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20th century changes in temperature and rainfall in New South Wales

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Mean annual maximum temperatures increased across nearly all of Australia during the 20th century. The major exception was in parts of central and eastern New South Wales where mean maximum temperatures decreased somewhat. Variations in mean maximum temperatures in New South Wales are strongly (negatively) associated with rainfall variations. Temperatures in New South Wales decreased very rapidly in the space of a few years in mid-century, and this decrease was associated with a similarly rapid rainfall increase. Since the middle of the century, mean maximum temperatures have increased, largely independent of any rainfall change. In the early 1970s mean maximum temperatures increased sharply, unaccompanied by any decrease in rainfall. The simultaneity of the rainfall increase and temperature decrease in mid-century suggests that this was a 'natural' fluctuation. The absence of a substantial decrease in rainfall accompanying the warming of the last few decades suggests that another process may be affecting the temperature. One candidate for this would be the enhanced greenhouse effect. Changes in the frequency or intensity of the El Niño – Southern Oscillation do not appear to be able to account for either the mid-century cooling or the late century warming.

Introduction

Mean minimum temperatures increased across virtually all of Australia during the 20th century (Torok and Nicholls 1996). Mean maximum temperatures also increased over most of the country, but decreased in central and eastern New South Wales, and isolated parts of southern Queensland (Fig. 1). A high-quality temperature dataset (Della-Marta et al. 2004), based on a dataset originally developed by Torok and Nicholls (1996), is used here, along with historical rainfall datasets, to investigate the nature of this cooling. Australian rainfall increased rapidly and substantially in the middle of the 20th century (Coughlan

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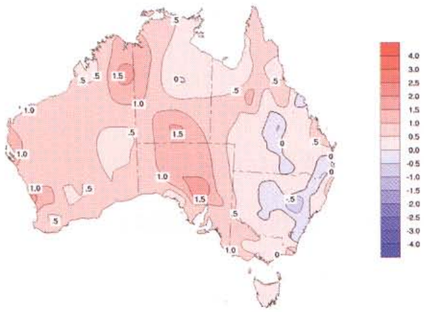
Fig. 1 Trend in mean annual maximum temperature, 1910-2002, using the updated high-quality annual temperature dataset of Della-Marta et al. (2004). The cooling trend in New South Wales is smaller than that reported in Torok and Nicholls (1996) partly because of the very warm temperatures in the recent years not available to Torok and Nicholls, and partly because further quality control measures by Della-Marta et al. have removed more suspect stations.



1978, Cornish 1977, Russell 1981, Pittock 1983, Nicholls and Lavery 1992). Was the decrease in temperature associated with this rainfall increase and, if so, what does this tell us about the possible cause of the temperature decline?

This study was undertaken because even though apparently inexorable warming since the mid-20th century (Nicholls 2003) has aggravated droughts in eastern Australia (Nicholls 2004), warm years are evident in the record from the early part of the century. Unless we can understand the causes of these warm years, and place the warming of the second half of the century within the context of the entire century, we will have difficulty ascertaining the cause of the recent warming, beyond reasonable doubt.

The next section briefly describes the datasets used in this study. The following section examines time series of annual mean maximum temperatures, averaged across New South Wales and identifies the timing of the various changes. This section also demonstrates the close relationship between maximum temperature and rainfall in New South Wales. This relationship is used to determine the portion of the temperature variations associated with rainfall variations. The residuals from this process, i.e., temperature variations not associated with rainfall variations, are examined for trends and we conclude the paper with a discussion of the likely causes of the various trends.

Datasets

The maximum temperature time series used in this analysis is calculated from a homogeneous or high-quality dataset originally developed by Torok and Nicholls (1996) and recently updated by Della-Marta et al. (2004). Where possible, each record in the dataset has been corrected for artificial discontinuities caused by changes in the observation regime (location, exposure, instrumentation or observation procedure) using a variety of statistical techniques, visual checks and station metadata.

Unfortunately, some stations in New South Wales were not exposed in a standard Stevenson screen until the 1940s (Nicholls et al. 1996a; Torok, 1996). This confounds the verification of the New South Wales cooling trend as the earlier, non-standard screens were generally warm-biased for maximum temperature. For example, some stations used Stevenson screens, but with an iron roof. Where sufficient evidence existed, such stations have been removed from the updated high-quality dataset. However, it is possible that other stations might have undocumented non-standard exposures during the early part of their records, resulting in a negative bias in their overall trend.

New South Wales annual mean maximum temperature anomaly values were determined by initially producing gridded analyses from the high-quality station temperature anomaly series using a successive correction analysis scheme (Jones and Weymouth 1997). Only those records identified as being free from the influence of urban warming were used (Della-Marta et al. 2004). Simple averages of the interpolated grid values within New South Wales were then used to produce the State's annual mean temperature anomaly series.

The New South Wales rainfall series used here is based on a gridded dataset of all available rainfall observations produced using the same objective analysis scheme used for temperature (Jones and Weymouth 1997). Good agreement has been shown between annual mean values for large regions determined using all-available observations and values determined from a high-quality subset of rainfall records developed by Lavery et al. (1997). The high-quality dataset was produced by rejecting records suspected of having homogeneity or data quality problems using a variety of graphical and statistical tests as well as available station history information.

Analysis and results

Time series of mean maximum temperature and rainfall

Figure 2 shows time series from 1910 to 2002 of New South Wales annual rainfall and annual mean

Fig. 2 **Time series of annual mean maximum temperature anomalies (red) and annual rainfall (blue) for New South Wales, 1910-2002. Eleven-year running means (centred) are shown as thick lines. Note that the temperature scale (right-hand side) is inverted.**

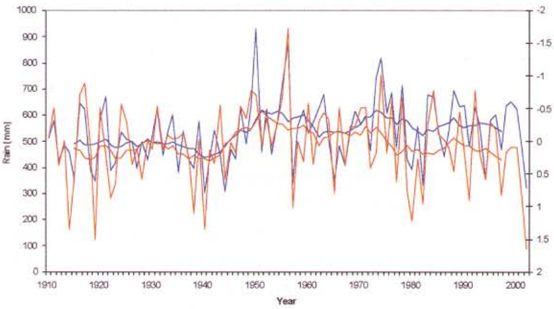
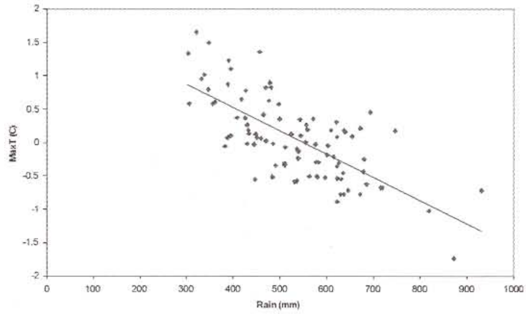


Fig. 3 **Scatter diagram of annual values of mean maximum temperature versus rainfall. Data from 1910-2002. Linear regression line shown.**



maximum temperature anomalies (note that the vertical scale is inverted for the latter). Temperature anomalies are calculated with respect to the standard 1961-1990 reference period. Eleven-year running means, plotted at the mid-point of the eleven years, are included to identify long-term variations. The most obvious change evident in the figure is the rapid increase in rainfall in the early 1950s. This was associated with a similarly rapid decrease in temperature.

Since the middle of the century, rainfall has varied on a decadal time-scale, but exhibited little evidence of any tendency to return to the rainfall levels of earlier years. Meanwhile, mean maximum temperatures have increased and are now similar to those exhibited prior to the mid-century changes.

Temperatures have also exhibited variations on decadal time-scales, matching those in rainfall. On shorter, interannual time-scales, the rainfall and temperature variations are closely related, as are the variations in the two variables on decadal time-scales prior to, and during, the mid-century changes. The warming since mid-century, and especially since the early 1970s, was not accompanied by a change in rainfall.

Relationship between rainfall and mean maximum temperature

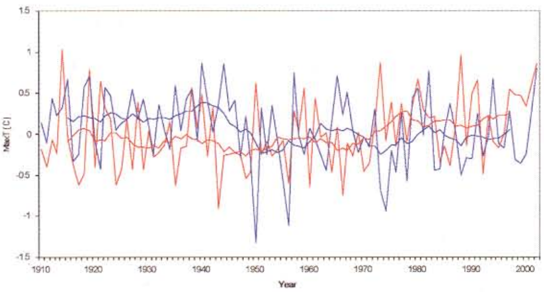
Figure 3 shows a scatter diagram between New South Wales annual rainfall and mean maximum temperature anomaly, using all years 1910-2002. There is a strong negative relationship between the variables, i.e., when rainfall increases mean maximum temperature decreases. The correlation is -0.71 (n = 93). The negative relationship reflects the tendency for wet years to have more cloud cover. This would tend to reduce solar insolation, leading to cooler temperatures during the day. Wet years also tend to have higher surface moisture leading to more evaporative cooling during the day. This would also tend to result in a negative relationship between rainfall and temperature. Given this strong relationship, the synchronicity of the changes in rainfall and temperature in mid-century is not surprising. However, it is surprising that the temperature has increased since mid-century although rainfall has not decreased.

The linear relationship between rainfall and mean maximum temperature anomaly evident in Fig. 3 can be used to partition the observed time series of mean maximum temperature anomalies into two portions – the portion associated with changes in rainfall, and the portion not so associated. The portion associated with rainfall variations can be estimated by using the observed rainfall in any year and the linear relationship between rainfall and mean maximum temperature anomaly, *viz.*:

$$\text{MaxT}(^{\circ}\text{C}) = 1.92 - 0.0035\text{Rain (mm)}$$

The residual (i.e., the observed value of the mean maximum temperature in any given year minus the portion associated with the observed rainfall as given by the above equation) is the portion of the mean maximum temperature variations not associated with rainfall variations. These two portions are plotted in Fig. 4.

Fig. 4 Time series of the portion of mean maximum temperature variability associated with rainfall variations (blue line - see text for details of calculation of this portion) and the portion not associated with rainfall variations, i.e., the residual (red line). Eleven-year running means (centred) shown as thick lines.



The rainfall-associated portion of the variations in mean maximum temperature drops rapidly in mid-century. This is not unexpected given the strong relationship between the two variables (Fig. 3) and the rapid rainfall increase in mid-century. After mid-century the rainfall-associated portion of the variations in mean maximum temperature varies on a decadal time-scale, but does not exhibit any clear tendency to warming or cooling.

The temperature variations not associated with rainfall variations (i.e., the residual time series in Fig. 4) shows little long-term variation until a rapid rise starting in the early 1970s. Subsequently, temperatures stay high – about 0.4°C warmer than before the 1970s.

These results (and Figs 3 and 4) were derived using ordinary least squares regression. Total least squares regression (which may be more appropriate for a situation where there are errors in measurements of the independent variable, de Groen (1996)) was also used to calculate the relationship between rainfall and temperature anomaly. The regressions were calculated using code from Benner et al. (1997). The total least squares regression was substantially different from that calculated using ordinary least squares, *viz.*:

$$\text{MaxT (°C)} = 3.52 - 0.0063\text{Rain (mm)}$$

However, none of the other observations noted above, including the rapid drop in the rainfall-associated portion of the temperature, nor the rapid rise in the portion of the temperature not associated with rainfall, were affected by use of this equation.

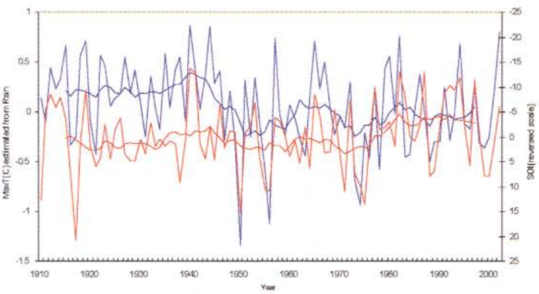
Discussion and conclusions

The separation of the variations of New South Wales mean maximum temperature anomalies into rainfall-associated variations and the residual (the portion not associated with rainfall variations) allows us to consider the possible causes of the variations. Since on all time-scales rainfall and temperature are strongly related (see Figs 2 and 3) one would be tempted to suggest that the mid-century cooling, which was associated with a rainfall increase, could be ascribed to natural causes. On the other hand, the fact that the warming in recent decades was not accompanied by a decrease in rainfall suggests that this warming would need to be attributed to some other, perhaps anthropogenic, cause. The possibility exists that this mid-century cooling and recent warming is the result of instrumental and exposure changes, although Torok and Nicholls (1996) and Della Marta et al (2004) have taken great care to reduce this possibility, in the construction of the high-quality temperature dataset used here. The possibility that such an artificial cause could explain such changes in temperature was also examined, and considered unlikely, by Nicholls et al. (1996b). Rainfall changes during the 1970s cannot be due to instrumental changes as no new types of rain gauge were introduced into the network until the introduction of automatic weather stations in the late 1980s.

The El Niño – Southern Oscillation is closely related to temperature and rainfall in eastern Australia (e.g. Coughlan 1978), so it is worth considering whether changes in the behaviour of this phenomenon could be the cause of the changes in mean maximum temperatures in New South Wales. Annual values of the Southern Oscillation Index (SOI, the standardised difference in pressure between Tahiti and Darwin) are strongly correlated with the time series of the portion of mean maximum temperature associated with rainfall variations ($r = -0.51$, $n = 93$) but only weakly associated with the residual portion of the mean maximum temperature ($r = -0.15$, $n = 93$). (The correlation between the SOI and the original mean maximum temperature time series is weaker ($r = -0.47$) than that with the portion of the mean maximum temperature associated with the rainfall, suggesting that the effect of the El Niño – Southern Oscillation on temperature is apparent only through the portion associated with rainfall variations.)

Figure 5 shows the time series of the SOI (scale reversed) and the portion of the mean maximum temperature estimated from the rainfall. The strong relationship between interannual and even interdecadal variations in the two time series is clear. However the shift in the relative location of the two time series,

Fig. 5 Time series of the portion of mean maximum temperature variability associated with rainfall variations from Fig. 3 (blue line) and the SOI (red line – note reversed scale). Eleven-year running means (centred) shown as thick lines.



with time, indicates that this relationship is not constant over time. This indicates that the observed changes in the SOI are probably not the cause of the observed secular changes in the mean maximum temperature. For instance, there is little suggestion of a trend in the SOI in mid-century that could explain the decline in temperature. On the other hand, the SOI decreased in the last two decades and this was not accompanied by an increase in the portion of the temperature variations estimated from rainfall. Nicholls et al. (1996b) have noted that the relationships between the El Niño – Southern Oscillation and Australian climate variability have changed in recent decades. The fact that the SOI does not exhibit behaviour likely to explain the mid-century decline in temperature somewhat argues against the theory that this decline is natural. However, others (Allan et al. 1996; Power et al. 1998; Kleeman and Power 1999) have demonstrated that the El Niño – Southern Oscillation and its influences are not stationary but vary over time.

One candidate explanation of the recent warming not associated with rainfall variations would be the enhanced greenhouse effect. Karoly (2001) and Stott (2003) have attributed the 20th century warming over Australia to anthropogenic causes. However, other possible causes would also need to be considered before a less tentative conclusion could be reached. For instance, Narisma and Pitman (2003) demonstrate that land cover changes may be influencing Australian climate. Additionally, changes in the Interdecadal Pacific Oscillation (IPO) (Power et al. 1999a,b; Kiem and Franks 2004) may have led to sufficient changes in regional circulation to cause the strong rainfall/temperature relationship to break down in the 1970s. Considerable research would be needed to identify the actual cause of this recent warming. In the interim it should be noted that the apparent 20th century cooling in New South Wales is composed of two episodes: a mid-century cooling associated with an increase in rainfall (and presumably 'natural'), and a late century warming not associated with rainfall changes and therefore rather surprising. The calculation of simple linear trends (e.g., Torok and Nicholls 1996) disguises this more complex, and interesting, temporal behaviour. Examination of time-varying relationship between physical quantities, as has been done here, provides a useful first step in identifying possible causes of trends and changes in climate variables.

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References

Allan, R., Lindesay, J., and Parker, D. 1996. *El Niño Southern Oscillation & Climatic Variability*. CSIRO Publishing, Collingwood, 405 pp.

Benner, P., Mehrmann, V., Sima, V., van Huffel, S. and Varga, A. 1997. SLICOT – a subroutine library in systems and control theory. *NICONET Report 97-3*. Software downloadable from http://www.win.tue.nl/wgs/slicot.html.

Cornish, P.M. 1977. Changes in seasonal and annual rainfall in New South Wales. *Search, 8*, 38-40.

Coughlan, M.J. 1978. Changes in Australian rainfall and temperature, in Pittock, A. B., Frakes, L. A., Jenssen, D., Peterson, J.A., and Zillman, J.W. (eds), *Climatic Change and Variability. A Southern Perspective*. Cambridge University Press, Cambridge, 194-9.

De Groen, P. 1996. An introduction to Total Least Squares. *Nieuw Archief voor Wiskunde, Vierde serie, 14*, 237-53.

Della-Marta, P.M., Collins, D.A. and Braganza, K. 2004. Updating Australia's high-quality annual temperature dataset. *Aust. Met. Mag., 53*, 75-93.

Jones, D.A. and Weymouth, G.T. 1997. An Australian monthly rainfall dataset. *Technical Report No. 70*, Bur. Met., Australia.

Karoly, D. 2001. Interannual and longer-term variations of Australian mean climate parameters from observations and model simulations. In: Understanding the climate of Australia and the Indo-Pacific region. Extended abstracts of presentations at the thirteenth annual BMRC modelling workshop, 14-16 November 2001, J. D. Jasper and P. J. Meighen (eds), *BMRC Research Report No. 84*, Bur. Met., Australia.

Kiem, A.S. and Franks, S.W. 2004. Multidecadal variability of drought risk, eastern Australia. *Hydrological Processes, 18*, 2039-50.

Kleeman, R. and Power, S. 1999. Modulation of ENSO on decadal and longer time-scales. In: *El Niño and the Southern Oscillation, Multi-scale Variability and its Impact on Natural Ecosystems and Society*. Edited by H.F. Diaz and V. Markgraf, 413-42, Cambridge, 496 pp.

Lavery, B., Joung, G. and Nicholls, N. 1997. An extended high-quality historical rainfall dataset for Australia. *Aust. Met. Mag., 46*, 27-38.

Narisima, G.T. and Pitman, A. J. 2003. The impact of 200 years of land cover change on the Australian near-surface climate. *J. Hydrometeorology, 4*, 424-36.

Nicholls, N. 2003. Continued anomalous warming in Australia. *Geophys. Res. Lett., 30*, 1370.

Nicholls, N. 2004. The changing nature of Australian droughts. *Climatic Change, 63*, 323-36.

Nicholls, N. and Lavery, B. 1992. Australian rainfall trends during the twentieth century. *Int. J. Climatol., 12*, 153-63.

Nicholls, N., Tapp, R., Burrows, K. and Richards, D. 1996a. Historical thermometer exposures in Australia. *Int. J. Climatol., 16*, 705-10.

Nicholls, N., Lavery, B., Frederiksen, C. and Drosdowsky, W. 1996b. Recent apparent changes in relationships between the El Niño – Southern Oscillation and Australian rainfall and temperature. *Geophys. Res. Lett., 23*, 3357-3360.

Pittock, A. B. 1983. Recent climatic change in Australia: implications for a CO_2 warmed earth. *Climatic Change, 5*, 321-40.

Power, S., Tseitkin, F., Torok, S., Lavery, B. and McAvaney, B. 1998. Australian temperature, Australian rainfall, and the Southern Oscillation, 1910-1996: coherent variability and recent changes. *Aust. Met. Mag., 47*, 85-101.

Power, S., Tseitkin, F., Mehta, V., Torok, S. and Lavery, B. 1999a. Decadal climate variability in Australia during the 20th century. *Int. J. Climatol., 19*, 169-84.

Power, S., Folland, C., Colman, A. and Mehta, V. 1999b. Interdecadal modulation of the impact of ENSO on Australia. *Climate Dynamics, 15*, 319-24.

Russell, J. S. 1981. Geographic variation in seasonal rainfall in Australia – an analysis of the 80 year period 1895-1974. *J. Aust. Inst. Agric. Sci., 47*, 59-66.

Stott, P. A. 2003. Attribution of regional-scale temperature changes to anthropogenic and natural causes. *Geophys. Res. Lett., 30*, 1728.

Torok, S. J. 1996. The development of a high quality historical temperature data base for Australia. Unpublished PhD thesis, University of Melbourne, 2 volumes.

Torok, S. J. and Nicholls, N. 1996. A historical annual temperature data set for Australia. *Aust. Met. Mag., 45*, 251-60.