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The simulated impact of land cover change on climate extremes in eastern Australia

Deo, R C[1, 2], Syktus, J I[2], McAlpine, C A[1] and Wong, K K[2]

[1] The University of Queensland, School of Geography, Planning and Environmental Management, Brisbane, Australia, [2] Department of Environment and Resource Management, Queensland Climate Change Centre of Excellence, Brisbane, Australia, Email: jozef.syktus@climatechange.qld.gov.au

Abstract: In this paper, we investigate the impact of historical land cover change on climate extremes in eastern Australia by analysing data from an ensemble of model simulations using CSIRO AGCM. The model simulations were performed for two sets of prescribed land surface parameters representative of pre-European and modern-day land cover conditions.

To evaluate the impact of historical land cover change on Australian regional climate, the CSIRO AGCM was used to complete two sets of model simulations (ensemble of 10 each) for the period 1951-2003. In this study, we used the CSIRO climate model consisting of atmospheric and land surface components forced by observed sea surface temperature and sea ice data for the period 1951-2003 (Rayner et al., 1996). This experimental set-up followed the design of the Climate of the 20th Century project (Folland et al., 2002) and allows for direct comparison between observed and model simulated ENSO events which are known to strongly influence Australian climate. The only difference between the experiments was the land surface characteristics for Australian continent used by the CSIRO model. The first set of model simulations used the modern-day and the second used the pre-European land cover characteristics. Outside Australia, the land cover characteristics were set at modern day conditions for both experiments.

The modern-day land surface conditions were derived using data from the AVHRR satellite imagery for the period 1981 to 2001 at an 8 km spatial footprint (Lawrence, 2004). The monthly long-term average values of vegetation cover class, leaf area index, vegetation fraction and surface albedo were used as an input to the Simple Biosphere Model (SiB) derivation methods described in Sellers et al. (1986) to compute land surface characteristics used by the CSIRO climate model. Pre-clearing land surface parameters of vegetation fraction, leaf area index, surface albedo and stomatal resistance were generated by extrapolating the modern-day monthly values of remnant native vegetation to the pre-European coverage (see Lawrence, 2004). The extrapolation was performed for the Australian continent at an ~8×8 km resolution and aggregated to ~200×200 km resolution used by CSIRO AGCM using the approach of Shuttleworth, (1991), thereby ensuring the seasonal dynamics captured by satellite imagery were represented in pre-European parameters.

The impact of land cover change on mean climate in Australia was described in McAlpine et al. (2007). The results showed a statistically significant increase in mean annual surface temperature and decrease in mean annual rainfall in southeast Australia. On a seasonal basis, the impact of land cover change was strongest during the summer season and was especially pronounced during strong El Niño events such as the 2002/03 event. In this paper, we focus on the impact of land cover change on the climate extremes by analysing the daily statistics of rainfall and temperature change over the period 1951-2003. To quantify the changes in annual distribution of daily rainfall and temperature, we computed the probability distribution functions (pdfs) of daily maximum surface temperature (t_{max}) and daily rainfall for selected locations in eastern Australia. In addition, the daily rainfall and temperature data was used to derive climate extreme indices of dry days (number of days with rainfall < 1 mm), daily rainfall intensity (total annual rainfall / number of rain days), rain days (number of days with rainfall ≥ 1 mm) and hot days (number of days with $t_{max} \geq 35$ºC) (Frich et al., 2002).

The analysis results showed statistically significant changes in the annual pdfs of rainfall and temperature in southeast Australia, which corresponds well with areas with largest fragmentation of pre-European vegetation cover. The fragmentation of vegetation resulted in an increase in the number of hot days, a decrease in daily rainfall intensity and a decrease in cumulative rainfall on rainy days in southeast Australia. These changes were especially pronounced during strong El Niño events.

Keywords: *Land Cover Change, Droughts, Climate Extremes*

1. INTRODUCTION

The human influence on the Earth's land surface is unprecedented (Lambin & Geist, 2006). There is emerging evidence that land cover change is having a significant impact on climate at regional scales (Roy and Avissar, 2002; Timbal and Arblaster, 2006; Zhao et al., 2001). This is primarily caused by changes in land surface properties (albedo, leaf area index, vegetation fraction, stomatal resistance), which governs the process of evaporation, transpiration and partitioning of energy into sensible and latent heat fluxes (Pielke et al., 2002).

The native vegetation in Australia has been modified extensively since the arrival of Europeans, with a continuous transformation taking place due to growing of human population, expansion of settlement and an increase in agricultural production (Kirkpatrick, 1999). This has resulted in the clearing of approximately 14% of the Australian continent (Barson et al., 2000). Extensive grazing now covers about 43% and intensive cropping and improved pastures about 10%, with a significant portion of this area affected by degradation (McKeon et al., 2004). This transformation of native vegetation has been paralleled by a marked decline in mean summer rainfall in coastal Queensland and New South Wales, and southwest West Australia since the 1950s (Smith, 2004), and in regional Victoria since the mid-1990s (Cai & Cowan, 2008). There has been a corresponding increase in average surface temperature over eastern Australia (Nicholls, 2006).

Climate records in Australia are also showing an increase in climate extremes but with considerable regional variations (Alexander & Arblaster, 2008; Gallant et al., 2007). Over the second half of the 20th century, the number of hot days (≥35°C) rose by 0.10 days yr^{-1} and hot nights (≥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 (≤15°C) and a decrease of 0.15 nights yr^{-1} in the number of cold nights (≤5°C) (Nicholls & Collins, 2006). In eastern Australia, droughts have become severe since 1973, with maximum temperatures during the 2002/03 El Niño drought in southeast Australia more than 1°C higher than during any previous drought (Nicholls, 2004). Severe droughts are reducing surface runoff and stream flows in the Murray Darling Basin (Cai & Cowan, 2008), and represent a significant economic cost to the nation (Adams et al., 2002).

For southwest of Western Australia, Nicholls (2006) found that the decrease in mean rainfall was likely due to a combination of factors such as increasing concentration of greenhouse gases, natural climate variability and land use pressures. Pitman et al. (2004) reported that land cover change in the same region had contributed to a drier climatic regime, while Timbal & Arblaster (2006) found that land cover change could act as an additional forcing to compound the changes in synoptic-scale mean sea level pressure and average declines in seasonal rainfall. Study by McAlpine et al., (2007) focussing on southeast Australia reported a statistically significant warming of 0.4-1.2ºC and ~5% reduction in rainfall during the summer, while Syktus et al. (2007) demonstrated an average warming of up to 3.6ºC during the 1982/83 El Niño event due to historical land cover change.

In addition to increases in mean surface temperatures, eastern Australia has experienced severe droughts during recent decades. Although the occurrence of droughts is a natural phenomenon, research is showing that anthropogenic activities that are continuously increasing atmospheric concentration of greenhouse gasses have a substantial influence on natural climate variability, and the duration and severity of droughts (Nicholls, 2006). However, the close coupling between the Earth's surface and atmosphere, and radiative contributions of land cover change provides strong rationale to the investigation of the role of land cover change in accentuating natural and forced climate variability and change, particularly with respect to droughts. These land-surface-climate feedbacks can compound the existing risks of increased frequency of climate extremes caused by increased concentration of greenhouse gases (McAlpine et al., 2009).

In this paper, an important question of "*What is the potential impact of land cover change on climate extremes in eastern Australia*" is addressed. To quantify the impact of land cover change on regional climate in eastern Australia, analysis of daily statistics of rainfall and temperature change was undertaken. We analysed output from two sets of ensembles of simulation with modern-day and pre-European land surface conditions over the 1951-2003 period.

2. METHODOLOGY

2.1 Experimental design

To evaluate the impact of historical land cover change on Australian climate, the CSIRO AGCM was used to complete two sets of model simulations (ensemble of 10 each) for the period 1951-2003. In this study, we used the CSIRO climate model consisting of atmospheric and land surface components forced by observed sea surface temperature and sea ice data (Rayner et al., 1996). This experimental set-up followed the design of the Climate of the 20th Century project (Folland et al., 2002) and allows for direct comparison between observed and model simulated ENSO events which are known to strongly influence Australian climate. The only difference between the two sets of experiments was in land surface characteristics for Australian continent used by the CSIRO model. The first set of model simulations used the modern-day and the second used the pre-European land cover characteristics. Outside Australia, the land cover characteristics were set at modern day conditions for both experiments.

The modern-day land surface conditions were derived using data from the AVHRR satellite imagery for the period 1981 to 2001 at an 8 km spatial footprint (Lawrence, 2004). The monthly values of vegetation cover class, leaf area index, vegetation fraction and surface albedo were used as an input to the Simple Biosphere Model (SiB) derivation methods described in Sellers et al. (1986) to compute land surface characteristics used by the CSIRO climate model. Pre-clearing land surface parameters of vegetation fraction, leaf area index, surface albedo and stomatal resistance were generated by extrapolating the modern-day monthly values of remnant native vegetation to the pre-European coverage (see Lawrence, 2004). The extrapolation was performed for the Australian continent at an ~8×8 km resolution and aggregated to ~200×200 km resolution used by CSIRO AGCM using the approach of Shuttleworth (1991), thereby ensuring that the seasonal dynamics captured by the satellite imagery were represented in monthly pre-European parameters.

2.2 Analysis and Statistical Testing

To evaluate the impact of land cover change on climate extremes, daily data for annual rainfall and surface temperature change were analysed. The changes in distribution of daily rainfall and temperature between modern-day and pre-European land cover conditions were quantified by computing the probability distribution functions (pdfs) of maximum temperature (t_{max}) and rainfall at selected locations in eastern Australia. The statistical significance of the differences in pdfs was assessed by applying a two-tailed Kolmogorov-Smirnov test at significance level $\alpha = 0.05$. Changes in indices of daily rainfall intensity (total annual rainfall / number of rain days), dry days (number of days with rainfall < 1 mm), and hot days (number of days with $t_{max} \geq 35$ºC) over the period 1951-2003 were derived following Frich et al. (2002). Statistical significance of changes in extreme indices was tested using a nonparametric bootstrapping procedure following Efron and Tibshirani, (1993). Further details of the statistical method are described in Deo et al. (2009).

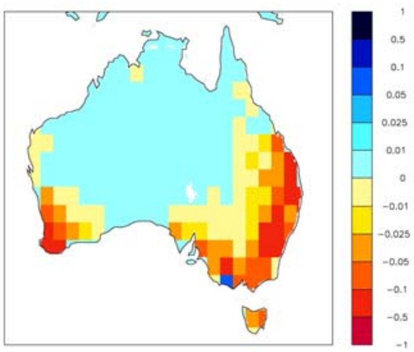

Figure 1. A map of Australia showing changes in vegetation fraction (dimensionless) used in the CSIRO climate model.

3. RESULTS

3.1 Land surface parameters used in CSIRO climate model

Figure 1 shows the changes in vegetation fraction from pre-European to modern-day land cover conditions as used in the CSIRO climate model. The most noticeable changes are in coastal eastern Australia, and southwest Western Australia. McAlpine et al. (2009) assessed the changes in area-averaged land surface parameters for the modern-day relative to pre-European land cover conditions and found a decrease in vegetation fraction by ~19%, decease in leaf area index by ~23%, and increase in surface albedo by ~7%. Furthermore, there was a corresponding reduction in surface roughness by ~46%, which resulted in a 9% increase in surface wind speed (McAlpine et al., 2007). The changes in land surface properties are expected to influence the balance of solar energy between the land surface and atmosphere and produce an impact on evaporation, transpiration and runoff, which can potentially contribute to changes in regional climate.

3.2 Changes in regional climate

The Kolmogorov-Simonov test demonstrated a discernable difference in the probability distribution functions of annual percentage of hot and dry days between the pre-European and modern-day land cover conditions (Figure 2). The differences for hot days were statistically significant over eastern Queensland and New South Wales and over most of Victoria. However, differences for dry days were significant only over coastal New South Wales and Victoria. Importantly, these differences are evident over regions of modified land cover (compare with Figure 1).

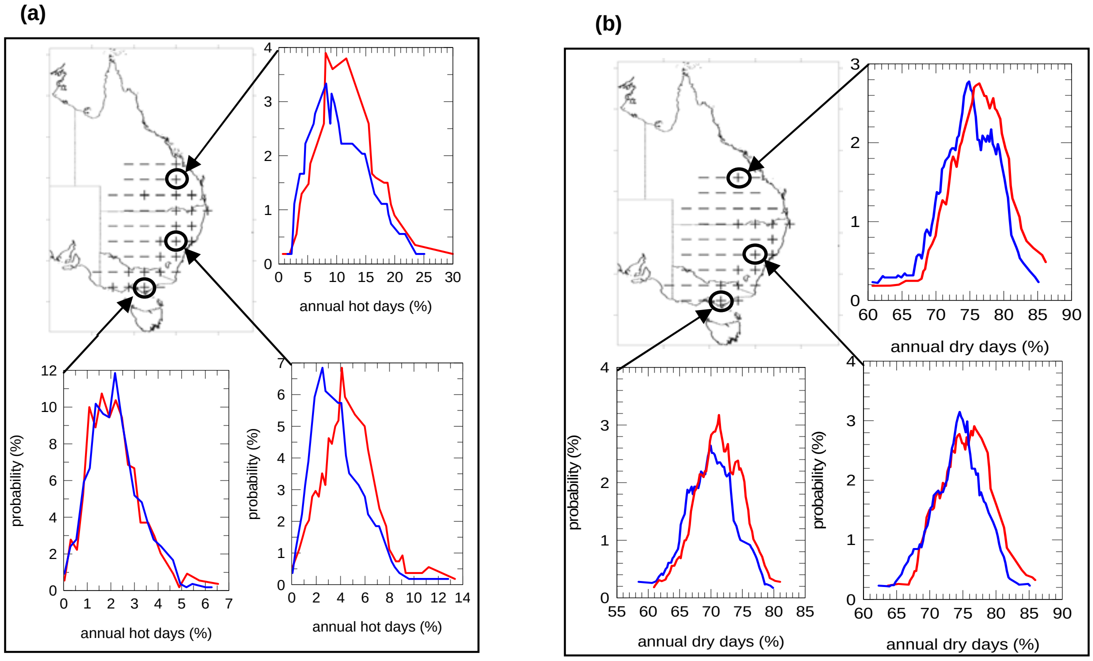

Figure 2. (a) The significance of differences in probability distribution functions of annual percentage of hot days (days with tmax ≥ 35ºC) over 1951-2003 for pre-European and modern-day vegetation cover conditions using a two tailed Kolmogorov-Simonov test, $\alpha = 0.05$, whereby + shows statistically significant and - shows not significant; and selected probability distribution functions. (b) The significance of differences in probability distribution functions of annual percentage of dry days (days with < 1 mm rainfall) over 1951-2003 for pre-European and modern day vegetation cover conditions using a two tailed Kolmogorov-Simonov test, $\alpha = 0.05$, whereby + shows statistically significant and – shows not significant; and selected probability distribution functions. Note: red for modern-day and blue for pre-European land cover conditions.

Figure 2 also shows the probability distribution functions of hot and dry days for two land cover conditions at three representative locations. The three plots show significant changes and substantial shifts in the pdfs for Queensland and New South Wales despite some skewness (Figure 2a). The tails for the pdfs of modern-day land cover conditions shifted towards an increasing frequency of hot days by ~5%, ~0.5% and ~0.25% for Queensland, New South Wales and Victoria respectively. However, for annual percentage of dry days, the pdfs underwent a smoother transition towards an increasing frequency of dry days as shown by the shift in tail by ~1% in coastal eastern Australia (Figure 2b).

It is important to note that the probability distribution functions were drawn from major regions where land cover change has taken place (see Figure 1). These changes in temperature and rainfall indicate that land cover change has produced a shift towards a mean warmer and drier climate regime, while shifts in the tails shows the increased frequency and intensity of climate extremes for modern day land cover conditions. These extremes are illustrated in analysis of daily indices of temperature and rainfall (Figure 3a, c) and are plotted alongside simulated changes in mean annual temperature and rainfall (Figure 3b, d).

The simulations showed statistically significant changes in extreme indices of temperature and rainfall, which corresponds with changes in the mean climate. There was an increase in the number of hot days by up to 3 days yr^{-1}, which corresponds with a warming of up to 1°C in coastal eastern Australia (Figure 1a, b). However, the increases in number of hot days in inland Queensland, and inland New South Wales showed less correspondence with mean temperature change. In terms of changes in rainfall, there was a spatially coherent and strong decrease in daily rainfall intensity of up to 12% in central Victoria and southern New South Wales for the modern-day land cover conditions, which corresponds with a decrease in mean rainfall of up to 6% in the same region. In southeast Australia, there was a statistically significant decrease in mean rainfall, which corresponds with a decrease in daily rainfall intensity (Figure 3c, d). The results of model simulations demonstrated that fragmentation of native vegetation has resulted in climate with more extremes.

4. DISCUSSION

This study shows that the clearing of native vegetation can have an effect on mean and extreme climate. In eastern Australia, land cover change has resulted in a significant decrease in vegetation fraction, leaf area index and surface roughness and an increase in surface albedo (McAlpine et al., 2009). These changes in surface properties are impacting the balance of energy between land surface and atmosphere which is influencing climate extremes in the region.

The conversion of native forests into bare soil, improved cropping and farming regions has produced an increase in surface albedo, causing more solar energy to be reflected in the atmosphere. Therefore, an accumulation of radiation in the atmosphere can intensify atmospheric heating. A change in vegetation fraction can cause a subsequent decrease in surface roughness as well as changes in the wind profile and turbulent mixing of air at the land surface (Foley et al., 2003). This can result in an increased fraction of available solar energy at the land surface being used for sensible heating, which can contribute to a higher surface temperature and more hot days. Conversely, the decrease in latent heating can result in changes in the hydrological cycle. Under a modified land cover, there is a reduction in moisture recycling due to less evapotranspiration, which can contribute to a decrease in humidity in the lower atmosphere (Durieux et al., 2003; Fu & Li, 2004). This can impact the boundary layer depth, leading to reduced cloud formation, less cumulative rain and more dry days (Lyons et al., 1996; Pielke et al., 2002). This

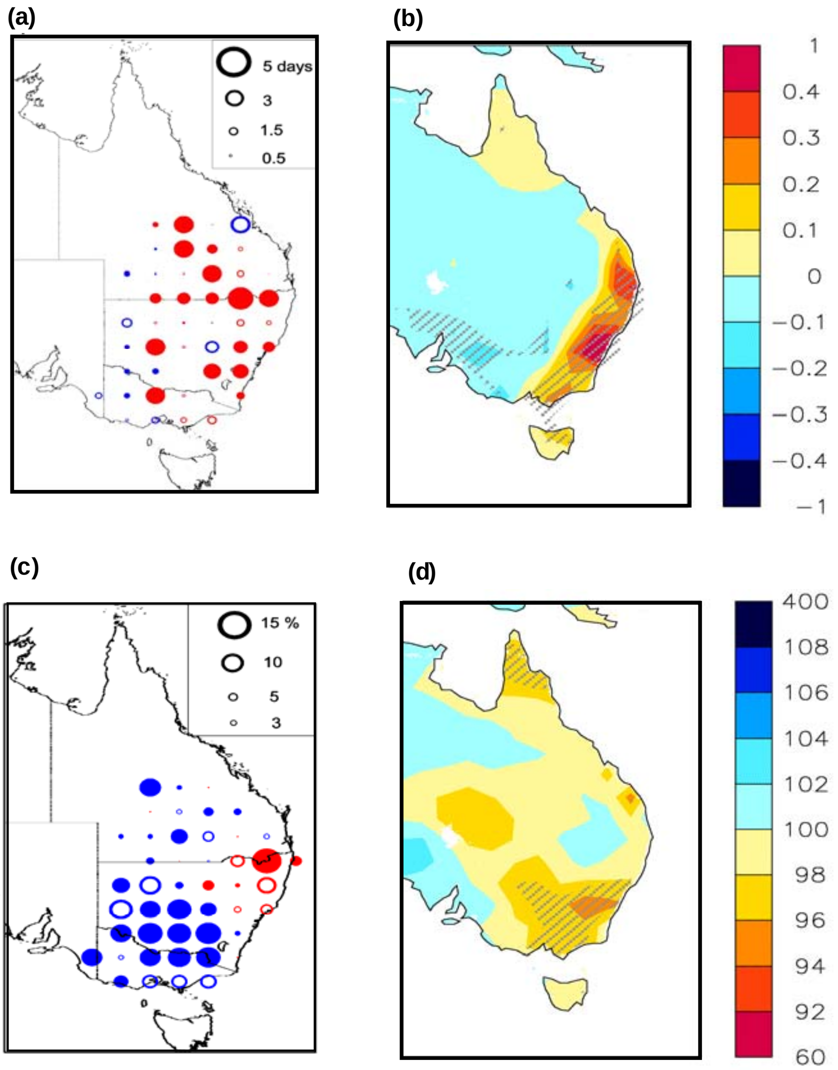

Figure 3. The simulated annual average changes in climate over the period 1951-2003 from pre-European to modern-day land cover conditions for: (a) number of hot days per year, (b) mean surface temperature (°C), (c) daily rainfall intensity (%), and (d) mean annual rainfall (%). For a & c, red is for increase, blue for decrease, closed symbol statistically significant and open symbol not significant (Deo et al., 2009); for b & d, hatches show statistically significant areas, (McAlpine et al., 2007).

increase in sensible heating and drying of lower atmosphere resulted in increase in number of hot and dry days and decreased rainfall intensity.

The simulated warmer and drier climate with enhanced climate extremes are cumulatively impacting the soil moisture and surface runoff, and are likely to be affecting turbulent transport of water vapour and partitioning of available surface water between surface runoff and evapotranspiration. This can have important, but largely unrecognized consequences for agricultural production, water security and strategies for water management. While further research is warranted, our study demonstrates the importance of considering the role of land cover change in future climate change projections.

5. CONCLUSIONS

This study has shown that land cover change in eastern Australia has contributed to a warmer and drier climate, and enhanced climate extremes. There were statistically significant changes in the probability distribution functions of rainfall and temperature in southeast Australia, which coincided with areas of largest fragmentation of natural vegetation. This fragmentation has resulted in an increase in the frequency of hot days, a decrease in daily rainfall intensity and a decrease in cumulative rainfall on rain days. These changes were statistically significant and especially pronounced during strong El Niño events (Deo et al., 2009). The study concludes that replacing native vegetation with cropping and improved pastures is likely to be contributing to severe droughts and increasing the pressures on already stressed land and water resources in eastern Australia.

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