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Trends in rainfall indices for six Australian regions: 1910-2005

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Trends in rainfall indices from January 1910 to August 2005 were examined using an updated high-quality rainfall data-set from the Australian Bureau of Meteorology. Nine indices, reflecting changes to mean annual/seasonal rainfall and extreme daily rainfall (defined by the 95th and 99th percentiles), were evaluated for six regions in the east and southwest of Australia. Seasonal and annual trends were calculated over two periods: long term (1910-2005) and medium term (1950-2005). In the Central region, since 1910 there have been significant increases in spring and annual rain days and extreme rainfall intensity (95th percentile), but significant decreases in spring and annual rain per rain day and the proportion of rainfall from extreme events. During spring, the Western Tablelands showed a decrease in rain per rain day over the period 1910-1930 and an increase over the period 1970-2005, most likely due to heavy-rain events. No significant changes were detected in the West region. In the Southwest, annual total rainfall has significantly decreased by 21 mm per decade since 1910 and by 24 mm per decade since 1950. These declines were accompanied by decreases in rain days and extreme rainfall indices. In the eastern Coastal region, since 1950, there has been a significant decrease of almost 55 mm per decade in annual total rainfall, along with decreases in rain days and extreme rain, particularly in summer and winter. In the Southeast, a significant decrease in annual total rainfall of 20 mm per decade since 1950 stems mainly from decreases during autumn. Generally, the direction of changes in extreme rainfall is consistent with changes in the mean.

Introduction

Understanding rainfall variability, shifts and trends is of primary importance when considering the potential for biophysical, social and economic impacts. An increase in mean rainfall could enhance agricultural production and water supply. However, if this increase is associated with more extreme rainfall events, it can enhance flood frequency and intensity. Conversely, decreases in mean rainfall can lead to droughts and greater fire risk. For example, in southwest Western Australia (SWWA), a sudden and sustained 15 to 20 per cent decline in rainfall during the 1970s has resulted in a 50 per cent decline in stream-

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flow to Perth dams (IOCI 2002). There is no apparent trend in the frequency of tropical cyclones in the Australian region since 1981 (when reliable satellite data became available); however, an increase in intense systems (very low central pressure) and a slight fall in weak and moderate systems have been observed (Hennessy 2004). Trends in thunderstorms and other weather phenomena are unknown due to the sparsity of suitable data (Nicholls and Collins 2006).

Analyses of Australian rainfall trends have been performed for many indices, using a number of data-sets over different time periods. A summary of recent papers on trends in both mean and extreme rainfall is shown in Table 1. Studies determining rainfall trends between the early 1900s and the 1990s have arrived at similar conclusions. Hennessy et al. (1999), Plummer et al. (1999) and Collins and Della-Marta (2002) reported an increasing trend in Australian-average rainfall since the beginning of the 20th Century. Nicholls and Lavery (1992), Suppiah and Hennessy (1998), Plummer et al. (1999) and Haylock and Nicholls (2000) describe increases in extreme and mean rainfall through much of eastern Australia from 1910. Nicholls and Lavery (1992) and Suppiah and Hennessy (1998) linked an increase in annual rainfall to increases observed during the summer half-year (defined as October/November to March/April respectively). Hennessy et al. (1999) also reported increases in mean and extreme rainfall over south-eastern Australia during this time.

On a shorter time-scale, some studies have noted significant trends since 1950. Hennessy et al. (1999) showed decreases in Tasmanian rainfall and Collins and Della-Marta (2002) noted decreases in rainfall along the east coast. Manton et al. (2001), Smith (2004) and Alexander et al. (2007) also reported some decreases in the southeast and along the east coast of the country. Studies listed in Table 1 (that considered the appropriate region) consistently reported a statistically significant decline in mean and extreme rainfall in SWWA and most reported increases in north-western Australian rainfall.

Few studies have comprehensively assessed trends in Australian daily rainfall since an update to the high-quality Bureau of Meteorology data-set in the mid-1990s. The present study builds on previous work and assesses regional changes to a number of rainfall indices that capture changes in intensity and frequency. These are calculated on annual and seasonal time-scales for an updated data-set from 1910 to 2005. While this paper does not attempt to determine causes of changes, it identifies new and potentially important changes to regional rainfall regimes in Australia. These are quantified by assessing the magnitude and statistical significance of trends from 1910-2005 and 1950-2005 in six regions.

Data

The Australian Bureau of Meteorology routinely updates the high-quality daily rainfall data-set originally created by Lavery et al. (1992) who identified spurious data using statistical methods and through determining changes in metadata. These included investigations into observer practices, exposure of rain-gauges, changes in location, changes in rain-gauge type and statistical tests to determine atypical drifts in frequency distributions. These tests resulted in the original nation-wide data-set of approximately 6600 stations being reduced to a high-quality set of 191 stations. Haylock and Nicholls (2000) removed a further ten stations from the set, based on a more rigorous assessment of observer practices. A second data-set containing a further 188 stations was produced by Lavery et al. (1997), by creating composite time series at selected sites from shorter overlapping records at nearby stations. Although this data-set contained more stations in data-sparse regions, it was not suitable for this study as it is a monthly data-set, not a daily one.

Multi-day rainfall accumulations were taken into account as they have the potential to produce artificial trends in daily rainfall. Viney and Bates (2004) demonstrated this by showing that many observers routinely did not take records on a weekend and instead, recorded an accumulated value at the beginning of the week. Accumulations over a number of days are recorded as large one-day totals and problems occur when this is incorrectly treated as a one-day total. Multi-day accumulations can skew a distribution toward larger rainfall totals and can over-estimate the frequency and magnitude of extreme rainfall events. Accumulations can be treated as missing data (Haylock and Nicholls 2000) or divided over the number of days of measurement (Hennessy et al. 1999). Both methods have been used in numerous studies and it was found by Hennessy et al. (1999) that splitting the accumulated value uniformly over the number of accumulation days does not significantly alter results. However, for simplicity this paper has treated accumulated values as missing data.

The recent update to the high-quality data-set means the data now span from the early 1900s to August 2005. January 1910 was chosen as the starting point for examining all daily rainfall stations, due to no data availability for several stations before this time. Some stations have been closed since the last update but were included in the study as they still met the criteria outlined below.

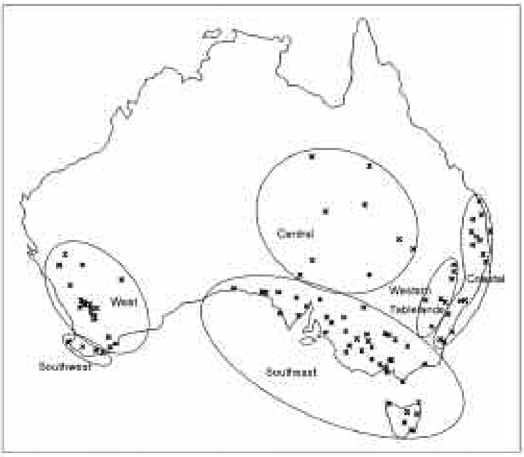
Even the best data-set will contain some missing values; in the case of rainfall, this may be due to many reasons, including equipment malfunction and observer illness. According to Haylock and Nicholls (2000), more than ten days of missing data in any given year

Table 1. Summary of studies since 1992 that have assessed changes in Australian rainfall.

Authors	*Data-set*	*Period*	*Region*	*Index type*	*Findings*
Nicholls and Lavery (1992)	191 stations	1910-1988	Eastern and south-western Australia	-Total rainfall	• Increases in summer half-year rainfall in eastern Australia • Decreases in SWWA winter rainfall since 1970s
Nicholls and Kariko (1993)	5 stations	1910-1988	Eastern Australia	-average annual rainfall -number of rain events -length of rain events -average intensity of rain events	• Increases in average annual rainfall • Significant increases in the number of rainfall events at 4/5 stations • General increases in length of events • General decreases in intensity of events except one significant increase at a Victorian station
Lavery et al. (1997)	379 stations	1890-1992	Northern half Australia, southern half Australia and all Australia	- Areal average rainfall	• Increase of 5mm/century across all of Australia • Decrease in northern summer half-year of 15mm/century • Decrease in southern winter half-year of 18mm/century • All trends calculated from 1890-1992
Lough (1997)	17 stations	1890-1995	Queensland	-2-month total rainfall	• No long-term trend considered unusual in the context of the 105-year series for summer, winter or annual rainfall
Suppiah and Hennessy (1998)	125 stations	1910-1990	Eastern and south-western Australia	-Total rainfall -Number of dry days -Heavy rainfall (90th and 95th percentiles)	• Increase in total and heavy rainfall in summer half-year over all stations • Decrease in total and heavy rainfall in winter half-year in SWWA, increases in other areas • Decrease in dry days for all areas except SWWA and some eastern stations
Hennessy et al. (1999)	379 stations	1910-1995	Australia-wide – trends calculated at individual stations. Data-sparse regions in the northwest	-Total rainfall -Number of rain days -Heavy rainfall (95th and 99th percentiles)	• Increase in total rainfall in Vic, NSW, NT and SA; negligible changes in WA and QLD; decreases in SWWA and TAS • Increases in heavy rainfall in SA summer and NSW autumn; decreases in SWWA • Increases in rain days in NT and NSW; decline in SWWA
Plummer et al. (1999)	379 stations	1910-1995	Australia divided into four quadrants	-Percentage wet and dry -Rainfall intensity	• Increase in the 99th percentile of rainfall during autumn in the southeast quadrant • Increases in summer rainfall and decreases in autumn rainfall for southwest quadrant • Decreases in winter rainfall for northeast quadrant
Haylock and Nicholls (2000)	91 stations	1910-1998	Eastern and south-western Australia	-Frequency, intensity and proportion of rainfall from extreme events (95th percentile) -Total rainfall -Rain days	• Increase in total rainfall and rain days in eastern Australia; decrease in both indices in SWWA • Decreases in extreme rainfall in SWWA • Decrease in percentage of rainfall falling in extreme events in southeast Australia
Manton et al. (2001)	13 stations	1961-1998	Stations chosen to represent all regions of Australia	-Rain days -Extreme, intensity and proportion of events above the 99th percentile	• Decreases in extreme intensity and frequency in SE Australia and SWWA; increases in these indices in central Australia
Collins and Della-Marta (2002)	271 stations	1900-2000	Country-wide with data-sparse regions in central and north-western Australia	-Annual total rainfall -Extreme high rainfall (above 90th percentile) -Extreme low rainfall (below 10th percentile)	• Increases in total rainfall over much of Australia except Tasmania, SWWA and small sections of the east coast of Australia • Increase in proportion of country experiencing extreme wet conditions
Smith (2004)	0.05°x0.05° gridded daily data	1901-2002	0.05°x0.05° grid over all of Australia	- Average rainfall	• Decreases in southeast Australia and SWWA during winter half-year • Increases in rainfall over much of inland Australia
Alexander et al. (2007)	0.25°x0.25° monthly gridded data and 91 stations	1901-2005 1951-2005	Gridded fields over whole of Australia and individual stations analysed	-95th and 99th percentiles -Number of days over 10/20mm -consecutive wet/dry days -annual totals	• 1910-2005: increases in inland rainfall in spring and summer • 1951-2005: strong decreases in east coast summer rainfall, southeast autumn rainfall and east coast and southwest winter rainfall
Gallant et al. (this study)	95 stations	1910-2005 1950-2005	Six regions in the south and east of Australia	-Total rainfall -Number of rain days -Mean rain per rain day -Extreme intensity, frequency and proportion for the 95th and 99th percentiles	• See Results section

will cause at least a ten per cent increase in the probability of one of these days containing a significant rainfall event. Consistency in the long-term record was considered important for this study. Therefore, if a station contained more than ten days of missing data per year for over ten per cent of the total number of years, it was discarded. A further five remote stations were discarded because their analyses could not be verified against neighbouring records. The net result is a total of 95 stations in the final updated data-set. Stations are primarily distributed in the eastern half and southwest of the country. A large data void in the central-west and north of Australia means trends were not computed in these regions. These expanses of missing data lead to an inability to perform important investigations into daily rainfall trends in these areas, highlighting the need for more high-quality rainfall records and ongoing monitoring.

Fig. 1 **The locations of the Australian Bureau of Meteorology's high-quality daily rainfall stations and regions used within this study**



Method

Regions for this study were initially chosen using the same method as Haylock and Nicholls (2000). Stations were separated into those dominated by winter rainfall or summer rainfall. Stations with a winter rainfall regime receive over 50 per cent of their rainfall from May to October, while those with a summer rainfall regime experience over 50 per cent of their rainfall from November to April. Stations in the south and west were found to be dominated by winter rainfall and stations in the central and northeastern parts of the country were dominated by summer rainfall. An eastern region with summer-dominated rainfall was split into three subregions: Central, Western Tablelands and Coastal. The Central region contains arid stations, the Western Tablelands have moderate rainfall on the western side of the Great Dividing Range, and the Coastal region has high rainfall on the eastern side of the Range. Definitions of the subregions are as follows: Central – stations west of the Ranges and below an elevation of 300 m; Western Tablelands – stations above 300 m and more than 150 km inland; and Coastal – less than 150 km inland. Stations in the southeast and southwest of the country had winter-dominated rainfall regimes. A subregion in the southwest of Western Australia was created due to a known significant decrease in rainfall in the area since the 1970s (IOCI 2002). This region was defined using the same boundary for the southwest corner as defined by IOCI (2002). The resulting six regions analysed in this study are shown in Fig. 1. To confirm the consistency of rainfall patterns within these regions and to validate the need for no other subregions, linear trends for all rainfall indices were plotted for each station. Visual analysis showed a general consistency in trends for each region.

Assessment of rainfall trends can also be sensitive to the sampling period (Manton et al. 2001). This study calculated trends over two periods, 1910-2005 and 1950-2005. The first period is simply the full record. The second period was guided by results from Vives and Jones (2005), who investigated abrupt changes to Australian rainfall from 1890 to 1989. Abrupt shifts were detected around 1890-1895, 1945-1950 and 1967-1972. The 1950 shift was also noted (but not tested) by Nicholls and Lavery (1992). This shift mainly affected the southeast and southwest of Australia.

For both periods, linear trends for various rainfall indices were computed in order to quantify changes in rainfall. While the use of linear trends brings some points of contention (as rainfall is a highly non-linear system), the analysis was performed so it could be directly compared to previous studies, most of which use a linear trend analysis. Linear analysis is also the simplest conceptual way to quantify absolute changes in rainfall. Due to inherent decadal and century-long variability, the time series was split into two periods and linear analysis performed on each. This was to illustrate changes occurring across the two general rainfall regime periods found by Vives and Jones (2005) through the 20th century. Regional-average trends were based on the arithmetic mean of time series from all stations within the region, i.e. station data were not area-weighted. The significance of the trend was evaluated using a two-sided Kendall-Tau test (Press et al. 1986). This test is a non-parametric approach that allows for detection of a monotonic trend in the data without assuming linearity. This approach was chosen to detect the significance of the general trend in rainfall while linear trends were used as a supplemental method of quantifying the size of changes in rainfall, as the Kendall-Tau test does not give this information. Nicholls (2001) noted the potential for important information to be lost by only using the conventional arbitrary threshold of the 95% significance level. Hence, non-significant (but substantial) changes were also highlighted in some cases as they may be considered potentially relevant for impact assessment.

The characteristics of rainfall analysed in this study included both average and extreme rainfall. Indices were designed to capture changes in a variety of aspects of the rainfall distribution (Table 2). Previous studies have generally calculated extreme daily rainfall in two ways, percentiles or exceedance of arbitrary thresholds. Using threshold values can mean a value considered extreme for one location may not be extreme at another due to differing climatic conditions. For assurance that extreme values were applicable to all regions, Hennessy et al. (1999), Haylock and Nicholls (2000) and Manton et al. (2001) used percentile thresholds. For the same reason, the 95th and 99th percentiles were chosen to represent extreme rainfall for this study. The percentiles were based on all days rather than rain days, to ensure that trends in extreme rainfall are not confounded by any trends in rain days. The 95th percentile is approximately equivalent to the 18th highest annual value or the 4th highest seasonal value, while the 99th percentile is approximately equivalent to the 4th highest annual value or the 2nd highest seasonal value.

Results

Seasonal and annual time series were calculated for the six regions and are shown in Fig. 1. As indicated above, a station was not considered valid for a particular year if it had more than ten days of data missing in that year. However, a station was still included in the trend analysis if the number of years for which this occurred was less than ten per cent of all years from 1910-2005. This meant the number of stations used for a region fluctuated slightly from year to year. A time series of the number of valid stations for each region is shown in Fig. 2. Maximum year-to-year fluctuations of 30 per cent, on average, appeared for all regions. The largest of these occurred from the 1980s when the number of valid stations for many regions declined primarily due to station closures.

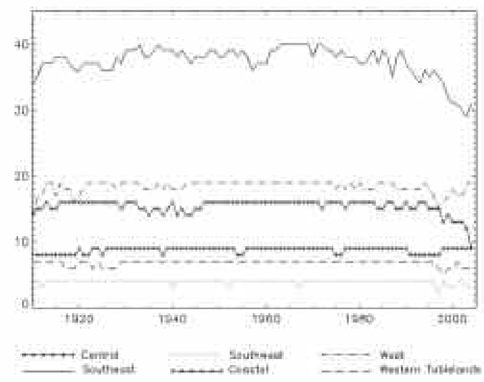
To help smooth interannual variability in the annual and seasonal time series, ten-year running means were plotted. While smoothing makes interdecadal and longer term trends more readily identifiable, information for the first and last five years of the time series is lost. A process of auto-regressive forecasting and hindcasting was applied to extrapolate smoothed data points to prevent this data loss. This involved applying the first/last ten values of the original series to an autoregression model to determine the first/last five smoothed points. However, because this is an extrapolation process, caution should be taken when considering the first and last five years of data shown for each time series. Though time series shown in Figs 3-9 are the smoothed time series, note that the linear trends and significance testing were performed using the original data.

A qualitative assessment of decadal-scale variability and trends for annual and seasonal rainfall for each

Table 2. Rainfall indices.

Index	*Definition*
Total rain	Total annual/seasonal accumulation of rainfall (mm)
Rain days	The number of days within a year/season with at least 1mm of rain
Rain per rain day	Total annual/seasonal accumulation divided by the number of rain days in that year/season
Extreme frequency (95th)	The number of events above the long term (1910-2005) annual/seasonal 95th percentile
Extreme frequency (99th)	The number of events above the long term (1910-2005) annual/seasonal 99th percentile
Extreme proportion (95th)	The proportion of total annual/seasonal rainfall coming from events above the annual/ seasonal 95th percentile (%)
Extreme proportion (99th)	The proportion of total annual/seasonal rainfall coming from events above the annual/ seasonal 99th percentile (%)
Extreme intensity (95th)	The intensity of the annual/seasonal 95th percentile (mm)
Extreme intensity (99th)	The intensity of the annual/seasonal 99th percentile (mm)

Fig. 2 The number of stations considered valid for each year in each of the six Australian regions.



region and rainfall index is first presented. As the time series was only extended to August 2005, annual and spring series and trends are only evaluated to 2004. This is followed by a quantitative analysis of linear trends for 1910-2004/05 and 1950-2004/05 for each region and rainfall index and an assessment of uncertainty in the direction and significance of trends.

Mean rainfall changes

Figures 3, 4 and 5 show time series of total rainfall, the number of rain days and rain per rain day, respectively. Both the eastern Coastal and Southeast regions showed increasing trends in annual total rainfall and rain days during the first half of the 20th century. In the eastern Coastal region, these indices steadily decreased over the period 1950 to 2005. Declines in the Southeast were not observed until the mid 1970s due to high decadal variability during the middle of the 20th century and a series of wet years in the early 1970s. The recent data update to 2005 has shown a continuation of decreases with recent values appearing as the lowest on record. Decreases in the eastern Coastal region are primarily due to decreases in winter and summer, and are reflected in a steady decrease in rain per rain day since the 1950s. In the Southeast, recent decreases in annual total rainfall and rain days are mainly due to a decline in autumn that shows a steady downward trend with very little variability since the late 1970s. Annual rain per rain day in the Southeast shows no trend, though a small decline during autumn is evident. Periods of high decadal variability appear between the 1940s and the 1970s for many regions in eastern Australia due to periods of very wet years during this time.

Fig. 3 Time series from 1910-2005 of ten-year running means of the total rainfall accumulation for six regions (see Fig. 1 for region definitions). Summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual time series are shown.

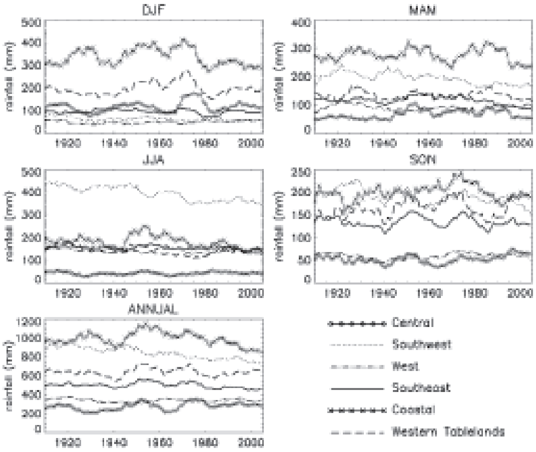
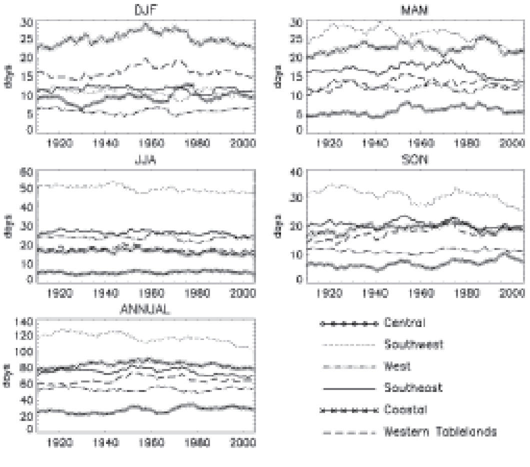
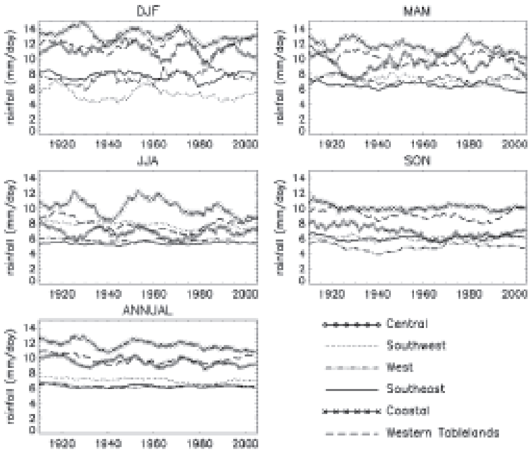


Fig. 4 Time series of ten-year running means of the number of rain days (rain >1 mm) from 1910-2005 for six regions (see Fig. 1 for region definitions). Summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual time series are shown.



Decreases in annual total rainfall and rain days were observed in the Southwest since 1910. These were attributed to large decreases in winter, autumn and spring. Annual rain per rain day steadily declined

Fig. 5 **Time series of ten-year running means of mean rainfall per rain day from 1910-2005 for six regions (see Fig. 1 for region definitions). Summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual time series are shown.**



over the period 1910 to 1970 before decreasing sharply. Around the mid 1980s the index increased due to increases during autumn and spring. Annual time series in the west showed a small decline in total rainfall over the period 1910-1940 and a general increase from 1940-2005 to levels similar to those in 1910, giving no net trend across the entire time series. Post-1940 annual increases stem from increases in summer rainfall. Rain days and rain per rain day showed no discernable trend from 1910-2005. Seasonal and annual mean rain indices were dominated by high decadal variability in the west.

Large decadal variability in the Central region was observed. A general increase in annual total rainfall and rain days has occurred since 1910, especially in spring, with a small decrease in rain per rain day. This indicates that the increase in total rainfall for the central region stems from an increase in the number of rain days, not from heavier rainfall events. This is confirmed by the decrease in extreme proportion indices, indicating that increases in total rainfall are greater than those in extreme rainfall. The Western Tablelands region showed an increase in annual total rainfall and rain days over the period 1910-1970, followed by a decrease to 2005, mostly due to changes in summer. There was a decrease in rain per rain day over the period 1910-1930, followed by a period of little change, then an increase from 1970-2005, indicating that increases in rainfall since 1970 are most likely due to increases in heavy rain events.

Extreme rainfall changes

The directions of changes in extreme rainfall were consistent with those of mean rainfall changes. This was also concluded by Alexander et al. (2007). Time series for the 95th percentile indices are shown in Figs 6-9. Results for the 99th percentile are not shown but were consistent with those for the 95th percentile, as discussed in the 'Regional changes' section.

The indices of annual extreme frequency and intensity showed decreases in the Southwest and eastern Coastal regions since 1950 (Figs 7, 9). The annual decreases in the southwest were due to strong decreases during autumn, winter and spring, and decreases in the Coastal region were due to winter and summer declines. The Southeast (Figs 6, 9) showed notable autumn declines since the 1970s, though this was not a prominent feature in the annual time series. High decadal variability was evident for most regions in eastern Australia during the middle of the 20th century due to wet periods in the 1950s and 1970s. Despite large decadal variability in the Central region (Figs 6, 9), increases in extreme frequency and extreme intensity occurred in all seasons since 1950. Small increases in extreme frequency and intensity in the Western Tablelands (Figs 7, 9) appear to be associated with large decadal variability. Though strong decadal variability dominated trends in the West region, summer extreme frequency (Fig. 6) and intensity (Fig. 9) showed a small increase since the 1930s and a small decrease in these indices in winter. Seasonal trends counteracted and produced no trend in the annual indices.

Fig. 6 **Time series of ten-year running means of the frequency of events above the long-term (1910-2005) 95th percentile (extreme frequency) for the Central, Southeast and West regions (see Fig. 1 for region definitions). Summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual time series are shown.**

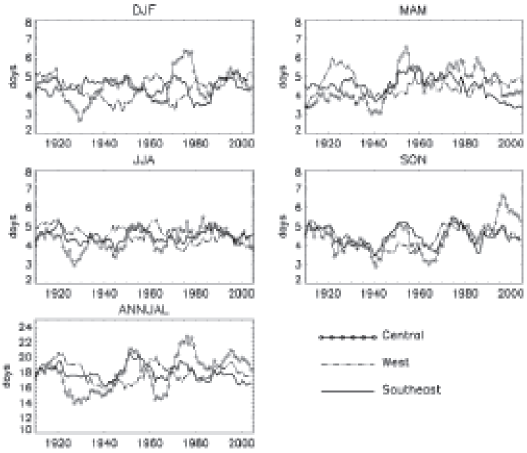


Fig. 7 **Time series of ten-year running means of the frequency of events above the long-term (1910-2005) 95th percentile (extreme frequency) for the Coastal, Southwest and Western Tablelands regions (see Fig. 1 for region definitions). Summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual time series are shown.**

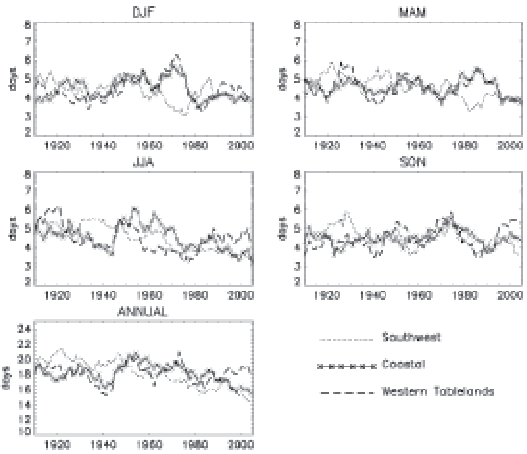


Fig. 8 **Time series of ten-year running means of the proportion of total rainfall due to events above the 95th percentile (extreme proportion) for six regions (see Fig. 1 for region definitions). Summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual time series are shown.**

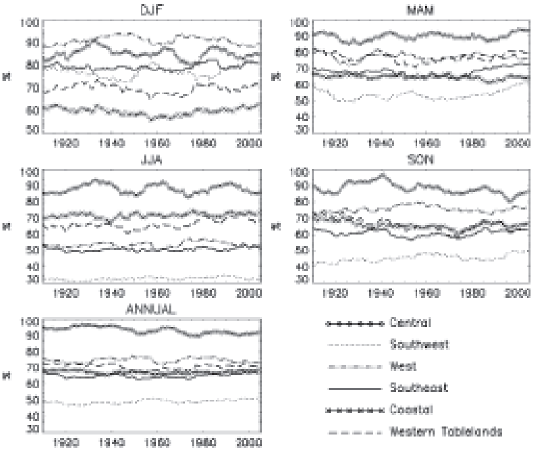
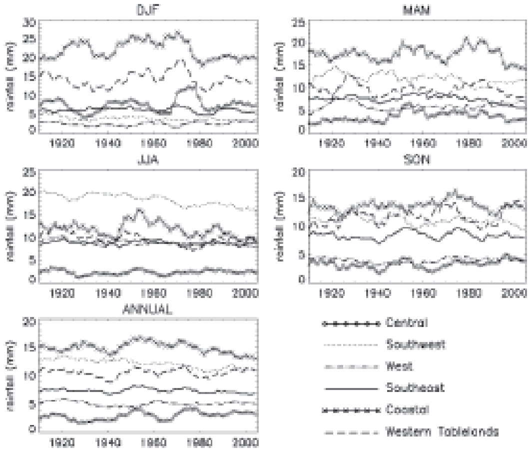


Fig. 9 **Time series of ten-year running means of the intensity of the 95th percentile (extreme intensity) for six regions (see Fig. 1 for region definitions). Summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual time series are shown.**



Because of the method of calculation, the extreme proportion index (Fig. 8) generally showed trends in the opposite direction to the other extreme indices. The extreme proportion (95th) was found by averaging all events above the 95th percentile for a given season/year and then dividing by the total rainfall for that season/year. The extreme proportion (99th) was calculated in the same way using the 99th percentile. This method is useful for understanding changes in extreme rainfall relative to changes in total rainfall and is the same as used in Haylock and Nicholls (2000). The method can be regarded as complementary to trends in rain days, from which an idea of whether total rainfall increases are stemming from one-day, extreme events can be formed. If the trend in the extreme proportion index is positive, the proportion of total rainfall stemming from extreme rainfall events is increasing; the opposite is also true. In the Southwest, Southeast and Coastal regions, both the total rainfall and extreme rainfall indices showed a decline. However, the changes in average intensities of extreme rainfall were smaller than those of total rainfall. This resulted in a positive trend in the extreme proportion index for these regions. Increases in the extreme proportion index were observed for the eastern Coastal and Southwest regions since the 1950s and in the Southeast since the 1970s. In the Central region a general decreasing trend in the annual extreme proportion index over the entire time series lends support to the notion of increasing rainfall due to an increase in the number of non-heavy rainfall days. The Western Tablelands showed increases in the annual extreme proportion from 1910 to 1950 and decreases from 1950 onwards.

Regional changes

A least-squares linear regression line was fitted to each time series for the two periods 1910-2005 and 1950-2005. Statistical significance was calculated for the 95% confidence level. Annual and seasonal results for all indices are presented for each region in Tables 3-8.

Central. Table 3 shows trends for the Central region were more significant over the long term (1910-2005) than the medium term (1950-2005). Statistically significant increases were found for the annual and spring number of rain days, the annual and spring 95th percentile intensity, and the annual 95th percentile frequency. There were significant decreases in annual and spring extreme proportion indices and rain per rain day, due to the general increase in total rainfall and rain days. The increase in annual total rainfall of approximately 5.6 mm per decade was not statistically significant. Trends calculated from 1950 onwards tended to be negative (except in spring) and insignificant. Annual total rainfall has declined by approximately 2.7 mm per decade since 1950.

Western Tablelands. The Western Tablelands (Table 4) did not exhibit many significant trends. The only significant trends over 1910-2005 were an increase in spring rain days of almost half a day per decade, a decrease in spring extreme proportion indices and an increase in the winter extreme proportion (99th percentile). In the medium term (1950-2005), there were significant increases in the autumn extreme proportion indices, the winter extreme proportion (99th) and the annual extreme proportion (95th), with a decrease in the annual extreme frequency (95th percentile). Though not statistically significant, the decrease in annual total rainfall of approximately 17.7 mm per decade is still substantial.

Coastal. In the eastern Coastal region, annual rain per rain day showed a statistically significant decline over the long term (1910-2005) while most other indices had non-significant decreases in the winter, summer and autumn and a slight increase in spring (Table 5). In the medium term (1950-2005), winter and summer decreases in total rainfall, rain days and extreme rainfall were statistically significant. Annual total rainfall has declined by almost 55 mm per decade since 1950. A decline in total rainfall along the Australian east coast was also reported by Collins and Della-Marta (2002) over the period 1900-2000.

Southeast. Long-term (1910-2005) trends in the Southeast (Table 6) showed a decline in most rainfall indices. This is contradictory to Hennessy et al. (1999), Suppiah and Hennessy (1998), Haylock and Nicholls (2000) and Nicholls and Lavery (1992), each of who found increases in most parts of southeastern Australia from 1910 (Table 1). Inconsistencies between those studies and the cur-

Table 3. Rainfall trends for the Central region, shown as the change in the index unit per decade. Bold indicates significance at the 95 per cent confidence level.

Central (1910-2005)	*Summer*	*Autumn*	*Winter*	*Spring*	*Annual*
Total rainfall (mm)	1.92	1.95	0.21	0.90	5.61
Rain days	0.23	0.18	0.08	**0.29**	**0.82**
Rain per rain day (mm/day)	-0.09	0.02	-0.02	**-0.20**	**-0.10**
Extreme intensity (95th) (mm/day)	0.12	0.11	0.02	0.10	**0.12**
Extreme intensity (99th) (mm/day)	0.58	0.61	-0.01	-0.07	0.11
Extreme proportion (95th) (%)	-0.08	0.32	-0.02	**-0.42**	**-0.54**
Extreme proportion (99th) (%)	-0.40	-0.03	-0.44	**-1.24**	**-0.66**
Extreme frequency (95th)	0.09	0.14	0.08	0.13	**0.42**
Extreme frequency (99th)	0.01	0.02	-0.01	-0.01	0.05

Central (1950-2005)	*Summer*	*Autumn*	*Winter*	*Spring*	*Annual*
Total rainfall (mm)	0.21	-6.21	0.03	2.55	-2.69
Rain days	0.08	-0.37	-0.04	0.42	0.21
Rain per rain day (mm/rain day)	-0.06	-0.17	0.02	0.02	-0.10
Extreme intensity (95th) (mm/day)	0.02	-0.38	-0.01	0.14	-0.03
Extreme intensity (99th) (mm/day)	0.10	-1.24	0.22	0.55	-0.29
Extreme proportion (95th) (%)	0.05	0.44	-0.28	-0.50	-0.19
Extreme proportion (99th) (%)	-0.18	1.58	-0.35	-0.90	-0.48
Extreme frequency (95th)	0.10	-0.35	-0.03	0.30	0.13
Extreme frequency (99th)	-0.01	-0.08	0.00	0.01	0.04

Table 4. Rainfall trends for the Western Tablelands region, shown as the change in the index unit per decade. Bold indicates significance at the 95 per cent confidence level.

Western Tablelands (1910-2005)	*Summer*	*Autumn*	*Winter*	*Spring*	*Annual*
Total rainfall (mm)	2.13	-0.65	-3.16	2.28	0.22
Rain days	0.14	0.06	-0.16	**0.43**	0.52
Rain per rain day (mm/rain day)	0.02	-0.09	-0.11	-0.10	-0.08
Extreme intensity (95th) (mm/day)	0.05	-0.09	-0.25	0.18	0.00
Extreme intensity (99th) (mm/day)	0.61	-0.20	-0.44	-0.41	-0.10
Extreme proportion (95th) (%)	-0.06	-0.15	**0.59**	**-0.92**	-0.17
Extreme proportion (99th) (%)	-0.02	-0.20	0.38	**-0.84**	-0.02
Extreme frequency (95th)	0.04	-0.04	-0.11	0.07	-0.02
Extreme frequency (99th)	0.03	-0.01	-0.03	-0.02	-0.01

Western Tablelands (1950-2005)	*Summer*	*Autumn*	*Winter*	*Spring*	*Annual*
Total rainfall (mm)	-6.96	-5.12	-1.82	-3.78	-17.72
Rain days	-0.55	-0.82	-0.58	-0.30	**-2.24**
Rain per rain day (mm/rain day)	0.05	0.13	0.19	0.02	0.10
Extreme intensity (95th) (mm/day)	-0.28	-0.35	-0.18	-0.09	-0.13
Extreme intensity (99th) (mm/day)	-0.94	-0.18	0.10	-0.59	-0.28
Extreme proportion (95th) (%)	0.63	**1.71**	**1.53**	0.49	**0.93**
Extreme proportion (99th) (%)	0.38	0.76	0.80	0.08	0.46
Extreme frequency (95th)	-0.12	-0.21	-0.04	-0.08	-0.37
Extreme frequency (99th)	-0.06	0.01	0.03	-0.04	-0.11

Table 5. Rainfall trends for the eastern Coastal region, shown as the change in the index unit per decade. Bold indicates significance at the 95 per cent confidence level.

Coastal (1910-2005)	*Summer*	*Autumn*	*Winter*	*Spring*	*Annual*
Total rainfall (mm)	-2.73	-0.96	-4.68	0.91	-7.03
Rain days	0.05	0.10	-0.26	0.16	0.10
Rain per rain day (mm/rain day)	-0.13	-0.15	-0.18	-0.05	**-0.12**
Extreme intensity (95th) (mm/day)	-0.17	-0.06	-0.28	0.07	-0.13
Extreme intensity (99th) (mm/day)	-0.21	-0.60	-1.01	0.19	-0.28
Extreme proportion (95th) (%)	-0.01	-0.20	0.26	-0.32	-0.04
Extreme proportion (99th) (%)	0.01	-0.16	0.35	-0.24	0.04
Extreme frequency (95th)	-0.03	-0.02	-0.13	0.01	-0.16
Extreme frequency (99th)	-0.02	0.00	-0.03	0.00	-0.04

Coastal (1950-2005)	*Summer*	*Autumn*	*Winter*	*Spring*	*Annual*
Total rainfall (mm)	**-19.66**	-6.84	**-21.91**	-5.16	**-54.84**
Rain days	**-0.9**	-0.24	**-0.90**	-0.35	**-2.40**
Rain per rain day (mm/rain day)	-0.18	-0.11	**-0.66**	-0.02	**-0.27**
Extreme intensity (95th) (mm/day)	**-1.00**	-0.32	**-1.18**	-0.17	**-0.75**
Extreme intensity (99th) (mm/day)	-2.53	-1.59	**-4.30**	-0.49	**-2.05**
Extreme proportion (95th) (%)	0.97	-0.09	0.68	0.46	0.37
Extreme proportion (99th) (%)	0.61	-0.03	0.65	0.33	0.27
Extreme frequency (95th)	**-0.25**	-0.11	**-0.54**	-0.05	**-0.98**
Extreme frequency (99th)	-0.07	-0.08	**-0.18**	-0.04	**-0.38**

Table 6. Rainfall trends for the Southeast region, shown as the change in the index unit per decade. Bold indicates significance at the 95 per cent confidence level.

Southeast (1910-2005)	*Summer*	*Autumn*	*Winter*	*Spring*	*Annual*
Total rainfall (mm)	-0.69	**-2.34**	-0.99	-0.42	-4.68
Rain days	-0.09	-0.22	-0.18	-0.09	-0.62
Rain per rain day (mm/rain day)	-0.03	-0.09	0.01	0.00	-0.02
Extreme intensity (95th) (mm/day)	-0.04	**-0.13**	-0.03	0.00	-0.05
Extreme intensity (99th) (mm/day)	-0.11	-0.39	-0.02	0.00	-0.08
Extreme proportion (95th) (%)	0.17	0.23	0.12	0.01	0.10
Extreme proportion (99th) (%)	-0.06	0.22	0.06	-0.06	0.06
Extreme frequency (95th)	0.00	-0.08	0.01	0.00	-0.10
Extreme frequency (99th)	0.00	-0.03	0.00	0.00	-0.03
Southeast (1950-2005)	*Summer*	*Autumn*	*Winter*	*Spring*	*Annual*
Total rainfall (mm)	-0.66	**-10.74**	-3.15	-3.63	-19.69
Rain days	-0.06	**-1.17**	-0.48	-0.60	-2.55
Rain per rain day (mm/rain day)	0.04	**-0.21**	-0.02	0.03	-0.05
Extreme intensity (95th) (mm/day)	-0.11	**-0.58**	-0.13	-0.19	-0.25
Extreme intensity (99th) (mm/day)	-0.14	**-1.36**	-0.24	-0.29	**-0.47**
Extreme proportion (95th) (%)	0.39	**1.83**	0.33	0.87	**0.75**
Extreme proportion (99th) (%)	0.20	**1.50**	0.25	0.65	0.46
Extreme frequency (95th)	0.04	**-0.44**	-0.04	-0.06	-0.59
Extreme frequency (99th)	0.01	**-0.13**	-0.02	-0.01	-0.17

rent study lie in the period over which trends were calculated. The present study calculated trends to 2005 while the previous studies only had data available to the mid 1990s or earlier. This indicates that the update to 2005 (and the associated continued decreases in rainfall over the Southeast) has contributed to the change in direction of the long-term record compared to those previous studies. The strongest trends in the present study occurred from 1950. The extension of the time series to 2005 has changed the appearance of trends in the region, with non-significant decreasing trends apparent for most indices from 1910-2005. Changes in the direction of the trend when calculated over differing time periods are also highlighted in Manton et al. (2001), where trends determined from 1961 differed from other studies. These differences highlight the need for constant, ongoing monitoring of such trends in rainfall indices and also caution against using these trends to imply future trends, especially for such a highly variable quantity as rainfall.

Significant decreases in total rainfall and the extreme intensity (95th percentile) indices have occurred during autumn (1910-2005). Non-significant decreases in total rainfall and rain days occurred in all other seasons. In the medium term (1950-2005) all autumn indices showed significant decreases, except the extreme proportion indices, which increased significantly. Total autumn rainfall has decreased by about 11 mm per decade since 1950, contributing to a significant decrease in annual total rainfall of 20 mm per decade. Extreme intensity indices and the extreme frequency (95th percentile) have decreased significantly, and the extreme proportion (95th percentile) has increased significantly, primarily due to large changes in autumn.

West. The West (Table 7) showed no significant trends in rainfall. However, some consistency in the direction of trends occurred for some seasons for both the 1910-2005 and 1950-2005 periods. Winter rainfall for both periods generally showed non-significant decreases. The summer and spring months showed fairly consistent increases in most indices. Annual total rainfall has increased by almost 3 mm per decade since 1950.

Southwest. For the Southwest (Table 8) many statistically significant rainfall decreases have occurred in both the long-term (1910-2005) and medium-term (1950-2005) records. This is consistent with the findings of other studies (Table 1). For

Table 7. Rainfall trends for the West region, shown as the change in the index unit per decade.

West (1910-2005)	*Summer*	*Autumn*	*Winter*	*Spring*	*Annual*
Total rainfall (mm)	0.81	-0.11	-1.60	0.33	-0.54
Rain days	0.01	-0.01	-0.11	0.02	-0.04
Rain per rain day (mm/rain day)	0.11	0.01	-0.03	0.02	0.00
Extreme intensity (95th) (mm/day)	0.03	0.03	-0.13	0.00	-0.02
Extreme intensity (99th) (mm/day)	0.40	-0.24	-0.02	0.14	0.00
Extreme proportion (95th) (%)	0.03	-0.03	0.14	0.06	0.06
Extreme proportion (99th) (%)	0.19	-0.17	0.21	0.10	0.11
Extreme frequency (95th)	0.02	0.01	-0.10	0.02	-0.06
Extreme frequency (99th)	0.03	0.01	-0.02	0.01	-0.01

West (1950-2005)	*Summer*	*Autumn*	*Winter*	*Spring*	*Annual*
Total rainfall (mm)	0.85	1.67	-1.14	1.30	2.77
Rain days	0.04	0.02	-0.10	0.26	0.27
Rain per rain day (mm/rain day)	0.00	0.05	-0.01	0.06	0.04
Extreme intensity (95th) (mm/day)	0.06	0.10	-0.07	0.08	0.04
Extreme intensity (99th) (mm/day)	0.39	0.13	-0.21	0.21	0.14
Extreme proportion (95th) (%)	-0.04	0.03	-0.16	-0.67	-0.33
Extreme proportion (99th) (%)	-0.23	-0.03	-0.16	-1.12	-0.15
Extreme frequency (95th)	0.06	0.02	-0.07	0.18	0.05
Extreme frequency (99th)	0.02	0.07	-0.01	0.02	0.02

Table 8. Rainfall trends for the Southwest region, shown as the change in the index unit per decade. Bold indicates significance at the 95 per cent confidence level

Southwest (1910-2005)	*Summer*	*Autumn*	*Winter*	*Spring*	*Annual*
Total rainfall (mm)	-1.52	**-5.0**	-10.34	-3.43	-20.66
Rain days	-0.20	**-0.44**	-0.48	-0.50	-1.64
Rain per rain day (mm/rain day)	-0.07	-0.06	-0.14	-0.01	-0.08
Extreme intensity (95th) (mm/day)	-0.11	-0.25	-0.37	-0.14	-0.26
Extreme intensity (99th) (mm/day)	-0.22	-0.39	-0.84	-0.22	-0.41
Extreme proportion (95th) (%)	0.20	**0.47**	0.19	0.61	0.28
Extreme proportion (99th) (%)	0.55	0.31	0.09	0.30	0.18
Extreme frequency (95th)	-0.10	-0.15	-0.22	-0.09	-0.62
Extreme frequency (99th)	-0.04	-0.03	-0.06	-0.01	-0.20

Southwest (1950-2005)	*Summer*	*Autumn*	*Winter*	*Spring*	*Annual*
Total rainfall (mm)	-4.07	**-7.26**	-9.15	-2.21	**-23.54**
Rain days	-0.27	**-0.79**	-0.18	-0.42	-1.71
Rain per rain day (mm/rain day)	-0.34	-0.03	**-0.17**	0.04	-0.09
Extreme intensity (95th) (mm/day)	-0.17	-0.27	**-0.50**	-0.07	**-0.28**
Extreme intensity (99th) (mm/day)	-1.17	-0.56	**-0.64**	-0.15	**-0.76**
Extreme proportion (95th) (%)	0.31	**1.32**	-0.19	0.32	0.11
Extreme proportion (99th) (%)	0.77	0.78	-0.02	0.17	0.23
Extreme frequency (95th)	-0.24	-0.15	**-0.24**	-0.06	**-0.79**
Extreme frequency (99th)	-0.13	-0.05	**-0.11**	0.04	**-0.39**

1910-2005, eight of the nine annual indices showed a decreasing trend that was statistically significant. This was reflected in the medium-term record for total rainfall, both extreme intensity indices and extreme frequency (99th percentile). Annual declines stemmed from large and significant changes in winter rainfall, and to a lesser extent autumn and spring rainfall. Annual total rainfall has decreased by 21 mm per decade since 1910, and by 24 mm per decade since 1950. The annual number of rain days has dropped by approximately 1.6 days per decade since 1910. Consistent decreases in all indices except the extreme proportion have occurred in all seasons, though magnitudes in summer are smaller and generally not significant.

Medium-term (1950-2005) changes were similar on an annual scale, with winter and autumn again showing large, statistically significant decreases. Decreases during spring were not significant. In summer, significant declines were evident in rain per rain day, and extreme intensity and frequency for the 99th percentile.

Uncertainty analysis

The number of stations used for time series calculation in each region fluctuated from year to year due to the requirement of years/seasons to have no more than 10% of daily data missing. For all regions the maximum number of missing stations was approximately 30% of the maximum number of stations. To test the dependency of trends on the selection of stations, 30% of stations were randomly removed in each region and trends were re-calculated. Each set of station combinations was unique. A limit of 100 combinations was set where over 100 combinations were possible. The analysis was undertaken over the two time periods (1910-2005 and 1950-2005) on the annual time series for each index.

Regions exhibiting statistically significant trends in the original analysis showed few changes in direction with random station removal. Only two of the originally statistically significant trends showed any directional change: one index showing a change in 1% of runs (Southeast, extreme 95th percentile frequency from 1950-2005) and the other in 28% of runs (Western Tablelands, 95th percentile extreme frequency from 1950-2005). Time series that were originally not statistically significant showed a change in the direction of the trend, on average, in 13% of runs. Maximum and minimum error bounds and the average time series of sampled runs are shown for one statistically significant index (Fig. 10) and one non-statistically significant index (Fig. 11).

Fig. 10 **Time series of regionally averaged total rainfall (in mm) for the Southwest region as calculated from all available stations (solid line). The upper and lower bounds (dotted lines) and the average (dashed line) of regional average total rainfall are shown after recalculation using all combinations of stations with one station randomly removed.**

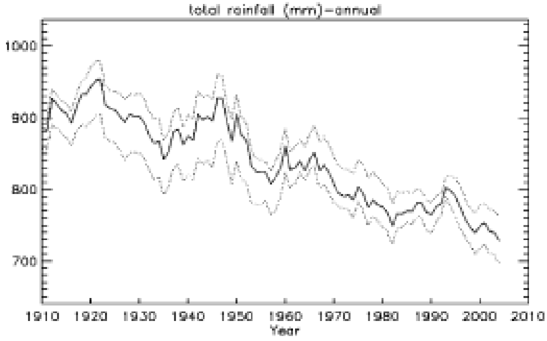
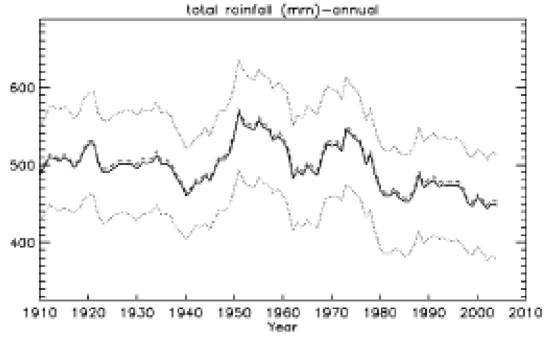


Fig. 11 **Time series of regionally averaged total rainfall (in mm) for the Southeast region as calculated from all available stations (solid line). The upper and lower bounds (dotted lines) and the average total rainfall (dashed line) after recalculation with 30 per cent of stations randomly removed are shown.**



As expected, statistical significance of the time series varied more than direction with random station removal. An envelope of ±10% of the original significance value was considered acceptable. Re-calculated time series for indices that originally exhibited statistical significance generally gave values outside the acceptable level for significance 13% of the time. Time series that were originally not statistically significant only gave acceptable significance (±10% of the original value) in an average of 50% of re-calculated time series.

From the uncertainty analysis, statistically significant trends and some non-significant trends with changes of large magnitudes were considered robust. Re-calculated time series with weak, non-significant trends were generally not considered robust. In the discussion that follows, attention is focused on more robust changes to rainfall.

Discussion

Australian rainfall is dominated by high interannual variability (Nicholls et al. 1997), some of which can be attributed to air-sea interactions such as the El Niño-Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) (Power et al. 1998; 1999). However, the importance of determining changes in Australian rainfall regimes can be highlighted by outlining the impacts extreme rainfall can have on the Australian economy and environment. The droughts of 1982-1983, 1991-1995 and 2002-2003 cost approximately A$3 billion, A$5 billion and A$10 billion, respectively (Adams et al. 2002; BoM 2006). Government drought relief averaged A$100 million per year from 1992-1999 (SOE 2001). Extremely wet years like 1955-1956, 1973-1975 and 2000 were associated with good crop yields (Pollock et al. 2001) and dam levels (Maheepala et al. 2004), but also significant flood and cyclone damage (BoM 2005). From 1967 to 1999, economic damages from weather-related events in Australia averaged A$960 million per year, mostly due to floods, severe storms and tropical cyclones. More recently, insurance claims following the southeast Australian storm on 2 February 2005 reached A$200 million (IDRO 2006).

Our study builds upon the growing body of evidence for regional changes in rainfall. Using an updated high-quality rainfall data-set from 1910-2005, we have re-assessed and extended previously documented decadal variability and trends in annual and seasonal rainfall, including daily extremes. Nine rainfall indices have been calculated in six regions in southern and eastern Australia from 1910-2005 and 1950-2005. This has provided insight into whether previously documented trends have strengthened or weakened, and new information about emerging trends.

In the Central region, significant increases in mean and extreme rainfall were evident from 1910-2005. This is consistent with increases in total rainfall observed from 1910 to the late 1980s in a similar region by Nicholls and Lavery (1992). It is also consistent with the findings of Suppiah and Hennessy (1998), Hennessy et al. (1999) and Haylock and Nicholls (2000) who found generally increasing trends from 1910 to the 1990s in a similar area. Increases in total rainfall and rain days, along with significant decreases in extreme proportion indices and rain per rain day, indicate that increases in rainfall are due to an increase in the number of days with light and moderate rainfall events.

A qualitative assessment of time series showed large decreases for both seasonal and annual rainfall since the 1950s in the eastern Coastal and Southwest regions and since the 1970s for the Southeast. This was then established quantitatively through the detection of large and significant decreases in rainfall for all regions since 1950 using linear trends and significance testing. All authors in Table 1 have previously documented rainfall declines in the Southwest. Our results strengthen their findings. The declines are primarily due to a southward shift in rain-bearing synoptic circulations since the 1970s, which has been partly attributed to natural variability, the enhanced greenhouse effect and stratospheric ozone depletion (IOCI 2002; Hope et al. 2006).

From the time series, it is clear that in the Southeast and eastern Coastal regions mean and extreme rainfall has recently decreased to a point lower than at any other time in the long-term record (Figs 3 to 8). Tables 5 and 6 show significant decreasing linear trends in many indices from 1950 onwards but few significant trends from 1910, though some are apparent. These large decreases have occurred primarily during autumn in the Southeast and during summer and winter in the eastern Coastal region. This study reinforces the direction of rainfall trends in these regions since the mid 20th century as reported in Manton et al. (2001), Smith (2004) and Alexander et al. (2007). However, it is now apparent that recent downward trends in rainfall are dominating the long-term record (1910-2005) in these regions, something that was not evident in previous studies (Table 1). Some cases, such as autumn rainfall in the Southeast, now show significance at the 95% level from 1910. It is especially clear that trend directions in the long-term record for these regions are generally opposite of many studies whose data finish in the mid 1990s (Nicholls and Lavery 1992; Suppiah and Hennessy 1998; Plummer et al. 1999; Hennessy et al. 1999; Haylock and Nicholls 2000). Nicholls and Lavery (1992) noted that there had been increasing summer rainfall for much of the 20th century in southeastern Australia, but that this had reverted towards decreasing rainfall in the 1980s. With the extension of the rainfall record it is now evident that this decrease in rainfall has continued and is now influencing the long-term trend, especially during the autumn months. The differences in trends (between past and current studies) emphasise the continuing need for updating and monitoring these trends.

Mechanisms causing rainfall in the Australian region occur on a number of time-scales. Interannual and interdecadal variability is influenced by large-scale climate systems and variability within these, while daily rainfall is influenced more through synoptic systems. Both of these long and short time-scale phenomena play a role in influencing trends in Australian rainfall. A primary mechanism dominating eastern Australian rainfall is ENSO, which causes anomalously high or low rainfall in the eastern States (McBride and Nicholls 1983; Allan 1988). Since the 1970s, the phase of ENSO has shifted toward more El Niños, which traditionally bring dry conditions (Suppiah 2004). This shift may be influencing the trends towards decreasing rainfall observed in some regions in the eastern half of the country during the latter half of the 20th century. On the synoptic scale, Simmonds and Keay (2000) and Fyfe (2003) examined trends in southern hemispheric (SH) mid-latitude cyclones using the National Centers for Environmental Prediction (NCEP) data and found evidence that the number of mid-latitude cyclones in the SH region has decreased from the 1970s to the late 1990s. Both studies partially attributed this to a warming in SH temperatures during this time. Fyfe (2003) simulated similar changes using a general circulation model inclusive of greenhouse gas and sulphate aerosol forcings, providing evidence that human-induced global warming could be contributing to the decline in mid-latitude cyclones. As much of southern Australia receives its rainfall from cold fronts stemming from these cyclones, or the cyclones themselves (SOE 2001), it is pertinent to consider that this decrease may be contributing to the observed rainfall decline in the Southeast region.

Increases to inland mean rainfall in the Central region and decreases to both mean and extreme rainfall in the Southwest strengthen previously documented trends in these areas (Table 1). Potential mechanisms for the increases in northwest Australia have been given by Rotstayn et al. (2007), who used a Global Climate Model (GCM) to show that increases in anthropogenic aerosols in southeast Asia have lead to increased cloudiness and rainfall during the 20th century over northwest Australia. Wardle and Smith (2004) simulated the increasing trends in observed surface temperature over Australia since 1950 by altering the surface radiation budget (through varying surface albedos) in a general circulation model. These surface changes induced trends in rainfall in northern Australia similar to those observed and consistent with a more active summer monsoon.

The strong statistical significance of trends in some regions demonstrates the importance of considering smaller coherent rainfall regions rather than trying to investigate large-scale changes on the continental scale. This is epitomised in the Southwest where only a very small region is significantly affected by a strong and persistent rainfall decline.

Conclusions

Nine rainfall indices measuring both mean and extreme rainfall were calculated for six regions in southern and eastern Australia for the periods 1910-2005 and 1950-2005. Decadal variability and trends have been assessed. Significant increases in annual rain days, rain per rain day and extreme rainfall have occurred in the Central region since 1910, mainly due to significant increases in spring. The number of spring rain days has also increased in the Western Tablelands, along with a decrease in the proportion of total spring rainfall attributed to extreme daily rainfall.

Strong declines were found in the Southeast, Coastal and Southwest regions for both mean and extreme rainfall. These decreases can be mostly attributed to changes occurring since the 1950s. Decreases in the Southeast region were due to a significant decrease in autumn rainfall indices while Coastal and Southwest changes were primarily due to significant decreases to mean and extreme winter rainfall indices. Although no significant changes were found in the West region, large and significant decreases were evident in the Southwest subregion, partially due to a southward shift in rain-bearing weather systems. Evidence from previous studies (Simmonds and Keay 2000; Fyfe 2003) has shown a decline in the number of southern hemisphere mid-latitude cyclones from the early 1970s to the late 1990s, which may partly explain the rainfall decreases in the Southeast. The increased frequency and severity of El Niño events since the 1970s may partially explain the decreases in rainfall in the eastern Coastal region as well as the Southeast.

Updated rainfall data-sets have provided new information on medium-term and long-term trends. Calculated time series have shown some new trends, emergent since the mid 1990s, as well as strengthened other trends found in previous studies. Most rainfall studies pre-2000 (Table 1) indicated non-significant increasing rainfall in parts of eastern Australia that, with the update to 2005, are now showing strong (and in some cases significant) decreases since 1910, including many significant decreases since 1950. Trends from this study are more consistent with findings from three recent studies. Collins and Della-Marta (2002) mentioned decreases in east coast and southwest rainfall as did Manton et al. (2001), who also mentioned declines from 1961 in the southeast.

Alexander et al. (2007) showed some seasonal declines in similar regions for an index comparable to total rainfall and highlights the recent autumn decreases from 1950 for the southeast of Australia.

While decreases in extreme rainfall in these areas decrease the risk of floods, trends in the Southeast and eastern Coastal regions should continue to be monitored due to the potential for significant biophysical impacts on these areas if trends in mean rainfall continue. These regions contain some of the most populous parts of the country. Stresses on agriculture and water resources in the area are already of some concern. If decreases in mean rainfall persist, problems would be further exacerbated.

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