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# Is Australia's continued warming caused by drought?

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Twenty years of additional data confirm a finding from the 1990s that interannual variations in Australian mean annual maximum temperature are closely related to rainfall variations, but that observed warming since about 1970 has been stronger than would be expected from the observed rainfall trends. While droughts exacerbate daily maximum temperatures and strongly influence interannual temperature variations, the long-term warming trend is not caused by any trend to decreased rainfall, or decreased cloudiness. The enhanced greenhouse effect seems the most likely explanation of this apparently inexorable anomalous warming.

## Introduction

Nicholls and Larsen (2011) demonstrated that daily maximum temperatures at Melbourne, Australia, tended to be higher during and following droughts than otherwise. Studies in Europe and elsewhere also have demonstrated that low soil moisture associated with a drought is a likely contributor to high temperatures (eg. Durre et al. 2000; Seneviratne at al. 2006, 2010; Fischer et al. 2007a, b; Dole et al. 2011). Temperatures averaged over Australia have been warming since the middle of the twentieth century (Fig. 1; CSIRO & Bureau of Meteorology 2012). The question arises, therefore, as to whether or not changes in drought and rainfall could be the explanation for this warming. Since droughts exacerbate daily maximum temperatures (e.g. Nicholls and Larsen 2011), does this mean that a trend towards lower rainfall might be the cause of the warming observed across Australia?

Coughlan (1979) and Nicholls et al. (1996) demonstrated that Australian annual mean temperature was negatively correlated with annual mean rainfall. Power et al. (1998) demonstrated that this out-of-phase relationship occurred throughout the country, and not just in Australia-wide averages. Nicholls et al (1996) identified, using data up to 1992, that the Australia-wide average of mean daily maximum temperature appeared to be increasing relative to the temperatures expected from the rainfall–temperature relationship. Nicholls (2003) extended the Nicholls et al. (1996) study by including data up to 2002 and demonstrated that this 'anomalous' warming had continued up to that year. Others (eg. Cai and Cowan 2008; Karoly and Braganza 2005) have used the changing relationship between temperature and rainfall to maximise the signal-to-noise ratio by removing the fraction of the temperature variability associated with rainfall variations and changes. The residual was then the basis for an attribution study aimed at identifying the physical cause of the warming. Cai et al. (2010) also demonstrated that the warming trend (at least in the Murray–Darling Basin) could not be explained by changes in cloudiness.

In this note, data up to 2011 have now been used to determine whether changes in rainfall averaged across Australia can account for the continued warming of Australian average temperature. This period includes the very long drought that affected much of southern Australia over the twelve years up to 2010. If droughts are a factor causing warming, then this extended drought may have at least contributed to the long-term warming across the country.

## Data and methodology

Annual rainfall totals, averaged across Australia, and annual average daily maximum temperature, also averaged across the country, were obtained from the Bureau of Meteorology (http://www.bom.gov.au/cgi-bin/climate/change/timeseries.cgi; data accessed 15 March 2012). Time-series of the rainfall and maximum temperature data were plotted (Fig. 1) and correlations calculated between the two series. The two series are closely related. The linear correlation between the two series (1910–2011 data) is –0.42 (n=102; $p<0.001$). The time-series were also detrended by calculating first differences (year-to-year changes); the correlation between the two series of year-to-year differences was –0.70 (n=101; $p<0.001$). Thus, rainfall changes from year-to-year account for almost half the interannual variations of annual average temperature. Such a strong relationship, along with the evidence that drought can exacerbate daily temperature

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Fig. 1 Annual average daily maximum temperature (red line) and rainfall (green line—scale reversed). Both variables averaged across Australia. Data from the Bureau of Meteorology, from 1910 to 2011. Cubic polynomial smooth lines also fitted to the time-series.

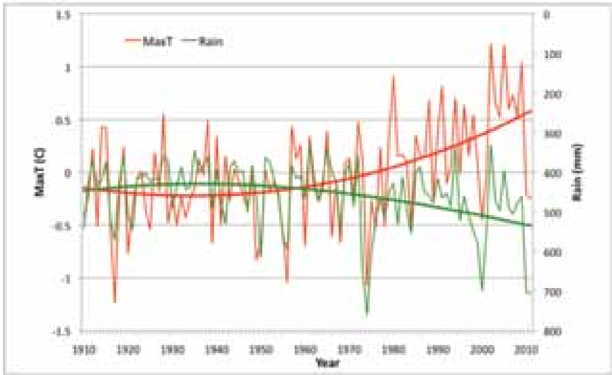
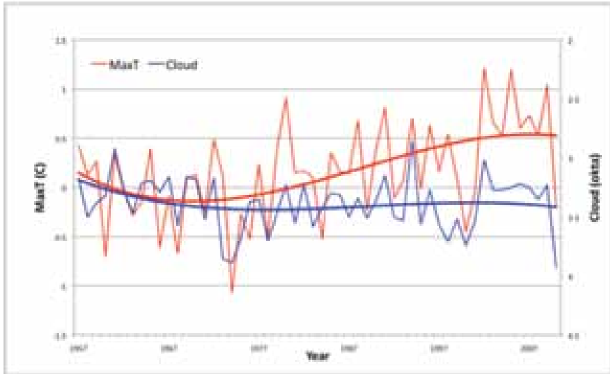



Fig. 2 Annual average daily maximum temperature (red line) and cloudiness (green line—scale reversed). Both variables averaged across Australia. Data from the Bureau of Meteorology, from 1957 to 2010. Cubic polynomial smooth lines also fitted to the time-series.




extremes as noted above, leads to the presumption that the continued warming might simply reflect decreasing rainfall averaged across the country, if in fact such a decrease had been taking place.

Afternoon (3.00 pm local time) quality-controlled and homogenised estimates of cloud cover, averaged across the year and country (Jovanovic, 2010), were also obtained from the Bureau of Meteorology web page. These data are only available from 1957 to 2010. The cloud data and maximum temperature data are shown in Fig 2. The linear correlation between cloud cover and maximum temperature was –0.55 ($n=45$; $p<0.001$). The correlation between the year-to-year cloud changes and the year-to-year temperature changes was –0.69 ($n=44$; $p<0.001$). So, the strong relationship between rainfall and temperature presumably reflects an influence of cloudiness on temperature, with decreased cloudiness leading to warmer maximum temperatures.

## Results

Figure 1 depicts the time-series of annual average rainfall and annual average daily maximum temperature, averaged across Australia. The strong relationship between low rainfall (note reversed scale for rainfall) and high temperatures is evident. Also plotted on the figure are cubic polynomial fits to the two time-series to illustrate the long-term non-linear trends. For the first half of the period depicted these polynomials exhibit little variation. However, from about 1970 temperature and rainfall both increase. The increase in rainfall is exactly opposite to the change that would be expected if rainfall trends were causing the warming. In fact, if the rainfall trend were affecting temperature in the same sense as the year-to-year variations, then the trend to increased rainfall would have led to cooling, offsetting some of the observed warming. The observed warming of Australian daily maximum temperatures cannot be attributed to any change in rainfall. It is 'anomalous' in the sense of not being due to rainfall trends. Nor is the warming due to decreased cloudiness (which, a priori, might also be expected given the strong negative correlation between maximum temperature and cloudiness noted above). Time-series of maximum temperature and cloud are plotted in Fig. 2, along with cubic polynomial fits to the two series. It is evident that the cloudiness data are not exhibiting a trend towards lower amounts that would be needed if the warming trend was the result of cloudiness trends.

It is of some interest to examine whether similar relationships and trends as evident in Figs. 1 and 2 are also found over specific parts of Australia. Figure 3 repeats the plot in Fig. 1, but for data from southern Australia (south of latitude 26°S) and for the southern wet season (April–November). Only data from 1950 are available directly from the Bureau of Meteorology web page for seasonal mean temperatures, restricting the period that can be analysed in this way. The plot demonstrates that low rainfall years tend to accompany high temperature years. Since 1950 it is evident that southern Australian wet season mean maximum temperature has increased substantially, by about 1.5°C, while rainfall has exhibited little overall trend (Figure 3). So we can conclude that the warming trend evident in Fig. 3 is not simply reflecting any decline in rainfall. Figure 4 is similar to Fig. 3, but for northern Australia (north of 26°S) and for the northern wet season (October–April). Once again, the very strong relationship between temperature and rainfall is evident, with wet years also tending to be cool years. In this case, unlike the southern Australia case, rainfall has increased. Despite this increase, mean maximum temperature has not decreased, as would have been the case if the rainfall trends were directly causing temperature trends.

## Conclusions and discussion

Updates to the data that were available to Nicholls et al. (1996) when they noted the strong relationship between rainfall and daily maximum temperatures (averaged across

Fig. 3 As in Fig. 1, but for southern Australia (south of latitude 26°S) and southern wet season (April–November).

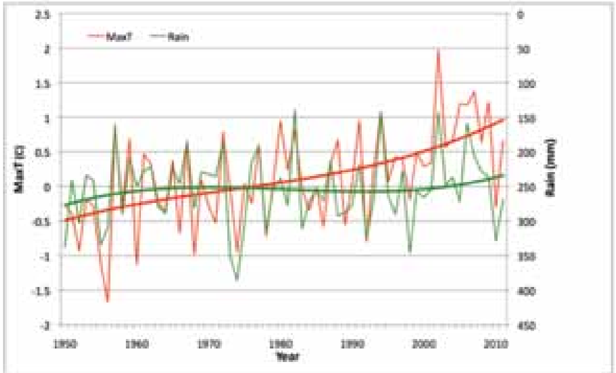
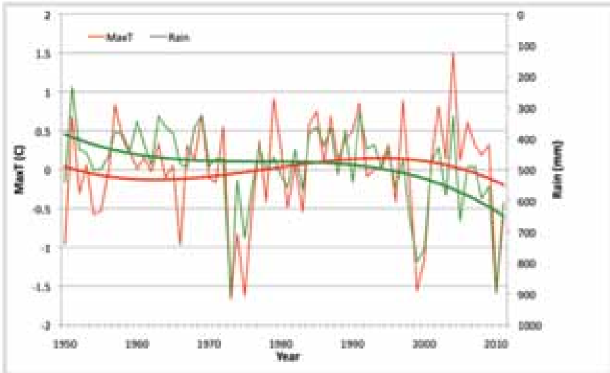



Fig. 4 As in Fig. 1 but for northern Australia (north of latitude 26°S) and northern wet season (October–April).




Australia and through the year) and the apparent warming trend relative to rainfall, have confirmed that this anomalous warming trend has continued for the subsequent twenty years. That is, there is little doubt that this warming is not simply reflecting rainfall trends or cloudiness trends. The most obvious explanation of this warming is the enhanced greenhouse effect, based on a solid body of independent studies and evidence (e.g. Nicholls 2003; Karoly and Braganza 2005). Nicholls (2003) discussed other possible explanations but found no evidence that these were likely. The continuation of the anomalous warming trend provides further evidence that the other potential explanations (such as data inhomogeneities) are unlikely. Examination of trends and variations in specific regions and seasons illustrate that although the trends in both variables are different in different regions and seasons, there is no evidence in any of the regions and seasons examined that rainfall trends are causing the observed temperature trends.

The relationships between rainfall and temperature in Fig. 1 and cloudiness and temperature in Fig. 2 provide a basis for a discussion about the cause of specific anomalies such as the relatively cool (relative to the past decade or so) temperatures during 2010 and 2011. Figure 1 is evidence that these relatively cool temperatures reflected the very wet conditions (in turn caused by the strong La Niña events of 2010–2012; CSIRO and Bureau of Meteorology, 2012). However, the figure also demonstrates that the temperatures in these two years, despite being cooler than recent years, were still considerably warmer than the earlier years with similar rainfall and cloudiness (1974, 2000).

The warmer years associated with recent years would likely lead to different impacts of recent wet years compared to the situation in the past when wet years were relatively cool. Insect numbers would, for instance, be affected differently by a cool wet year to a warm wet year. Nicholls (2004) made a similar point regarding recent droughts (which are also warmer than were earlier years with low rainfall).

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