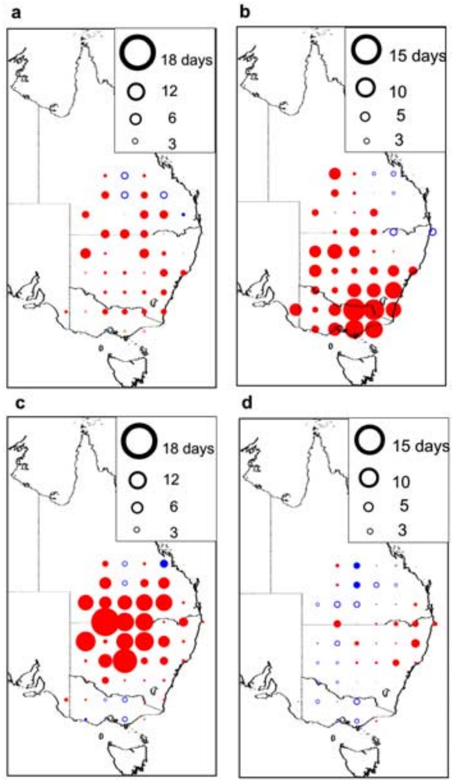

Figure 2. Differences in ensemble average of daily surface temperature and rainfall indices during the summer (NDJFM) of El Niño events for (a) 1982/83 number of hot days, (b) 1982/83 number of dry days, (c) 2002/03 number of hot days, and (d) 2002/03 number of dry days. Symbols: red (+) for increase, blue (-) for decrease, closed symbols are statistically significant, open symbols are statistically not significant at $\alpha = 0.01$.

El Niño was less severe. The model results show the number of dry days during both events was sensitive to LCC and corresponded with spatial patterns in the observed rainfall anomaly (Figures S3b and S3d). Similarly, the number of hot days was sensitive to LCC, and corresponded with observed surface temperature anomalies (Figures S3a and S3c). This spatial correspondence was especially pronounced during the 2002/03 El Niño event. The results imply that native vegetation had a strong moderating impact on extreme climatic conditions associated with El Niño events in eastern Australia.

4. Discussion

[16] This study confirms the hypothesis that the clearing of native vegetation is having a significant effect on climate extremes including the duration and severity of droughts in eastern Australia. In general, climate extremes are caused by subtle changes in the mean climate due to shifts in the tails of the PDF of the variable towards one side of the distribution [*Mearns et al.*, 1984]. A shift to a warmer mean climate can produce heat waves, while a shift to a drier climate impacts the duration of drought episodes [*Planton et al.*, 2008]. This study showed a good correspondence between simulated changes in mean rainfall and daily rainfall intensity, but less so for mean surface temperature and number of hot days yr^{-1} for the 1951–2003 period (Figure S4) [*McAlpine et al.*, 2007].

[17] The conversion of native forests to crops and grazing pastures in eastern New South Wales and Victoria, the region with the most extensive LCC, has resulted in a significant decrease in vegetation fraction, leaf area index and surface roughness, and an increase in albedo [*Lawrence*, 2004; *McAlpine et al.*, 2009]. The modification of these land surface characteristics in this region resulted in substantial changes in the partitioning of available energy at the land surface from latent heat to sensible heat. For this region, the long-term (1951–2003) summer (DJF) and area-averaged latent heat flux decreased by 4.8 Wm^{-2} while the sensible heat flux increased by 1.1 Wm^{-2}. This change in the Bowen ratio has contributed to a warmer land surface.

[18] The partitioning of the available energy at the land surface in eastern New South Wales and Victoria was much larger during the strong El Niño events. For example, during the 1982/83 event, the summer values of area-averaged sensible heat flux increased by 18.8 Wm^{-2} with a compensating decrease in latent heat flux of 20.3 Wm^{-2}. The direction of change during the 2002/03 El Niño event was similar but of a lesser magnitude. It is important to note that while changes in the long-term average values of heat fluxes are relatively small (typically 2–7% of total seasonal flux), changes during El Niño-induced droughts are much more pronounced and in the order 5–22%. Hence the conversion of native vegetation to crops and pastures has resulted in an increased fraction of available energy at the land surface used for sensible heating which has contributed to higher average surface temperatures and more hot days. Conversely, the decrease in latent heating has resulted in changes to the hydrological cycle. The increased number of hot days has contributed to a drier lower atmosphere resulting in a decrease in regional rainfall and evapotranspiration, manifested in an increase in the number of dry days. This was especially pronounced during the El Niño events and demonstrates that LCC has the potential to exacerbate climate anomalies in eastern Australia related to these events.

[19] We acknowledge that our study was a sensitivity experiment and has a number of limitations such as not considering transient land cover change and not using a fully coupled climate model. Nevertheless, the results illustrate the urgent need to consider: i) how the changing land surface conditions interact with natural climate variability; and ii) how the changes in atmospheric composition (e.g., elevating concentrations of CO_2) may interact with changes in land cover to influence regional climate. While these questions deserve further research effort, our study demonstrates the importance of considering the role of LCC in researching the impact of climate change and climate variability at a regional scale.

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