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# Analysis of Australian rainfall data with respect to climate variability and change

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**Predictions by general circulation models of changes in rainfall rates over Australia under the double carbon dioxide scenario are conflicting. As it will be some time before the quality of these predictions improves, our best indicator of rainfall variability and change is the analysis of the behaviour of recorded data over time. This paper presents the results of statistical analysis of annual and monthly rainfall data for 69 rainfall stations around Australia. The annual and monthly time-series are analysed for trend and jump in the mean. Graphical plots of the rainfall data indicate low frequency variations but there is no significant or conclusive evidence of climate change impacts within the analysed annual rainfall records. However, the data from a third of the stations indicate a change in winter rainfall, with the change points being late in the last century or early in the present century.**

## Introduction

In recent years there has been growing concern about the enhanced greenhouse effect on world climate. Several studies, using general circulation models (GCMs), give different and sometimes conflicting predictions for future climate under doubled carbon dioxide conditions (Schlesinger and Mitchell 1987; Mitchell et al. 1989). With respect to changes in rainfall rates, Zillman (1989) shows that the predicted changes from five GCMs range from −2 mm/day to +2 mm/day for the summer period (Dcember, January and February) at the same site (Central Australia). The discrepancies in the model predictions are mainly attributed to the different ways in which the physical processes are formulated in different GCMs. Also, the present model predictions are not very reliable because of the primitive way the cloud dynamics are modelled and the inadequate coupling of the atmosphere and oceans. While an enormous amount of effort is being directed at improving the GCMs and hence their predictions, it is very relevant to look for evidence of any change in climate from the observed rainfall records.

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## Review of earlier studies on rainfall variability

Several analyses of long-term rainfall series have been published by a number of research workers (Tyson et al. 1975; Rodhe and Virji 1976; Nicholson 1980; Corona 1978, 1979; Tabony 1981; McGuirk 1982; Mooley and Parthasarathy 1984; Hakkarinen and Landsberg 1981; Barnett 1985). Ellsaesser et al. (1986) give a comprehensive review of the global trends in recorded rainfall data. The general conclusion from the above studies is the existence of cyclic variations of different periods, but no significant long-term trends.

In Australia, a number of studies have also been carried out and these have conflicting conclusions. Analysis of long-term rainfall series from Victoria and New South Wales (Kraus 1953) showed a decrease of summer rainfall to a minimum about the turn of the century and fifty years of gradual increase since then. This is in agreement with Deacon (1953), who showed that the summer rainfall over much of the southern part of Australia for the period 1911–1950 was considerably greater than that in the previous 30 years. From the analysis of annual and monthly rainfall totals for 99 stations throughout New South Wales, Cornish (1977) observed an increase in annual and summer rainfall in central New South Wales.

In examining the variation in summer and winter rainfall from 200 widely spread stations in Australia over the 80-year period (1895–1974), Russell (1981) found significant increases in summer rainfall at 42 stations, mostly in southeastern Australia. Only two stations showed significant decreases. In contrast, only seven stations showed significant increases in winter rainfall and five showed significant decreases.

McGilchrist and Woodyer (1975) found that there was no significant change in the mean value of annual rainfall at Wallgett, New South Wales, for the period 1878 to 1965. From the rainfall data at 43 stations, for the period 1890–1980, Doran and McGilchrist (1983) found that only eight stations showed significant change and hence concluded that there was no evidence of continental climate change.

Using 180 years of flood stage records at Windsor and 90 years of discharge data at Penrith, Warner (1987) defined alternating flood dominated and drought dominated regimes for the Hawkesbury-Nepean River System. The periods of drought dominated regimes are 1821–1863 and 1901–1948, and those of flood dominated regimes are 1799–1820, 1864–1900 and 1949 onwards.

Pittock (1975, 1983) analysed 66 years (1913 to 1978) of Australian rainfall data and found an abrupt increase in rainfall circa 1945–46 over most of the continent. He attributes this to a change in climate. Srikanthan and Stewart (1989) analysed the annual rainfall at 80 stations throughout Australia and found that the variations in the parameters for the recent period were within the natural variability of annual rainfall.

The apparent contradiction between the above two analyses can be attributed to the different data lengths used in the two studies. If one uses rainfall data covering only one drought dominated period followed by one flood dominated period, an upward trend will be observed most of the time. Pittock's studies used only one drought dominated period followed by a flood dominated period (as defined by Warner above) and consequently an upward trend was observed. The latter study used longer records covering, in most cases, two flood dominated periods and one drought dominated period. Consequently, the variations in the parameters for the recent period (flood dominated regime) were similar to those in the early part of the records which were again in another flood dominated regime.

In a recent study, Kite (1989) analysed long series of lake levels in the USA and Uganda and river flows in Canada. He found no statistical components that could be ascribed to greenhouse-induced climatic change.

In this paper, annual and monthly rainfall totals recorded at 69 Bureau of Meterology rainfall stations were analysed on an individual station basis and regionally for any trends or change in mean value.

## Rainfall data

The rainfall records of the Bureau of Meteorology were examined to obtain a network of stations which had consistent and homogeneous records. Consistency relates to the type and techniques of measurement, the sampling interval and the manner of processing data. Over the years this has not changed with regard to daily measurement of rainfall. An eight-inch rain gauge is used and readings are taken at 9 am every day. The units of rainfall measurement changed from points to millimetres in 1972, but this should not affect the monthly or annual totals significantly. Recently, at some stations, rainfall has not been recorded on Sundays or public holidays, but again this should not affect the analysis of monthly and annual rainfall totals, nor should the use of daylight saving time in the eastern States.

Homogeneity relates to the constancy of the measurement site and its environmental conditions, and to the lack of artificial disturbance of the climate and hydrological processes. A total of 92 stations were initially selected for analysis. Closer examination of the data indicated a number of months of missing data. Missing data were infilled using nearby station data. It was not possible to reliably estimate the missing data for 12 of the stations and these were omitted from the analysis. The station history files for the remaining stations were examined to determine changes in instrumentation or location over the period of record. It should be noted that very little information on changes prior to the 1910s is available. Approximately 50 per cent of the stations had been moved. However, this was on average a distance of only a few hundred metres. While no changes in instrumentation had been recorded, there had been changes in the gauge height at a small number of stations. A more significant factor may be changes in the observer. Double mass curves for each site were plotted using adjacent stations. These curves were examined in conjuction with the station history records to determine any deviations in the record which could have resulted from any of the above disturbances. On the basis of this evaluation, eleven more stations were omitted from the analysis. This resulted in 69 stations (Table 1) with an average length of record of 110 years. Their locations are shown in Fig. 1.

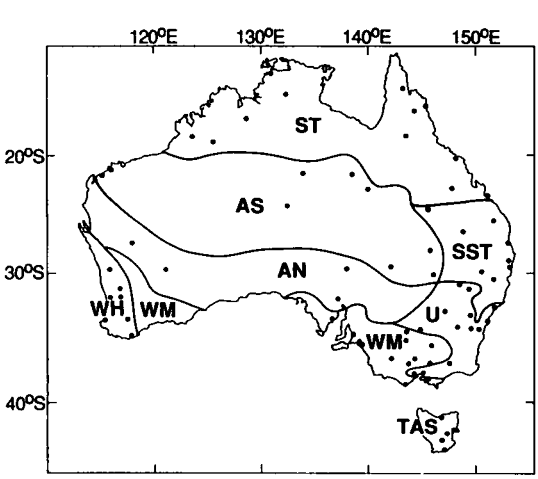
As stated above, information necessary to establish the consistency and homogeneity of these rainfall data collection sites is poor, especially prior to the 1910s, and thus this data set is less than optimal. It is therefore recommended that additional work be undertaken to produce a more consistent and homogeneous rainfall data set for Australia.

Since trends from single stations may be unreliable due to errors associated with exposure and change of site and instrumentation, regional mean

**Table 1. List of rainfall stations.**

| Station number | Station name | Mean (mm) | record Years | Station number | Station name | Mean (mm) | record Years |
|---|---|---|---|---|---|---|---|
| 02016 | Kununurra | 603 | 92 | 43030 | Roma P.O. | 579 | 95 |
| 03006 | Fitzroy Crossing | 533 | 95 | 44026 | Cunnamulla P.O. | 365 | 109 |
| 03030 | La Grange | 484 | 97 | 46037 | Tibooburra P.O. | 223 | 97 |
| 04035 | Roebourne | 311 | 102 | 48013 | Bourke P.O. | 349 | 110 |
| 05008 | Mardie | 263 | 97 | 49002 | Balranald P.O. | 320 | 100 |
| 05016 | Onslow P.O. | 270 | 98 | 50014 | Condobolin P.O. | 443 | 108 |
| 07017 | Cue P.O. | 224 | 93 | 51010 | Coonamble P.O. | 499 | 103 |
| 08025 | Carnamah | 390 | 100 | 54029 | Warialda P.O. | 685 | 111 |
| 09034 | Perth R.O. | 869 | 112 | 56002 | Armidale R.S. | 777 | 111 |
| 09500 | Albany Town | 933 | 111 | 58012 | Yamba P.S. | 1461 | 110 |
| 09515 | Busselton | 828 | 105 | 58063 | Casino Airport | 1111 | 109 |
| 10058 | Goomaling | 367 | 79 | 61055 | Newcastle | 1134 | 121 |
| 10144 | York P.O. | 452 | 112 | 63004 | Bathurst Gaol | 626 | 116 |
| 10579 | Katanning P.O. | 488 | 93 | 64008 | Coonabarabran | 734 | 109 |
| 12052 | Menzies P.O. | 241 | 91 | 66062 | Sydney R.O. | 1218 | 130 |
| 14015 | Darwin P.O. | 1592 | 119 | 68045 | Moss Vale P.O. | 993 | 119 |
| 14902 | Katherine | 967 | 102 | 70025 | Crookwell P.O. | 866 | 104 |
| 15525 | Barrow Creek | 312 | 115 | 73056 | Young P.O. | 652 | 117 |
| 15557 | Tempe Downs | 256 | 102 | 74009 | Berrigan P.O. | 448 | 114 |
| 16056 | Yudnapinna | 209 | 103 | 75031 | Hay P.O. | 364 | 108 |
| 17031 | Marree | 161 | 103 | 77042 | Swan Hill P.O. | 346 | 103 |
| 18014 | Cleve P.O. | 398 | 91 | 79023 | Horsham | 450 | 115 |
| 23000 | Adelaide | 530 | 141 | 81003 | Bendigo Prison | 550 | 126 |
| 24518 | Meningie P.O. | 470 | 125 | 83025 | Omeo | 676 | 109 |
| 27005 | Coen P.O. | 1163 | 102 | 86071 | Melbourne R.O. | 655 | 132 |
| 28004 | Palmerville | 1038 | 99 | 87021 | Duridwarrah | 687 | 112 |
| 30018 | Georgetown P.O. | 829 | 117 | 88001 | Alexandra P.O. | 711 | 110 |
| 31016 | Cooktown P.O. | 1804 | 110 | 88043 | Maryborough | 531 | 111 |
| 33007 | Bowen P.O. | 1012 | 116 | 90015 | Cape Otway L.H. | 889 | 125 |
| 35019 | Clermont P.O. | 671 | 117 | 91057 | Low Head L.H. | 681 | 106 |
| 36143 | Blackall P.O. | 526 | 106 | 92038 | Swansea P.O. | 609 | 104 |
| 37043 | Urandangie P.O. | 294 | 96 | 93014 | Oatlands P.O. | 561 | 91 |
| 38003 | Boulia P.O. | 263 | 103 | 94010 | Cape Bruny L.H. | 947 | 118 |
| 39039 | Gayndah P.O. | 779 | 114 | 95003 | Bushy Park | 582 | 114 |
| 40214 | Brisbane R.O. | 1156 | 129 | | | | |

**Fig. 1 Locations of rainfall stations.**




series were formed and plotted. Based on the Bureau of Meteorology (1975) seasonal rainfall zones, Australia was divided into eight rainfall regions (Fig. 1). Even though Tasmania is in the winter rainfall region, it is considered as a separate region for this analysis. The number of rainfall stations in each region is given in Table 2.

**Table 2. Number of rainfall stations in each climatic region.**

| Region | No. of stations |
|---|---|
| Summer Rainfall Tropical (ST) | 11 |
| Summer Rainfall Subtropical (SST) | 8 |
| Uniform Rainfall Temperate (U) | 13 |
| Winter Rainfall (Heavy) Temperate (WH) | 7 |
| Winter Rainfall (Moderate) Temperate (WM) | 11 |
| Winter Rainfall (Tasmania) Temperate (TAS) | 5 |
| Summer Rainfall Arid (AS) | 10 |
| Non Seasonal/Winter Rainfall Arid (AN) | 4 |

A regional mean series was formed for each region by first standardising individual station data to have zero mean and unit variance and then averaging the standardised series.

$$X_{im} = (x_{im} - \bar{x}_m) / s_m \qquad \ldots 1$$

$$Y_i = (1/k) \sum_{m=1}^{k} X_{im} \qquad \ldots 2$$

where $x_{im}$ — actual value in year i at station m
$\bar{x}_m$ — mean value at station m
$s_m$ — standard deviation at station m
$X_{im}$ — standardised value in year i at station m
$Y_i$ — region mean value for year i
k — number of stations in a given region.

## Methods of analysis

### Time-series plots

Time-series plots enable a quick visual detection of any apparent trend or change in mean value in the plotted series. An eleven-year moving average and an 11-point Gaussian filter were also used to smooth the series and the smoothed curves plotted for visual inspection of any trend or change in mean value.

### Statistical tests

The following six statistical tests were applied to the two data sets. The first two tests are used to detect any linear trend in the data, while tests 3, 4 and 5 are used to detect any change in the mean value. The last test detects any change in the slope of the regression line. All of the tests, except 5, assume that the data are normally distributed. More than 75 per cent of the annual data have non-significant skewness at the 5 per cent level, while less than 5 per cent of the monthly rainfall have non-significant skewness at the same level.

1. Mann-Kendall rank correlation
2. Spearman rank correlation
3. Cumulative sum test
4. Likelihood ratio test
5. Distribution-free CUSUM technique
6. Two-phase regression

The above numbering system is used to refer to the tests in the results provided in Tables 7 and 8. The statistical tests are described in the Appendix.

## Discussion of results

### Annual rainfall data

The time-series, moving average and Gaussian filter plots for regional mean annual rainfall are shown in Figs 2 to 9. The smoothed values were plotted at the centre point. Due to a limitation in the graphics package used, the first five values of the annual series are not plotted. All stations in a given region did not contribute to the regional mean, especially in the early part of the record. Table 3 shows the number of stations contributing to the regional mean series for each of the regions analysed. It can be seen from this table that all regions had at least five stations contributing to the regional mean by 1898 (except AN which had only four stations in total). High rainfall is observed in the region ST (Fig. 2) in the 1970s. In the region SST (Fig. 3), we observe high rainfall in the 1890s, distinctly low rainfall from 1910 to 1945 and high rainfall (but not as high as the 1890s) afterwards. In the region U, high rainfall is observed in the periods 1865–1900 and 1945–1985

**Fig. 2 Regional mean of annual rainfall for the summer rainfall tropical region with 11-year moving average (. . .) and Gaussian filter (– – –).**

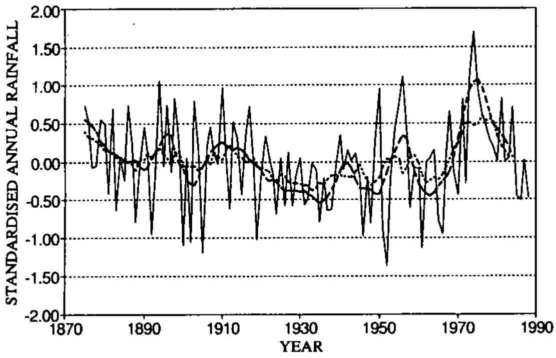



**Fig. 3 Regional mean of annual rainfall for the summer rainfall subtropical region with 11-year moving average (. . .) and Gaussian filter (– – –).**

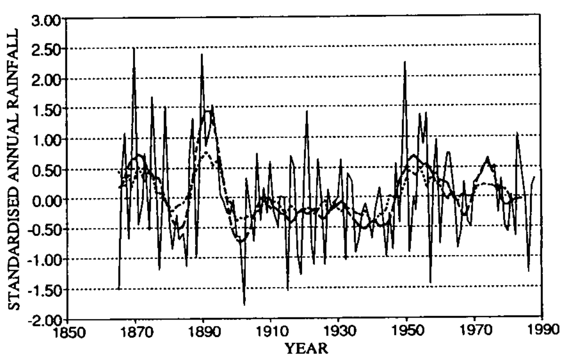


**Table 3. Stations contributing to the regional mean series and year of start.**

| *Region* | *No. of stations* 1 | 3 | 5 | 7 | 9 | *ALL* |
|---|---|---|---|---|---|---|
| ST | 1870 | 1871 | 1878 | 1887 | 1891 | 1896 |
| SST | 1860 | 1878 | 1879 | 1880 | — | 1894 |
| U | 1856 | 1867 | 1870 | 1874 | 1880 | 1886 |
| WH | 1876 | 1877 | 1888 | 1910 | — | 1910 |
| WM | 1839 | 1864 | 1875 | 1878 | 1887 | 1897 |
| TAS | 1871 | 1883 | 1898 | — | — | 1898 |
| AS | 1874 | 1879 | 1887 | 1890 | 1892 | 1892 |
| AN | 1885 | 1895 | — | — | — | 1897 |

(of the same order of magnitude). Low rainfall is observed in the middle period (Fig. 4). For regions AS and AN (Figs 5 and 6), high rainfall is observed in three periods (1915–1925, 1945–1955, and 1970–1980). Low rainfall is observed in two periods (1890–1905 and 1925–1935 onwards). The latter is not as severe as the former. In region WM, rainfall peaks and troughs occur frequently. The last peak in the 1970s is similar in magnitude to the first one in the 1850s (Fig. 8). For the Tasmanian region, high rainfall is observed in the early and latter parts of the record. The last peak is slightly larger than the earlier ones (Fig. 9).

**Fig. 4 Regional mean of annual rainfall for the uniform rainfall temperate region with 11-year moving average (. . .) and Gaussian filter (– – –).**

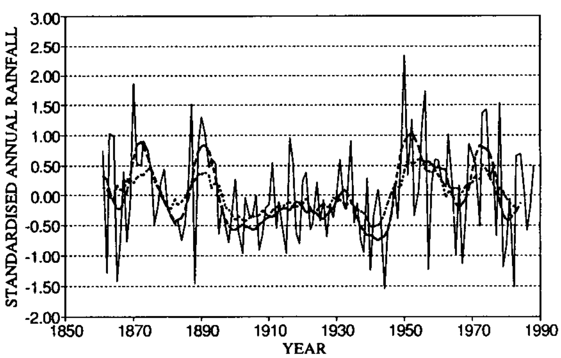



**Fig. 6 Regional mean of annual rainfall for the non seasonal/winter rainfall arid region with 11-year moving average (. . .) and Gaussian filter (– – –).**

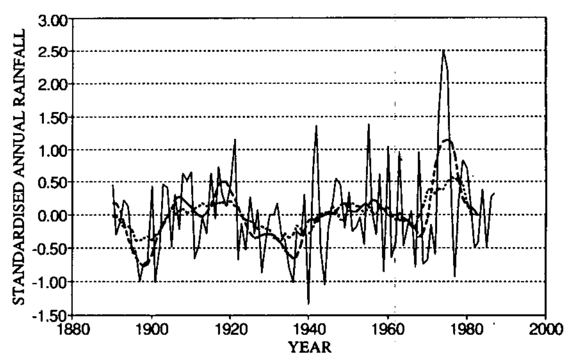



**Fig. 5 Regional mean of annual rainfall for the summer rainfall arid region with 11-year moving average (. . .) and Gaussian filter (– – –).**

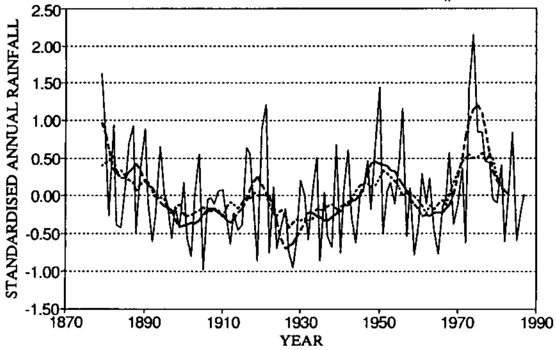



**Fig. 7 Regional mean of annual rainfall for the winter rainfall (heavy) temperate region with 11-year moving average (. . .) and Gaussian filter (– – –).**

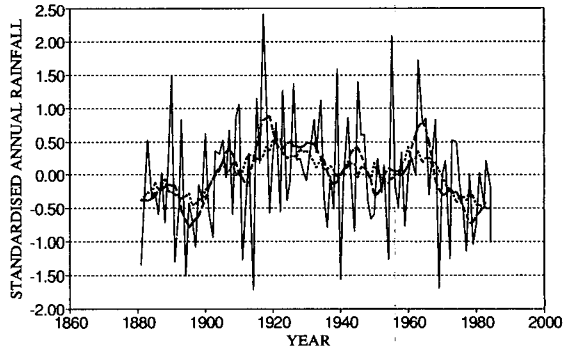


**Fig. 8 Regional mean of annual rainfall for the winter rainfall (moderate) temperate region with 11-year moving average (. . .) and Gaussian filter (- - -).**

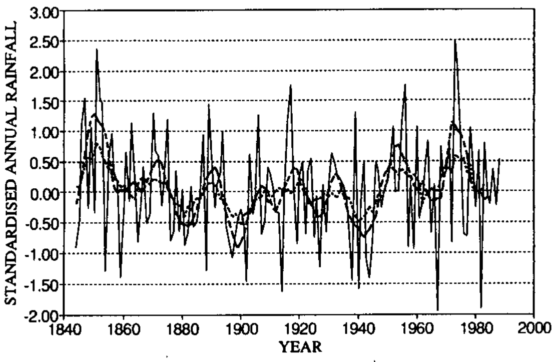
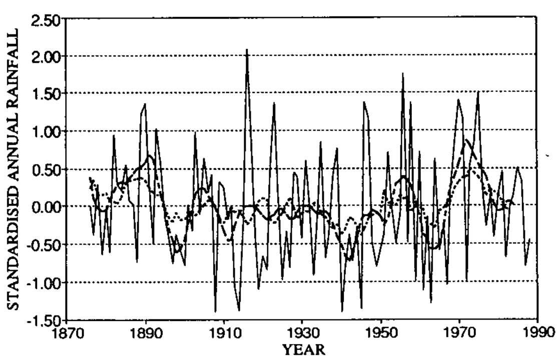



**Fig. 9 Regional mean of annual rainfall for the winter rainfall (Tasmania) temperate region with 11-year moving average (. . .) and Gaussian filter (- - -).**




Even though we visually observe apparent high and low rainfall periods, none of the first five tests indicated any significant trend or change in the mean value (at the 5 per cent significance level). Test 6 indicated significant changes for three cases only (ST in 1935, WH in 1917 and AS in 1901). Since the percentages of variance explained by the regression lines are less than 6 per cent for both cases, one cannot have much confidence in the results from this test.

When the statistical tests were applied to individual station data, the number of stations indicating significant trend or change in the mean value varies from 2 to 12 (Table 4). For the two-phase regression test, only three of the 11 cases have regression equations explaining more than 10 per cent of the variance and hence the outcomes of this test cannot be considered reliable.

**Table 4. Number of stations indicating significant trend or change in mean value at 5 per cent level.**

| *Test* | *No. of stations* |
|---|---|
| Mann-Kendall | 3 |
| Spearman | 3 |
| Cumulative sums | 12 |
| Likelihood ratio | 10 |
| Distribution-free CUSUM | 2 |
| Two-phase regression | 11 |

For each station, the number of tests indicating significant trend or change in the mean value are summarised in Table 5.

If we assume for this analysis that a significant result in at least three of the six tests applied to each data sequence should indicate change, then six (~9 per cent) stations have significant changes in their record (Table 5).

In addition to the above analysis, annual means were calculated for flood and drought dominated periods given by Warner (1987) and the results are given in Table 6. With the exception of 12 stations, the data exhibit the expected pattern of high-low-high.

**Table 5. Number of stations indicating significant trend or change in mean value in a given number of tests.**

| *No. of tests indicating change* | *No. of stations* |
|---|---|
| 6 | 0 |
| 5 | 0 |
| 4 | 2 |
| 3 | 4 |
| 2 | 6 |
| 1 | 10 |

**Monthly rainfall data**

The regional mean monthly rainfall time-series, moving average and Gaussian filter plots were examined visually. As in the annual case, most months exhibited alternating periods of high and low rainfalls. When the statistical tests were applied, only a few cases indicated significant trend or change in mean value at the 5 per cent level. Only the months and regions indicating significant change are given in Table 7.

Table 7 shows only three cases, region WM (January), region AN (February) and region TAS (November), having three of the six tests indicating significant change.

The results from the application of the stat-

**Table 6. Annual mean during flood dominated and drought dominated periods.**

| Station number | Station name | Mean (mm) F1 | D1 | F2 | Station number | Station name | Mean (mm) F1 | D1 | F2 |
|---|---|---|---|---|---|---|---|---|---|
| 02016 | Kununurra | 610 | 605 | 602 | 43030 | Roma P.O. | 513 | 541 | 630 |
| 03006 | Fitzroy Crossing | 628 | 520 | 528 | 44026 | Cunnamulla P.O. | 396 | 326 | 385 |
| 03030 | La Grange | 548 | 465 | 503 | 46037 | Tibooburra P.O. | 203 | 195 | 254 |
| 04035 | Roebourne | 370 | 298 | 313 | 48013 | Bourke P.O. | 418 | 301 | 367 |
| 05008 | Mardie | 204 | 254 | 299 | 49002 | Balranald P.O. | 324 | 283 | 369 |
| 05016 | Onslow P.O. | 192 | 256 | 308 | 50014 | Condobolin P.O. | 472 | 400 | 486 |
| 07017 | Cue P.O. | 218 | 227 | 229 | 51010 | Coonamble P.O. | 546 | 440 | 545 |
| 08025 | Carnamah | 364 | 414 | 371 | 54029 | Warialda P.O. | 740 | 642 | 710 |
| 09034 | Perth R.O. | 845 | 916 | 832 | 56002 | Armidale R.S. | 805 | 744 | 789 |
| 09500 | Albany Town | 867 | 1004 | 891 | 58012 | Yamba P.S. | 1513 | 1354 | 1572 |
| 09515 | Busselton | 757 | 868 | 808 | 58063 | Casino Airport | 1183 | 1040 | 1149 |
| 10058 | Goomaling | | 366 | 369 | 61055 | Newcastle | 1251 | 1033 | 1146 |
| 10144 | York P.O. | 443 | 461 | 455 | 63004 | Bathurst Gaol | 639 | 569 | 698 |
| 10579 | Katanning P.O. | 442 | 497 | 486 | 64008 | Coonabarabran | 780 | 651 | 816 |
| 12052 | Menzies P.O. | 181 | 245 | 247 | 66062 | Sydney R.O. | 1252 | 1089 | 1312 |
| 14015 | Darwin P.O. | 1590 | 1501 | 1699 | 68045 | Moss Vale P.O. | 1031 | 923 | 1034 |
| 14902 | Katherine | 1039 | 920 | 995 | 70025 | Crookwell P.O. | 838 | 845 | 912 |
| 15525 | Barrow Creek | 316 | 298 | 330 | 73056 | Young P.O. | 668 | 602 | 692 |
| 15557 | Tempe Downs | 240 | 230 | 296 | 74009 | Berrigan P.O. | 471 | 414 | 469 |
| 16056 | Yudnapinna | 194 | 203 | 227 | 75031 | Hay P.O. | 369 | 334 | 401 |
| 17031 | Marree | 144 | 152 | 179 | 77042 | Swan Hill P.O. | 347 | 320 | 379 |
| 18014 | Cleve P.O. | 286 | 395 | 413 | 79023 | Horsham | 433 | 455 | 457 |
| 23000 | Adelaide | 514 | 543 | 508 | 81003 | Bendigo Prison | 544 | 517 | 592 |
| 24518 | Meningie P.O. | 473 | 454 | 485 | 83025 | Omeo | 665 | 653 | 708 |
| 27005 | Coen P.O. | 1084 | 1136 | 1211 | 86071 | Melbourne R.O. | 638 | 649 | 664 |
| 28004 | Palmerville | 1024 | 1035 | 1038 | 87021 | Durdiwarrah | 667 | 652 | 744 |
| 30018 | Georgetown | 920 | 732 | 875 | 88001 | Alexandra P.O. | 698 | 691 | 744 |
| 31016 | Cooktown P.O. | 1796 | 1704 | 1948 | 88043 | Maryborough | 511 | 506 | 573 |
| 33007 | Bowen P.O. | 1055 | 961 | 1036 | 90015 | Cape Otway L.H. | 862 | 866 | 945 |
| 35019 | Clermont P.O. | 737 | 627 | 683 | 91057 | Low Head L.H. | 672 | 690 | 680 |
| 36143 | Blackall P.O. | 565 | 500 | 543 | 92038 | Swansea P.O. | 694 | 590 | 597 |
| 37043 | Urandangie P.O. | 300 | 265 | 323 | 93014 | Oatlands P.O. | 436 | 572 | 557 |
| 38003 | Boulia P.O. | 288 | 245 | 274 | 94010 | Cape Bruny L.H. | 978 | 895 | 992 |
| 39039 | Gayndah P.O. | 802 | 752 | 799 | 95003 | Bushy Park | 579 | 575 | 597 |
| 40214 | Brisbane R.O. | 1283 | 1017 | 1185 | | | | | |

F1 – Flood dominated regime 1864–1900
D1 – Drought dominated regime 1901–1948
F2 – Flood dominated regime 1949 onwards

istical tests to individual station data are summarised in Table 8. The number of stations indicating significant change varies from zero to 26. Again, if we assume that a significant result in at least three of the six tests applied to each data sequence should indicate change, then the number of stations indicating changes for different months are given in Table 9. The three winter months (June, July and August) show 15 to 19 stations with significant changes. Relatively few stations indicate change in summer and autumn months.

## Conclusions

Information related to the consistency and homogeneity of data recorded prior to 1910 is almost nonexistent. The present study has assumed that the data for a station is consistent if the double mass curves with neighbouring stations did not indicate any inconsistency.

Graphical plots of annual and monthly rainfall data indicate alternating high and low rainfall periods in the past. The patterns are consistent with the observations made by Deacon (1953) and Kraus (1954) for rainfall observed in the latter part of the last century and the earlier part of the present century. They are also consistent with the results obtained by Cornish (1977), Russell (1981) and Pittock (1983) for the data recorded in this century. Statistical tests on both the regional and station annual data do not support the hypothesis that the climate has changed recently. However, about a third of the stations indicate significant changes in winter rainfall. The change points are either late in the last century or early in the present century. Because of the fact that annual rainfalls failed to indicate any change, one can conclude that the monthly rainfall pattern, within a year, has changed for those stations at different times in the past.

**Table 7. Results of the statistical analysis of regional mean monthly rainfall time-series for the climatic regions.**

| Month | Region | Test 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Jan | WM | S | S | | | S(1932) | |
| | AS | | | | S(1878) | | S(1882) |
| Feb | AN | S | S | S(1937) | | | |
| Mar | AN | | | | | | S(1921) |
| Apr | SST | | | | S(1987) | | |
| | AS | | | | S(1891) | | |
| May | ST | | | | | | S(1898) |
| Jun | SST | | | | | S(1924) | |
| Jul | AN | S | S | | | | |
| Aug | ST | | | | S(1870) | | S(1873) |
| | SST | | | | S(1863) | | S(1862) |
| | WH | | | | S(1864) | | |
| | TAS | | | | S(1880) | | S(1888) |
| | AS | | | | | S(1951) | |
| | AN | | | | S(1887) | | |
| Sep | U | | | | S(1859) | | S(1861) |
| | AS | | | | S(1880) | | |
| Oct | | | | | | | |
| Nov | WM | | | | S(1839) | | |
| | TAS | | | | S(1885) | | S(1896) |
| Dec | AN | | | | | | S(1889) |

**Table 8. Number of stations indicating significant trend or change in mean value at 5 per cent level.**

| Month | Test 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| January | 14 | 11 | 9 | 8 | 5 | 2 |
| February | 4 | 4 | 4 | 6 | 1 | 6 |
| March | 4 | 0 | 0 | 4 | 0 | 4 |
| April | 13 | 4 | 1 | 10 | 2 | 6 |
| May | 13 | 7 | 3 | 8 | 4 | 9 |
| June | 21 | 26 | 17 | 14 | 20 | 1 |
| July | 22 | 22 | 8 | 11 | 12 | 5 |
| August | 21 | 24 | 9 | 15 | 19 | 12 |
| September | 16 | 10 | 3 | 6 | 9 | 6 |
| October | 9 | 9 | 8 | 12 | 8 | 4 |
| November | 7 | 7 | 4 | 10 | 6 | 8 |
| December | 3 | 7 | 1 | 8 | 2 | 7 |

**Table 9. Number of stations indicating significant trend or change in mean value in a given number of tests.**

| Month | No. of tests indicating change 1 | 2 | 3 | 4 | 5 | 6 | >2 |
|---|---|---|---|---|---|---|---|
| January | 6 | 4 | 5 | 3 | 2 | 0 | 10 |
| February | 10 | 5 | 0 | 1 | 0 | 0 | 1 |
| March | 5 | 3 | 0 | 0 | 0 | 0 | 0 |
| April | 13 | 10 | 0 | 0 | 0 | 0 | 0 |
| May | 10 | 10 | 4 | 0 | 0 | 0 | 4 |
| June | 7 | 5 | 6 | 3 | 9 | 1 | 19 |
| July | 4 | 10 | 8 | 5 | 1 | 1 | 15 |
| August | 10 | 8 | 10 | 4 | 5 | 0 | 19 |
| September | 9 | 7 | 8 | 2 | 0 | 0 | 10 |
| October | 8 | 9 | 6 | 1 | 0 | 0 | 7 |
| November | 11 | 3 | 5 | 2 | 0 | 0 | 7 |
| December | 3 | 6 | 2 | 0 | 0 | 0 | 2 |

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# APPENDIX

## Statistical tests

**Mann-Kendall rank correlation.** The Mann-Kendall rank correlation statistic, T, is defined as

$$T=[4\sum_{i=1}^{n-1} n_i]/[n(n-1)]-1 \qquad \ldots A1$$

where $n_i$ is the number of observations larger than the $i^{th}$ observation in the series subsequent to its position in the series of n values. The expected value of T is zero and the variance is given by

$$\text{Var}(T)=(4n+10)/[9n(n-1)] \qquad \ldots A2$$

**Spearman rank correlation.** The Spearman rank order correlation coefficient, r, between the observations $x_t$ in the series and time, t, is used as a basis for the test. One set of ranks gives $R_t$ the rank of $x_t$ in the series and the other set $T_t$ being 1, 2, . . ., n. The coefficient is computed as

$$r=1-6\sum_{t=1}^{n}(R_t-T_t)^2/(n^3-n) \qquad \ldots A3$$

The test statistic

$$t=r[(n-2)/(1-r^2)]^{1/2} \qquad \ldots A4$$

is distributed as Student's t with (n−2) degrees of freedom.

**Cumulative sums test.** The purpose of this test is to detect the existence of a jump in the mean after m observations

$$E(x_t) = \begin{cases}\mu & t=1,2,\ldots,m\\ \mu+d & t=m+1,\ldots,n\end{cases} \qquad \ldots A5$$

where μ is the mean value before the jump and d is the jump in the mean value. The basic assumptions of this test are that the observations are independent and normally distributed. The test can still be applied when there are slight departures from normality.

Let $S_0=0,\ S_k=\sum_{t=1}^{k}(x_t-x)\ \ k=1,2,\ldots,n \qquad \ldots A6$

$$D^2=\sum_{t=1}^{n}(x_t-x)^2/n \qquad \ldots A7$$

$$S_k^*=S_k/D \quad k=1,2,\ldots,n \qquad \ldots A8$$

The test statistic is

$$Q=\max_{0\leq k\leq n}|S_k^*| \qquad \ldots A9$$

Percentage points of the statistic Q are given in Buishand (1982).

**Likelihood ratio test.** This test uses the cumulative departures $S_k$ calculated above and defines a new variable $Z_k$ as

$$Z_k=[k(n-k)]^{-1/2}S_k/D \qquad \ldots A10$$

The test statistic is

$$W=(n-2)^{1/2}V/(1-V^2)^{1/2} \qquad \ldots A11$$

where $V=\max_{1\leq k\leq n-1}|Z_k|$

Percentage points of the statistic W are given in Worsley (1979).

**Distribution-free CUSUM technique.** The distribution-free CUSUM technique uses estimates of $U_t$ defined by

$$U_t=\sum_{i=1}^{n} g(x_i-\tilde{x}) \qquad \ldots A12$$

where $\tilde{x}$ = sample median
and $g(x)=1$ if $x\geq 0$
$=-1$ if $x<0$

The test statistic is $U=\max|U_t|$ and the upper 5 per cent value is $1.92\sqrt{M}$ where $n=2M$.

In the above tests, the position of maximum $|S_k^*|$, $|Z_k|$ or $|U_k|$ can be taken as an estimate of the change point m.

**Two-phase regression.** The two-phase regression model (Solow 1987) is written as

$$x_t=a_0+b_0t+e_t \quad t=1,2,\ldots,m \qquad \ldots A13$$
$$=a_1+b_1t+e_t \quad t=m+1,\ldots,n$$

where $a_0$, $b_0$, $a_1$ and $b_1$ are regression coefficients and $e_t$ is an independent sequence with zero mean and unknown variance $\sigma^2$. The abscissa of the intersection of the two regression lines is

$$c=(a_0-a_1)/(b_1-b_0) \qquad \ldots A14$$

The null hypothesis $H_0: b_1-b_0=0$;
alternative hypothesis $H_1: b_1-b_0\neq 0$

Because no closed form expression for c is available, it is necessary to search for the likelihood function to find its maximum. Equation A13 can be rewritten as

$$x_t=a_0+b_0t+b(t-c)I(t)+e_t \qquad \ldots A15$$

where $I(t)=0$ if $t\geq c$
$=1$ if $t>c$
and $b=b_1-b_0$

The likelihood ratio statistic is

$$L = [(S_0 - S)/3]/[S/(n-4)] \quad \ldots A16$$

where $S_0$ is the residual sum of squares from fitting the null model

$$x_t = a_0 + b_0 t + e_t \quad \ldots A17$$

and S is the residual sum of squares from fitting the alternative model (A15). The asymptotic distribution of L under the null hypothesis of no change is the F distribution with 3 and n–4 degrees of freedom.