Secular Variation in Rainfall Intensity and Temperature in Eastern Australia

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ABSTRACT

It is generally assumed that rainfall intensity will increase with temperature increase, irrespective of the underlying changes to the average rainfall. This study documents and investigates long-term trends in rainfall intensities, annual rainfall, and mean maximum and minimum temperatures using the Mann–Kendall trend test for nine sites in eastern Australia. Relationships between rainfall intensities at various durations and 1) annual rainfall and 2) the mean maximum and minimum temperatures were investigated. The results showed that the mean minimum temperature has increased significantly at eight out of the nine sites in eastern Australia. Changes in annual rainfall are likely to be associated with changes in rainfall intensity at the long duration of 48 h. Overall, changes in rainfall intensity at short durations (<1 h) positively correlate with changes in the mean maximum temperature, but there is no significant correlation with the mean minimum temperature and annual rainfall. Additionally, changes in rainfall intensity at longer durations (≥1 h) positively correlate with changes in the mean annual rainfall, but not with either mean maximum or minimum temperatures for the nine sites investigated.

1. Introduction

Rainfall is likely to change as a consequence of climate change (Trenberth 1998). In addition, rainfall is expected to increase in its intensity and/or frequency of occurrence, and storm duration may be shortened in a CO₂-warmed world (Trenberth 1998, 1999; Trenberth et al. 2003). An increase in global temperature would lead to an increase in moisture content in the atmosphere, which could increase the rate of precipitation (Trenberth 1998).

Changes in heavy rainfall, annual rainfall, and temperature have been investigated in several regions in the world (Groisman et al. 2005; Alexander et al. 2006; Cannarozzo et al. 2006; Krishnakumar et al. 2009). The results show that changes in extreme rainfall are more significant than those in annual rainfall (Trenberth et al. 2003; Groisman et al. 2005). Groisman et al. (2005) examined the trends in rainfall around the world and found that some regions have experienced an increase in heavy rainfall; however, for these regions there is either no change in annual rainfall or even a decrease in annual rainfall.

Australia has a significantly high rainfall variability; therefore, many studies have examined rainfall variations throughout Australia (Yu and Neil 1993; Nicholls and Kariko 1993; Nicholls et al. 1996; Haylock and Nicholls 2000; Nicholls 2003; Hardwick Jones et al. 2010; Li et al. 2011). Haylock and Nicholls (2000) also examined the trends in Australian extreme rainfall and found that rainfall intensity increased in eastern and southern Australia from 1910 to 1998. Nicholls and Kariko (1993) found that the variation in annual rainfall was highly related to the variation in rainfall intensity (mm day⁻¹) in eastern Australia. Nicholls et al. (1996) examined the relationship between the spatial average annual rainfall
and temperature for Australia from 1910 to 1992. They applied the Theissen polygon coefficients to the whole of Australia and found a significant negative correlation between annual maximum temperature and annual rainfall. This correlation was based on spatial averages, which excluded changes between regions.

The majority of research has examined changes in annual, seasonal, monthly, and daily rainfall. However, to date, only limited work has considered the evaluation of changes in subdaily rainfall (Fujibe et al. 2005; Lenderink and van Meijgaard 2008; Hardwick Jones et al. 2010; Jakob et al. 2011a, 2011b) since daily rainfall data are more readily available than subdaily data. Hardwick Jones et al. (2010) used daily precipitation, 60-min precipitation, and mean daily temperature to analyze the relationship between precipitation intensity and temperature. They found that when temperature increased, 60-min precipitation decreased in northern Australia but increased in eastern Australia. Jakob et al. (2011a, b) used peak over threshold to derive rainfall intensity at durations between 6 min and 72 h, and they investigated changes in rainfall intensities for southeastern Australia using a modified Mann–Kendall trend test at a significance level of 10%.

Although subdaily rainfall has been examined in Australia by many researchers, trends in short-duration rainfall intensities have not been tested for northeastern Australia. In addition, the relationships between short-duration rainfall intensities (e.g., less than 1 h in duration) and both annual rainfall and mean maximum/minimum temperatures have not been identified. The aim of this study is to develop an understanding of climate change impacts on rainfall in eastern Australia. In addition, this is addressed by answering the following research questions: 1) Have rainfall and temperature gradually changed? and 2) Have rainfall and temperature changed from earlier to later 30-yr periods and can relationships between these changes be identified? The objectives of this study are 1) to detect trends in annual mean maximum and minimum temperatures, annual rainfall, and short-duration rainfall intensities; 2) to find the relationship between annual mean temperature and short-duration rainfall intensities; 3) to find the relationship between annual mean minimum temperature and short-duration rainfall intensities; 4) to find the relationship between annual rainfall and short-duration rainfall intensities for a range of locations in eastern Australia. The data and methodologies used for the purpose of this study are described in the next section. It is argued in this study that these changes in rainfall may lead to significant implications for infrastructure management. For example, current physical infrastructure such as roads and bridges could be adversely affected under future climate conditions with subsequent impact on emergency services.

2. Data and methods

a. Data

From 1905 to 2005, all available annual rainfall and temperature data from these sites were used for the trend analysis. Annual mean maximum and minimum temperatures were calculated as the average of all available daily maxima and minima air temperatures for the year. Pluviograph data that have been published by Australian Bureau of Meteorology (BOM) were used in this study. In addition, the pluviograph data provide rainfall data at 6-min intervals. A long-term and continuous period is necessary for examining trends and changes. As there is no pluviograph station that has more than 60 years of pluviograph data in the western or central parts of Australia, this research only examines the eastern part of Australia. As there are only nine pluviograph stations that have more than 60 years of data, these sites were chosen in this study for analysis of subdaily and subhourly rainfall intensities. Note that these sites are identified in Fig. 1. Harvey et al. (2000) categorized the regions where these sites are located, with Cairns and Rockhampton being in a tropical zone, Brisbane in a subtropical zone, and the remaining six sites in a temperate zone.

Analysis of the pluviograph records indicates that there are some missing data for several events. It appears that much of the missing data occurs at either the beginning or end of the events. Consequently, the daily rainfall data were used in this study for analyzing rainfall durations of 24 h. Daily rainfall is recorded from 0900 to 0900 LT in Australia. The total daily rainfall from a weather station may be lower than a maximum 24-h rainfall from pluviograph data, but the former is much more complete.

The annual maximum and the partial duration series are the most commonly used for analyzing hydrological extremes from a long time series (Takeuchi 1984). The selections for extremes are different in these two methods. For the annual maximum series, the maximum rain intensity is selected for each calendar year. For the partial duration series, the highest rainfall intensity that exceeds a threshold is selected over the entire period. The advantage of the annual maximum series is that it is more objective, whereas the partial duration series may miss some small events. Therefore, the annual maximum series was used for deriving rainfall intensities in this study. Rainfall intensities at durations of 0.1, 0.5, 1, 2, 3, 6, 12, 24, and 48 h at each
site were performed in this study, as adopted from Canterford et al. (2001).

**b. Method for trend analysis**

The nonparametric Mann–Kendall trend test (Hamed and Rao 1998; Serrano et al. 1999; Hamed 2008) was used to detect statistically significant trends in annual mean maximum and minimum temperatures, annual rainfall, and rainfall intensities at durations of 0.1, 0.5, 1, 2, 3, 6, 12, 24, and 48 h.

The Mann–Kendall statistic \( S \) (Mann 1945; Biggs and Atkinson 2011) is calculated as

\[
S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sign}(x_j - x_i),
\]

\[
\text{sign}(x_j - x_i) = \begin{cases} 
1 & \text{if } x_j - x_i > 0 \\
0 & \text{if } x_j - x_i = 0, \text{ and} \\
-1 & \text{if } x_j - x_i < 0 
\end{cases}
\]

\[
\text{VAR}(S) = \frac{1}{18} \left[ n(n-1)(2n+5) - \sum_{k=1}^{m} t_k(t_k-1)(2t_k+5) \right],
\]

where \( x_i \) and \( x_j \) are the data at time \( i \) and \( j \), respectively, \( \text{VAR}(S) \) is the variance of \( S \), \( n \) is the number of data, and \( t_k \) is the number of data in the \( m \)th tie.

The normalized test statistic \( Z \) is calculated as follows:

\[
Z = \begin{cases} 
\frac{S - 1}{\sqrt{\text{VAR}(S)}} & \text{if } S > 0 \\
0 & \text{if } S = 0 \\
\frac{S + 1}{\sqrt{\text{VAR}(S)}} & \text{if } S < 0 
\end{cases}
\]

A positive \( Z \) value indicates an upward trend and a negative value indicates a downward trend.

In this study, a trend is considered to be statistically significant when the \( p \) value is less than 0.05. The data were tested in an ordered time series; therefore, all available observed data for each site were used in this study.

A linear regression is applied for those trends that are statistically significant:

\[
y = ax + b,
\]

where \( y \) is a climatic variable, \( x \) is time in year, \( a \) is an estimate of the rate of change in the climatic variable, and \( b \) is a constant. In this study, the rate of change in temperature is expressed in degrees Celsius per decade. The rate of change in annual rainfall and rainfall intensities are all expressed as percentage of the mean value per decade. For example, if the rate of change in annual rainfall is 10 mm yr\(^{-1}\) and the long-term average annual rainfall is 1000 mm yr\(^{-1}\), then rate of change in annual rainfall would be presented as 10% change of the long-term mean per decade.
c. Method for correlation analysis

To examine the relationship between short-duration rainfall intensities and temperatures as well as the relationship between short-duration rainfall intensities and annual rainfall, nonoverlapping periods are required. The World Meteorological Organization (WMO) suggests that 30 years is a standard period for the estimation of the climatic variables characterized; therefore, two pairs of 30-yr climatology were identified for each study site. Each pair of 30-yr periods was selected to represent the highest and lowest 30-yr mean temperatures for each site. If the 30-yr periods of the highest and lowest mean values are overlapping, the second highest or lowest mean is then used, so these two 30-yr periods are nonoverlapping and assumed to be independent.

The statistically significant difference between each pair of 30-yr data was tested by using the standard t test. In addition, significant changes, that is, p values less than 0.05, in temperatures, annual rainfall, and rainfall intensities were then identified for correlation analysis. For example, if two pairs of 30-yr annual mean maximum temperature distributions are significantly different (p value < 0.05), changes in means of 30-yr rainfall intensities that have p values less than 0.05 are plotted against changes in mean 30-yr mean maximum temperature. Linear correlations between statistically significant changes from earlier to later periods in mean maximum temperature and rainfall intensities, as well as in mean minimum temperature and rainfall intensities, were applied.

Table 1 shows 1) the study locations and site numbers, 2) the recorded period of all available data, 3) each pair of the selected 30-yr periods, and 4) the mean of annual maximum and minimum temperatures and annual rainfall of each pair of 30-yr periods for each site.

3. Results and discussion

a. Trends

The series of annual mean maximum and minimum temperatures, annual rainfall, and rainfall intensity for different durations were tested for trends by using the Mann–Kendall trend test for each site in eastern Australia (Fig. 2). Statistically significant trends (p values less than 0.05) are indicated by arrows and rates of change in climatic variables are presented in parentheses in Fig. 2. Rates of change in temperature are shown in degrees Celsius per decade, and rates of change in annual rainfall and rainfall intensities are presented in percentage of the long-term average per decade.

Seven out of nine locations have statistically significant upward trends in the annual mean maximum temperature. With the exception of Launceston in Tasmania, all
FIG. 2. Mann–Kendall trend test criss-cross is no significant trend, upward arrow is significant upward trend, and downward arrow is significant downward trend in annual rainfall, annual temperature, and rainfall intensities for different durations; rates of change per decade are in parentheses.
the sites have significant upward trends in annual mean minimum temperature. Apart from Adelaide, these trends are in general agreement with global temperature trends and findings from previous investigations (Yu and Neil 1991; Nicholls et al. 1996; Trenberth 1998, 1999). The temperatures in Adelaide are becoming less extreme as annual mean maximum temperature has decreased 0.13°C decade\(^{-1}\) while the annual mean minimum temperature has increased 0.11°C decade\(^{-1}\) during the same period.

The Mann–Kendall trend test also showed that annual rainfall has decreased in Rockhampton and has increased in Brisbane. During 1943–2005, annual rainfall has decreased 4.2% of the long-term average per decade in Rockhampton. This downward trend in annual rainfall, if it continues, would have implications for water supply and water resources management for the area.

Rainfall intensity at 0.1-h duration has increased significantly in Rockhampton, Canberra, and Melbourne during the study periods. Canberra and Melbourne also have a statistically significant upward trend in rainfall intensities at 0.5-h duration. Short-duration rainfall intensities play a key role in the estimation of the peak runoff rate in small catchments. This would have implications for design of small hydraulic structures if the same risk of failure is to be maintained.

Apart from Brisbane, all study sites did not show statistically significant trends in rainfall intensities at durations between 1 and 24 h. Brisbane has a significant upward trend in rainfall intensity at 48-h duration, and Rockhampton has significant downward trends in rainfall intensity at 48-h duration.

The analysis of the temperature and rainfall trends at all of the sites in eastern Australia has not shown any trend in annual rainfall, except at Rockhampton and Brisbane. The results for Rockhampton and Brisbane show the same trend for annual rainfall and rainfall intensity for the 48-h duration. This is similar to the results by Nicholls and Kariko (1993), who showed that the variation in annual rainfall was highly related to the variation in daily rainfall. Although Nicholls et al. (1996) found a negative correlation between annual mean maximum temperature and annual rainfall for Australia as a whole, the current study found no similar trends across eastern Australia for these sites investigated apart from Rockhampton. At this site, there was an upward trend in the annual mean maximum temperature and a downward trend in the annual rainfall.

b. Correlations

Two pairs of annual mean maximum and minimum temperature distributions were analyzed to determine whether they differed at a statistically significant level using the \(t\) test. Similarly, the \(t\) test was also applied to annual rainfall and rainfall intensities at 0.1, 0.5, 1, 2, 3, 6, 12, 24, and 48-h durations for each pair of contrasting periods. The changes in mean 30-yr annual mean maximum temperature, annual mean minimum temperature, annual rainfall, and rainfall intensities that have \(p\) values less than 0.05 are shown in Figs. 3 and 4.

Changes in mean 30-yr annual rainfall and mean 30-yr rainfall intensities are presented as percentages of earlier periods, and changes in 30-yr mean maximum and minimum temperatures are shown in degrees Celsius.

As seen in Fig. 3, the changes in rainfall intensity for durations shorter than 1 h have a positive correlation with changes in annual mean maximum temperature from earlier periods to later periods. With higher annual mean maximum temperature, short-duration rainfall intensities could possibly increase. Though rainfall intensities for 0.1- and 0.5-h durations have gradually increased in Melbourne (Fig. 2), this increase in rainfall intensities does not appear in Fig. 3. This is because the periods for analysis are different: 1925–2005 was used for the trend test and 1929–58 and 1976–2005 were used for the correlation analysis for Melbourne. The results from the \(t\) test showed a significant change in mean annual temperature from the earlier to the later periods in Melbourne. The changes in 0.1- and 0.5-h rainfall intensity were, however, not significant at the site.

Annual mean maximum temperature does not correlate with rainfall intensity at durations longer than 1 h. Annual mean minimum temperature does not correlate with rainfall intensities at durations between 0.1 and 48 h. In addition, rainfall intensities increase in some locations and decrease in others while annual mean minimum temperatures have increased at all nine sites.

Figure 4 shows that there is no significant correlation between annual rainfall and rainfall intensity at 0.1-h duration. The rainfall intensities for durations longer than 1 h in Brisbane, Sydney, and Hobart show significant changes that have a positive correlation with changes in the mean annual rainfall. This could explain the results from the trend test that annual rainfall and rainfall intensity at 48 h have the same trends in Rockhampton and Brisbane.

The correlation analysis in this study is based on nine individual locations from different climate zones (tropics, subtropical, and temperate). The mechanism of the correlations between rainfall and temperature was not analyzed in this study. Further study could target on analyzing the correlations by collecting more rainfall and temperature data within each climate zone.

4. Conclusions

To investigate whether rainfall has significantly changed, how rainfall has changed, and whether the
change is related to trends in temperature, this study examines changes in annual temperature and rainfall and the relationship between the two. Attempt was made to test for significant changes and trends in annual mean maximum and minimum temperatures, annual rainfall, and short-duration rainfall intensities over the past 100 years at nine sites around eastern Australia. All available weather data were used. Two 30-yr climatologies for each of the nine sites with the greatest differences in the mean annual rainfall and temperatures were selected. Based on these contrasting periods, correlations between mean maximum/minimum temperatures and rainfall intensities as well as correlations between annual rainfall and rainfall intensities were investigated for the selected nine sites.

Seven out of the nine sites have shown significant upward trends in annual mean maximum temperature, and eight out of the nine sites have shown significant

![Fig. 3. Relationships (a) between significant changes in 30-yr mean maximum temperature and rainfall intensity and (b) between significant changes in 30-yr mean minimum temperature and rainfall intensity for durations (left) less than 1 h and (right) longer than 1 h.](image-url)

![Fig. 4. Relationship between significant changes in mean annual rainfall and rainfall intensity for (left) 0.1-h duration and (right) durations longer than 1 h.](image-url)
upward trends in annual mean minimum temperature, which is broadly similar to global temperature trends. Significant changes in rainfall characteristics and temperature were more consistent in the temperate climate zone than in the tropical climate zone. Only one of the two sites in the tropics (i.e., Cairns and Rockhampton) showed significant changes in rainfall (Cairns). This shows that variations in rainfall changes at various time scales can occur both between and within climatic zones.

Rainfall intensities at longer durations (>1 h) were found to be positively correlated with annual rainfall, and rainfall intensities at durations less than 1 h were positively correlated with annual mean maximum temperature. While statistical in nature, the observed significant correlation between rainfall intensities at short duration and mean maximum temperature would have practical implications for the impact on small hydraulic infrastructure in a CO2-warmed world.

REFERENCES


