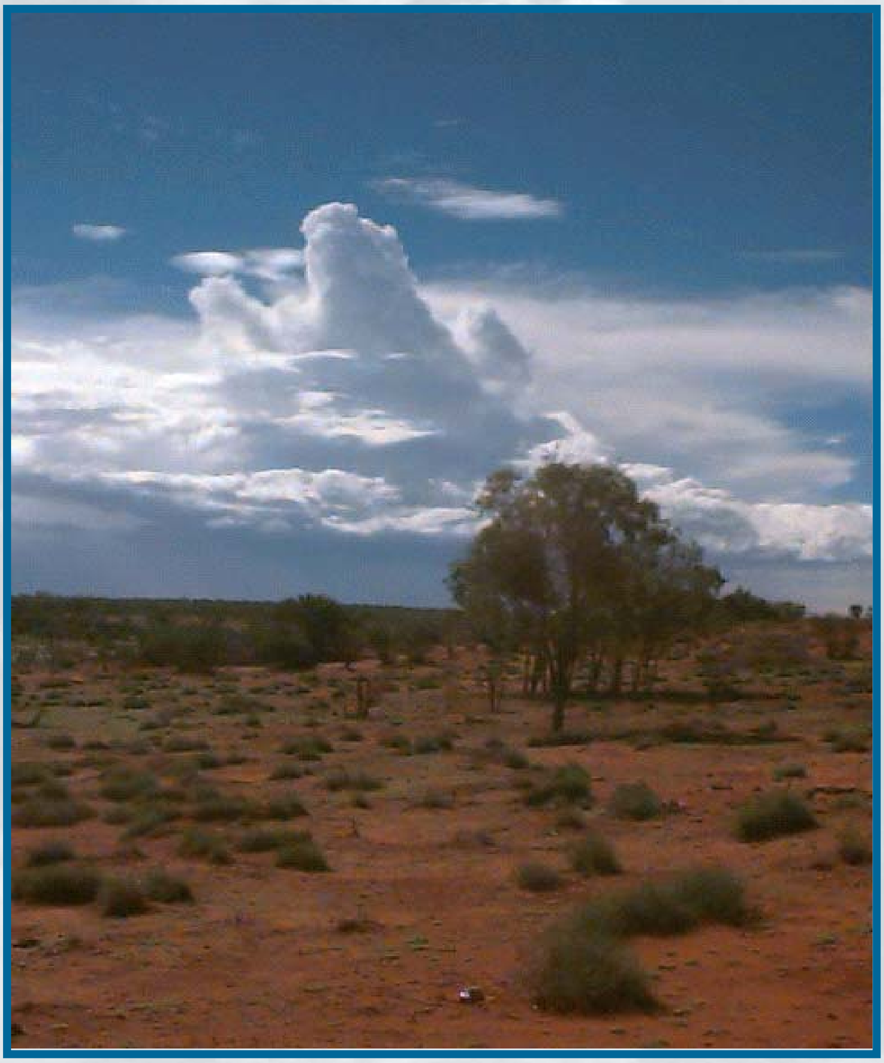
Detection of abrupt changes in Australian decadal rainfall (1890-1989)

Benjamin Vivès[1] and Roger N. Jones



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Abstract

The bivariate test is used to identify abrupt changes in Australia's rainfall record for the period 1890–1989. This statistical test is applied to the extended historical high-quality dataset and all other rainfall records longer than 60 years. Climatic step-like changes have been identified in the mean value on an annual and half-yearly basis. The detection of such shifts in mean in an independent time series has been carried out comparing a random series versus the observed time series. Results are successfully compared to the outputs of the more specifically designed Lepage test and the relevant literature on historical rainfall change. The results from the bivariate test and historical analyses display a greater coherence than the Lepage test results. Together, they provide evidence of three climatic (rainfall-dominated) shifts occurring during the past 100 years. The most noticeable is the well-known shift toward greater precipitation in eastern Australia in the late 1940s. The two others correspond to a global decrease in the mid-1890s and a regional downward shift in Western Australia in the end of the 1960s. An assessment of the resulting hydrological impacts suggests that knowledge of the dynamics and statistics of changes in rainfall regime will be of benefit in adapting to future climate.

Contents

1 Introduction

The sustainable management of water-reliant systems in Australia requires the understanding of rainfall variability in all its forms. Rainfall varies on a wide range of time scales, from individual events to decades and centuries:

1. Event variability
2. Daily rainfall variability
3. Intra-annual, seasonal and instraseasonal rainfall variability
4. Interannual rainfall variability
5. Century and decadal-scale rainfall variability
6. Climate change (Natural and human-induced)

Because short-term variability has the most visible impact on human affairs, much effort has been spent on understanding its statistical and dynamic properties. For example, Australian interannual rainfall variability is amongst the highest in the world, leading to significant research largely focussed on the El Niño–Southern Oscillation (ENSO) phenomenon and related teleconnections.

Longer term variability in rainfall is less well understood. Despite many efforts over the years to define predictive elements of long-term variability from observations of the rainfall record, these efforts have largely been unsuccessful. Proposals have not stood up to rigorous statistical analysis, often failing to satisfy the null hypothesis significance test (NHST; Nicholls, 2000), or have not shown sufficient skill to survive as forecasting systems. More recently, the development of climate models has offered the possibility of understanding the underlying dynamics of long-term variability, but the relatively brief historical record makes validation of simulated long-term dynamics difficult.

Describing the mean rainfall and accompanying short-term statistical properties of a place requires an assumption of stationarity. This assumption requires that there are no trends or phase shifts that will lead to an inadequate description being made. Often the NHST has been used to suggest that because a particular trend is below a given level of probability (that level itself arbitrarily chosen), it cannot be attributed to a non-random cause, i.e. it resides in the noise of chaos. This is despite the evidence of long-term persistence in rainfall records that appear to influence the mean and/or modulate shorter-term variability.

Often, inappropriate statistical tests are used. For example, time series are often analysed using tests that quantify the significance of linear trends. Such tests are inappropriate for analysing step changes in time series. Where interannual climate variability is very high, such as Australia, a change needs to exceed most or all of that variability to register as statistically significant, so all phenomena below that threshold are overlooked.

We take a much more practical approach to the identification of long-term rainfall variability. The practical questions that might arise are "has there been a change in climate that is statistically significant", or if there has been a change in variability, "what type of change was it and how may it affect the management of water-reliant systems?" Because decadal variability can produce large variations in mean rainfall and shorter-term rainfall variables (e.g. daily rainfall intensity) averaged over several decades, it will influence the outcomes of such an investigation. In a changing climate, the attribution of trends to decadal variability or a longer term secular change becomes problematic. With decadal rainfall variability occurring independently of possible trends due to greenhouse induced climate change, it may take many decades before possible rainfall changes can be properly attributed (Hulme et al., 1999).

This paper investigates abrupt changes in decadal mean rainfall in the Australian record using a statistical test normally used for testing for inhomogeneities in climate records. The bivariate test has been used for testing inhomogeneities for rainfall (Potter, 1981) and temperature (Bücher and Dessens, 1991). The hypothesis explored here is that if large numbers of rainfall stations change simultaneously and this change is not an artefact of large-scale changes in the observing system, that change must have a climatic origin. This follows on from the application by Jones (1995) of the bivariate test to rainfall stations in south-western Victoria where about half of all long-term stations in displayed a statistically significant upward shift in 1946. Jones (1995) speculated that these changes had a similar origin to decadal rainfall regimes identified in eastern New South Wales by Warner (1987). Likewise, in south-western Western Australia, a decrease in rainfall from the mid-1970s has resulted in significant water shortages, requiring substantial investment in infrastructure to secure water supply and the consequent establishment of the Indian Ocean Climate Initiative to explore the cause of the change and its possible longevity (IOCI, 2002). Here, we analyse all the Australian rainfall records of over 60 years in length from 1890–1989 to determine when and where abrupt changes in rainfall have occurred in the instrumental record. Finally, the implications for managing long-term risks arising from such changes are discussed.

2 Australian precipitation data

2.1 Previous studies on Australian rainfall and its variability

2.1.1 General characteristics

Australian rainfall records began in the mid 19th century. The earliest readings commenced with the aim of assessing the 'average' condition of the new country. However, it was soon realised that high interannual rainfall variability separated Australia from recollected conditions of Europe. As records became longer, fluctuations in the rainfall record were analysed. Deacon (1953), Kraus (1954) and Gentilli (1971) all noted a wetter period in the late 19th – early 20th century then a drier period in the first half of the 20th century. Pittock (1975) analysed 20th century rainfall records, examining the influence of the high pressure belt and the Southern Oscillation Index on interannual rainfall patterns, locating a significant rainfall increase in the late 1940s. Later, Pittock (1983) speculated whether this change was due to global warming. Utilising both 19th and 20th century Australian rainfall records Srikanthan and Stewart (1991) interpreted this shift as part of longer term variability.

Lavery et al. (1992, 1997) produced a high quality historical rainfall data set for Australia analysed from 1910 by Nicholls and Lavery (1992). They detected no significant changes in mean rainfall, although the influence of ENSO and a changed relationship between rainfall and temperature in El Niño periods since 1976 has been noted (Nicholls et al., 1996). Using the same data set, Suppiah and Hennessy (1998) and Hennessy et al. (1999) showed significant increases in extreme rainfall (based on annual values of 95th and 99th percentile daily falls) over the century for most of the continent except in south-west Western Australia (SW WA).

Using records of river floods and flow discharge (Warner, 1987) partitioned eastern Australian rainfall into flood-dominated (FDR) and drought-dominated regimes (DDR) covering the 19th and 20th centuries. This hypothesis was rejected by Kirkup et al. (1998) on both statistical and conceptual grounds. On the other hand, Whetton et al. (1990) noted an abrupt change in river flows from the Darling River in the Murray Darling Basin in the early 1890s that coincided with changes in the Nile and in Northern China. Franks (2002) and Franks and Kucszera (2002) have also investigated the effect of decadal rainfall variability using flood gauge data from New South Wales, that supports Warner's hypothesis and confirms the abrupt nature of changes noted by Whetton et al. (1990). A more recent decrease in rainfall in SW WA (Allan and Haylock, 1993) has lead to significant decreases in long-term water storage in that state (IOCI, 2001).

More recent research has concentrated on the relationship between Australian rainfall and other climatic variables and indices to better understand climate variability. Nicholls et al., 1996 and Power et al. (1998) examined relationships with the El Niño – Southern Oscillation, whereas Power et al. (1999a and b) examined recent aspects of decadal climate variability. Other studies will be raised in the discussion.

2.2 Rainfall datasets and basic analysis

Two different datasets of Australian precipitation were used in the analysis. The high-quality historical rainfall dataset for Australia provided a baseline dataset largely free of artefacts for the study. The other major dataset used was Australia's complete daily rainfall record, described in section 2.2.2.

2.2.1 High-quality historical rainfall data set for Australia

After an exhaustive search of documentation on measurement sites, coupled with statistical tests, Lavery et al. (1992) compiled a 191 station high-quality long-term rainfall data set. Some records of shorter duration were later used to build composite records, extending this dataset to 379 records (Lavery et al., 1997). The selection process vetted changes in observing practices, exposure of the rain gauge (or the rain-gauge type) and station location. Stations with discontinuities were immediately rejected those discontinuities could not be explained climatologically. Trends were closely examined and, if there was any suspicion that an observed trend was non-climatic, the station was rejected. The final testing was based on the method outlined in Craddock (1981) to compute a cumulative deviation term referred to as a 'bias statistic'. This bias statistic tests a time series for a station and flags any excessive drift from the expected climate.

Data from 363 rainfall stations out of the 379 described by Lavery et al. (1997) in the article were available to us. These records are referred as the High-Quality Dataset (HQD). Because the complete daily rainfall dataset discussed in the next section set only extended to 1990 at the time of analysis, the HQD was utilised for the period 1890–1989.

The distribution of first and last years of these records are presented in Figure 2.1 and record length in Figure 2.2. Only stations with a record length greater or equal to 60 years during this 100-year period have been selected. This restriction reduces the number of stations to 348. More than 30% of the stations (with a record length greater or equal to 60 years in between 1890–1989) have data prior to 1890 and almost all (98%) have records until at least 1989. More than 90% of the stations have at least 80 years of record during the 1890-1989 period (30% cover the whole 100 years).

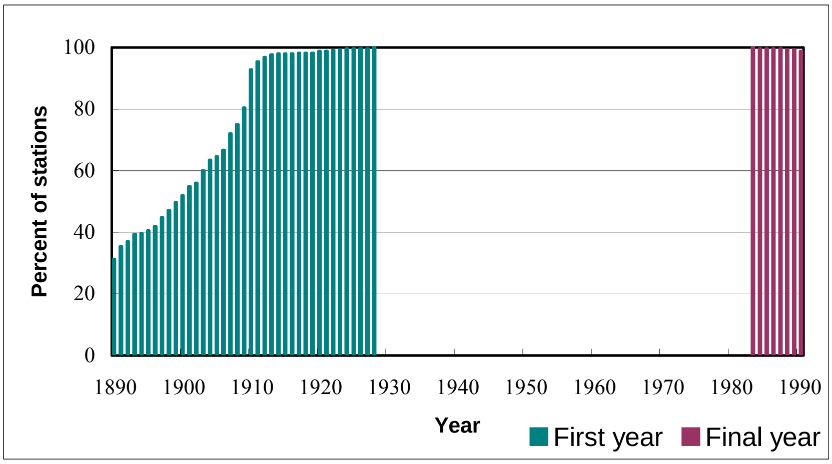


Figure 2.1 Cumulative percentage of record start and end years of the high quality rainfall data set.

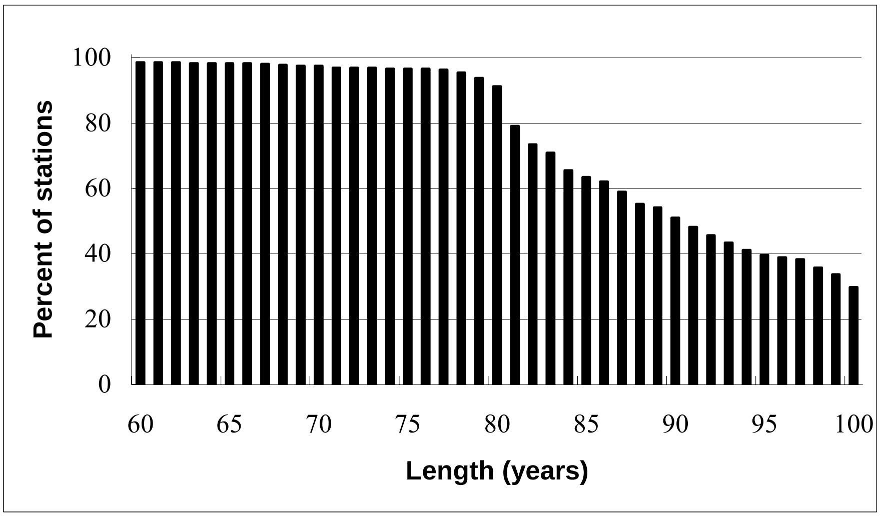


Figure 2.2 Percent of stations with a given record length from the high quality rainfall data set.

2.2.2 Daily rainfall dataset

These files cover 15,425 stations across Australia, comprising the entire daily data record from the Australian Bureau of Meteorology, and include the high-quality stations presented above. Many contain only a few years of record or have numerous gaps. Only 3,539 stations provided years of 60 years or greater in length. Their data homogeneity has not been tested so may contain unrepresentative shifts related to station relocation, changes in observing schedules and practices, changes in instrument exposure, etc. The assumption made here is that these shifts should be spread randomly among the period studied (since no globally unrepresentative shift has been described for the Australian rainfall data, including the change from the British Units to the International System of Units in 1974, Lavery et al., 1992). Likewise, these unreliable shifts should be randomly spatially distributed. Both assumptions are used to distinguish changes with a climatic origin from artefacts of measurement.

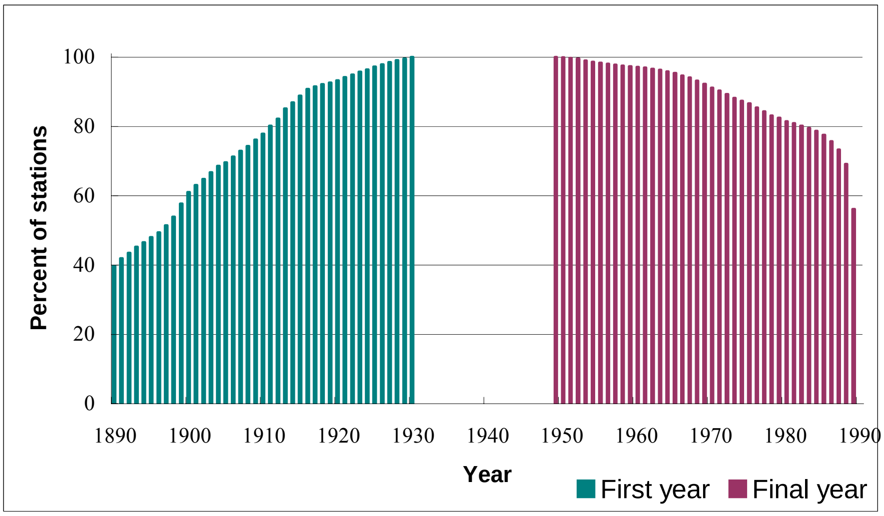


Figure 2.3 Cumulative percent of record start and end years for all Australian rainfall stations >60 years in length.

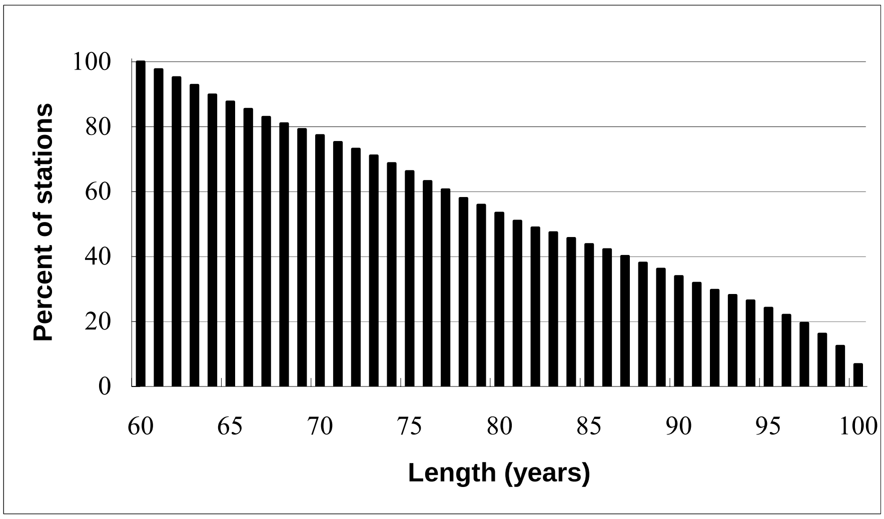


Figure 2.4 Percent of all Australian rainfall stations with a given record length of >60 years.

Almost 40% of the stations with a record length greater or equal to 60 years during the 1890–1989 period have data prior to 1890 (Figure 2.3) and more than 56% have records until 1989. Year 1989 is the last year available from this database. Only 53% of the stations have at least 80 years of records during the 1890-1989 period (7% cover the whole 100 years; Figure 2.4).

2.3 Clustering

To meet the bivariate test requirements and build homogeneous and stationary regional series, the records were clustered into groups of closely related stations, based on analyses carried out by Nicholls and Lavery (1992). They clustered the data of Lavery et al. (1992) into 10 groups based on similar variations of annual rainfall over the period 1910-1988, using the VARCLUS algorithm (SAS, 1985). For convenience, we have set the cluster limits of the larger HQD by following the meteorological districts used by the Australian Bureau of Meteorology (this allowed the computer program to straightforwardly sort out the different stations by using their identification number). See Figure 2.5 and Table 2.1 below.

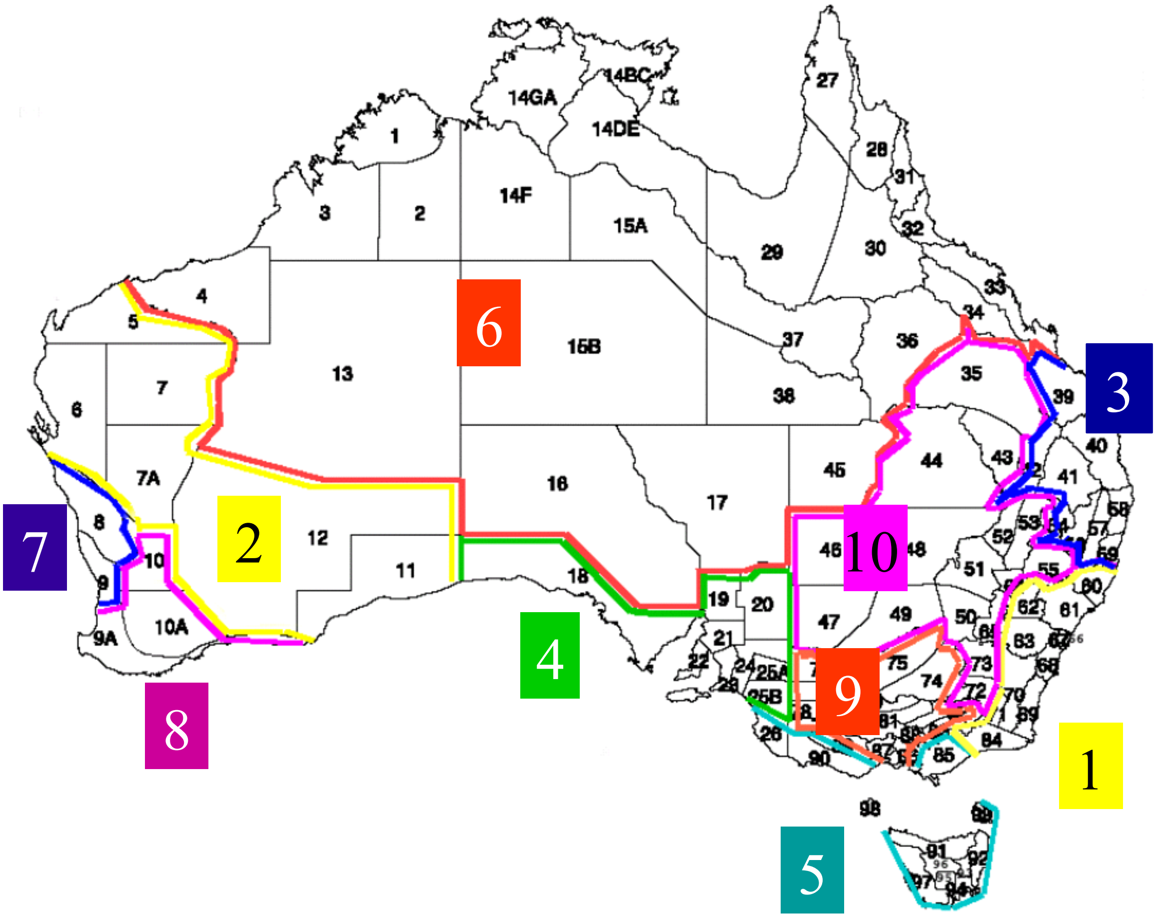


Figure 2.5 Climatological working chart, Australian rainfall districts (1–99) and the derived clusters (1–10).

Table 2.1 Summary of the clusters and the number of stations selected.

Cluster number	Cluster name	Districts included	Number of stations	
			HQD	National rainfall dataset
1	Eastern New South Wales	60, 61, 62, 63, 66, 67, 68, 69, 70, 71, 84	19	311
2	Western Australia	5, 6, 7, 11, 12	44	170
3	South-east Queensland	39, 40, 41, 42, 54, 56, 57, 58, 59	30	430
4	South Australia	18, 19, 20, 21, 22, 23, 24, 25	45	440
5	Tasmania	26, 85, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99	27	285
6	North-east Australia	1, 2, 3, 4, 13, 14, 15, 16, 17, 27, 28, 29, 30, 31, 32, 33, 34, 36, 45	76	464
7	South-west Western Australia	8, 9, 10	9	321
8	South coast Western Australia	9A, 10A	23	
9	Victoria	76, 77, 78, 79, 80, 81, 82, 83, 86, 87, 88, 89	35	547
10	Inland New South Wales	35, 43, 44, 46, 47, 48, 49, 50, 51, 52, 53, 55, 64, 65, 73, 72	40	571
TOTAL			**348**	**3539**

Note that because cluster 7 and 8 have two common rainfall districts (9 and 10), they were merged while processing the national rainfall dataset for easier management.

3 The bivariate test

3.1 Presentation

3.1.1 General background

Maronna and Yohai (1978) developed the bivariate test to detect a single systematic change in mean in an independent time series, based on a second correlated series which is assumed to be unchanged. It not only indicates whether or not a change has occurred, but also gives the maximum likelihood estimates and the time and magnitude of change.

In climatology, the most common application of the bivariate test is to determine whether there is a shift in the mean of one station relative to a reference series, neighbouring stations or a regionally representative series, that might be evidence of an artefact in measurement or station characteristics. Potter (1981) tested annual precipitation series from the northeast United States for homogeneity using the bivariate test. Results were excellent, even in cases where there was more than one shift in the precipitation mean. Bücher and Dessens (1991) successfully used the test to check inhomogeneities in time series of surface temperature from an elevated observatory in the Pyrenees in France. The bivariate test has also been used to demonstrate abrupt shifts in climatological variables that have a climatic origin. Lettenmaier et al. (1994) used the bivariate test to evaluate the relative changes in streamflow relative to precipitation, streamflow relative to temperature, and precipitation relative to temperature across the United States. Gan (1995) computed similar analysis comparing precipitation versus maximum temperature for Canada and North-eastern USA.

3.1.2 Step by step description

The test should ideally be applied to a serially independent sequence $\{x_i, y_i\}$ of n two-dimensional random vectors, each of them distributed normally. It is also assumed that the sequence is stationary, with the exception of a possible shift in the mean in $\{y_i\}$.

<u>Hypothesis</u>

H_0: $\{x_i, y_i\}$ have the same bivariate normal distribution, $N(\mu_x, \mu_y, \sigma_x^2, \sigma_y^2, \rho)$, with all parameters unknown.

H_1: For some $0 < i_0 < n$ and $d \neq 0$, the distribution of $\{x_i, y_i\}$ is $N(\mu_x, \mu_y, \sigma_x^2, \sigma_y^2, \rho)$, for $i \leq i_0$ and is $N(\mu_x, \mu_y + d, \sigma_x^2, \sigma_y^2, \rho)$ for $i > i_0$.

The likelihood ratio test of H_0 against H_1 is based on the following statistics.

<u>Series standardisation</u>

Let $\{x'_j\}$ be the regional series of length n and $\{y'_j\}$ be the test series of length n. It is necessary to standardise $\{x'_j\}$ and $\{y'_j\}$ by their mean and standard deviation to be able to use the critical values of the statistic T_0, computed by Maronna and Yohai (1978), under the null hypothesis N $(0,0,1,1,\rho)$.

Let $\overline{X} = \frac{1}{n}\sum_{j=1}^{n} x'_j$, $\overline{Y} = \frac{1}{n}\sum_{j=1}^{n} y'_j$

$$S_x = \left[\frac{1}{n}\sum_{j=1}^{n} (x'_j - \overline{X})^2 \right]^{1/2}$$

$$S_y = \left[\frac{1}{n}\sum_{j=1}^{n} (y'_j - \overline{Y})^2 \right]^{1/2}$$

$$x_j = \frac{(x'_i - \overline{X})}{S_x},\ _j\ y_j = \frac{(y'_i - \overline{Y})}{S_y} \quad \text{for all } j$$

<u>Compute test statistics</u>

Let $X_i = \frac{1}{i}\sum_{j=1}^{i} x_j$ and $Y_i = \frac{1}{i}\sum_{j=1}^{i} y_j$ for all i < n

$$\mathrm{S}_{\mathrm{xy}} = \sum_{j=1}^{n} x_j y_j$$

$$F_i = n - \frac{\left[X_i^2 ni\right]}{(n-i)} \quad \text{for all } i < \text{n}$$

$$\mathrm{D_i} = \frac{(\mathrm{S_{xy}} X_i - nY_i)n}{(n-i)F_i} \quad \text{for all } i < \text{n}$$

$$\mathrm{T_i} = \frac{i(n-i)\mathrm{D_i^2 F_i}}{(n^2 - S_{xy}^2)} \quad \text{for all } i < \text{n}$$

$$\mathrm{T_0} = \max_{\mathrm{i<n}} \left[\mathrm{T_i}\right] \text{ and } i_{\mathrm{o}} \text{ is the value of } i \text{ for which } \mathrm{T_i} \text{ is a maximum}$$

<u>Conduct test</u>

Maronna and Yohai (1978) computed, under the null hypothesis, T_i critical values by simulation for n=10, 15, 20, 30 and 70 and Potter (1981) extended the results to n=100. These are given in Table 3.1.

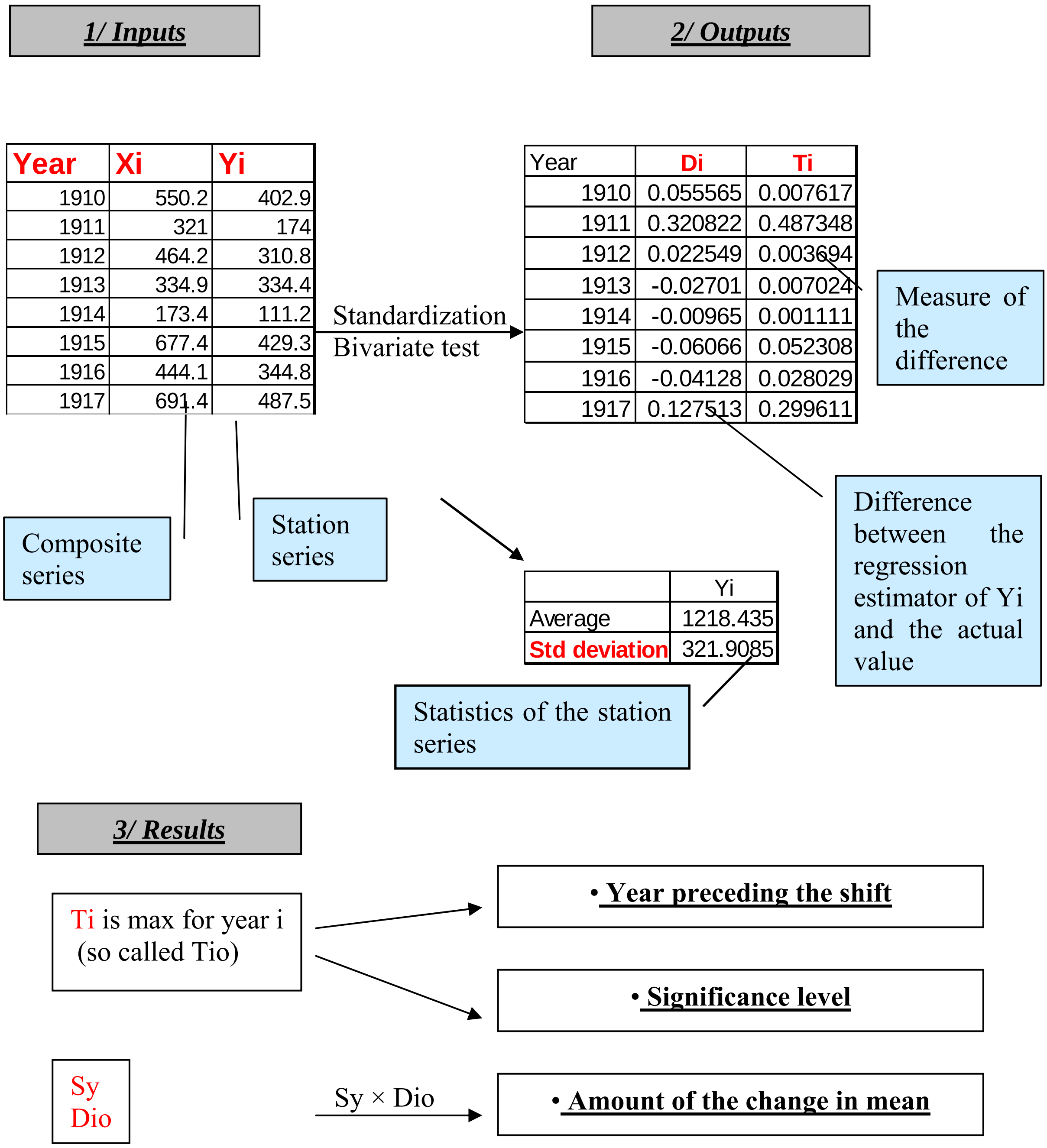
T_0 has to be compared to the critical value for the appropriate n and the desired significance level. If T_0 exceeds the critical value, one has to reject the null hypothesis. That is assumed that the mean of y has changed in the year after i_0 by an amount equal to ($D_{io} \times S_y$).

Table 3.1 Critical values of T_0 (Potter, 1981).

n (years)	**Significance level**			
	0.25	**0.10**	**0.05**	**0.01**
10	4.7	6.0	6.8	7.9
15	4.9	6.5	7.4	9.3
20	5.0	6.7	7.8	9.8
30	5.3	7.0	8.2	10.7
40	5.4	7.3	8.7	11.6
70	5.9	7.9	9.3	12.2
100	6.0	7.9	9.3	12.5

3.1.3 Applicability for rainfall analysis

Potter (1981) showed that for annual precipitation series, the assumption of normality does not pose a problem. However, this can be different in regions of low rainfall. The assumption of independence may not be strictly satisfied, but it is probable that the serial dependence is not strong enough to substantially alter the conclusion of the test (Potter 1981). Likewise, the assumption of stationary is generally satisfied. Most annual precipitation series are assumed to be stationary. A flow diagram of the application of the test on an Excel® spreadsheet is shown in Figure 3.1.



Year	Xi	Yi
1910	550.2	402.9
1911	321	174
1912	464.2	310.8
1913	334.9	334.4
1914	173.4	111.2
1915	677.4	429.3
1916	444.1	344.8
1917	691.4	487.5

Year	Di	Ti
1910	0.055565	0.007617
1911	0.320822	0.487348
1912	0.022549	0.003694
1913	-0.02701	0.007024
1914	-0.00965	0.001111
1915	-0.06066	0.052308
1916	-0.04128	0.028029
1917	0.127513	0.299611

	Yi
Average	1218.435
Std deviation	321.9085

Figure 3.1 Flow diagram of the application of the bivariate test on an Excel® spreadsheet.

3.2 Application of the test

To apply the bivariate test to Australian rainfall, we tried several combinations of reference station and subject series. This section briefly describes some of those trials and outlines the successful analytical design. To create cluster and national reference records, we converted individual stations into anomalies based on the 1960–89 rainfall and averaged those anomalies. For each station, T_0 is chosen and tested for significance. Even if there may be several jumps in a record for this study we chose only the most significant.

3.2.1 Cluster reference series

The first trial used as the reference series the average HQD rainfall anomaly for each cluster. Note that the level of significance (SL) shown is >10% (P>0.1) and will remain so for all the results presented.

<u>High-Quality Dataset</u>
Trial 1 tested each of the 348 HQD station against its mean cluster anomaly for all clusters. Of those, 140 stations (40%) show a significant change in their rainfall mean during the 1890-1989 (Figure 3.2). They are randomly spread, the most important peak being 1965 with only 2.2% of all stations showing a significant change. This confirms that the HQD is, by and large, homogeneous.

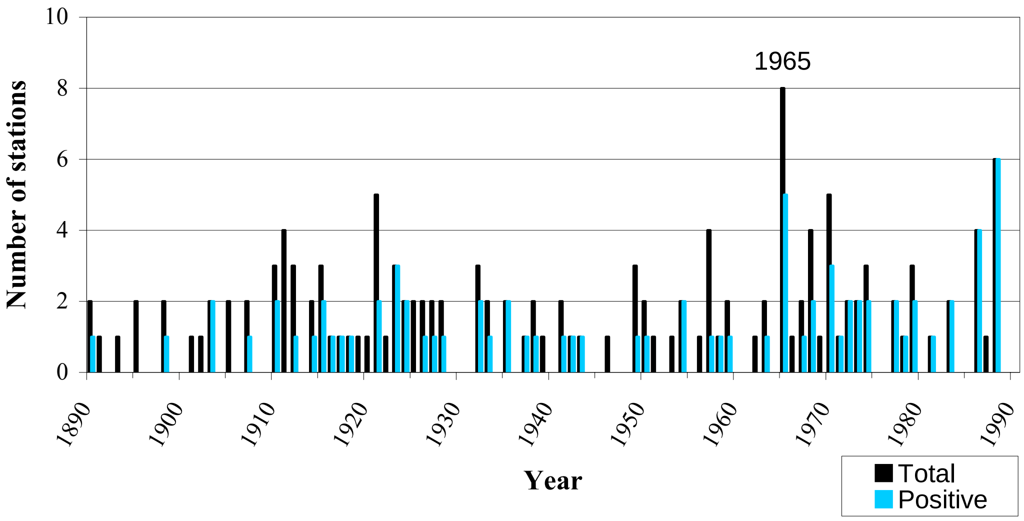


Figure 3.2 Temporal distribution of shifts in annual rainfall from the HQD compared to each cluster average, SL >0.1 (Trial 1).

<u>National rainfall dataset</u>
Trial 2 tested the full data set for each cluster against each mean cluster anomaly of the HQD (as above). This time, 1,191 stations (33%) show a peak in the period of interest (Figure 3.3). As for the HQD, results are spread relatively evenly, with little evidence of a change of climatic origin. Events in 1972, the largest peak, accounts for less than 1.5% of the total number of stations.

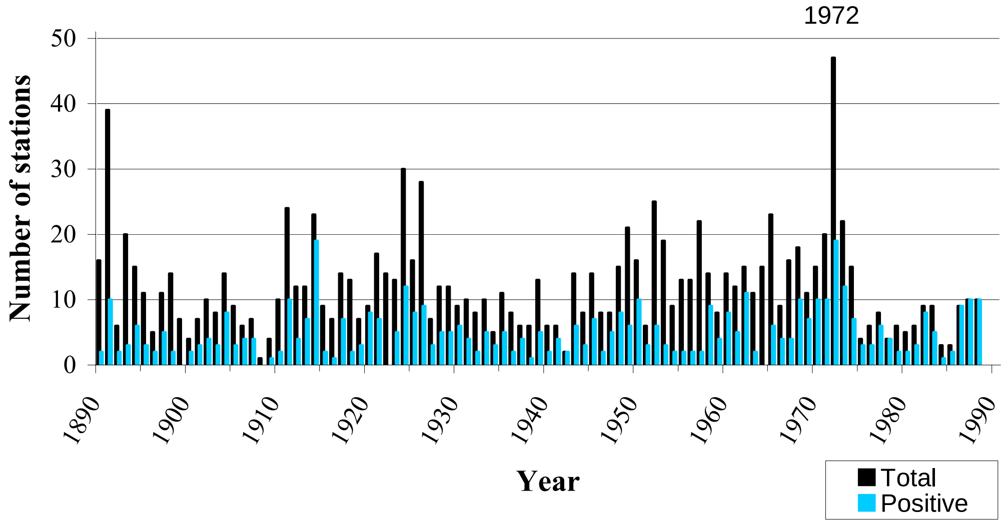


Figure 3.3 Temporal distribution of shifts in annual rainfall from all Australian records >60 years compared to each cluster average, SL > 0.1 (Trial 2).

3.2.2 National reference series

In Trials 3 and 4 we used an Australia-wide reference series created from the average annual anomaly of the HQD. From the results of Trials 1 and 2, we concluded that there was little evidence of climate changes when stations within clusters were tested against the mean anomaly for each cluster. In Figure 3.2 and Figure 3.3, most inhomogeneities appeared to be random, consistent with the likely spread of measurement artefacts. Therefore, we hypothesized that if any regional changes had occurred they would have affected the whole cluster as part of regional homogeneity (e.g. the recent downturn in rainfall in SW WA). Trials 3 and 4 tested every precipitation series >60 years against the reference series.

High-Quality Dataset

Trial 3 for the HQD against the national average anomaly showed little difference to Trial 1 (Figure 3.4). One third (32%) of the stations tested showed a significant shift in the mean with the most important peak representing 2% of all 348 stations occurring in 1971. Individual cluster results (not shown) also did not indicate any particular pattern of shifts. The most important peak was in cluster 3 (South-east Queensland) with 3.2% of the stations showing a shift in 1974.

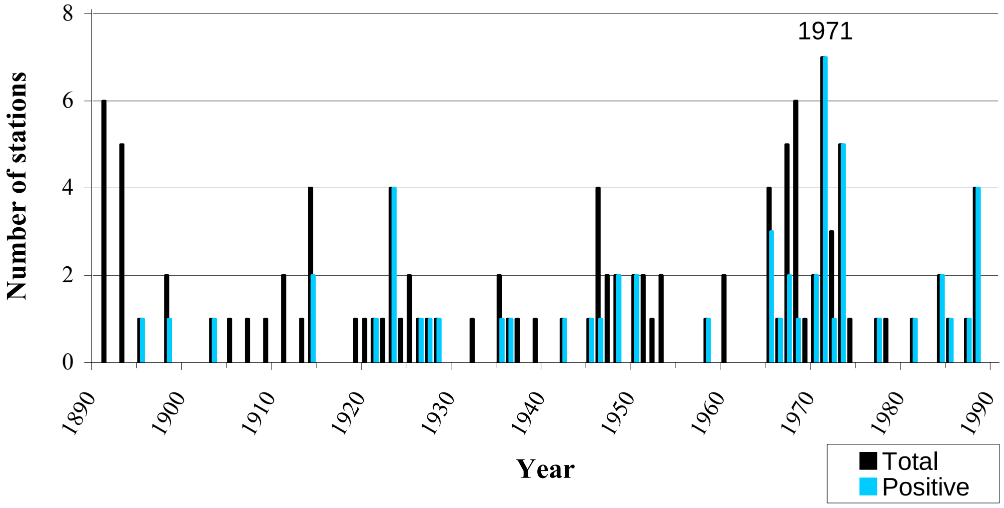


Figure 3.4 Temporal distribution of shifts in annual rainfall from the HQD compared to a national average from the HQD, SL >0.1 (Trial 3).

National rainfall dataset

Trial 4, testing all stations >60 years in length against the HQD national anomaly shows 1,067 stations (30%) with an abrupt change in the precipitation series (Figure 3.5). The distribution of shifts is now much more distinct, with peaks in the early 1890s, in the late 1940s and in the late 1960s/early 1970s. The two most important peaks, 1891 and 1948, comprise 2.2% and 2.3% of the total number of stations, respectively.

The spatial distribution and relative importance of these shifts are shown in Table 3.2, where the results are presented for each cluster. The relative importance refers to the percentage of stations for which a shift has been detected compared to the total number of stations of the national rainfall dataset. The direction of change corresponds to a shift to higher precipitation (positive shift) or lower precipitation (negative shift).

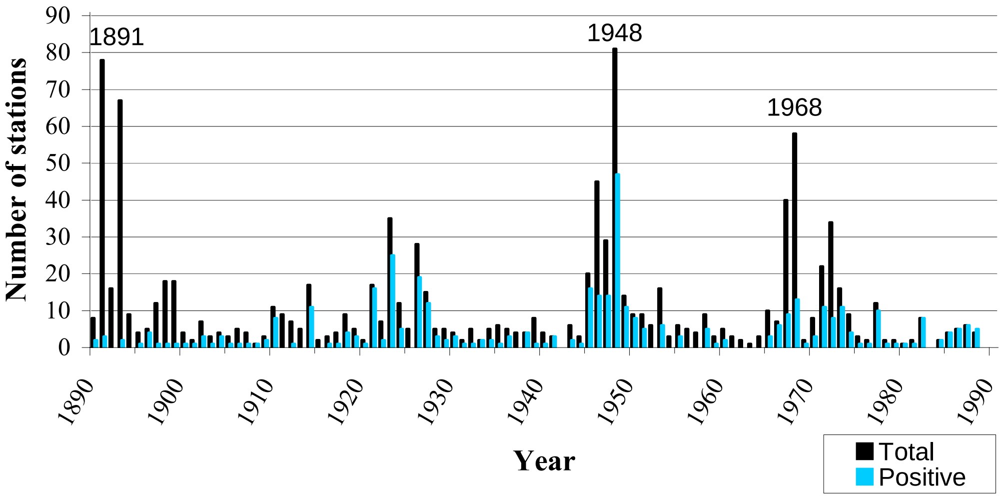


Figure 3.5 Temporal distribution of shifts in annual rainfall from all Australian records >60 years compared to a national average from the HQD, SL >0.1 (Trial 4).

Table 3.2 Proportion of the shifts and direction of change for each cluster (national rainfall dataset).

Cluster	Year	Number of stations	Proportion of total	Direction of change
1	1893	18	5.8%	100% negative
	1948	36	11.6%	100% positive
2	No peak with more than 5% of the stations involved			
3	1893	45	10.5%	100% negative
4	1948	24	5.5%	100% negative
6	No peak with more than 5% of the stations involved			
7&8	1946	24	7.5%	100% negative
	1967	31	9.7%	100% negative
	1968	45	14%	100% negative
9	No peak with more than 5% of the stations involved			
10	1891	52	9.1%	100% negative

The peaks in Figure 3.4 exceed 5% of the total number of stations in several clusters (Table 3.2). The early 1890s are significant in clusters 1, 3 and 10 (New South Wales and Queensland) with negative shifts. The late 1940s are significant in cluster 1, 4, and 7&8 (New South Wales, South Australia and Western Australia). The shifts are negative in South and Western Australia and positive in New South Wales. Another downward shift in occurs Western Australia in the late 1960s. We conclude that this is the decrease noted by a number of other authors (e.g. Allan and Haylock, 1993).

3.2.3 Random number reference series

For Trials 5 and 6, we used a random number reference series. We interpret the results from Trials 3 and 4 as shown in Figure 3.4 and Figure 3.5, as representing shifts of both artificial and climatic origin. The larger peaks appear to be due to abrupt shifts (step-like changes) of a climatic origin. However, due to the range of different climates and the poor spatial coverage of some regions (especially central Australia), this series is not ideal. Moreover, for the cluster series and perhaps the national series, if there is any climatic shift represented in the series average, the bivariate test may not properly detect it.

We hypothesised that the detection of abrupt climatic shifts within a time series caused by complex system responses would be best using a random series with similar statistical properties that shows no such shifts itself. We therefore created an independent, stationary series using generated random numbers (μ_x=0, σ_x^2=1). Two series with no obvious trends or shifts were selected (time series have been plotted with a different running average) and tested with the bivariate test against one another. The bivariate test did not detect any significant shift, so one of the series has been used as a reference series. Trial 5 and 6 used the HQD and national rainfall dataset with this series.

<u>High-Quality Dataset</u>

For Trial 5 the percentage of stations showing a significant shift is similar to the national series (31%) but the results display much more temporal coherence. Significant peaks are consistent with a climatic origin. The percentage of stations involved in each peak is still low but larger than previously (2% of the total number of stations in 1890 and 1893, 3% in 1946 and 4% in 1972; Figure 3.6).

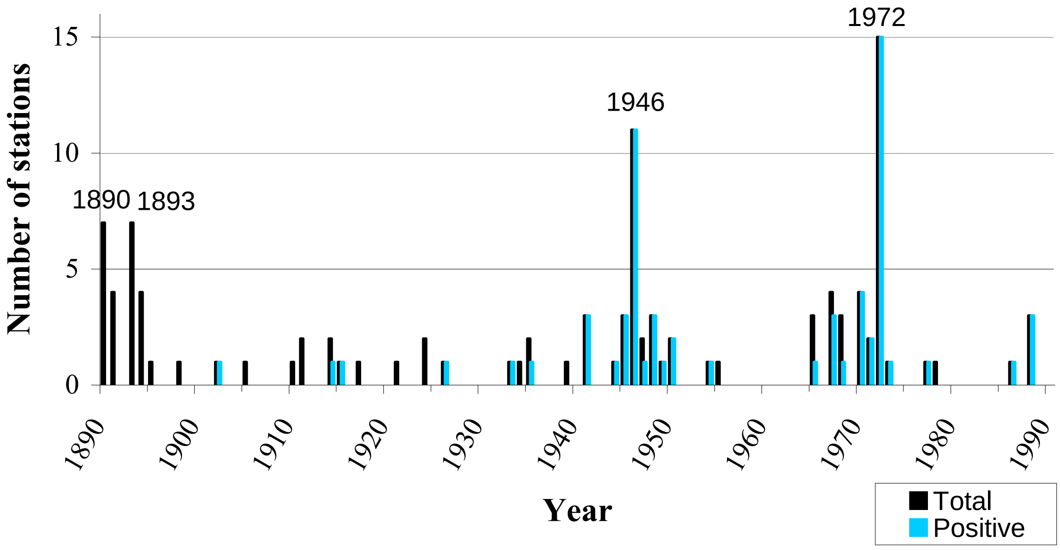


Figure 3.6 Temporal distribution of shifts in annual rainfall from the HQD compared to a random series, SL >0.1 (Trial 5).

<u>National rainfall dataset</u>
For Trial 6, 29% (1,034) of all stations show significant shifts, a similar number to Trial 4. But the temporal distribution of these changes is much more precise, with three major groups (1890–1895, 1945–1950, 1967–1972) accounting for more than 70% of the total number of shifts detected, and occurring in only 16% of the length of the time series (Figure 3.7).

The agreement between Trials 5 and 6 is also important, since it indicates that these events cannot be attributed to the record quality – in Trials 1 and 3 the HQD was shown to be largely homogenous with the mean regional and national average anomalies as Lavery et al. (1992, 1997) intended. Therefore, this method, using an independent random series as required by the bivariate test, is the best method for testing abrupt shifts of climatic origin. We present the results of these tests in the next chapter.

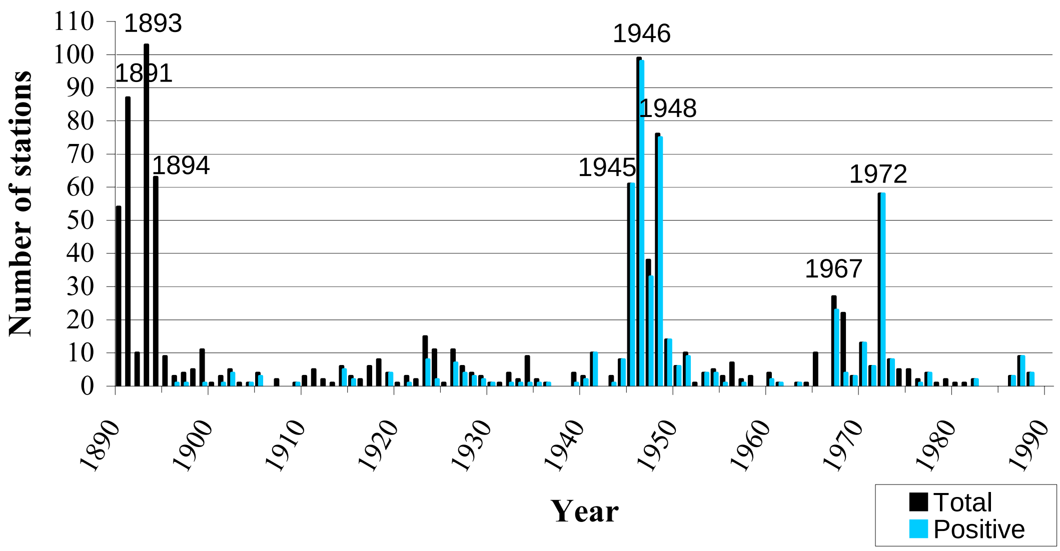


Figure 3.7 Temporal distribution of shifts in annual rainfall from all Australian records >60 years compared to a random series, SL > 0.1 (Trial 6).

3.2.4 Selected results with different reference series

In this section we show how the bivariate test works for individual time series. Annual precipitation and the results of the bivariate test on a given station from the HQD, Canary Island (Victoria, Cluster 9) are shown in Figure 3.8. The results are shown using the Cluster 9 mean anomalies, the national HQD average anomalies and the randomly generated series as a reference.

Figure 3.8 (lower) shows the annual precipitation series and its five-year running mean during the 100-year period from 1890 to 1989. The mean for the entire period is 364 mm. It is evident that a relatively dry period before 1950 was followed by a relatively wet period (Table 3.3). This is particularly noticeable for the 5-year running mean.

After 1950, annual average precipitation increased by 25% compared to the pre-1950 average, with an even more important variation in interannual variability (standard deviation increased by 30%). This station was selected by Nicholls and Lavery (1992) as one of the ten representative stations for Australia (one for each cluster). They have also described 'an increase in rainfall after 1950'.

Figure 3.8 (upper) shows the time series of the bivariate statistic (Ti) for the three tests. The advantage of using the random series is it gives more accurate results than the other two (Measured by comparing the magnitude of increase in Table 3.4 with that in Table 3.3). This confirms the use of a random series as an absolute reference against which to test climatically-driven step changes as contrasted with a regional or national series. The latter two will be preferred for testing inhomogeneities with an artificial origin.

Although using the cluster series as a reference in Figure 3.8 gives the highest value of T_0, if the complete sequence of Ti is carefully studied, the bivariate test detects another significant shift in 1907 (with a significant level >0.1). But the comparison of the 1890–1907 period and the following one (1908–1954) does not reveal any significant difference between them. The average value remains in the same order (respectively 321mm and 334mm) and the standard deviation is almost the same (95mm and 98 mm).

The use of a random series as a reference has proved to be the best series to use to detect shifts which have a climatic original (characterised by a coherent spatial and temporal distribution) because it eliminates regional climatic influences of averaged time series (cluster or nation-wide) and provides a realistic estimate of the magnitude of the shift. Therefore, in the rest of this study, the bivariate test is conducted using the random series as a reference. Further tests, shown in Appendix 4, investigating the behaviour of the bivariate test using known departures from a random series, further demonstrate its suitability for the task in question.

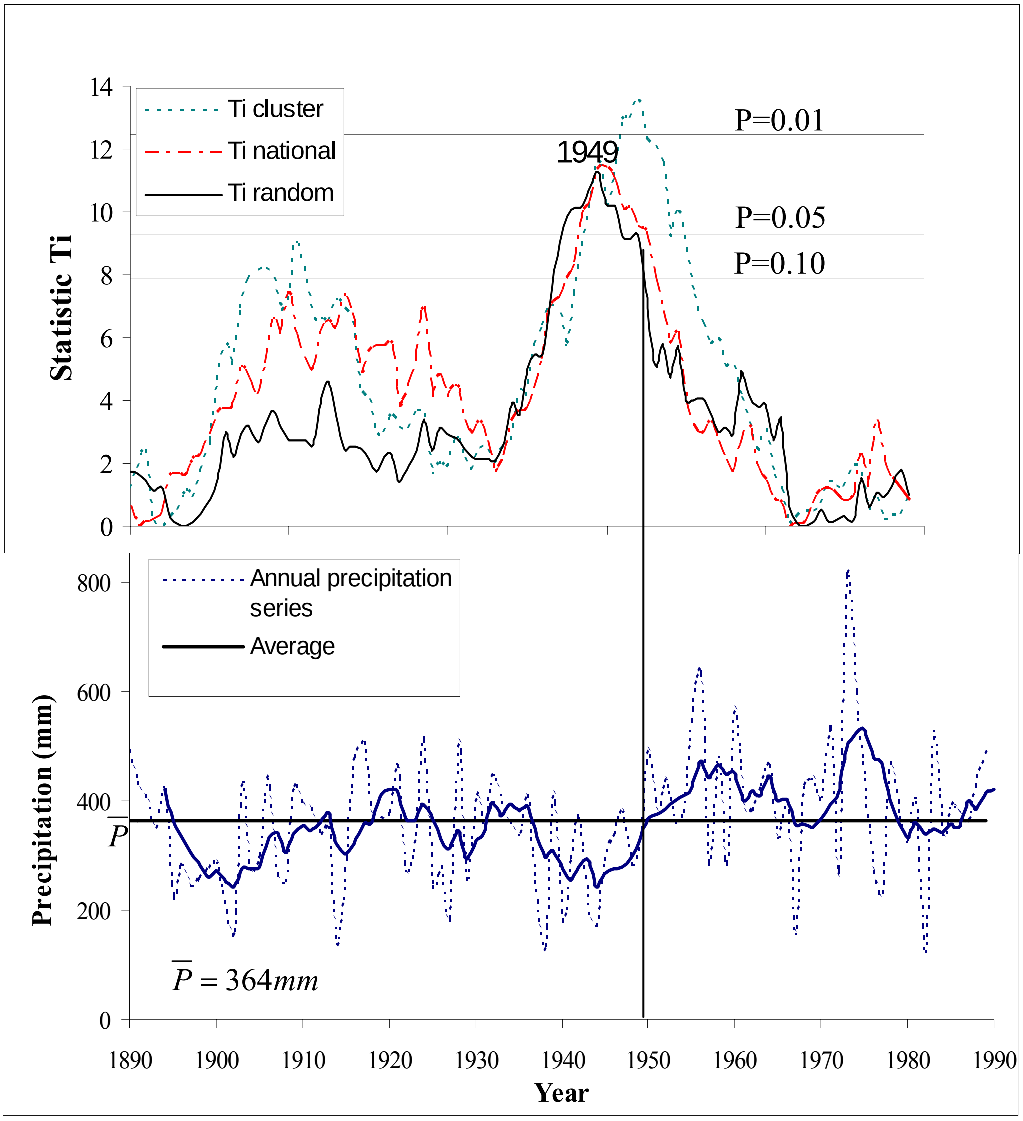


Figure 3.8 Annual rainfall with 5-year running mean for Canary Island (lower panel), with bivariate test results using three different reference series (upper panel).

Table 3.3 Means and standard deviation for annual precipitation for two successive periods at Canary Island, showing change in mean.

Period	**1890–1949**	**1950–1989**
Mean (plus change)	332 mm	412 mm (+80mm)
Standard deviation	97 mm	127 mm
Coefficient of variance	29%	31%

Table 3.4 Results of the bivariate test. Years of occurrence of T_0 at Canary Island, with three different reference series.

Reference series	**Cluster average**	**National average**	**Random**
Year with max. Ti (T_0)	1954	1950	1949
Value (significance level)	13.6 (>0.01)	11.4 (>0.05)	11.3 (>0.05)
Change (mm)	+ 35.5	+ 50	+ 78

4 Results of the bivariate test

This chapter presents the results of the bivariate test on an annual and seasonal basis, and for selected periods between 1890 and 1989, addressing the location, regional importance and order of magnitude of changes. Independently, two simple parameters (mean and standard deviation) are computed from the data to confirm the validity of the bivariate test outcomes.

4.1 Australia-wide results

4.1.1 Major peaks

National results for the stations of the national rainfall dataset were presented in Figure 3.6. Results for the summer half of the year (November–April) and the winter half of the year (May–October) are shown in Figure 4.1 and Figure 4.2, respectively.

Figure 4.1 shows that abrupt changes in the summer half of the year after 1900 are dominated by increases, with the largest changes occurring in the late 1940s. Earlier studies of rainfall trends by Deacon (1953), Kraus (1954), Cornish (1977), Russell (1981) and Pittock (1983) found that summer rainfall had increased over much of south-eastern Australia since the start of the 20th century. Compared to the annual shifts shown in Figure 3.6, the 1890s is less pronounced, a series of minor peaks occur in the 1920s, the 1940s remain significant, the late 1960s/early 1970s less so and the mid 1980s, insignificant in the annual set, becomes the second-most prominent. From the results shown in Appendix 4, this latter prominence may be overstated by the sensitivity of the bivariate test to changes close to the beginning and end of time series.

Winter changes show some differences with the annual results. The 1890s are dominated by decreases and involve a large number of stations. The 1920s show a small downward shift, compared to the upward shift in summer seen in summer (with little movement seen annually, Figure 3.7, inferring a change in variability but not in mean). The late 1940s are dominated by increases, 1968 by decreases and 1972 by increases. Slight increases are also apparent in 1982.

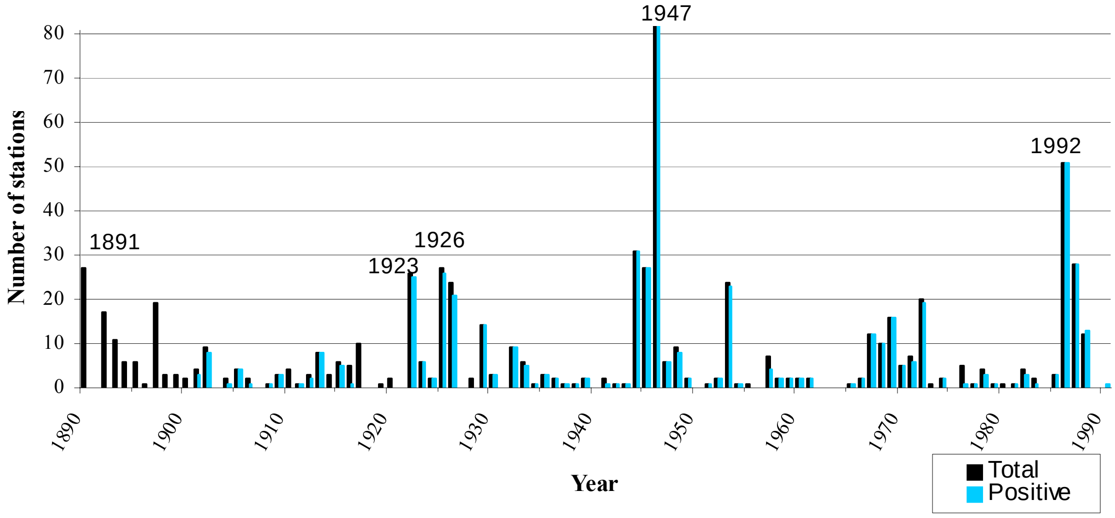


Figure 4.1 Temporal distribution of shifts in summer (November to April) rainfall from all Australian records >60 years compared to a random series, SL >0.1.

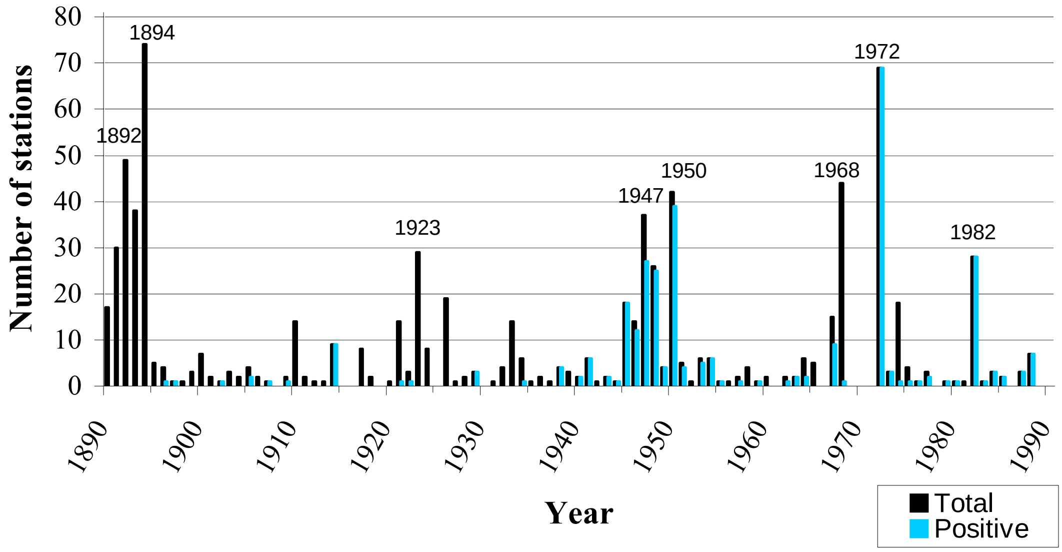


Figure 4.2 Temporal distribution of shifts in winter (May to October) rainfall from all Australian records >60 years compared to a random series, SL >0.1.

From the two last figures, it becomes obvious that the 1890–95 shifts are mainly due to a decrease in the winter precipitation as are the ones in 1968 and 1974. The period 1945–50 is dominated by increases in both seasons.

4.1.2 Other shifts

Changes in the 1920s appear to have a climatic origin with summer increases and winter decreases having little effect on the change in mean (Figure 3.7). The winter decreases are mainly located in South Australia (cluster 4) and in a less important extent in Western Australia (clusters 7 and 8). The summer variations are mainly located in Victoria, Tasmania and south-east Queensland (respectively clusters 9, 5 and 3). Maps are presented in Appendix 2. Shifts in annual precipitation involve fewer stations. This is due to these regions also being subjected to the more important 1890–95 and 1945–50 shifts. These shifts could be investigated by truncating series to avoid the largest shifts, i.e. investigating the period 1895–1945.

In the 1980s, as maps in Appendix 3 show, the majority of May to October shifts are located in tropical and sub-tropical regions (southeast Queensland) where most of rainfall occurs during the summer. This could explain why these changes are not important enough to influence the overall annual series. However, as shown in Appendix 4, significant shifts at the end of a series may have less statistical significance than those in its midst.

4.2 1890–95 shifts

4.2.1 Results summary

Table 4.1 presents a summary of the bivariate test results for this period. The bivariate results are on the left part of the table and the raw data from the same stations are on the right. The mean value and the standard deviation before and after the year of the change are computed but are not significant due to the available sample size for 1890–95. In the ideal case, the change in mean should correspond to the bivariate estimate – most of these values are very close. Changes where the proportion of stations showing shifts in each cluster exceeds 20% are outlined in blue if the shift is towards higher rainfall or red in the case of a decrease.

Table 4.1 Bivariate test results obtained for the 1890–95 shifts (national rainfall dataset).

Cluster	Dataset	Shifts detected by the bivariate test (SL > 0.1)					Precipitation data for 1890-95 / 1895-1989			
		Number of stations	Percentage of stations	Percentage of all shifts	Nature of change	Change in mm	Mean rainfall in mm		Standard deviation in mm	
1	Annual	38	12%	24%	negative	-471	1342	883	158	237
	Summer	12	4%	7%	negative	-353	920	570	214	207
	Winter	19	6%	33%	negative	-296	619	328	99	122
2	Annual	0	0%	0%	-	-	-	-	-	-
	Summer	0	0%	0%	-	-	-	-	-	-
	Winter	0	0%	0%	-	-	-	-	-	-
3	Annual	95	22%	54%	negative	-618	1556	948	209	260
	Summer	24	5%	16%	negative	-792	1538	757	240	275
	Winter	11	2%	48%	negative	-192	431	242	70	106
4	Annual	19	4%	22%	negative	-298	694	402	19	102
	Summer	0	0%	0%	-	-	-	-	-	-
	Winter	10	2%	10%	negative	-191	431	242	33	73
5	Annual	7	2%	11%	negative	-301	912	616	98	158
	Summer	0	0%	0%	-	-	-	-	-	-
	Winter	11	4%	15%	negative	-275	604	335	73	105
6	Annual	38	8%	33%	negative	-611	1136	547	139	233
	Summer	18	4%	20%	negative	-644	966	320	0.4	320
	Winter	43	9%	43%	negative	-171	277	109	37	73
7&8	Annual	3	1%	3%	negative	-454	1025	584	0	135
	Summer	0	0%	0%	-	-	-	-	-	-
	Winter	4	1%	3%	negative	-439	902	477	0	120
9	Annual	7	1%	6%	negative	-188	594	410	80	120
	Summer	1	0%	2%	negative	-89	218	130	102	63
	Winter	12	2%	13%	negative	-140	437	299	72	88
10	Annual	119	21%	52%	negative	-410	858	462	61	164
	Summer	12	2%	1%	negative	-340	218	130	102	63
	Winter	103	18%	65%	negative	-153	366	215	44	85
Total	**Annual**	**326**	**9**	**31%**	**negative**	**-488**	**1138**	**662**	**123**	**204**
	Summer	**67**	**2**	**10%**	**negative**	**-582**	**1018**	**484**	**144**	**234**
	Winter	**213**	**6**	**27%**	**negative**	**-184**	**403**	**222**	**51**	**88**

This decrease in precipitation (almost one third of the total shifts detected in the annual series happen during this five-year period) requires supporting evidence to be interpreted as a climatic event. Because it appears at the very beginning of the record, one can argue that this shift is overestimated in significance and may only be due to a short-lived wet period being exaggerated by its presence near the beginning of the series (see Appendix 4). However, the mean rainfall value for these stations falls from 1,138 mm a^{-1} to 662 mm a^{-1}, a similar amount to that indicated by the bivariate test. This decrease is confirmed by other evidence that will be presented later.

Comparison of the change in mean calculated by the bivariate test agrees with that calculated by the difference in the averages either side of the date of change. The change given by the bivariate estimate is -488 mm compared to -476 mm (1,138 decreasing to 662 mm a^{-1}). The large increases in standard deviation and decreases in mean in Table 4.1 will be affected by the short length of the period before the shift; therefore will not accurately represent the magnitude of change in the climate regime.

4.2.2 Location

Figure 4.3 shows the location of the shifts in annual rainfall listed in Table 4.1 which are dominated by decreases. Each station was plotted as occupying one square in a 0.5° grid; if two or more stations are plotted in the same location they are averaged. Few stations were in operation outside the area shown to be affected.

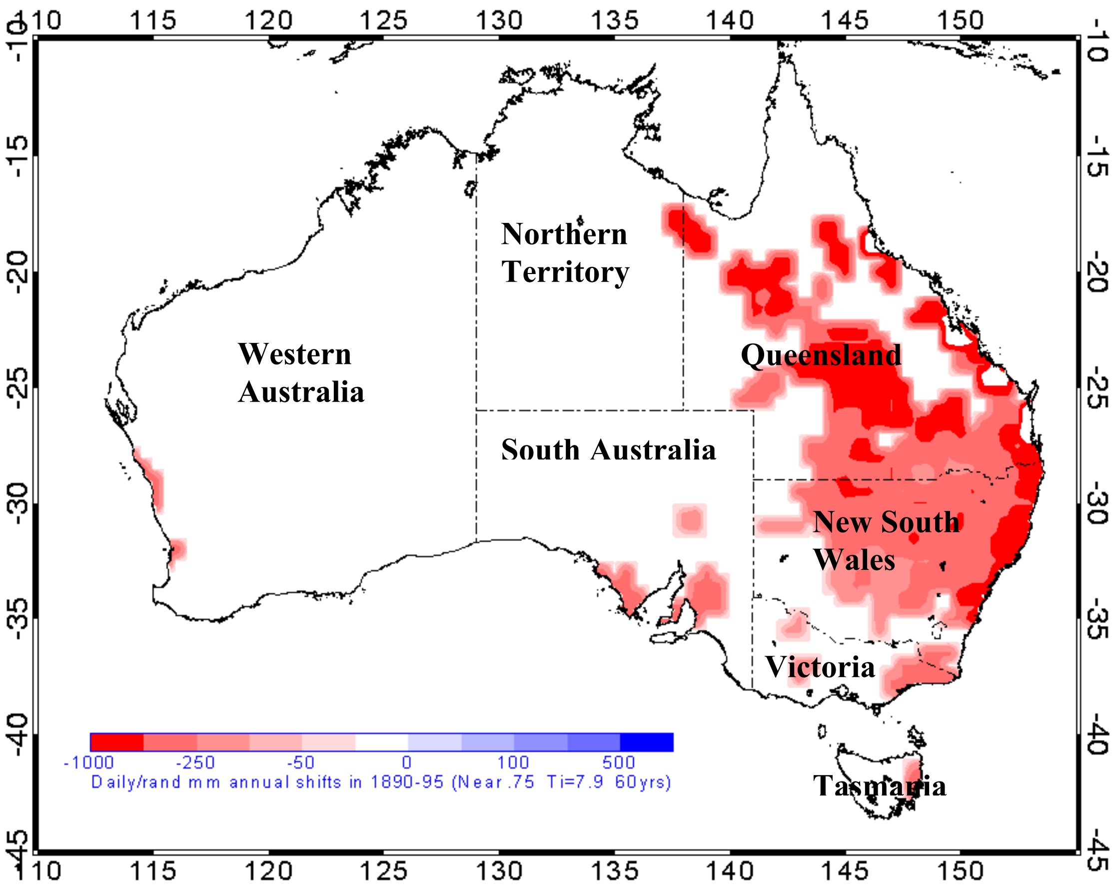


Figure 4.3 Location and amplitude (in mm) of the 1890–95 shifts (national rainfall dataset).

4.3 1945–50 events

4.3.1 Results summary

Shifts occurring in the 1945–50 period are almost as numerous as those in 1890–1895. Most stations show an abrupt increase in precipitation in both seasons. The estimated average change by the bivariate test is +161mm for the annual precipitation series compared to a +150 mm difference in averages (818–668). Because this change occurs at the halfway point of most of the records, sample length is unlikely to influence the significance of the result. In clusters 7 and 8 the lower value can be explained by the mean rainfall decrease (Table 4.2).

Table 4.2 Bivariate test results obtained for the 1945–50 shifts (national rainfall dataset).

Cluster	Dataset	Shifts detected by the bivariate test (SL > 0.1)					Precipitation data for 1890-1950 / 1950-1989			
		Number of stations	Percentage of stations	Percentage of all shifts	Nature of change	Change in mm	Mean rainfall in mm		Standard deviation in mm	
1	Annual	111	36%	70%	positive	218	804	1009	200	298
	Summer	73	23%	44%	positive	138	396	529	134	199
	Winter	16	5%	28%	positive	124	326	441	326	441
2	Annual	0	0%	0%	-	-	-	-	-	-
	Summer	0	0%	0%	-	-	-	-	-	-
	Winter	0	0%	0%	-	-	-	-	-	-
3	Annual	21	5%	12%	positive	218	936	1147	234	315
	Summer	1	1%	1%	positive	121	474	593	136	174
	Winter	19	4%	33%	positive	94	256	346	110	137
4	Annual	3	1%	5%	pos. (80%)	20	419	440	105	130
	Summer	1	1%	4%	negative	-48	139	92	31	58
	Winter	2	1%	2%	positive	47	145	190	55	60
5	Annual	20	7%	11%	positive	151	765	907	135	170
	Summer	1	1%	2%	positive	84	399	468	110	128
	Winter	29	9%	39%	positive	81	391	469	87	111
6	Annual	5	1%	4%	positive	101	555	656	153	182
	Summer	3	1%	3%	positive	282	1012	1240	255	282
	Winter	2	1%	2%	positive	52	87	137	38	72
7&8	Annual	5	2%	6%	negative	-87	555	470	110	85
	Summer	2	1%	6%	positive	71	123	161	55	71
	Winter	16	5%	12%	negative	-99	618	522	126	101
9	Annual	58	11%	53%	positive	109	530	633	122	140
	Summer	0	0%	0%	-	-	-	-	-	-
	Winter	46	8%	50%	positive	78	362	436	76	90
10	Annual	71	12%	31%	positive	130	490	601	137	186
	Summer	58	10%	46%	positive	96	276	364	104	142
	Winter	11	2%	7%	positive	89	176	250	66	92
Total	**Annual**	**294**	**8%**	**28%**	**pos. (99%)**	**161**	**668**	**818**	**164**	**225**
	Summer	**139**	**4%**	**20%**	**pos. (99%)**	**121**	**354**	**467**	**122**	**173**
	Winter	**141**	**4%**	**18%**	**pos. (88%)**	**66**	**357**	**419**	**115**	**141**

4.3.2 Location

Figure 4.4 shows the dominance of the positive shift in precipitation in the eastern part of the continent. Interestingly, the south-west part of Western Australia experienced decreases during the same period; 16 (5%) of stations from clusters 7 and 8 show decreases in winter.

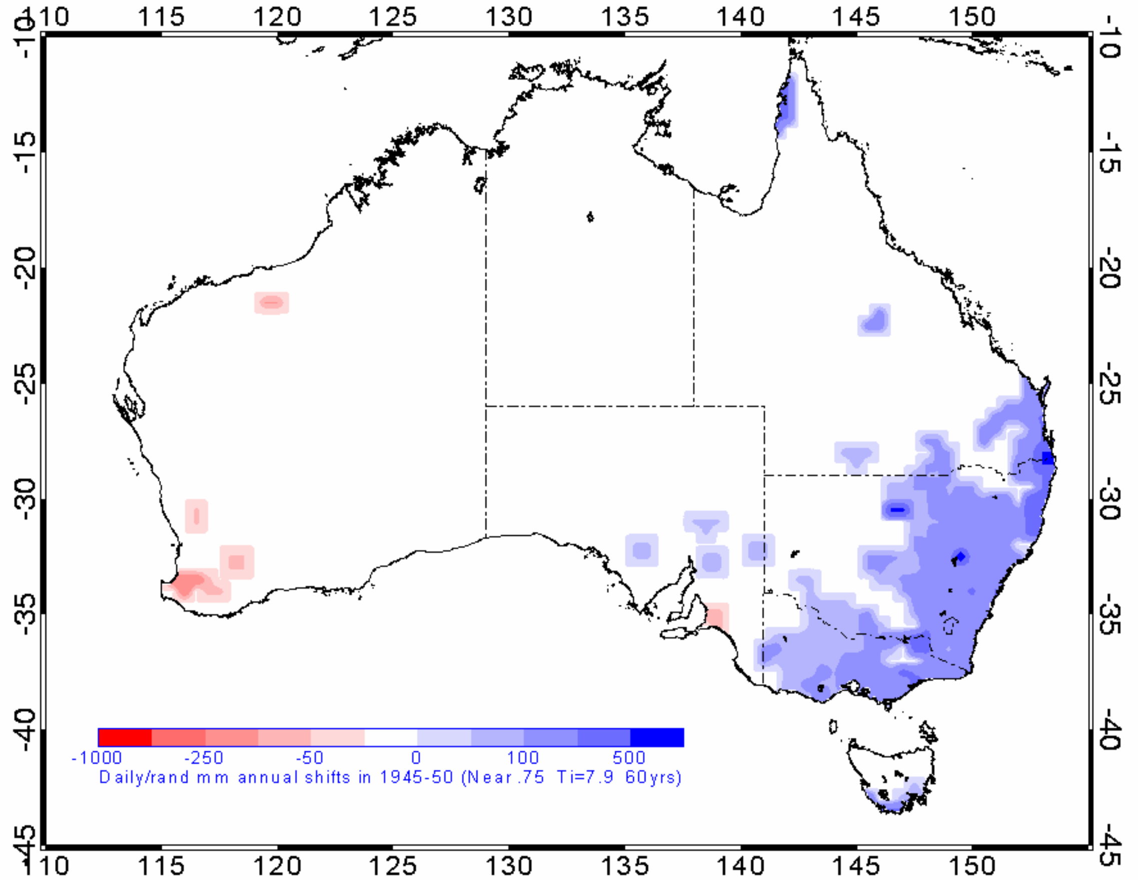


Figure 4.4 Location and amplitude (in mm) of the 1945–50 shifts (national rainfall dataset).

4.4 1967–72 events

4.4.1 Results summary

The period 1967–73 can be divided in two. All the decreases detected in south-west Western Australia occur during 1967–68. In south-west Western Australia (clusters 7 and 8), 26% of the shifts (22 stations) in the annual series are detected during these years and severe decreases in standard deviation are noticeable. The decrease in mean rainfall is more than 18% compared to previous mean (from 798 mm a^{-1} to 653 mm a^{-1}). This decline occurs mainly in winter.

In contrast, parts of South Australia (cluster 4) undergo a 24% increase in annual precipitation (from 310 mm a^{-1} to 407 mm a^{-1}). This increase is widespread across the continent during 1969–1972, except in south-west Western Australia (Table 4.3).

Table 4.3 Bivariate test results obtained for the 1967–72 shifts (national rainfall dataset). Due to low numbers, shifts >20% in Cluster 2 are not shaded.

Cluster	Dataset	Shifts detected by the bivariate test (SL > 0.1)					Precipitation data for 1890-1967 1967-1989			
		Number of stations	Percentage of stations	Percentage of all shifts	Nature of change	Change in mm	Mean rainfall in mm		Standard deviation in mm	
1	Annual	0	0%	0%	-	-	-	-	-	-
	Summer	6	2%	5%	positive	269	483	720	184	230
	Winter	0	0%	0%	-	-	-	-	-	-
2	Annual	1	1%	11%	positive	168	199	315	93	187
	Summer	2	1%	25%	positive	249	103	223	84	178
	Winter	9	2%	40%	positive	54	82	132	48	66
3	Annual	3	1%	2%	positive	215	773	967	185	199
	Summer	7	2%	5%	positive	170	492	648	155	195
	Winter	2	1%	3%	positive	141	224	346	100	209
4	Annual	26	5%	30%	positive	122	310	407	90	130
	Summer	3	1%	13%	pos. (66%)	86	129	195	64	78
	Winter	20	4%	20%	positive	65	172	230	60	78
5	Annual	7	5%	11%	positive	175	775	928	139	161
	Summer	2	1%	5%	pos. (50%)	-1	382	380	110	106
	Winter	6	2%	7%	positive	130	461	569	44	88
6	Annual	31	7%	27%	positive	236	515	717	182	258
	Summer	23	5%	25%	positive	278	365	582	152	261
	Winter	15	3%	15%	positive	71	68	126	44	88
7&8	Annual	22	3%	26%	negative	-158	798	653	156	124
	Summer	0	0%	0%	-	-	-	-	-	-
	Winter	49	14%	30%	negative	-100	474	380	103	84
9	Annual	17	3%	15%	positive	189	390	517	107	173
	Summer	14	2%	23%	positive	161	164	290	71	138
	Winter	9	2%	10%	positive	104	201	269	68	101
10	Annual	22	4%	10%	positive	141	241	355	98	171
	Summer	13	1%	1%	positive	235	205	368	96	170
	Winter	19	3%	12%	positive	71	113	167	52	75
Total	**Annual**	**129**	**4%**	**12%**	**pos. (83%)**	**119**	**476**	**570**	**132**	**176**
	Summer	**70**	**2%**	**10%**	**pos. (97%)**	**218**	**301**	**470**	**122**	**196**
	Winter	**129**	**4%**	**16%**	**pos. (62%)**	**10**	**276**	**279**	**73**	**84**

4.4.2 Location

Figure 4.5 shows the decreases in rainfall over south-west Western Australia, contrasting with increases in rainfall occurring over a large part of the continent. The patchy response in central Australia is due to the low density of the input data. There are only five stations involved, but the area covered is wide because of the lack of neighbouring stations in this desert-like region.

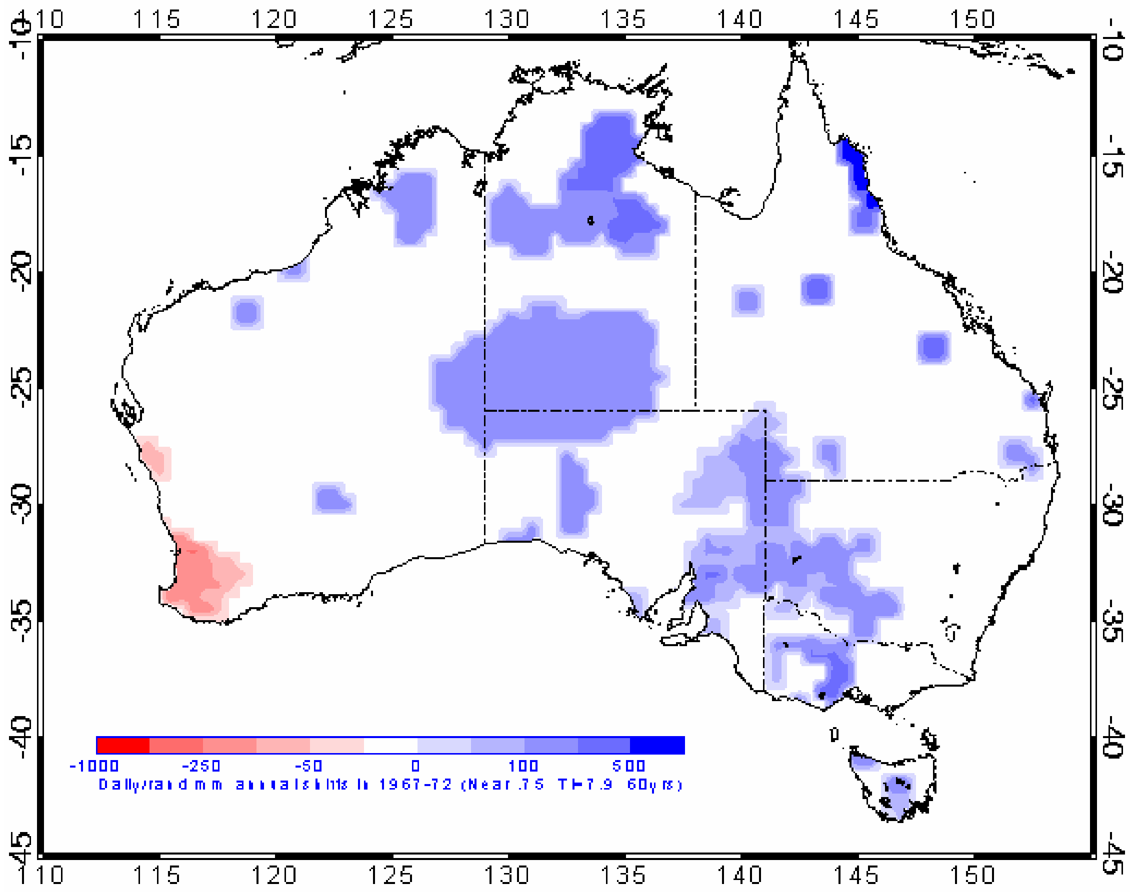


Figure 4.5 Location and amplitude (in mm) of the 1967–72 shifts (national rainfall dataset).

4.5 Conclusion of the bivariate test results

A large number of stations show a shift during three major time periods, clustered around 1890–95, 1945–50 and 1967–72. The changes in mean from the bivariate test correspond closely with means calculated by the difference of the two time periods in question. More evidence of a climatic origin of these step-like increases or decreases in the rainfall regime comes from analysing the location of these events. In the following part of this study the relevance of these shifts will be compared with the results of the Lepage test and with previous scientific work analysing historical records of Australian rainfall and related phenomena.

5 The Lepage test

5.1 Presentation of the test

5.1.1 General background

Another test that has been used to detect step-like changes in rainfall is the Lepage test. This statistical test is a non-parametric, two-sample test for location and dispersion (Lepage, 1971). The Lepage test has been used to detect changes such as long-term trends, cyclic variations and step-like changes for rainfall (Yonetani, 1993). This latter characteristic allows comparison with the bivariate test. Moreover, the Lepage test does not rely upon a reference series. This major difference with the bivariate test allows us to check the validity of the previous results.

5.1.2 Step by step description

The test statistic, *HK* (which plays the same role as T_i in the bivariate test), is a sum of the squares of the standardised Wilcoxon's and Ansari-Bradley's statistics. This approximates to the chi-squared distribution with two degrees of freedom if a sample size is sufficiently large. Therefore when HK exceeds 4.605 / 5.991 / 9.210, a difference is judged with a 10% / 5% / 1% significance level between the two samples.

$$HK = \frac{\{W-E(W)\}^2}{V(W)} + \frac{\{A-E(A)\}^2}{V(A)}$$

The *HK* is calculated as follows: Let $\{x_i\}$ and $\{y_i\}$ be two independent samples of size n_1 and n_2, respectively. It is assumed that $u_i=1$ if the i-th smallest observation in a combined sample of size $2n=(n_1+n_2)$ belongs to $\{x_i\}$ and $u_i=0$ if it belongs to $\{y_i\}$. Then each term of the above equation can be expressed as:

For the Wilcoxon statistics

$$W = \sum_{i=1}^{2n} iu_i$$

$$E(W) = \frac{1}{2} n_1(n_1 + n_2 + 1)$$

$$V(W) = \frac{1}{12} n_1 n_2 (n_1 + n_2 + 1)$$

For the Ansari-Bradley statistics

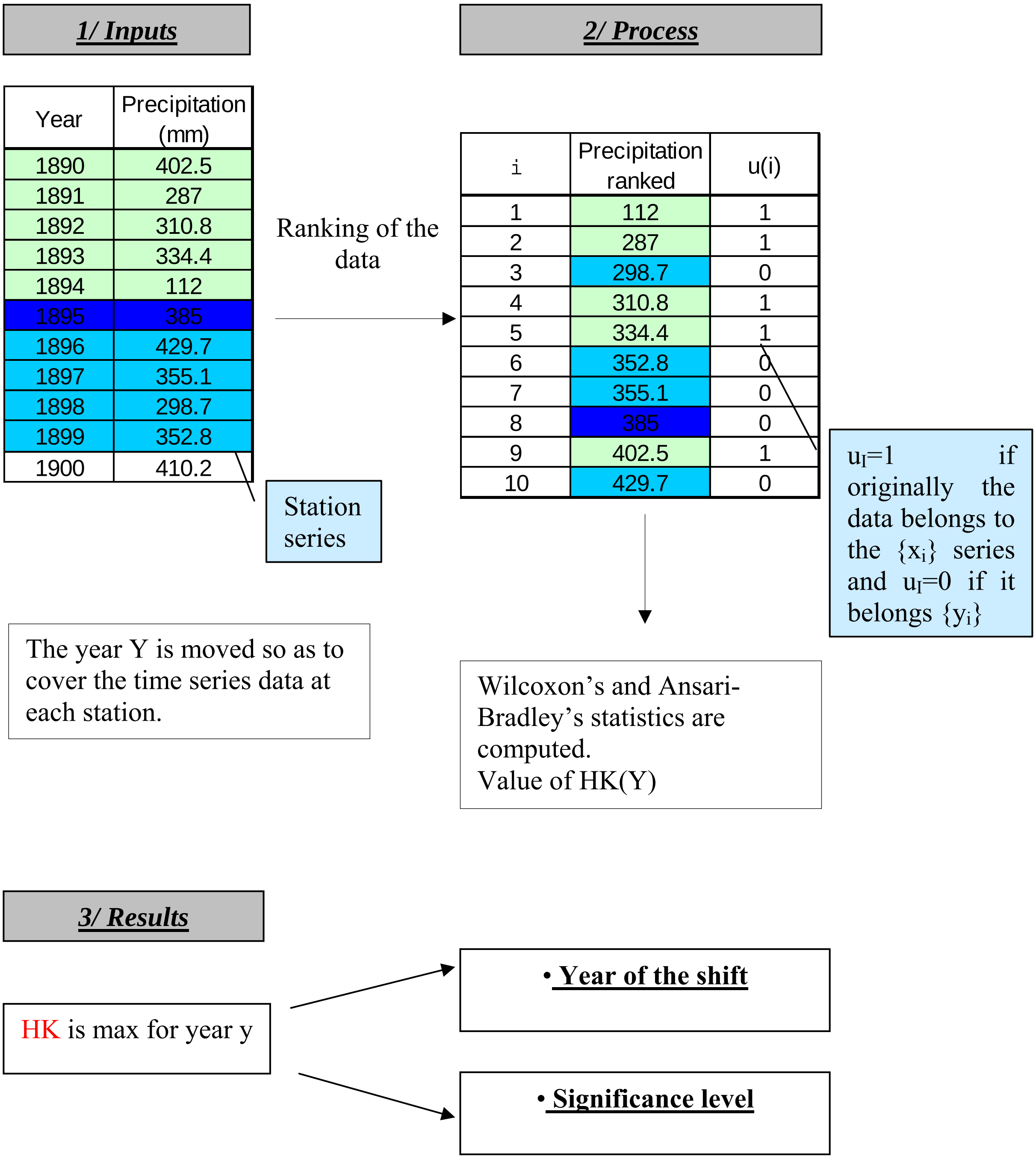
$$A = \sum_{i=1}^{n} iu_i + \sum_{i=n+1}^{2n} (2n - i + 1)u_i$$

$$E(A) = \frac{1}{4} n_1(n_1 + n_2 + 2)$$

$$V(A) = \frac{n_1 n_2 (n_1 + n_2 - 2)(n_1 + n_2 + 2)}{48(n_1 + n_2 - 1)}$$

5.1.3 Procedure

Changes are detected in the following way: Note a certain year Y (in the example 1895), and take the time series for n years (here n=5 years for both samples) after the year Y (sample $\{x_i\}$ including Y) and those before the year Y-1 (sample $\{y_i\}$, including Y-1). If the Lepage test shows a difference between the two samples $\{x_i\}$ and $\{y_i\}$ with 1%, 5% or 10% of the significance level, then the change is judged to occur in the year Y.



Year	Precipitation (mm)
1890	402.5
1891	287
1892	310.8
1893	334.4
1894	112
1895	385
1896	429.7
1897	355.1
1898	298.7
1899	352.8
1900	410.2

i	Precipitation ranked	u(i)
1	112	1
2	287	1
3	298.7	0
4	310.8	1
5	334.4	1
6	352.8	0
7	355.1	0
8	385	0
9	402.5	1
10	429.7	0

Figure 5.1 Flow diagram of the application of the Lepage test.

5.2 Applicability of the Lepage test

The Lepage test has an optimal sample size for detecting step-like changes for any series (Yonetani, 1993). On the one hand, large samples tend to detect less noticeable changes; on the other hand, pinpointing the time at which a change occurs becomes vague when the sample size is too large. In Yonetani's paper, the duration n is the same for both samples ($\{x_i\}$ and $\{y_i\}$). The same scheme is retained here.

The Lepage is carried out with different values of n to determine which is the most suitable. The first range of values tested was n= 10, 20, 30 and 40 years (Appendix 5). When n=10, all the changes detected with the other values of n were detected and peaks were the largest obtained. Thus the ranges of n are reduced to 5, 10 and 15 years. The results Australia-wide are shown below (Figure 5.2).

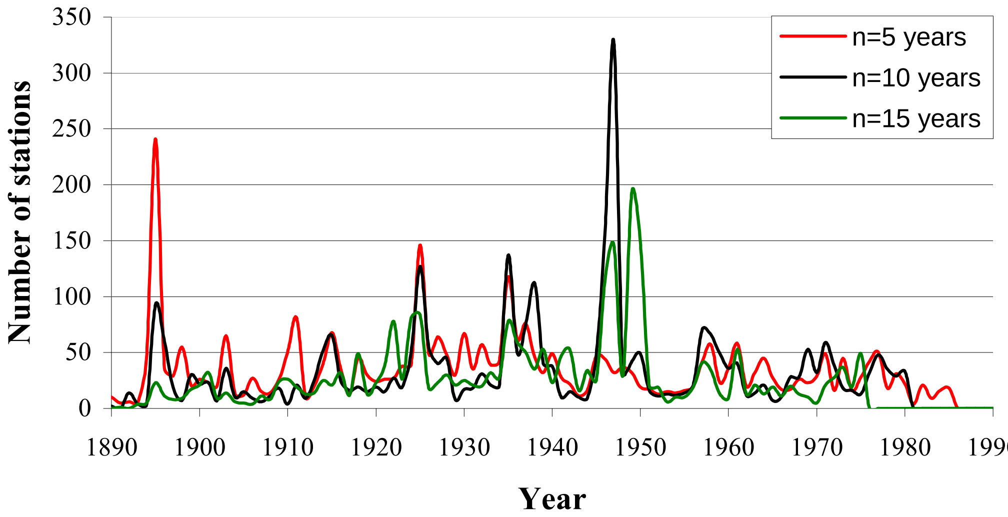


Figure 5.2 Results of the Lepage test on the national rainfall dataset (annual series) with different sample sizes.

Where n=5, the test detects many changes but the largest response is obtained when n=10 years with the exception of the mid-1890s peak. In this latter case, the calculation of HK can only begin n years after the beginning of the record. The same rainfall records used previously are used here, but to best cover this period, the entire record length was used (i.e. including records before 1890). One quarter of all records >60 years in length began before 1885 (so *HK* can be calculated from 1890 if n=5years) but only one eighth began before 1880. This explains why the run with n=5 years produces the highest peaks for the early 1890 changes.

5.3 Results

National results for the stations of the national rainfall dataset are presented below. They are similar to the outcomes for the high-quality stations.

The pattern in Figure 5.3, showing a majority of negative shifts at the end of the 19th century and early the 20th century, resembles that from the bivariate test (Figure 3.6). However, the Lepage test reveals a larger number of shifts involving a greater number of stations. The most important annual shift detected with the bivariate test during 1945–50 is 99 stations in 1946; the Lepage test detects up to 319 stations in 1947. This is due to its greater sensitivity (90% of the stations tested show a significant shift compared to 29% using the bivariate test) and its dependence upon the sampling interval.

We compared the results of the Lepage test with those for the bivariate test during the key events of 1890–95, 1945–50 and 1967–72. Since the Lepage test does not estimate the nature (positive or negative) or the magnitude of the change, the difference (in mm) between the average value of the rainfalls before and after the year of the shift was computed from the records.

Figure 5.4 shows the importance of the change in the south-eastern part of the country. Results are similar to the bivariate test outputs both for the location and the nature of the shift detected but the areas covered are much smaller. Both south-west South Australia and Queensland show no response whereas the bivariate test showed important negative shifts.

This may an artefact of the record length. As noted earlier, the shifts occurring in 1890 can only be computed by the Lepage test if the record begins in 1880. Only 8.8% of cluster 6 data (which include most of north and west Queensland) begin in 1880 (compared to 35% in 1890). Although in South Australia (cluster 4), 25% of the stations have data available from 1880, the Lepage test does not reveal any downward shift. The positive shifts detected in central Australia concern only three stations.

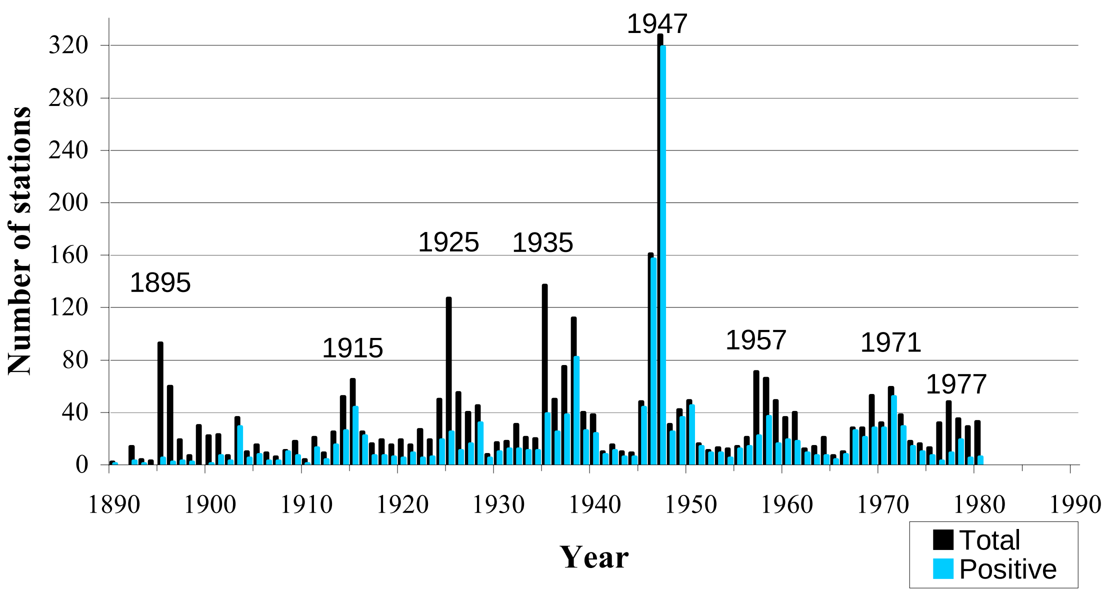


Figure 5.3 Results of the Lepage test on the Australian annual precipitation series of the same national rainfall dataset used with the bivariate test. Sample size is 10 years, level of significance is 10%.

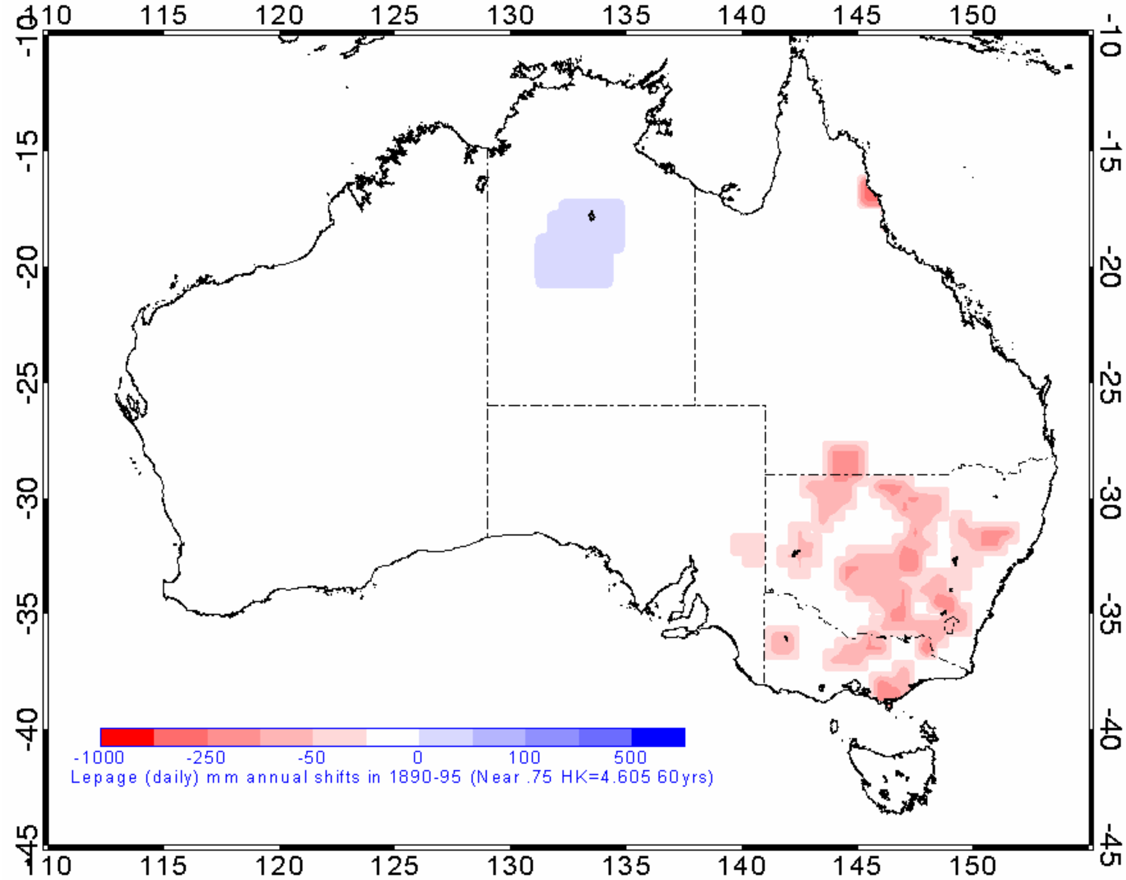


Figure 5.4 Results of the Lepage test for 1890–95 shifts (changes in mm).

Despite the results of the Lepage test showing a more complex pattern of shifts occurring in 1945–50, the main characteristics of this period remain similar (Figure 5.5). Major increases in the precipitation series occur in the eastern part of Australia with a largely negative shift occurring in Western Australia. Positive shifts cover a larger area than revealed by the bivariate test. The Lepage test also indicates significance with changes at a lower magnitude than the bivariate test. For instance, most of the regions with light blue (change of less than 50mm) were not represented in the bivariate test results.

While the results obtained for the 1967–68 period largely agree with the bivariate test (important decreases in the south-west part of Western Australia) during the 1970–72 period there are spatial differences. Negative shifts dominate in south-western Western Australia while the rest of the continent is covered by a patchy network of increases (Figure 5.6).

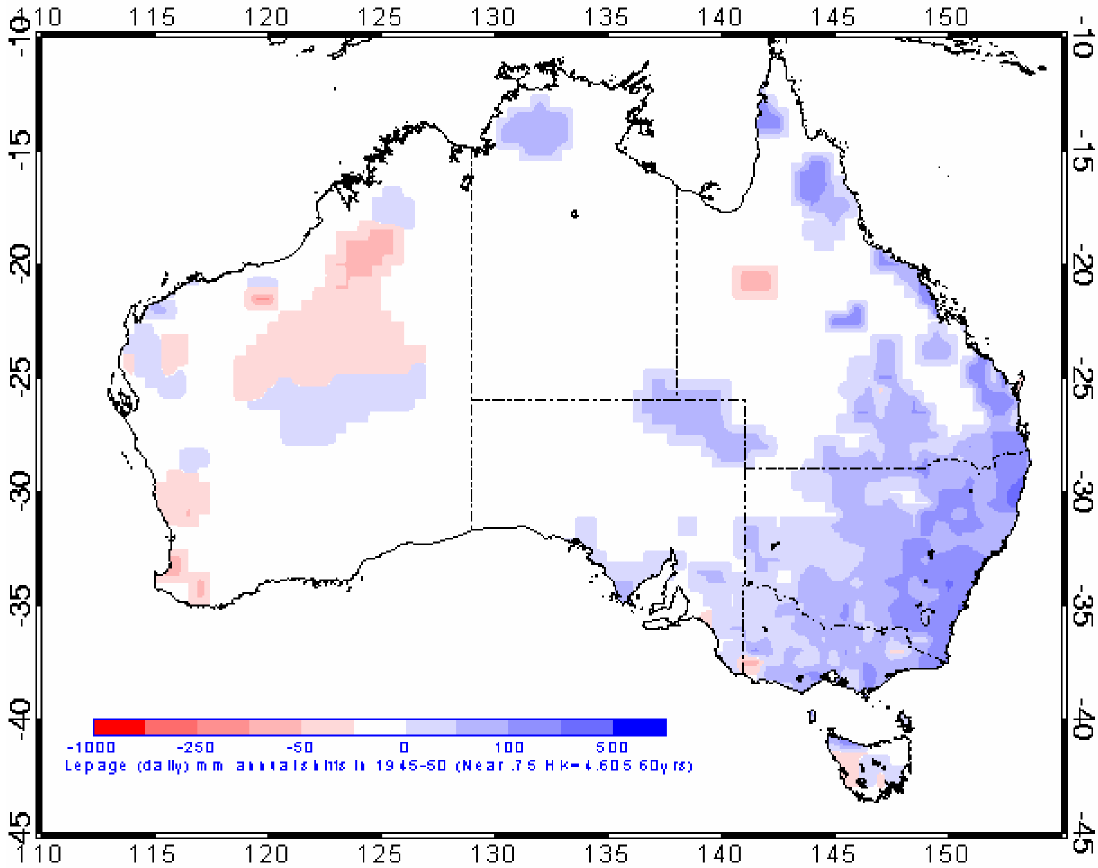


Figure 5.5 Results of the Lepage test for 1945–50 (changes in mm).

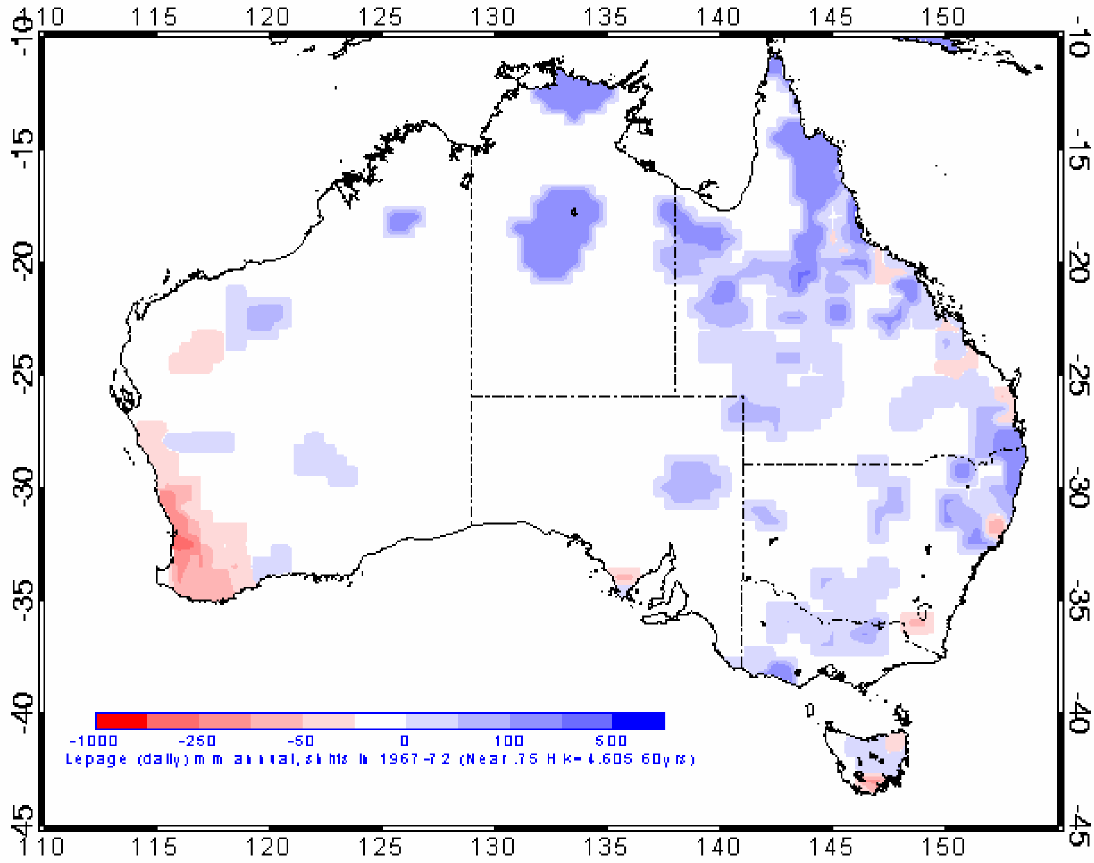


Figure 5.6 Results of the Lepage test for 1967–72 (changes in mm).

5.4 Conclusion for the Lepage test

The use of a test with a completely different mathematical structure from the bivariate test produces similar patterns for the key periods of 1890–95, 1945–50 and 1967–72 but locates a larger number of "step-like" changes within the rainfall record at other times. The Lepage test is much more sensitive to short-term variations (~10 years) in climate and therefore detects shifts in station records with changes below the threshold of statistical significance for the bivariate test, especially when n is low.

The main disadvantages of the Lepage test are its dependence on the sample size (see Figure 5.2) and its sensitivity to short-term perturbations in a time series where the perturbation is $\leq n$. Here, we are interested in abrupt changes in mean rainfall on a decadal scale, rather than short-term departures of several wet years. Due to these disadvantages, the Lepage test is less suitable for assessing step changes in climatic records than the bivariate test. Further tests on the bivariate test shown in Appendix 4 demonstrate its superiority for determining step-like changes in mean, while being able to distinguish these from the short-term fluctuations in interannual variability.

6 Decadal climate variability

The bivariate and Lepage tests have been used to detect large scale abrupt shifts in mean decadal rainfall in rainfall over Australia between 1890 and 1989. In this chapter, we attempt to reconcile these results with aspects of decadal climate variability investigated by other authors. Power et al. (1998) characterise decadal variability as:

1. Chaotic variability extending to decadal timescales,
2. Interdecadal modes that demonstrate a level of predictability, and
3. Evolving responses to greenhouse-induced climate change.

Setting aside c) for the present; to manage water-reliant systems, we need to understand the statistics behind mode 1 and the statistics and dynamics behind mode 2. When a rapid shift that initiates a climate regime lasting for several decades or more is identified, how much of that regime is chaotic and how much is predictable? At least two forms of decadal variability may be implicated in the answer:

a. The modulation of interannual variability on a decadal scale, and
b. Step-like changes in decadal rainfall regimes, affecting average rainfall and rainfall intensity at the decadal scale.

Longer-term climatic influences may modulate shorter-term variability; for example, decadal scale modulations of interannual variability comprise 10–40% of the total variance of Australian rainfall (Power et al., 1999a). The supporting evidence for step changes in climatic regimes is more difficult to locate – while there is widespread evidence in hydrological systems, palaeoclimatic proxies and within rainfall statistics, a climatic understanding of such phenomena is harder to find.

In this chapter, we review the evidence for decadal rainfall variability to try and distinguish between these modes. We also briefly explore the impacts of decadal rainfall regimes and outline possible benefits that may be obtained via risk management and prediction. Finally, some of the limitations of this analysis and how improvements may inform future studies of rainfall are discussed.

6.1 Decadal rainfall variability in the period 1890–1989

6.1.1 Timing

In this paper, the bivariate test has been used to identify and analyse the evidence for step changes in historical Australian rainfall records. Using this test on all Australian rainfall series >60 years in length from 1890–1989 with an independent, random reference series, we have shown that Australian rainfall has experienced three abrupt shifts in mean over that period. These shifts cannot be explained as artefacts of measurement, and in this section we review the evidence from other sources.

The first shift occurred in the early 1890s and affected most of Australia, especially eastern Australia. Both summer and winter rainfall was affected. Although this shift took part in the early part of the record when the bivariate test will react more sensitively to changes, extensive evidence from river flows both in Australia and overseas (Nile, Yangtze etc) indicates that a large-scale climate shift occurred at this time (Figure 6.1; Whetton et al., 1990).

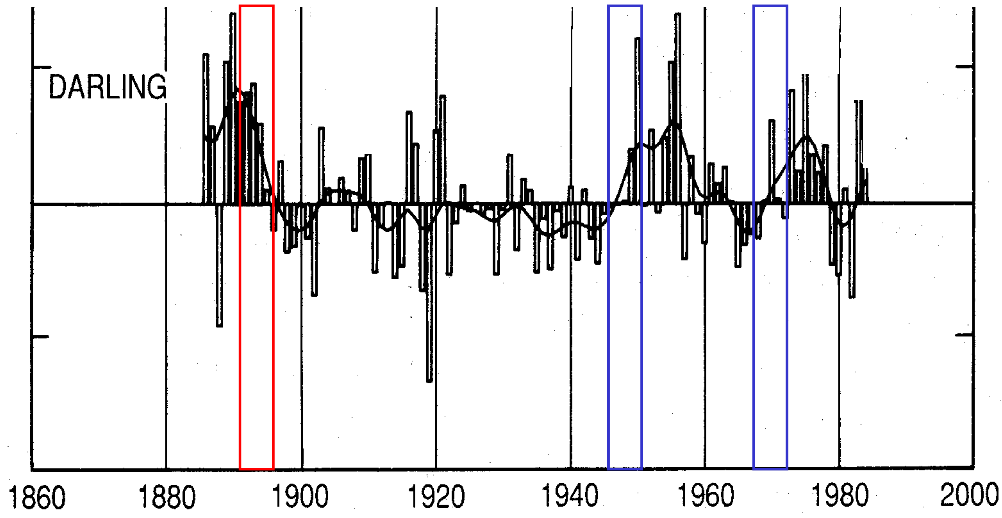


Figure 6.1 Time series representation of the Darling River stream flow at Wilcannia (32ºS, 143ºE; Whetton et al., 1990). Red shows the 1890–95 decrease and blue shows the 1945–50 and 1967–72 increases.

Gentilli (1971) showed that mean yearly rainfall decreased over most of the northern and eastern Australia from the period 1881–1910 compared to the period 1911–1940, and increased over south western Western Australia over the same period. Kraus (1950a, b) identified this feature in a number of tropical and subtropical rainfall records in both hemispheres. Supporting evidence in the form of good rains in the 1880s followed by drought in the 1890s has been cited as influencing grazing success and stock numbers in Western New South Wales (Williams and Oxley, 1979) and cropping in northern South Australia, later coined as the famous Goyder's line, which moved south at about that time (Nicholls, submitted).

The next major shift occurred in the late 1940s, and was concentrated over eastern Australia, signalling the end of a dry period of just over fifty years' duration. This shift was almost overwhelmingly positive, except for a downward shift in winter in south-west Western Australia. Different mathematical tools ranging from the simple change in mean (Pittock, 1975) to continuous wavelet transforms (Nakken, 1999) have been used to describe the increase in precipitation in eastern Australia over this period, centred on changes in 1948–9. Figure 6.2 is consistent with the shifts identified in Figure 4.4. Pittock (1975) reported that a major increase in annual rainfall occurred in the middle to late 1940s over much eastern Australia. The negative changes in south-west Western Australia are also indicated in Figure 6.2.

Pittock (1975) correlated the change seen in Figure 6.2 with an L index, which essentially measures the latitude of the high pressure belt over eastern Australia. The second most important pattern he produced (the first was related to ENSO) is very similar to the winter patterns of change from the bivariate test in 1945–50 (the latter not shown) that shows increases in eastern Australia and decreases in SW WA. This suggests that the shifts in rainfall may be related to the latitude of mid-latitude and sub-tropical weather systems, but subsequent work has not confirmed this link. Later analyses have tended to concentrate on post 1950 climate data for reasons of quality. Correlations and empirical orthogonal function analysis using this data tend to identify ENSO as the largest contributor to interannual variability and Pacific and Indian decadal oscillations (that modulate interannual variability) as the second most important (see Smith et al., 2000; p. 1914). However, long-term decreases in sea level pressure consistent with the latitudinal movement of weather systems have occurred in concert with decreases in rainfall in SW WA (Smith et al., 2000).

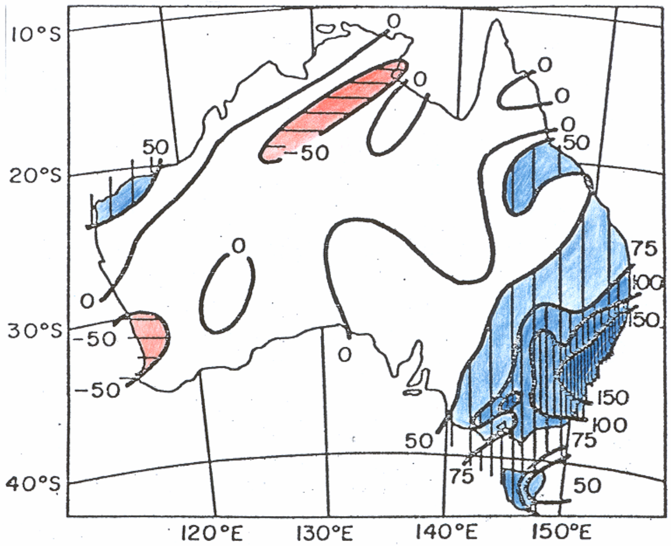


Figure 6.2 Distribution of changes in mean annual rainfall (mm) between the intervals 1913–1945 and 1946–1974 (Pittock, 1975).

The third shift occurred over the interval 1967–72, manifesting as a decrease in SW WA in the late 1960s and an increase in eastern Australia in the early 1970s. It is not clear whether these events are connected. The bivariate test is a statistical test, so may not correctly identify the year of a change. A decrease may not be registered in the exact year it happened. For example, a decrease may be associated with a nearby drought year and an increase with a nearby flood year. This may be the case during 1967–72 where 1967–8 was a drought year and associated with a downward shift and 1973, a flood year associated with an upward shift (Figure 3.7 and Figure 4.5).

The rainfall decrease in south west Western Australia has attracted a great deal of recent attention (Allan and Haylock, 1993; Yu and Neil, 1993; Ansell et al., 2000; IOCI, 2002) in particular, as to whether it is part of natural climate variability or climate change. The analysis presented here indicates that the latest shift follows a series of quasi-periodic shifts in rainfall. This view is complicated by the possibility that if there is long-term warming in the Australian region, and greenhouse climate change has accelerated this warming – how is one to tell the difference in terms of changes in rainfall variability (IOCI, 2002) who conclude that both natural variability and greenhouse-induced climate change may be implicated in the recent observed rainfall decreases.

Whether the increase in eastern and central Australia in the early 1970s qualifies as a step change similar to those in the 1890s and 1940s is not clear. This increase followed a series of dry years in the 1960s (Gibbs, 1975). As mentioned earlier, the rapid onset of a series of wet years of one or two decades' duration following a gradual decline may be sufficient to produce a statistically significant response. This possibility is tested using artificially perturbed series in Appendix 4.

6.1.2 Magnitude

Estimating the magnitude of step changes in rainfall from the bivariate test is not easy for the following reasons:

1. Only one result (T_0) from each time series was chosen, despite the fact that several significant changes may have occurred within a particular record. Selection by significance also means that the highest values of change in mean (D_0S_y) are sampled.
2. It was not possible to screen individual stations for documented evidence of potential inhomogeneities caused by measurement artefacts. Although random inhomogeneities occur at a relatively low frequency, they have a slight influence on the results.
3. Station records are of different length, due to closures and missing data, making average changes in shift for a period of consistent length difficult to calculate.
4. Stations of different exposure will not respond uniformly to the same climatic shift due to different rates of aerodynamic gauge loss, which are a function of wind speed at gauge height. High wind speeds lead to a greater proportion of gauge loss, but increasing rainfall intensity reduces gauge loss. If a step change in rainfall occurs this change will be greater at an exposed and windy site compared to a sheltered site (Jones, 1995). Therefore, it is not possible to estimate mean rainfall change from a region where significant losses are registered in gauges with a range of exposures. A spatial approach using rainfall records corrected for aerodynamic gauge loss would be required to estimate the magnitude of changes with any accuracy.

Tables 4.1, 4.2 and 4.3 list average changes in mean for the three periods. The 1890–95 changes suggest a decrease of 40% annually, 50% in summer and 45% in winter (the changes for the two seasons will average 40% because of the different number of stations affected). The 1890–95 changes are likely to be over-estimated because they are comparing the average of ≤5year with >55 year periods. In 1945–50, the increase for all clusters except SW WA was 25%, 30% and 25% for annual, summer and winter periods, respectively. In SW WA, the decrease was 15% annually and in winter. In 1967–73, the increase for all stations except SW WA was 35%, 55% and 40% for annual, summer and winter periods, respectively. The large changes in percentage terms are largely due to many of these occurring across the arid interior of Australia. In SW WA, the decrease was 20% annually and in winter. These must be considered maximum changes.

6.1.3 Hydrological evidence

Several assessments have diagnosed changes in rainfall regimes through observations of change in streamflow and/or riverine morphology. Based on long-term flood stage records, Warner (1987, 1995) nominated periods of DDR and FDR for the Nepean–Hawkesbury catchment west of Sydney. He nominated the period 1799–1819 as flood dominated, 1820–1856 as drought dominated, 1857–1899 as flood dominated, 1900–1948 as drought dominated and 1949–1988 as flood dominated. The 1899 and 1948 dates broadly agree with those diagnosed here (1988 marks the end of the data rather available to Warner than a regime change).

In a study of rainfall and river flow variability linked with El Niño, Whetton et al. (1990) illustrate seven time series of streamflow from major rivers in Africa, China, India and Australia, including the Darling River in Australia. Major variations in the total annual flow for the Darling are similar to those of the other main rivers of inland eastern and north-east Australia over the period 1884–1984. Flohn (1986) notes a 25% fall in streamflow on the Nile after 1898–99 referenced to the period 1871–1926. This suggests that the change in regime in eastern Australia at the end of the 19th century may have part of a global or hemispheric phenomenon.

Franks (2002) and Franks and Kucszera (2002) also investigated the effect of decadal rainfall variability using flood gauge data from New South Wales. Franks (2002) used the Mann-Whitney test to analyse changes in annual maximum flood for 40 gauges in New South Wales and from a regional index compiled from those records. The results showed a change occurring in 1945, indicating that flood behaviour before and after that date were significantly different.

6.2 Regional studies of decadal climate variability

The studies described above have assembled a significant body of evidence showing that abrupt changes in rainfall have affected large proportions of Australia at least three times over the century spanning 1890 and 1989. Such large changes would be expected to manifest in other aspects of climate variability. In the following sections we examine some of that evidence.

6.2.1 Australian studies

Power et al. (1999b) examined high quality Australian rainfall (Lavery et al., 1997) and temperature (Torok and Nicholls, 1996) datasets to assess climate variability over the 20th century. Total annual rainfall was filtered to remove <8 year variability and detrended (removing a small positive trend over 1910–92). They found that the ratio of decadal to total variance of Australian rainfall (interannual and greater) ranged from 10 to 40% of total variance.

As mentioned earlier, there are at least two possible modes of decadal variability: step-like changes in variables and the modulation of interannual variability. The bivariate test diagnoses shifts in decadal mean climate that persist for several decades. Further trials with the bivariate test show that other variables which also shift with the mean include standard deviation, number of raindays and annual daily rainfall extremes marking the 95th and 99th percentile. For example, step changes in raindays and rainfall extremes consistent with changes in average pre- and post-1946 rainfall have been identified for New South Wales and Queensland rainfall (unpublished data). This suggests that aspects of both rainfall quantity and variability are tied to these regimes.

Decadal oscillations in ENSO modulating its impact on interannual climate variability is the other mode of decadal variability. Power et al. (1999a) investigated this relationship, describing how the Interdecadal Pacific Oscillation (IPO) alters the relationship between ENSO and Australian rainfall. When the IPO is positive this relationship has low predictability and when it is negative, predictability is high.

The IPO phases discussed by Power et al. (1999a; Figure 6.3) shows a different periodicity to the shifts detected here in this paper (15–25 years compared with 20–50 years). The drought-dominated period during 1895–1945 contains two positive phases of the IPO and one minor negative phase; the next positive phase is from the mid 1970s to the late 1990s, clearly not a drought-dominated period. The period from the late 1940s to the mid 1970s has a negative IPO, as does the period since 1999. However, major excursions of the IPO from one sign to the other, occur at about 1895 and the late 1940s so there may be a link, though not a direct one. The next major excursion of the IPO occurred in 1976 but this is not linked to a significant date within the bivariate test results. Therefore, we do not think rapid changes in climatic regimes and the modulation of interannual variability are the same phenomena. They appear to be different, operating on different timescales, although they may be responding in part to the same root cause.

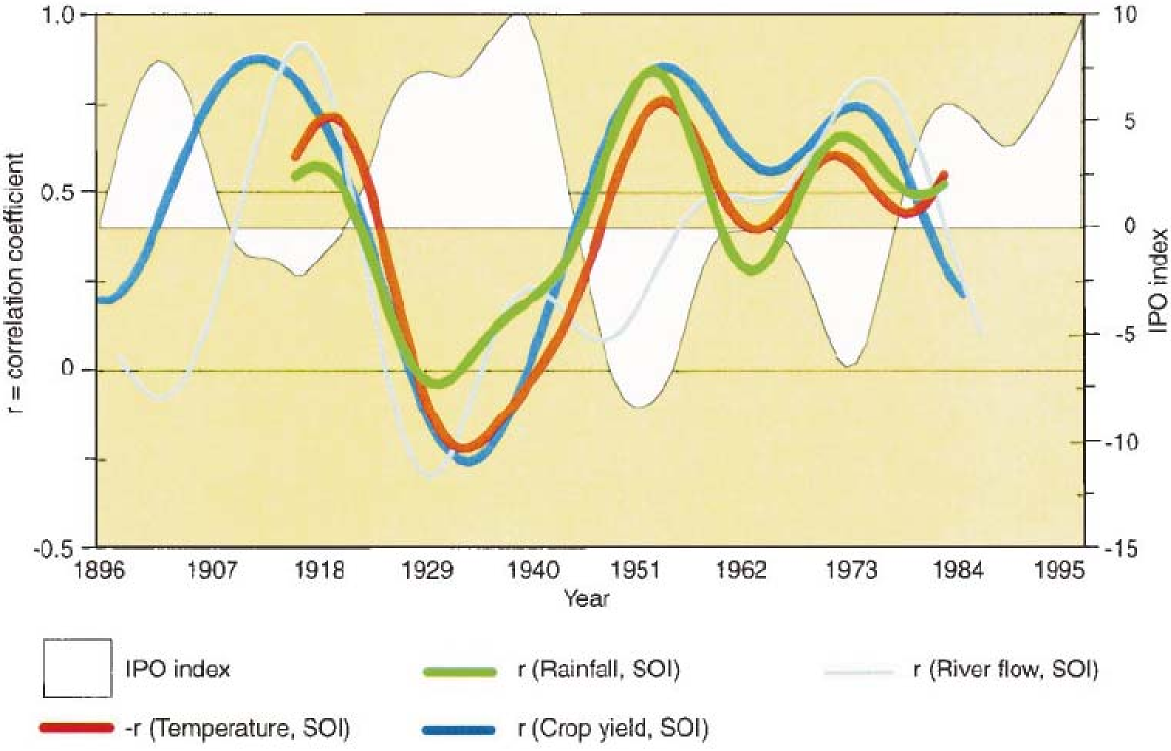


Figure 6.3 Correlation coefficients between the Southern Oscillation Index and various Australian compared to the Interdecadal Pacific Oscillation (IPO) Index. The correlations between temperature and the SOI have been multiplied by 1 to facilitate comparison (from Power et al., 1999a).

Franks (2002) has investigated the late 1940s shift using flood data in eastern New South Wales and ascribes the FDR and DDR to phase reversal in the IPO, predicting that with its reversal in 1999/2000, eastern Australia will soon be returning to a flood-dominated regime. For the above reasons we do not think this is the case; phase changes in the IPO are implicated but are not the root cause. Kadonaga et al. (1999) also found differences between the Pacific Decadal Oscillation (a related index) and flood/drought regimes for the Pacific north-west of the USA.

Studies centred on SW WA have attempted to determine the nature and cause of decreases in winter rainfall during the 20th century. Our analysis suggests successive step-like changes occurred in 1948 and again in 1966–68. Allan and Haylock (1993) identified a strong negative correlation between mean sea level pressure and winter rainfall in the region. They identified both decadal-multidecadal pulses and a long term trend in the relationship associated with increasing MSLP/decreasing rainfall. Ansell et al. (2000) narrowed the frequency of these pulses to 8–9 years and showed that MSLP was much more relevant to variations in regional rainfall than sea surface temperatures in the Indian Ocean. They also confirmed that relationships between local rainfall and regional MSLP and SST were different to those elsewhere in southern Australia. Smith et al. (2000) analysed time series of Indian Ocean sea surface temperatures and SW WA winter rainfall and found that the first two empirical orthogonal functions (EOFs) appeared to reflect much of the longer term variability. Both

EOF time series appear to contain structural elements linking them to the downward shifts in rainfall but their underlying drivers remain unknown (Smith et al., 2000).

Li et al. (2005) have undertaken a probability over threshold analysis of extreme daily rainfall in eight stations within SW WA, concluding that a significant decrease occurred in 1965, similar to our results, also determined statistically. They hypothesise that this is related to a contemporaneous change in the behaviour of the Antarctic Oscillation.

6.2.2 International studies

The evidence of hydrological change that results in extended periods of floods, with high streamflow and elevated lake levels alternating with droughts, low stream flow and low lake levels is accumulating. However, finding consistent patterns amongst this evidence is extremely difficult. Records of quality that are long enough to span several such changes are rare (most only deal with one, to at most two changes). Furthermore, proxy information from longer records is often difficult to constrain in terms of timing or the relationship between climate variables and impacts.

Decadal and century scale rainfall regimes are shown to have persisted throughout the Holocene, especially the past several thousand years. For example, the Nile shows three distinct epochs, AD 622–1078, 1079–1325 and 1326–1470, coinciding with larger scale climate changes: a relatively cool age, the Little Climatic Optimum of the Middle Ages, and an interim period before the Little Ice Age (Fraedrich et al., 1997). Long periods of drought and flood have also been diagnosed with proxy data in the USA (e.g. Kadonaga et al., 1999; Fritz et al., 2000).

For the North Pacific, Minobe (1977) has identified phase reversals in pentadecadal and bidecadal oscillations in the North Pacific Index in 1922–4, 1946–9 and 1975–7. He suggests that oscillations will occur when the two oscillations change simultaneously. Interestingly, the bivariate test detected a cluster of increases in summer and decreases in winter in 1923–5, the large change detected in 1946–9 is similar, but the 1967–72 shifts precede 1975–7. In the southern Pacific, three phases of the IPO have been identified during the 20th century: a positive phase (1922–1944), a negative phase (1946–1977) and another positive phase (1978–1998; Salinger et al., 2001). The IPO influences decadal climate trends and modulates ENSO throughout the western Pacific; two break points occur in 1945 and 1976 – these are associated with different phases of the IPO, changes in decadal climate and changes in the modulation of ENSO within the western pacific (Salinger et al., 1996).

Kripalani and Kulkarni (2001) identified a number of departures in mean lasting several decades over China, India and Japan. The Indian series shows shifts around 1895, 1930 and 1963 with the period 1895–1930 depicting below (above) average rainfall and 1930–1963 representing above average rainfall. Chinese rainfall shows shifts around 1906, 1945 and 1972 with the period 1906–1945 depicting below average rainfall and 1945–1972 depicting above average rainfall. For Japan the major shift occurs around 1937, moving from a drier to a wetter regime. Kripalani and Kulkarni (2001) also identified teleconnections and modulations of interannual climate that move in and out of phase between the three regions over these periods.

While regional investigations of changes in decadal climates continue to raise similar dates – 1895, 1945 and 1976 – it remains unclear as to exactly what is happening at each of those times, the spatial extent of such events and what the cause may be. Can the increase in annual precipitation over the western half of Japan around 1950 (Yonetani, 1992) have the same origin as the one detected in eastern Australia? And more recently, can the downtrend in Western Australia be linked to the severe drought period 1968-75 over 11 western African countries (c.f. Motha et al., 1980).

The two processes mentioned at the start of this chapter: the modulation of interannual variability and longer term changes in rainfall regime, cannot be easily separated on the basis of the research literature. The relationships between different manifestations of decadal variability do not appear to remain constant and the relationships between these and underlying trends also remains uncertain. However, the concentration on recent high quality data lasting only a few decades will constrain the results.

6.3 Hydrological impacts of shifts in decadal rainfall regimes

Changes in rainfall regimes would only hold academic interest, but for their impacts on hydrological systems. Warner (1987, 1995) studied the relationship between rainfall regimes and floodplains and channels in eastern New South Wales. Very large floods in the second half of the 20th century initiated significant changes in the coastal rivers of that state, including rivers where anthropogenic impacts have been relatively low.

For example, the mean annual flood stage at Windsor in the Hawkesbury-Nepean River is 9m during a flood-dominated regime and about 6m during a drought-dominated regime (Warner 1995). The morphological impacts are largest in unconsolidated and/or narrow floodplains where there is limited floodplain storage. A change from a DDR to an FDR can results in substantial ongoing changes to banks and floodplains that may not be complete before the next regime change. Impacts are less on a large floodplain with adequate storage, but many of these have been limited due to the narrowing of floodplains for human activities. During a DDR, a narrow floodplain may be set inside the main floodplain which may then be removed in the next FDR. Where human-induced changes have affected catchments, ongoing degradation processes may be hastened in a FDR. Warner (1995) considers channel and flood plain management to be considerably more problematic in an FDR, compared to a DDR, even where anthropogenic effects are severe. This situation would be exacerbated under climate change.

Jones and Pittock (2002) analysed the impacts of decadal rainfall regimes on flows in the Macquarie River Basin, in the eastern Murray-Darling Basin. The baseline analysis used inputs of historical daily rainfall and potential evaporation from 1890–1996 applied to 1996 infrastructure and supply management rules, i.e. it simulated how today's river would behave under historical conditions. The results show a 20th century of two halves.

Between 1895–1946 simulated irrigation allocations fell below 50%, 38% of the time; flows into the Macquarie Marshes were below 300,000Gl (preventing good bird breeding) 48% of the time; and storage in the largest dam was below 500,000 Gl 38% of the time. From 1947–1995, these occurrences fell to 8%, 16% and 16%, respectively. Under the National Land and Water Resources Audit, the Macquarie catchment was classified as over allocated (NLWRA, 2001) – this is in a flood-dominated climate – we can only assume that if a DDR similar to the early 20th century returned, hardship would increase markedly.

Under climate change, critical thresholds for irrigation and bird breeding sequences were exceeded when long-term mean annual flow changed by -10% due to climate change during a DDR; at -20% due to climate change during a 'normal' regime and -30% due to climate change during an FDR (Jones and Pittock, 1992). This shows that the phase of decadal rainfall regime is just as important as climate change; assessments that attempt say which is more important or to apportion 'blame' are clearly counterproductive.

Jones and Pittock (2002) and Warner (1995) have identified different risks associated with a decadal rainfall regime interacting with climate change. The current phase of rainfall regime in the eastern states is unknown, but it is possible that a return to drought-dominated conditions may soon occur (assuming that a shift to an FDR occurred in the late 1940s). If that was the case, the major risks would be associated with droughts rather than flood-related phenomena. However, as Warner (1995) points out, an FDR will come about eventually, changing the magnitude and frequency of flooding, and requiring a change in management from a DDR to an FDR. Either way, we currently have no way to distinguish between the two without the benefit of considerable hindsight.

In SW WA, Sadler et al. (1988) investigated the relationship between declining winter rainfall and water supply. They adopted a scenario of a decrease in rainfall to -20% in 2040 declining linearly from the mean rainfall of Perth from 1880–1970. In fact, the downward shift in the rainfall regime in late 1960s was of this magnitude. Despite major investments being put towards new water storages in Western Australia, average storage levels have declined to <25% of total capacity during the 1990s. These factors have led to a multi-agency collaboration called the Indian Ocean Climate Initiative, which is attempting to understand the reasons for the decline in rainfall. Despite a broader understanding of the factors affecting the region, the reasons remain inconclusive (IOCI, 2001, 2002). The current perception is, having projected a decline of -20% due to climate change which has already happened due to climate variability, a further decline due to climate change is possible.

7 Conclusion

The bivariate test has shown to be effective in detecting detect step-like changes in Australia's rainfall regime. Results were compatible but also noticeably more comprehensible than the outputs of the specifically designed Lepage test. Three distinct periods were detected in the rainfall record:

1. A preceding flood-dominated regime shifted into a drought-dominated regime around 1895, persisting until about 1945. A shift towards greater variability in 1922–23 through increases in summer rainfall and decreases in winter rainfall over much of eastern Australia did not change the prevailing mean rainfall.
2. A flood-dominated regime in Eastern Australia began in 1946–1948, and a drought-dominated climate commenced in SW WA at the same time.
3. Further decreases in SW Western Australia and increases in eastern Australia occurred during the period 1967–73. It is not clear whether this shift represented the re-establishment of a flood-dominated (drought-dominated) regime in eastern (south western) Australia after a brief period of drier (wetter) conditions.

Studies in both eastern and western Australia indicate that hydrological systems are sensitive to drought-dominated conditions, a sensitivity that its likely to be exacerbated by decreases in runoff and streamflow under greenhouse induced climate change. Recent water shortages in eastern Australia and continuing shortages in SW WA have accentuated this sensitivity.

The long-term persistence of drought- or flood-dominated rainfall regimes will affect risk profiles for floods (Warner, 1995; Franks, 2002) and droughts (Jones and Pittock, 2002). Srikanthan and McMahon (2001) stress the need to incorporate long-term persistence into the stochastic generation of climate data to be used in planning and managing catchments and water supply.

The climatic state a particular region is in, whether 'drought-dominated', normal or 'flood-dominated', will affect the types and magnitude of risks that need to be managed. At present, we have no way to ascertain whether a shift has occurred without the benefit of considerable hindsight. The causes of such shifts are also obscure. Two lines of investigation are needed:

1. Long sequences of historical or proxy data, rather than being restricted to <50 years of 'high quality' data that will produce low quality assessments
2. Model studies where analyses are directly linked to analyses of observed data. Models have the potential to simulate climate in three dimensions and over time. Understanding the dynamics of hydro logically significant changes in rainfall regime may allow firstly, and diagnostic capacity and secondly, a forecasting capacity.

Precipitation is a complex phenomenon showing a range of temporal and spatial influences. Many models and measurements assume linear relationships and stationary behaviour in rainfall systems (Einfalt et al., 1998). The use of statistical tests that investigate one aspect of rainfall to the exclusion of others may overlook particular aspects of rainfall important for managing climate risk. Under global warming, different aspects of rainfall will change in different ways. The heterogeneity of rainfall renders any notion of stationarity conditional, so while some relationships between rainfall and other climatic phenomena may remain constant, others may change over time. Rainfall studies need to become more inclusive of these different aspects, dealing with each aspect individually in the traditional scientific manner to better understand the whole.

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Appendix 1 Bivariate computer program: description and achievements

A1.1 The computer program

The Fortran computer program, created in order to perform the bivariate test on the previous clusters (also called regional series), contains three main parts.

Reading Bureau of Meteorology files and creating $\{x_i, y_i\}$ series
The HQD available from the Bureau of Meteorology contains station identification number, date, amount of the monthly and yearly rainfalls plus a quality control sequence of digits. The daily rainfall data files are presented in a different format. The station identification number is solely given in the filename, the file itself gives the year, month, a control number (indicating 5 if the data is missing), the number of raindays, the monthly rainfall and the amount of rainfall for each day within the month.

In applying each test, both the tested station and the cluster series were standardized by their sample means and standard deviation, so that the critical values based on the null hypothesis N(0,0,1,1,ρ) could be used. That is the way the station and cluster anomalies are created. Note that the regional series are built and computed from the HQD solely.

Computing T_i
After series standardization, the test statistics are computed following the procedure supplied by Potter (1981). Years without yearly precipitation data are automatically removed from the test, so they do not influence the final result. Note that the so-called cluster series can be different when used for different stations of the same cluster. This is due to missing data in the station data record. The bivariate test can only be applied to a serially independent sequence $\{x_i, y_i\}$ of n two-dimensional random vectors so both series must have the same length n.

Conduct test
The test statistic T_0 (corresponding to the maximum T_i value obtained for the station) is then compared to the critical values computed by Maronna and Yohai (1978). Results can be sorted out according to the file length (number of years), the level of statistical significance of T_0, or both.

A1.2 Program achievements

The program uses the different aspects of the test and gives different output files.

Station files
Each station is given a file containing the date, $\{x_i, y_i\}$ and Ti value, since the bivariate test can be sensitive to multiple shifts in the mean (even though it is formulated to detect a single change) this can be useful for further studies.

Cluster summary files
These files list the T_0 for each station (with the corresponding date, $\{x_i, y_i\}$, change in mean, effective number of years, the start and end year of the station record) included in a cluster. If desired, it is possible to only include stations with a T_i of a fixed significant level or a certain period length.

Ti max distribution files
For a better understanding of the cluster anomalies, a summary file containing the start and end year distribution besides the T_0 one is written for each cluster. It gives a straightforward overview of the shift occurrence.

A1.3 Program control

Program using the HQD records
A complete comparison of the Fortran program results with an Excel file containing the bivariate formulas has been undertaken. For convenience reasons, the smallest cluster (cluster 7, SW WA, comprising 9 stations) is selected. The Excel file computes the same gross Bureau of Meteorology yearly data, so that the Fortran program results can be fully compared to the Excel ones (Table A1.1).

Both tests show the same year for T_0 (1902 for station 8091 and 1958 for station 8066) but a slightly different value in T_0. This is due to a different decimal precision in the computation and does not affect the application of this test.

Table A8.1 Comparison of the Fortran program/Excel bivariate test for HQD.

Station	**8091**		**8066**	
Period	1900–2000		1900–2000	
Peculiarity	None		Missing data in1900–1907 and 1997	
Results	Excel	Fortran	Excel	Fortran
Cluster series average	0.1542	0.1555	0.1524	0.1512
Cluster series standard deviation	0.9051	0.9094	0.905	0.9215
Station series average	0.1247	0.1259	0.0173	0.0174
Station series standard deviation	1.0825	1.0878	1.0385	1.0431
T_0	2.6363	2.7603	12.6149	13.3922
Year of occurrence	1902	1902	1958	1958
Difference in T_0		+4.8%		+5.8%

Appendix 2 Bivariate results: shifts in the 1920's

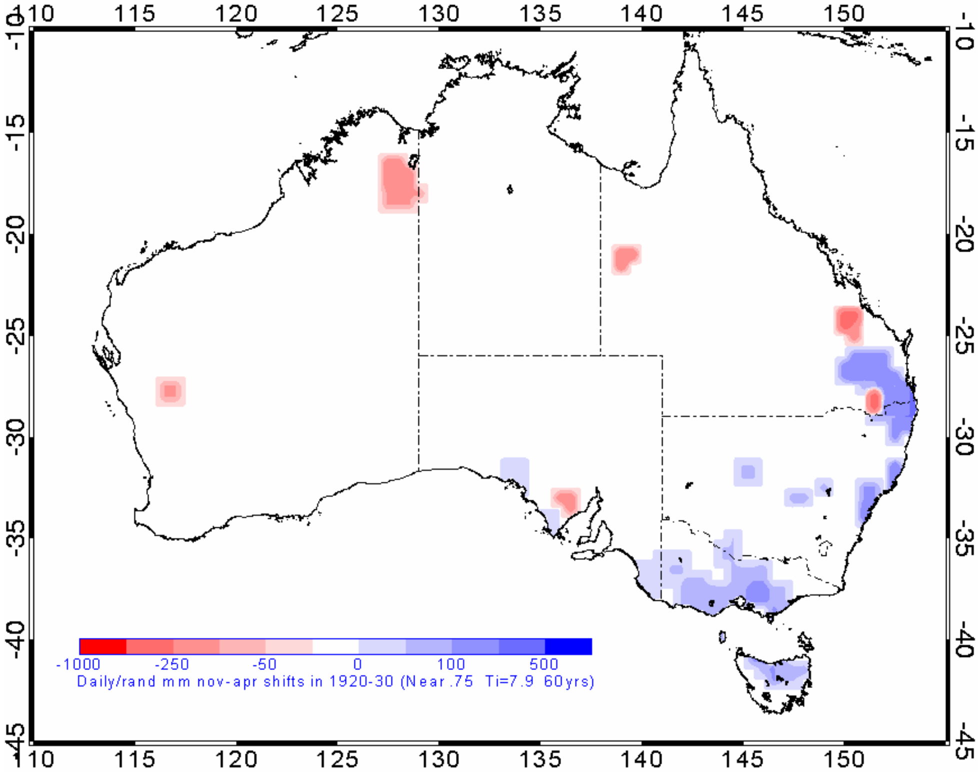

Figure A2.1 Location of the 1920s shifts in the summer series

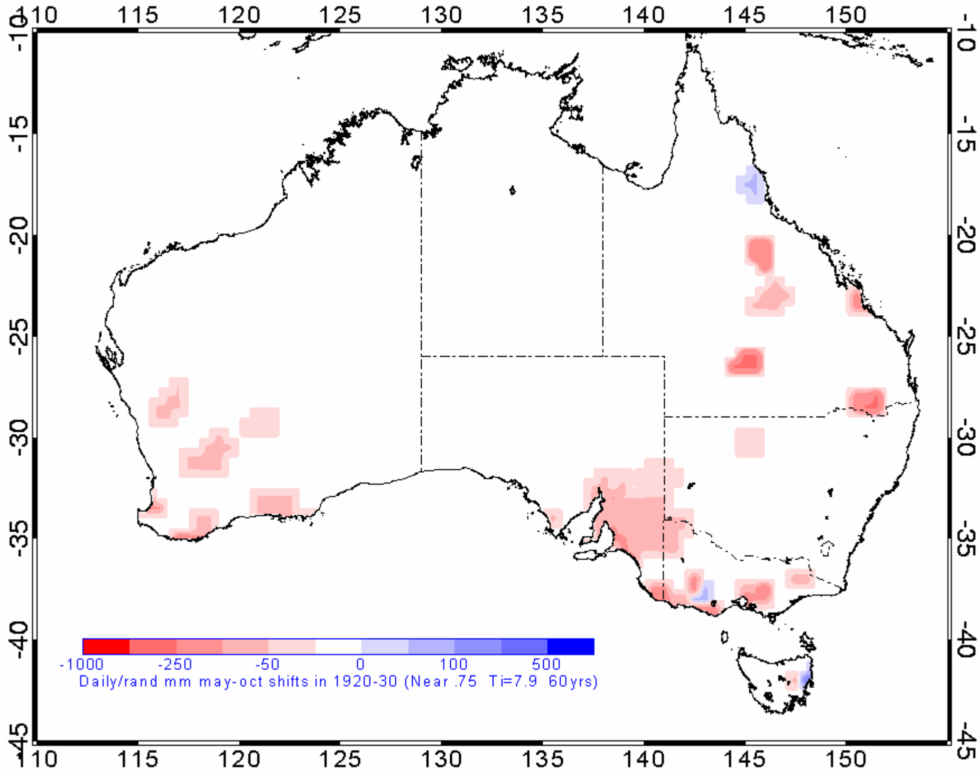

Figure A2.2Location of the 1920s changes in the winter series.

Appendix 3 Bivariate results: shifts in the 1980s

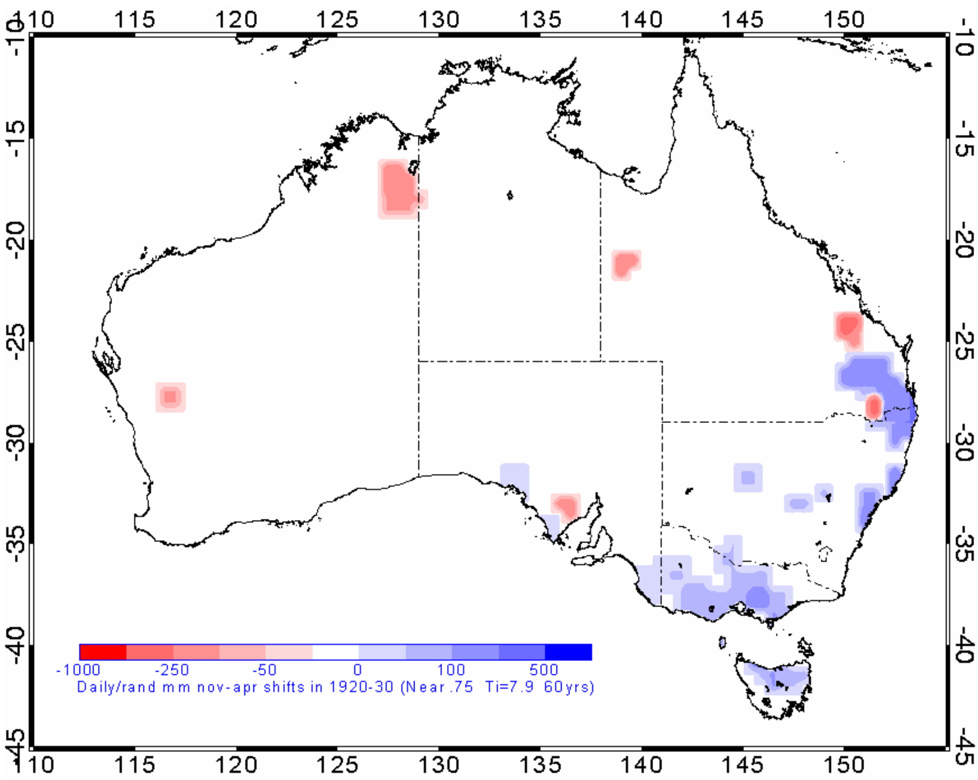

Figure A3.3 Location of the 1980s changes in the summer series.

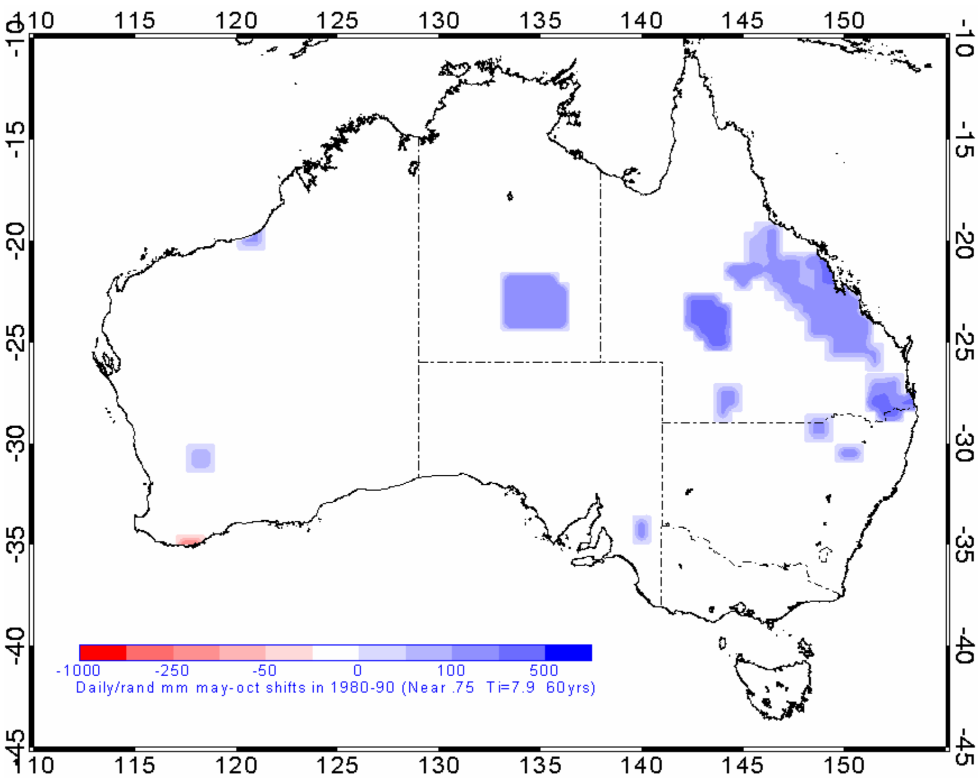

Figure A3.4 Location of the 1980's changes in the winter series.

Appendix 4 Bivariate results: random time series

The purpose of this appendix is to present tests known excursions from a homogeneous time series and thus to understand how the bivariate test responds to various decadal scale changes in mean. The technique used was to calculate 101 random numbers for a Gaussian distribution with a mean of zero and standard deviations of ±1. The final series had a mean of -0.08 and a standard deviation of 1.03. Figure A4.1 provides a summary of some of the tests run to determine how Ti would be affected by known departures from the mean. In each case, the reference series was the unperturbed time series.

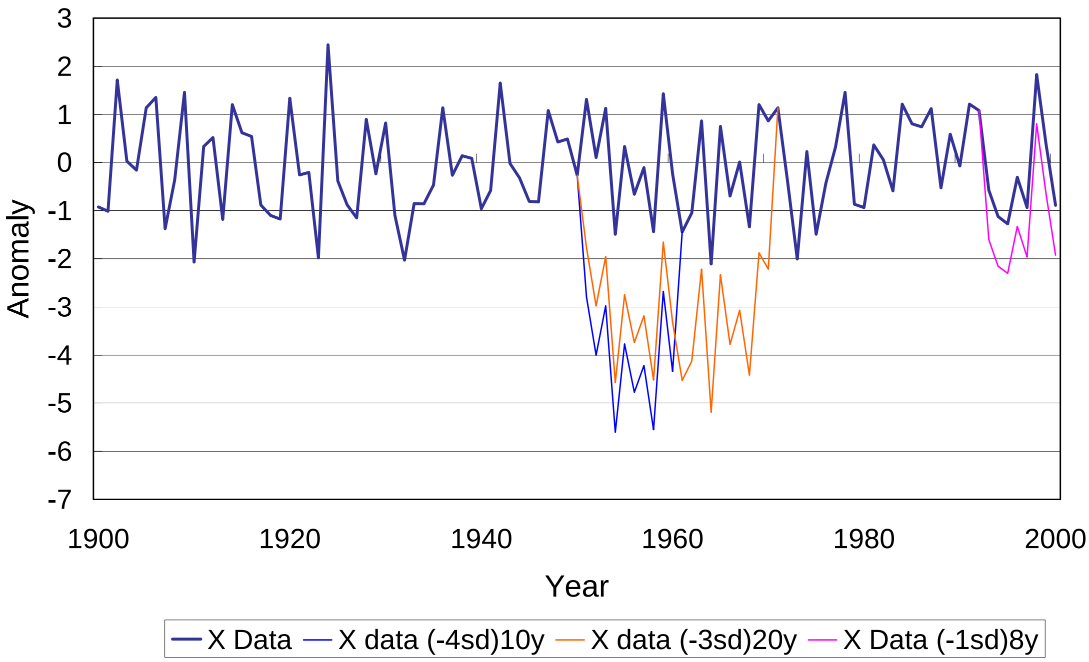

Figure A4.4 Anomalies from an artificial data set showing known departures in mean. They are a 10-year reduction of 4σ and a 20-year reduction of 3σ at the midpoint of the series and an 8-year reduction of 1σ at the end of the series.

Figure A.4.2 shows the results from each of the tests shown in Figure A4.1, plus another with a departure of 1 standard deviation from nominal years 1951–2000. These tests show that a 4σ reduction of 10 years is P<0.1, whereas a 20-year reduction of 3σ is significant to P>0.01. The longer the departure, the more significant it is; a 50-year reduction of 1σ is also significant to P>0.01. However, the bivariate test is sensitive to deviations in mean at the beginning and of time series. An eight-year reduction of 1σ is significant to P>0.01. This shows that while the test is sensitive to long-term departures from a homogeneous time series, it is sensitive to departures without return close to the beginning and end of timer series. Therefore, the test should be applied with caution in these situations.

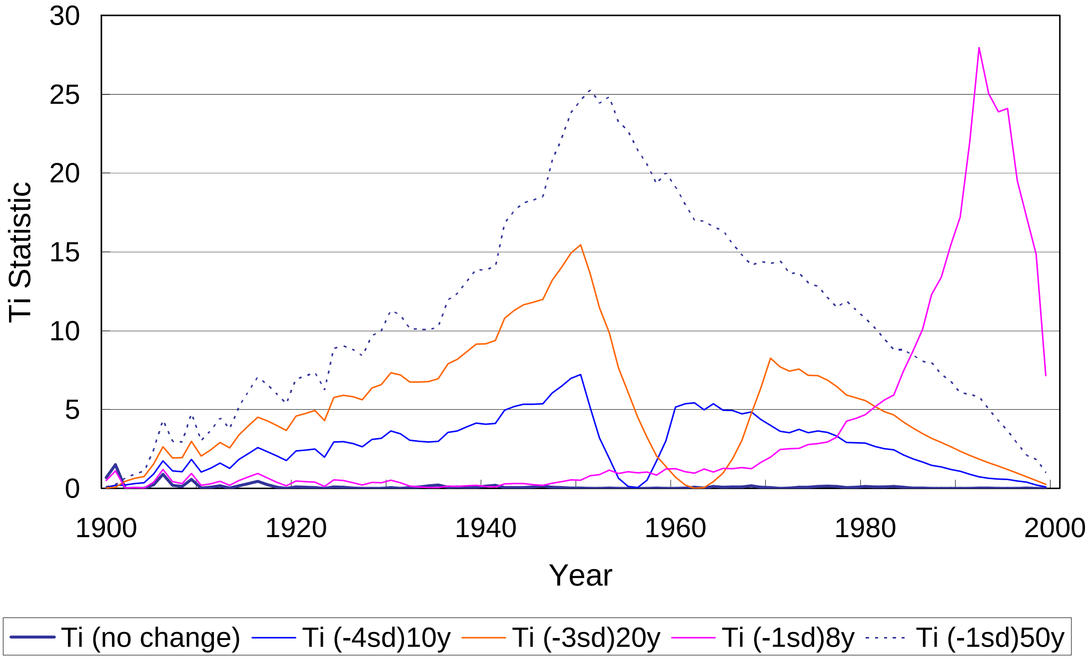

Figure A4.4 Ti statistic results for the departures shown in Figure A4.1. They are a 10-year reduction of 4σ, a 20-year reduction of 3σ and a 50-year reduction of 1σ at the midpoint of the series and an 8-year reduction of 1σ at the end of the series.

Appendix 5 Lepage test adaptability

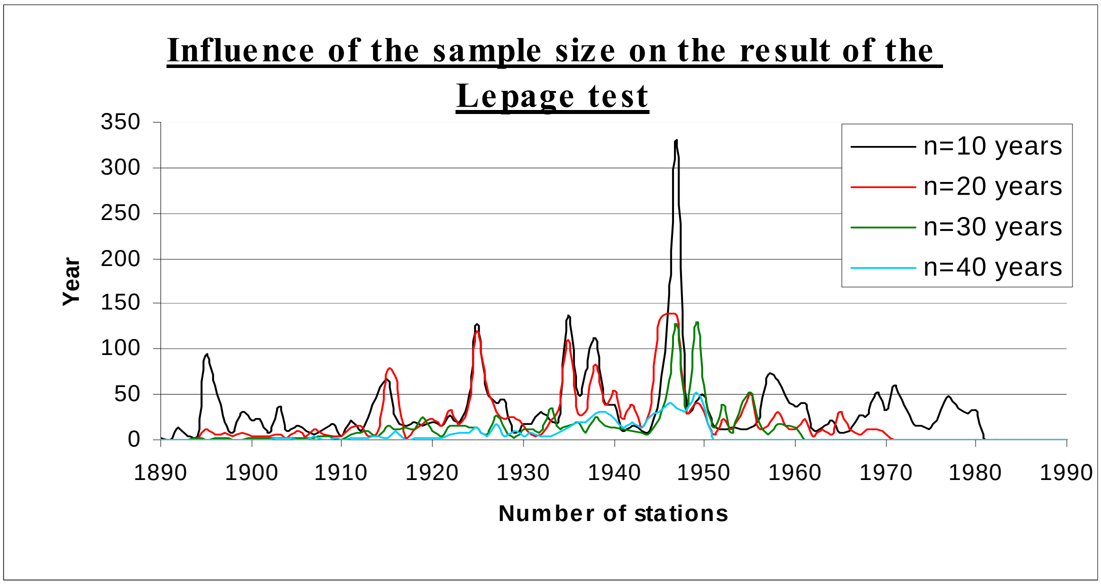

Figure A8.5 Results of the Lepage test with different sample sizes.

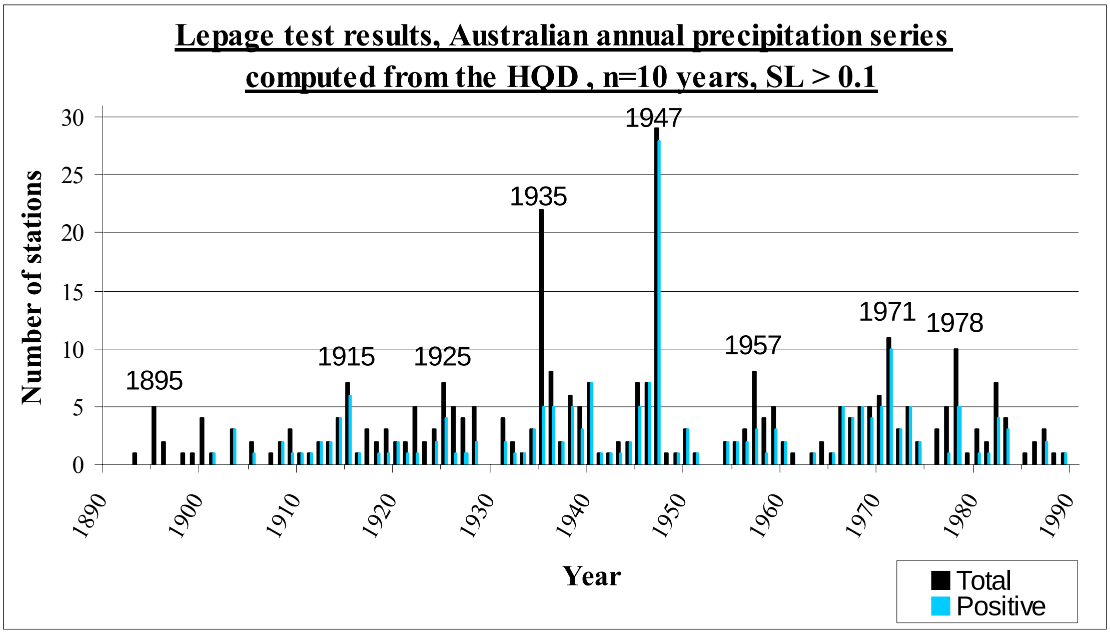

Figure A8.6 Results of the Lepage test with the High Quality Dataset