.

Australian rainfall changes, 1910-1995

Kevin J. Hennessy, Ramasamy Suppiah, Cher M. Page

CSIRO Atmospheric Research, Aspendale, Australia

(Manuscript received September 1997; revised April 1998)

Annual and seasonal trends in heavy daily rainfall, total rainfall and the number of rain days were calculated for the whole of Australia and each State/Territory from 1910 to 1995, using high-quality daily data from 379 stations. Trend significance was determined using the Kendall-tau test and trend magnitudes were computed from linear regression. While many statistically significant trends were found, non-significant trends judged to be of special interest are noted.

From 1910-1995, annual total rainfall has undergone secular changes with a significant 14 per cent increase in Victoria and non-significant increases of 15-18 per cent in New South Wales (NSW), the Northern Territory (NT) and South Australia (SA). When analysed seasonally, non-significant changes of 10-40 per cent were found in some States.

Heavy rainfall indices were defined as the 99th and 95th percentiles (the highest and 5th highest daily amounts, respectively, in each three-month season). Australian areal-mean heavy rainfall has not changed significantly in any season. However, on a regional basis significant increases in heavy rainfall emerged in SA in summer and NSW in autumn, while significant decreases occurred in southwest Western Australia (SWWA) in winter. Important non-significant increases of 10-45 per cent were also found in some States.

There has been a significant 10 per cent rise in the annual Australian-average number of rain days. Significant increases of almost 20 per cent were found in the NT and NSW despite a significant 10 per cent decline in SWWA. Regionally, significant increases of 20-50 per cent have occurred in some States, with large changes in the frequency of light rainfall.

Strong correlations exist between interannual variations in temperature, total rainfall, heavy rainfall and the number of rain days. Increases in Australian rainfall since 1910 are generally linked to an increase in heavy rainfall and the number of rain days. ENSO variability is partly responsible, as is enhanced monsoon activity in the 1970s and changes in other large-scale circulation features. Decreased rainfall in southwest WA is also linked to circulation changes.

Introduction

Numerous studies have analysed Australian rainfall data using a variety of techniques, climate stations, regions and periods (e.g. Gibbs et al. 1978; Russell 1981; Gregory 1991; Allan and Haylock 1993; Butterworth and Arthur 1993; Lough 1993, 1997; Nicholls and Kariko 1993 (and papers cited within); Yu and Neil 1993; Mollah and Cook 1996; Nicholls et al. 1996; Lavery et al. 1997; Nicholls et al. 1997). In broad terms, these studies have concluded that summer rainfall has increased in eastern Australia over the past century, and winter rainfall has decreased in the southwest, with large decadal-scale fluctuations.

Changes in heavy rainfall intensity have been reported for various Australian regions. Yu and Neil (1991) found no trends in events over 40 mm/day at 17

Corresponding author address: Kevin J. Hennessy, CSIRO Atmospheric Research, Private Bag No. 1, Aspendale 3195, Australia. e-mail: kjh@dar.csiro.au

stations in southeast Australia from 1889 to 1985. In another study, Yu and Neil (1993) reported that while annual average rainfall in southwest Western Australia decreased during the period 1911-1990, heavy rainfall increased, particularly in spring and summer. Nicholls and Kariko (1993) investigated rainfall data at five representative stations in east Australia from 1910 to 1988 and found an increase in rainfall which was mainly due to more rain days rather than higher rainfall intensity. Lough (1993) found that periods of increased summer rainfall in Queensland were largely due to increases in heavy rainfall exceeding 50 mm/day, while increases in winter stemmed mainly from increases in events exceeding 10 mm/day. Suppiah and Hennessy (1996) found increases in the 90th percentile threshold for daily rainfall over most parts of tropical Australia for the months September to April from 1910 to 1990, but statistically significant increases occurred at only 10 of the 53 stations considered. Subsequently, Suppiah and Hennessy (1998) analysed 90th and 95th percentiles at 125 high-quality sites over the whole of Australia and found widespread significant increases, except for significant decreases in winter over southwest Western Australia.

Some studies focused on specific regions and some focused on representative stations to determine trends in rainfall intensity. In the present study, various characteristics of rainfall over Australia have been investigated using 379 well-distributed stations considered to have high quality on a monthly time-scale (Lavery et al. 1997). Further refinement of these data was undertaken to produce a new set of stations with high quality at the daily time-scale. A new perspective is advanced for temporal and spatial characteristics of Australian rainfall over the past century on the continental scale and within political boundaries, using daily data which have been screened for inhomogeneities.

The present study has three aims: (a) to improve the reliability of results by using a new set of high-quality daily data for the whole of Australia from 1910 to 1995, (b) to consider changes in total rainfall, rain days and extremely high rainfall events, and (c) to compute the magnitude and significance of annual/seasonal trends in regions defined by political boundaries.

Data and methods

Data quality

Daily (24-hour total) rainfall data from 379 high-quality stations (Lavery et al. 1997) were analysed from December 1909 to November 1995 (86 years). Figure 1 shows the locations of stations used in this study. This set of 379 stations is an extension of the set of 191 highFig. 1 Locations of the 379 high quality rainfall stations used in the study. Asterisks indicate locations of 191 single-station sites and circles indicate the additional 188 composite-station sites. Composite stations include data from two neighbouring stations and single stations have data from one station. Source: Lavery et al. (1997).



quality stations identified by Lavery et al. (1992). The additional 188 stations were created from composites of two or three neighbouring stations by Lavery et al. (1997). In fact, the 188 composite stations are constructed from a total of 383 stations (documented by the National Climate Centre), so the entire analysis involved 574 stations (191 + 383). All stations passed homogeneity tests performed by Lavery et al. (1992, 1997) which analysed changes in rain-gauge locations, observing practices, conversion of rainfall records to the metric system, and urban influences. This dataset is acceptable on a monthly time-scale. However, many stations still have problems with daily rainfall data due to missing values. Therefore we performed two additional checks to produce a high-quality daily rainfall dataset.

Firstly, rainfall records were checked for missing data and a station was accepted in a particular year if it had less than 10 per cent of days missing and less than five consecutive days missing. Secondly, records were checked for accumulated rainfall data. Sometimes rain gauges were not read for several days, so rainfall records appear as an accumulated total followed by flags indicating the accumulation period and the number of rain days in that period. A station was accepted in a given season or year if it had (a) less than 10 per cent of rain days in accumulated rainfall records and (b) less than five consecutive days of accumulated data in a year. Of the remaining stations with an acceptable amount of accumulated data, each rain day in an accumulation period was assigned the value of the accumulated total divided by the number of rain days. For example, a total of 20 mm accumulated over three days including two rain days would be replaced by two days of 10 mm and one day of 0 mm. Suppiah and Hennessy (1996) found that calculated rainfall trends were insensitive to the method of replacement of accumulated values.

Since the 1970s, there has been an increase in the number of rainfall accumulations recorded at many stations. The National Climate Centre (Neil Plummer, personal communication) believes this reflects a decline in recording of weekend rainfall. Plummer et al. (1997) show a marked decrease in frequently reporting rainfall stations around the early to mid 1970s. At many of the post office stations, this is because Australia Post went from a 5.5 day a week operation to 5 days from 23 Feb 1974. Restrictions to site access may have been increased around this period (Thompson, personal communication) and the rise in records of weekend rainfall accumulation may also reflect a decline in observer interest or increased observer mobility (Nicholls, personal communication). The tendency for more accumulations since 1970 may have abated in the last 3-5 years since many post offices have ceased recording rainfall and an increasing number of automated weather stations run seven days per week.

The smaller number of accumulation records in the first half of the century is most likely a true reflection of observer diligence, rather than failed reporting of actual accumulations. This is supported by the fact that, when accumulated rainfall records are removed from the analysis, average Monday rainfall in each decade is similar to that recorded on all other days of the week (Groisman, personal communication). If failed reporting of weekend rainfall had occurred, excessive Monday rainfall would be expected. However, it appears as though Sunday rainfall has not been recorded reliably in each decade because average Sunday rainfall is about 10 per cent lower than that for other days of the week.

A possible source of bias in the trends may stem from the conversion from imperial to metric units in 1974. Before 1974, rainfall was registered if at least 0.005 inches (0.127 mm) fell, but after 1974 rain amounts of at least 0.1 mm were registered. Hence there may be an artificial rise in the number of rain days after 1974 due to metrication. To test the effect of metrication on rain-day trends in the present study, results for two rain-day definitions were compared. The increasing trend is enhanced when a rain-day is defined as more than 0 mm/day rather than at least 1 mm/day. Time series show a clear discontinuity in rain days around 1974 when the former definition is used. To avoid the artificial discontinuity in rain days around 1974 when using the 0 mm/day threshold, we use the 1 mm/day threshold throughout this study. The choice of rain-day definition made no difference to the trends for total rainfall or heavy rainfall, which is consistent with the conclusions of Lavery et al. (1992) and Nicholls and Kariko (1993) who found no obvious bias in rainfall variability due to metrication.

For each year, different combinations of stations passed the above quality checks. The number of acceptable stations increased from 1910 to 1988 (266 in 1910, 327 in 1930, 354 in 1950, 361 in 1970, 370 in 1988), then declined rapidly due to missing data and station closures (347 in 1991, 305 in 1993, 236 in 1995). Prior to 1907, fewer than 150 stations passed the quality check.

Variables analysed

In those years when a station passed the quality checks, seasonal and annual values of heavy rainfall, total rainfall and the number of rain days were computed. Heavy rainfall was defined in two ways: the 99th and 95th percentiles of daily rainfall which, in a three-month season (90-92 days), are represented by the highest and 5th highest values, respectively. Annual 99th and 95th percentiles are the 4th highest and 18th highest values, respectively. The 95th and 90th percentiles were used in two other Australian studies of heavy rainfall (Suppiah and Hennessy 1996, 1998), and the 99th percentile is used here to represent very heavy rainfall.

Upper percentile thresholds provide an objective measure of extremes for a country like Australia which has high spatial variations in rainfall. For example, at 53 stations in northern Australia, the mean 95th percentile threshold for the wet months from September to April ranges from 3 to 45 mm/day, with larger values occurring near the coast (Suppiah and Hennessy 1996). Extreme rainfall in the north is associated with tropical cyclones, monsoon depressions and local thunderstorms. In southeast Australia, the summer 95th percentile is 4 to 28 mm/day and the winter 95th percentile is 4 to 21 mm/day. In southwest WA the winter 95th percentile is 7 to 20 mm/day and summer rainfall is low. In southeast and southwest Australia, extreme summer rainfall is associated with convective activity while in winter it is linked with mid-latitude frontal systems and extratropical low pressure systems. Changes in the magnitude of the upper percentiles are used here to determine changes in heavy rainfall intensity.

Note that the 99th and 95th percentiles are computed from all days in a given season, not just rain days. This means that in dry regions/seasons with few (<15) rain days, the 95th percentile (5th highest amount) may be as low as the median rain intensity, and therefore not particularly extreme. However, in wet regions/seasons with many (>45 rain days), the 95th percentile adequately represents extreme rainfall. To supplement the analysis of changes in the intensity of heavy rainfall, changes in the frequency of heavy rainfall are computed for thresholds of 25.4 mm/day (1 inch) and 50.8 mm/day (2 inches). Changes in light (1-5 mm/day) and moderate (5-15 mm/day and 15-25 mm/day) rainfall are also computed so that shifts in frequency distributions can be determined.

As stated earlier, rain days were defined as records with at least 1 mm. Total rainfall is computed from the sum of days with at least 1 mm of rain.

Spatial interpolation

After computing annual or seasonal values of total rainfall, heavy rainfall and number of rain days at each station, an aggregation procedure was applied to each variable in order to produce areal average time series for various regions of interest.

Since stations are irregularly spaced, each station was weighted according to the area it represents. Stations with more-distant neighbours represent larger areas and were given higher weight using a modification of the Thiessen Polygon method used by Torok and Nicholls (1996) and Lavery et al. (1997). Weights were calculated for each station and could vary from year to year because surrounding stations were excluded if they failed the quality check. This method of calculation of weights is the same as that used by Lavery et al. (1997) except that we compute weights for every station every year whereas Lavery et al. (1997) calculated weights every ten years. Hence the regional and continental rainfall time series presented in this paper optimises the available data in each year, whereas the time series produced by Lavery et al. (1997) are derived from a set of stations whose number changes in decadal steps.

To compute an area-weighted rainfall index in a given year, the Thiessen Polygon weight was multiplied by the value of the rainfall variable. Rainfall indices were computed for each Australian State or Territory except the ACT. Southwest Western Australia is given special attention because previous studies have shown a marked drying trend in the last 50 years (e.g. Pittock 1983; Allan and Haylock 1993).

In data-sparse regions where single high-quality stations failed to span the entire period, Lavery et al. (1997) combined records from two or more neighboring stations with shorter overlapping records to form a composite long-term record. When rainfall records from two stations were composited, a conversion factor was used to modify data from the secondary station in order to extend the primary record. The conversion factor was based on the average difference between annual rainfall totals of the pair of records in the overlap period. This is appropriate for creating composite annual rainfall time series, but it is not suitable for seasonal time series of daily rainfall. More sophisticated correction factors would be needed to create composite daily time series. However, since the focus of this paper is on arealaverage time series and trends, a simple alternative to station-composite daily time series can be applied. When records for the primary station are missing, uncorrected records from the secondary station are used with an area weighting determined by the same method described above, rather than applying a correction factor to records at the secondary station. In essence, we use the same high-quality stations as Lavery et al. (1997) but apply differential area weighting rather than annual correction factors to fill data gaps in records at neighboring stations.

Use of regions defined by political boundaries, rather than climatological or other geographical boundaries, was chosen to meet the growing need for such information by government departments and the Australian community. Given the discrepancy between the area of each State/Territory, trends in quadrants of approximately equal area have also been analysed in a related paper (Plummer et al. in press).

Trend analysis

For each region, area-weighted rainfall indices were computed year by year, then plotted as a time series. To test the significance of changes in rainfall over time, we used the Kendall-tau test (Press et al. 1986). This non-parametric method requires no assumptions about the underlying data distributions and assesses the degree of independence between two time series x and y. If the x values are arranged in increasing order, the extent to which their corresponding y's depart from increasing order indicates the weakness in the correlation between x and y. The number of ranking changes among the y's that will put them in the same order as the x's is called the number of inversions Q. Kendall's tau coefficient is defined as

$$\tau = 1 - 4Q/(n(n-1))$$

where *n* is the sample size. If *x* and *y* are independent $\tau = 0$, if x and y have a perfect positive correlation $\tau = 1$, and a perfect negative correlation gives $\tau = -1$. To reject independence at the five per cent significance level, τ must lie outside the limits $\pm 4/(3\sqrt{n})$. For univariate rainfall observations *y* ordered in time from 1910 to 1995, *x* is simply the time variable and *n* is 86. Henceforth, we call trends 'significant' if they reach the five per cent significance level.

Since this test only determines the sign of significant trends, we supplemented this method with a linear regression analysis to determine the magnitude of rainfall changes from 1910 to 1995. For each region, we fitted a regression line defined by rainfall $R=R_{1910} + b$ (year-1910), where R_{1910} is the rainfall value for the year 1910 on the regression line. The percentage change over the 86 years from 1910 to 1995 has been calculated as 100*86 b/R_{1910} . Note that this percentage change is relative to the 1910 rainfall value on the regression line.

In this study we are seeking signals amongst relatively noisy time series, using standard statistical methods to decide whether trends are statistically significant. As is well known, such methods are designed to make it relatively unlikely that a trend is falsely detected when none exists; the conventional five per cent significance level is used here. However, given that the early detection of long-term trends is of great practical importance to hydrologists, climatologists, farmers, policy-makers, etc., in our application we are also concerned with the converse failure to detect a trend when one exists. Accordingly we have indicated statistically non-significant apparent trends which are judged to be of special interest; all such cases are explicitly identified below.

Results

Total rainfall

Year-to-year changes in annual total rainfall (from daily events of at least 1 mm) averaged over the whole of Australia are shown in Fig. 2. Underlying decadal-scale variability is evident. Total Australian rainfall was greatest around 1910-1920, 1950-1960 and 1970-1980, particularly during the La Niña year of 1974. The low average rainfall in 1994 was similar to that in 1952, 1961 and 1970, while 1965 was the driest since 1910.

The annual average rainfall of Australia (AUS) is about 470 mm, but varies from 200 mm in South Australia (SA) to over 1100 mm in Tasmania (TAS) (Fig. 3(a)). In Figure 2, the linear regression line shows that from 1910 to 1995 there has been a non-significant six per cent increase in annual total rainfall in Australia. Figure 3(b) shows that this is comprised of a significant 14 per cent increase in Victoria (VIC), nonsignificant increases of 15-18 per cent in the Northern Territory (NT), New South Wales (NSW) and SA, negligible changes in Western Australia (WA) and Queensland (QLD), and a small non-significant decrease in Tasmania. Previous studies (Wright 1974b; Allan and Haylock 1993; Yu and Neil 1993) have indicated that one of the few areas of Australia to have experienced a major rainfall decline this century is southwest Western Australia (SWWA), so we analysed this region separately and found a significant decrease of 19 per cent.

Seasonal mean rainfall for individual States and for the whole continent are shown in Fig. 4(a). The dominance of summer rainfall in the three largest States of WA, NT and QLD is reflected in the Australian average. SA has relatively low and uniform rainfall. While NSW and VIC have similar annual total rainfall, NSW has a summer peak while VIC has a winter peak. TAS and SWWA also have winter peaks due to rainfall produced by frontal systems in mid-latitude westerly wind Fig. 2 Australian annual total rainfall (mm) from 1910 to 1995. A least-squares regression line has been fitted.



Fig. 3 (a) Annual total rainfall (mm) averaged over 1910 to 1995 for the whole of Australia (AUS), each State/Territory (WA, QLD, NT, SA, NSW, VIC, TAS) and southwest Western Australia (SWWA). (b) Percentage changes in annual total rainfall in each region. Asterisks indicate where changes are significant at the five per cent level using the Kendall-tau test.



Fig. 4 Same as in Fig. 3, but for different seasons. Summer (DJF), autumn (MAM), winter (JJA) and spring (SON).



regimes. In WA, the northern half of the State receives over 70 per cent of annual rainfall in summer and autumn, while the far southwest receives over 70 per cent in winter and spring. The seasonal contributions from each region, weighted by area, are reflected in the seasonal averages for Australia; more rainfall in summer and less in winter and spring.

Changes in seasonal rainfall from 1910 to 1995 are shown in Fig. 4(b). Australian summer rainfall has increased by almost ten per cent and by slightly more in autumn. A six per cent decrease has occurred in winter along with a three per cent increase in spring. None of these changes is significant.

The only significant seasonal change was a 25 per cent winter decrease in SWWA. In seasons with relatively high mean rainfall, there are a number of non-significant changes which may have hydrologically important impacts, e.g. changes of 10-40 per cent occur in NT (autumn increase of 41 per cent), VIC (autumn [winter] spring increase of 12 [18] 18 per cent), NSW (summer [autumn] spring increase of 28 [31] 18 per cent, with a winter decrease of 11 per cent), SA (summer [autumn] spring increase of 42 [32] 14 per cent), QLD (winter decrease of 28 per cent) and SWWA (autumn [spring] decrease of 16 [17] per cent).

Heavy rainfall

There is large variability in the spatial pattern of heavy rainfall in Australia. In summer and autumn, the monsoon is active in northern Australia and storms are common along the north and east coasts. Figure 5 shows the Fig. 5 Spatial pattern of the mean 99th percentiles of daily rainfall (mm/day) from 1910 to 1995 in (a) DJF, (b) MAM, (c) JJA and (d) SON. Regions exceeding 30 mm/day are shaded. Contours are drawn for 10, 20, 30, 40, 50, 60, 80, 100 and 120 mm/day.



spatial pattern of the mean 99th percentile rainfall intensity in each season, derived from fitting a gridded surface to the data using spline interpolation (Hutchinson and Bischof 1983). The mean 99th percentile (heaviest seasonal event) reaches 50-80 mm/day in summer and autumn over northern and eastern Australia, exceeding 100 mm/day on the northeast coast, and falling below 30 mm/day in the south. In winter, the 99th percentile is 30-60 mm/day on the west coasts of SWWA and TAS, and along the east coast. In spring, areas of 30-60 mm/day exist within about 400 km of the east coast, in western TAS and over the northern half of NT.

The interannual variability in total rainfall evident in Fig. 2 is also reflected in the temporal behaviour of the annual indices of Australian-average heavy rainfall shown in Fig. 6. Maxima occur around 1910-1920, 1950-1960 and 1970-1980, particularly from 1973 to 1975. The Australian annual 99th and 95th percentile trends are not statistically significant. However, strong correlations between total rainfall and the 99th percentile ($\mathbf{r} = 0.96$) suggest that the interannual variability and underlying trend in total rainfall are largely dependent on the behaviour of heavy rainfall.

The seasonal average intensities of the indices of heavy rainfall are shown in Fig. 7. Heaviest rainfall occurs in summer in most States, particularly northern States affected by monsoonal weather systems. This fact is also reflected in the Australian average intensity of rainfall. However NSW, VIC and SA have a relatively small seasonal variation in heavy rainfall intensity, while southwest WA and TAS receive heaviest rainfall in winter.

Fig. 6 Australian annual 99th and 95th percentiles of daily rainfall (mm/day) from 1910 to 1995. A least-squares regression line has been fitted.



Fig. 7 Seasonal mean 99th and 95th percentiles of daily rainfall (mm/day) averaged over 1910 to 1995 for the whole of Australia, each State/Territory and southwest Western Australia.



Percentage changes in heavy rainfall intensity from 1910 to 1995 are shown in Fig. 8. In general, there has been an increase in Australian-average heavy rainfall in all seasons except winter, but none of these changes is significant. On a regional basis, several significant trends in heavy rainfall emerged: a 31 per cent increase in the autumn 99th percentile in NSW, an increase of more than 100 per cent in the summer 95th percentile in SA, and decreases of 13-17 per cent in both winter indices in SWWA. A number of regions have changes of 10-45 per cent which are non-significant but hydrologically important. For example, a 17-33 per cent increase in heavy summer rainfall indices in NSW, a 26-47 per cent increase in the autumn indices in NT, an 8-16 per cent increase in winter and spring indices in VIC, a 10-19 per cent increase in the summer indices in WA, and an 8-21

Changes in the frequency of heavy rainfall have been determined by fitting linear trends to time series of the number of days with rainfall exceeding 25.4 mm (1 inch) and 50.8 mm (2 inches). Annual mean results for the whole of Australia are shown in Fig. 9, along with time series for lighter rainfall categories: 1-5 mm, 5-15 mm and 15-25 mm. The 4-7 per cent increase in the frequency of heavy rainfall is not significant, largely due to the decline in the 1990s, but there has been a significant 15 per cent increase in light rainfall events (1-5 mm/day). When analysed seasonally and regionally, there are no significant increases in the frequency of

per cent decrease in the autumn indices in WA.

Fig. 8 Percentage changes in seasonal 99th and 95th percentiles of daily rainfall in each region. Asterisks indicate where changes are significant at the five per cent level using the Kendall-tau test.



Fig. 9 Australian annual total number of days within selected rainfall categories: 1-5 mm/day, 5-15 mm/day, 15-25 mm/day, > 25.4 mm/day, and > 50.8 mm/day. A least-squares regression line has been fitted to each time series.



heavy rainfall, but a few significant decreases emerge, including winter decreases of 41-59 per cent in SWWA. Non-significant changes in the frequency of days over 50.8 mm which may be hydrologically important include increases of over 20 per cent in NT (21 [45] per cent in summer [autumn]), SA (65 per cent in summer), NSW (67 [57] per cent in summer [autumn]), VIC (54 per cent in autumn), and TAS (119 per cent in winter).

Rain days

The Australian annual average number of rain days in Fig. 10 shows an increasing trend with strong interannual variability. The annual average of 43 rain days reflects the high aridity of central and western Australia. Most frequent rain days occurred in the wet periods around 1910-1920, 1950-1960 and 1970-1980. The correlation between annual total rainfall (Fig. 2) and the number of rain days is +0.91 which is statistically significant at the 1 per cent level.

Figures 11 and 12 show the average number of rain days and their changes from 1910-1995. The winter rainfall regions of VIC, TAS and SWWA have far more rain days than the other States which have relatively dry winters. There has been a significant 10 per cent rise in the annual Australian-average number of rain days (Fig. 11(b)), reflected in significant increases of almost 20 per cent in NT and NSW despite a significant 10 per cent decline in SWWA. On a seasonal basis (Fig. 12(b)), Australian-average rain days increased in all seasons except winter, but none of these changes was significant. Regionally, significant increases of 20-50 per cent have occurred in SA (43 per cent in summer), NT (46 per cent in autumn) and NSW (20 [28] per cent in summer [spring]), but SWWA rain days have declined by 13 per cent in winter. In each

Fig. 10 Australian annual number of rain days ≥ 1 mm/day) from 1910 to 1995. A least-squares regression line has been fitted.



Fig. 11 (a) Annual mean number of rain days ≥ 1 mm/day) averaged over 1910 to 1995 for the whole of Australia (AUS), each State/Territory and southwest Western Australia. (b) Percentage changes in annual number of rain days in each region. Asterisks indicate where changes are significant at the five per cent level using the Kendall-tau test.



case, the change in total rain days was strongly reflected by changes in light rain days (the 1-5 mm/day range). Since the increase in annual total rain days (ten per cent) exceeds that for total rainfall (six per cent), annual mean rain per rain day has decreased. This is largely due to an increased frequency of light rainfall.

Discussion

Comparison with previous studies

The general increase in Australian annual total rainfall with decreased winter rainfall in the southwest confirms results of previous studies (e.g. Nicholls and Lavery 1992). Decreases in the southwest have been linked to



changes in large-scale circulation features associated with a westward extension of the continental anticyclone, a southward shift in storm tracks, increased Indian Ocean temperatures (Wright 1974a, b; Allan and Haylock 1993) and decreasing cyclonicity south of WA (Plummer et al. in press). Our results confirm the increase in heavy summer rainfall in SWWA from 1911-1990 documented by Yu and Neil (1993), but the increase in spring is not as obvious in our analysis.

The decrease in winter rainfall in Queensland has not been documented previously, but none of the decreases in total or heavy rainfall in Queensland are statistically significant, and average rainfall in this season is relatively low. The increased total and heavy summer rainfall in QLD from 1921-1987 reported by Lough (1993) is not evident in our analysis from 1910-1995.

Annual mean rain per rain day increased in VIC due to larger contributions from increases in heavy rainfall (>25.4 mm) rather than increases in light-moderate rainfall (1-5 mm, 5-15 mm, 15-25 mm). In NSW and TAS, annual mean rain per rain day did not change; in NSW this was due to approximately equal absolute contributions from changes in light-moderate events and heavy events, while in TAS this was mainly due to changes in light-moderate events. In QLD, annual rain per rain day declined due to no change in total rainfall with an increase in rain days, and the increased rain from lightmoderate events offset the decreased rain from heavy events. These findings are broadly consistent with those of Nicholls and Kariko (1993) who studied rainfall trends at five representative stations in eastern Australia from 1910-1988.

The anomalously wet conditions in the 1970s are related to La Niña phases of the El Niño – Southern Oscillation (ENSO) in 1970, 1971, 1973, 1974 and 1975 (Lavery et al. 1992; Nicholls and Kariko 1993; Nicholls 1996). These wet years had stronger summer monsoon activity over northern Australia (Butterworth and Arthur 1993). Northeastern Australia has also experienced numerous droughts in the early 1990s, largely related to a series of El Niño events during 1991-1995 and 1997.

One of the main findings of this study is that increases in Australian rainfall since 1910 are generally linked to increases in heavy rainfall and rain days. However, there are a couple of exceptions: (a) the reductions in total winter rainfall in SA, QLD and NSW, and the fall in total autumn rainfall in TAS, are due to the reduced frequency of all rainfall intensities, and (b) reductions in total rainfall in winter in WA and in all seasons except autumn in TAS are due to a decline in light and moderate rain outweighing the increase in heavy rain.

There are very few analyses of extreme rainfall trends in other countries. Karl et al. (1995) found an increasing trend in rainfall exceeding 50.8 mm/day (2 inches/day) over the USA, but little change in the former Soviet Union and China. Iwashima and Yamamoto (1993) analysed daily rainfall data from 1890 to 1980 at 55 Japanese stations and found a significant increasing trend in the number of stations recording their highest, 2nd highest or 3rd highest rainfall events. Similar analyses are required for other regions before any assessment can be made of global-scale changes in heavy rainfall over land, and this has been undertaken for eight countries by Groisman et al. (in press).

For the years 1910 to 1992, Torok and Nicholls (1996) found an increase in Australian continentalaverage annual maximum temperature of 0.05°C per decade and an increase in minimum temperature of 0.10°C per decade. Satellite observations and Clausius Clapeyron theory indicate that a warmer atmosphere can hold more moisture and produce more precipitation (Stevens 1990; Gordon et al. 1992). The release of additional latent heat of condensation in convective storms may lead to an additional enhancement of rainfall intensity. This theoretical increase in rainfall intensity under warmer conditions is found in comparisons of daily rainfall frequency distributions for warm/cool seasons at a given site, and between low and mid-latitude sites. Warmer conditions (lower latitudes, summer) generally tend to be associated with higher intensity rainfall (Fowler and Hennessy 1995) but regional factors are important and lead to some exceptions. Hence, from theoretical reasoning and observational evidence, it is possible that the observed increase in heavy rainfall intensity is related to the increase in temperature in the Australian region.

Interannual correlations between our rainfall indices and temperature data from Torok and Nicholls (1996) were computed (Table 1). Maximum temperature and rainfall indices show strong negative relationships, but the relationships between minimum temperature and rainfall indices are positive and weak. The results for annual rainfall, maximum and minimum temperatures are in agreement with recent studies (Nicholls et al. 1996; Power et al. 1998). Figure 13 shows the year-toyear variability of Australian average maximum temperature and 99th percentile rainfall intensity. The correlation is -0.53 which is statistically significant at the 1 per cent level. The negative relationships shown in Table 1 and Fig. 13 are probably due to the link between rainfall and surface cooling, but the influence of other factors on seasonal and daily time-scales may also be important. On multi-decadal time-scales, maximum temperature and heavy rainfall both show increasing trends (a weak positive correlation despite a negative interannual correlation), indicating the influence of other mechanisms such as decadal-scale natural variability and anthropogenic factors. Extrapolation of these relationships to the warming predicted over the next few decades would imply further secular increases in heavy rainfall and a continued negative interannual relationship between heavy rainfall and maximum temperature.

Suppiah and Hennessy (1996) analysed trends in heavy rainfall over tropical Australia from 1910-1990 and found that increases at most stations remained even when the influence of ENSO was removed. This implies that ENSO variations are only partly responsible for the observed changes in heavy rainfall.

However, at this stage, it is not clear what proportion of the observed increase in rainfall intensity is due to natural variability or anthropogenic influences such as land-use change, biomass burning, ozone depletion and increased levels of greenhouse gases. Attribution of cause and effect is unlikely to be a simple task. Identifying links between various atmospheric circulation indices, sea surface temperature and rainfall intensities needs further investigation.

Table 1. Pearson Product Moment Correlation coefficients for Australian annual average maximum
temperature, minimum temperature, and rainfall parameters considered in this study.
Correlations were based on data from 1910 to
1992. Asterisks indicate correlations which are
statistically significant at the one per cent level.

	95th percentile	99th percentile	Total Rainfall	Rain days
Max. temp.	-0.59*	-0.53*	-0.56*	-0.56*
Min. temp.	0.02	0.01	0.03	0.16

Fig. 13 Interannual variability of Australian average maximum temperature (°C, dotted line, from Torok and Nicholls 1996) and 99th percentile rainfall (mm/day, dot-dash line) from 1910 to 1992. The solid lines are 11-year running means.



Scenarios of future rainfall change

Regional climate-change scenarios for Australia have been issued by CSIRO (1996). The scenarios are based on information about future global warming and regional patterns of climate change from global climate models (GCMs). Allowance is made for quantifiable uncertainties in projected greenhouse gas emissions, global climate sensitivity to changes in greenhouse gas concentrations, and regional patterns of climate response. Allowance is also made for the regional cooling effect of sulfate aerosols.

By the year 2030, a warming of 0.3 to 1.4°C is estimated for various parts of Australia, increasing to 0.6 to 3.8°C by 2070. In winter, rainfall decreases of up to 8 per cent are simulated over much of the continent by 2030. This would represent a continuation of the observed drying trend in southwest WA, NSW, QLD, TAS and SA, but a reversal of the observed increase in VIC. In summer, rainfall increases and decreases of up to 10 per cent by 2030 are possible. This wide range of uncertainty is due to disagreement between two types of GCMs regarding the future summer rainfall tendency (slab-ocean models indicate increases, while coupledocean models indicate decreases except in the southeast and southwest where wetter conditions are equally likely). An increase in summer rainfall would represent a continuation of trends observed in most States since 1910, although eastern States have experienced little change or drier conditions since the mid-1970s.

Where rainfall increases, global climate models simulate an increase in heavy rainfall and a decrease in light rainfall (Houghton et al. 1992; 1996, Pittock et al. 1991; Gordon et al. 1992; Whetton et al. 1993; Gregory and Mitchell 1995; Fowler and Hennessy 1995; Hennessy et al. 1997). For an equilibrium doubling of present carbon

dioxide concentrations, which may occur by late next century, three climate models indicate a 10-25 per cent increase in the intensity of Australian daily rainfall with a return period of at least one year (Hennessy et al. 1997). Similar results were found for the USA, India and Europe. Simulated synoptic circulation patterns that produce heavy rainfall during summer in central Australia tend to become stronger under enhanced greenhouse conditions (Suppiah 1994). The simulated tendency for increased heavy rainfall under warmer conditions is evident in Australian observations since 1910 in many regions (see Fig 8). While the decline in rain days simulated for next century is not evident in Australian trends averaged over 1910-1995 (except in TAS, SWWA and winter in some other States), yearly data in Fig. 10 suggest that the general increase in rain days up to the mid-1970s has stabilised since 1980 and rain days have declined with the series of El Niños in the 1990s.

A critical issue for regional rainfall projections is the ability of climate models to simulate large-scale circulation features like ENSO, changes in cloud properties, and subgrid-scale processes affecting convection and the recirculation of moisture. These aspects are captured with mixed success in climate models and remain as a significant source of uncertainty. Understanding how ENSO may change with global warming is essential for many aspects of future climate impact assessment.

Conclusions

Annual and seasonal trends in heavy daily rainfall, total rainfall and the number of rain days were calculated for the whole of Australia and each State/Territory from 1910 to 1995, using a new set of high-quality daily data from 379 stations. This provides a reliable and extensive assessment of variability and trends in Australian rainfall, with a unique focus on average seasonal changes within political boundaries.

From 1910-1995 there has been a non-significant six per cent increase in annual total rainfall in Australia. This is comprised of a significant 14 per cent increase in VIC, non-significant increases of 15-18 percent in the NT, NSW and SA, negligible changes in WA and QLD, and a small non-significant decrease in TAS. When analysed seasonally, the only significant change was a 25 per cent decline in SWWA in winter, but non-significant changes of 10-40 per cent were found in some States.

Australian areal-mean heavy rainfall has not changed significantly in any season. However, on a regional basis significant increases in heavy rainfall emerged in SA in summer and NSW in autumn, while significant decreases occurred in southwest WA in winter. Important non-significant increases of 10-45 per cent were also found in some States. There has been a significant 10 per cent rise in the annual Australian-average number of rain days, reflected in significant increases of almost 20 per cent in NT and NSW despite a significant 10 per cent decline in SWWA. Regionally, significant increases of 20-50 per cent have occurred in some States, with large changes in the frequency of light rainfall.

Strong correlations exist between interannual variations in temperature, total rainfall, heavy rainfall and the number of rain days. Increases in Australian rainfall since 1910 are generally linked to an increase in heavy rainfall and rain days. There are some exceptions where total rainfall has decreased due to a decline in the frequency of all rainfall intensities, or a decline in light and moderate rain outweighing an increase in heavy rain.

This study reveals systematic changes in daily rainfall behaviour in Australia. ENSO variability is partly responsible, as is enhanced monsoon activity in the early 1970s and changes in large-scale circulation features associated with the continental anticyclone, the long wave trough over the Southern Ocean and sea-surface temperatures. Further investigation is needed to fully understand the causes for such changes in rainfall characteristics.

Acknowledgments

Comments from Mr Simon Bentley, Dr Graeme Pearman, Dr Ian Smith and Dr Peter Whetton of CSIRO Atmospheric Research were very useful. Discussions with Dr Pasha Groisman from the US National Climate Data Center regarding data quality were particularly helpful. Mr Robin Hicks from the National Climate Centre of the Australian Bureau of Meteorology provided rainfall data and Ms Beth Lavery supplied the program to compute regional-average rainfall. Ms Joanne Richmond of CSIRO prepared Fig. 1. This work is a product of the CSIRO Climate Change Program, funded in part by Environment Australia, and the Governments of the Northern Territory, Western Australia, Victoria, New South Wales and Queensland.

References

- Allan, R.J. and Haylock, M.R. 1993. Circulation features associated with the winter rainfall decrease in southwestern Australia. *Jnl Climate*, 7, 1356-67.
- Butterworth, I. and Arthur, J. 1993. Rainfall trends over the Northern Territory Top End. *Research Papers 2*, Bureau of Meteorology, Darwin, 111-16.
- CSIRO 1996. Climate Change Scenarios for the Australian Region. CSIRO Division of Atmospheric Research, Melbourne, Australia, 8 pp.
- Fowler, A.M. and Hennessy, K.J. 1995. Potential impacts of global warming on the frequency and magnitude of heavy precipitation. *Natural Hazards*, 11, 283-303.

- Gibbs, W.J., Maher, J.V. and Coughlan, M.J. 1978. Patterns of shortterm change and variability. 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, 135-50.
- Gordon, H.B., Whetton, P.H., Pittock, A.B., Fowler, A.M. and Haylock, M.R. 1992. Simulated changes in daily rainfall intensity due to the enhanced greenhouse effect: implications for extreme rainfall events. *Climate Dynamics*, 8, 83-102.
- Gregory, J.M. and Mitchell, J.F.B. 1995. Simulation of daily variability of surface temperature and precipitation over Europe in the current and 2 x CO₂ climates using the UKMO climate model. *Q. Jl R. met. Soc.*, 121, 1451-76.
- Gregory, S. 1991. Spatial patterns of annual July-June rainfall fluctuations in tropical Queensland, 1900/01 to 1979/80. Aust. Geogr. Studies, 29, 93-113.
- Groisman, P., Karl, T., Easterling, D., Knight, R., Jamason, P., Hennessy, K., Suppiah, R., Page, C., Wibig, J., Fortuniak, K., Razuvaev, V., Douglas, A., Førland, E. and Zhai, P. (in press). Changes in the probability of extreme precipitation: important indicators of climate change. *Climatic Change*.
- Hennessy, K.J., Gregory, J.M. and Mitchell, J.F.B. 1997. Changes in daily precipitation under enhanced greenhouse conditions. *Climate Dynamics*, 13(9), 667-80.
- Houghton, J.T., Callander, B.A. and Varney, S.K. (eds) 1992. Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment. Cambridge Uni. Press, Cambridge, U.K., 200 pp.
- Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K. (eds) 1996. Climate Change 1995. The Science of Climate Change. Cambridge Uni. Press, U K, 572 pp.
- Hutchinson, M.F. and Bischof, R.J. 1983. A new method for estimating the spatial distribution of mean seasonal and annual rainfall applied to the Hunter Valley, New South Wales. *Aust. Met. Mag.*, 31,179-84.
- Iwashima, T. and Yamamoto, R. 1993. A statistical analysis of the extreme events: Long term trend of heavy daily precipitation. J. met. Soc. Japan, 71, 637-40.
- Karl, T.R., Knight, R.W. and Plummer, N. 1995. Trends in high-frequency climate variability in the twentieth century. *Nature*, 377, 217-20.
- Lavery, B.M., Kariko, A.P. and Nicholls, N. 1992. A high-quality historical rainfall data set for Australia. Aust. Met. Mag., 40, 33-9.
- Lavery, B., Joung, G. and Nicholls, N. 1997. An extended high quality historical rainfall data set for Australia. Aust. Met. Mag., 46, 27-38.
- Lough, J.M. 1993. Variations in some seasonal rainfall characteristics in Queensland, Australia: 1921-1987. Int. J. Climatol., 13, 391-409.
- Lough, J.M. 1997. Regional indices of climate variation: temperature and rainfall in Queensland, Australia. Int. J. Climatol., 17, 55-66.
- Mollah, W.S. and Cook, I.M. 1996. Rainfall variability and agriculture in the semi-arid tropics - the Northern Territory, Australia. Agri. Forest Met., 79, 39-60.
- Nicholls, N. 1996. Climate variability climate change. Proceedings of the Second Australian Conference on Agricultural Meteorology. The University of Queensland, 1-4, October 1996, 49-53.
- Nicholls, N., Drosdowsky, W. and Lavery, B. 1997. Australian rainfall variability and change. *Weather, 52*, 66-72.
- Nicholls, N. and Kariko, A. 1993. East Australian rainfall events: interannual variations, trends, and relationships with the southern oscillation. Jnl Climate, 6, 1141-52.
- Nicholls, N. and Lavery, B. 1992. Australian rainfall trends during the twentieth century. Int. J. Climatol., 12, 153-63.
- Nicholls, N., Lavery, B., Frederiksen, C., Drosdowsky, W. and Torok, S. 1996. Recent apparent changes in relationships between the El Niño-southern oscillation and Australian rainfall and temperature. *Geophy. Res. Lett.*, 23, 3357-60.
- Pittock, A.B. 1983. Recent climatic change in Australia: implications for a CO₂ warmed earth. *Climatic Change*, 5, 321-40.
- Pittock, A.B., Fowler, A.M. and Whetton, P.H. 1991. Probable changes

in rainfall regimes due to the enhanced greenhouse effect. Proceedings of the International Hydrology and Water Resources Symposium, Perth, Australia, October 1991.

- Plummer, N., Trewin, B.C., Hicks, R., Nicholls, N., Torok, S.J., Lavery, B.M. and Leighton, R.M. 1997. Australian data for documenting changes in climate extremes. In: CLIVAR/GCOS/WMO Workshop on Indices and Indicators for Climate Extremes, Asheville, NC, USA, 3-7 June 1997.
- Plummer, N., Salinger, M.J., Nicholls, N., Suppiah, R., Hennessy, K.J. Leighton, R.M., Trewin, B. and Lough, J.M. (in press). Twentieth century trends in climate extremes over the Australian region and New Zealand. *Climatic Change*.
- Power, S., Tseitkin, F., Torok, S., Lavery, B., Dahni, R. and McAvaney, B. 1998. Australian temperature, Australian rainfall and the Southern Oscillation, 1910-1992: Coherent variability and recent changes. Aust. Met. Mag., 47, 85-101.
- Press, W.H., Flannery, B.P., Teukolsky, S.A. and Vetterling, W.T. 1986. Numerical Recipes: The Art of Scientific Computing. Cambridge University Press, Cambridge, 488-493.
- 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.
- Stevens, G.L. 1990. On the relationship between water vapour over the oceans and sea surface temperature. *Jnl climate*, *3*, 634-45.
- Suppiah, R. 1994. Synoptic aspects of wet and dry conditions in central

Australia: Observations and GCM simulations for 1xCO₂ and 2xCO₂ conditions. *Climate Dynamics*, 10, 395-405.

- Suppiah, R. and Hennessy, K.J. 1996. Trends in the intensity and frequency of heavy rainfall in tropical Australia and links with the Southern Oscillation. Aust. Met. Mag., 45, 1-17.
- Suppiah, R. and Hennessy, K.J. 1998. Trends in seasonal rainfall, heavyrain days, and number of dry days in Australia, 1910-1990. Int. J. Climatol., 18(10), 1141-1164.
- Torok, S.J. and Nicholls, N. 1996. A historical annual temperature data set for Australia. Aust. Met. Mag., 45, 251-60.
- Whetton, P.H., Fowler, A.M., Haylock, M.R. and Pittock, A.B. 1993. Implications of climatic change due to the enhanced greenhouseeffect on floods and droughts in Australia. *Climatic Change*, 25, 289-317.
- Wright, P.B. 1974a. Seasonal rainfall in southwestern Australia and the general circulation. Mon. Weath. Rev., 102, 219-32.
- Wright, P.B. 1974b. Temporal variations in seasonal rainfalls in southwestern Australia. Mon. Weath. Rev., 102, 233-43.
- Yu, B. and Neil, T.D. 1991. Global warming and regional rainfall: the difference between average and high intensity rainfalls. Int. J. Climatol., 11, 653-61.
- Yu, B. and Neil, T.D. 1993. Long-term variations in regional rainfall in the south-west of western Australia and the difference between average and high intensity rainfalls. *Int. J. Climatol.*, 13, 77-88.