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CLIMATE VARIABILITY AND PREDICTABILITY FOR SOUTH-WEST WESTERN AUSTRALIA

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Phase 1 report to the

Indian Ocean Climate Initiative

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SUMMARY

BMRC has, through the first phase of the IOCI (1998-99), been investigating the following problems, for the south-west of Western Australia:

- Selection of high-quality climate data for the south-west
- How surprising is the decrease in rainfall?
- Has extreme rainfall declined as well as total rainfall?
- Is the rainfall decrease due to changes in atmospheric circulation?
- Is the rainfall decrease attributable to changes in Indian Ocean SSTs?
- Can we develop better methods for seasonal prediction in the south-west?
- How does the El Niño - Southern Oscillation affect south-west rainfall?
- Can climate models help us in seasonal prediction in the south-west?

Our achievements and preliminary conclusions from this work include:

- We have selected stations with high-quality daily/monthly rainfall, and daily temperature data over a long period, for analysis. These data sets can be made available to others interested in using high-quality climate data for the south-west.
- We have fitted statistical models to station rainfall and estimated the likely frequency of the observed runs of dry years in recent decades. They are unusual, in the historical context. We have also estimated breakpoints in the rainfall data series, where there is a sudden change in mean rainfall. The date of these breakpoints shows considerable spatial consistency, indicating that the breaks are real physical phenomena.
- Changes in the numbers of days of rain, and the amount of rain falling in extreme events, both have contributed to the decline in total rainfall.
- About half of the observed decline in rainfall is related to changes in regional atmospheric circulation, as represented by Perth atmospheric pressure. Part of the

observed increase in Perth pressure represents changes in the El Niño - Southern Oscillation, as measured by the SOI. However, little of the observed rainfall decline is attributable to long-term changes in the El Niño - Southern Oscillation.

- Interannual variations in Indian Ocean SSTs are only weakly related to south-west rainfall, and even this weak relationship simply represents the effect of the El Niño - Southern Oscillation on both Indian Ocean SST and south-west rainfall, rather than an independent effect of the SSTs on rainfall. Since the interannual variations are not related, it seems unlikely that the long-term changes in both Indian Ocean SSTs and south-west rainfall are causally related. This conclusion is supported by the inability of climate models, when forced with observed SSTs over the 20th century to reproduce the observed decline in south-west rainfall.

- Secular changes have confounded the interannual relationships between the SOI and south-west rainfall, disguising some of the predictability achievable through the use of the SOI. An approach using year-to-year differences in the SOI has been proposed to overcome this confounding effect.

1. BACKGROUND

Nicholls and Lavery (1992), using a specially-selected set of high-quality rainfall stations, examined Australian rainfall trends over the 20th century. They confirmed trends noted in earlier studies: an abrupt increase in summer rainfall around mid-century over much of eastern Australia, and a smoother trend towards lower rainfall in the south-west of the continent, again from about mid-century. The extent of the decline in the south-west is illustrated in Figure 1, which shows winter half-year (May-October) rainfall for Manjimup (116.20E, 34.15S). In this and subsequent time-series, the thin line shows the values from year-to-year, while the thick line is the result of applying a distance-weighted least square smoother to these data. Manjimup is used throughout this report to represent rainfall trends and variability in the south-west. Manjimup May-October rainfall has a correlation of 0.84 with a 12-station regional average rainfall, indicating that it does provide a good example of variations in south-west rainfall. Figure 1 shows that since the middle of the century, Manjimup May-October rainfall has declined by about 25% (from about 800 mm to about 600 mm). Such a substantial and sustained decrease has obvious implications for water supply and use in the region.

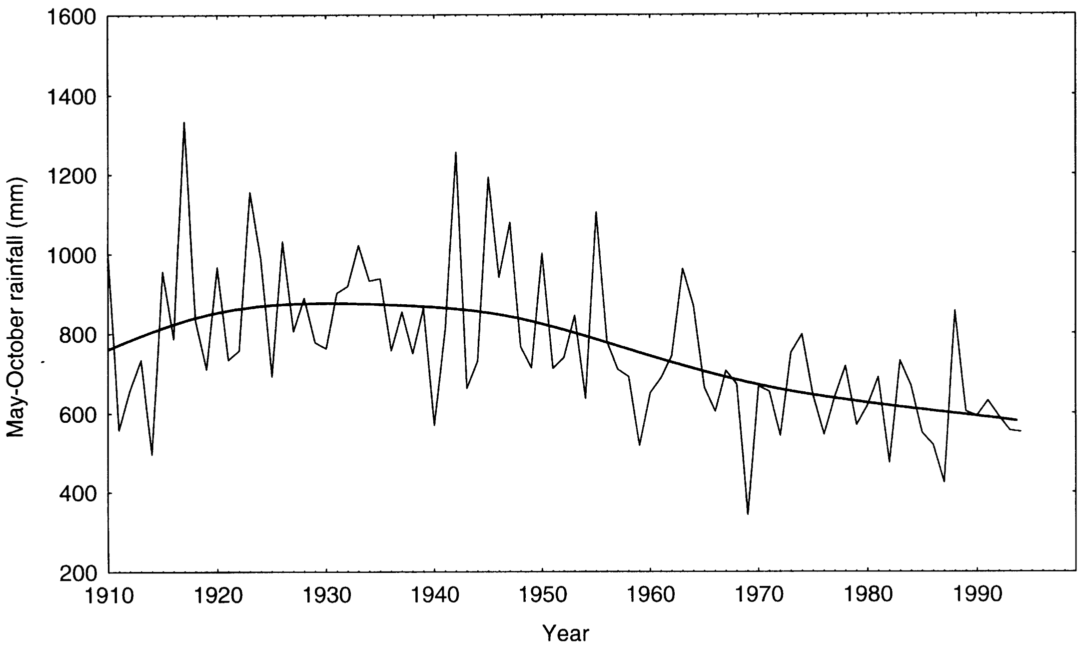


Figure 1 Manjimup May-October rainfall

Considerable work has already been completed, in earlier years and by a variety of authors, on climate variability in south Western Australia, including the decline in rainfall over the last few decades (e.g. Allan and Haylock, 1993; Ansell *et al*., 1999; Smith *et al*., 1999; Williams, 1991; Wright, 1974; Yu and Neil, 1993). Some of the conclusions of this work can be summarised thus:

- The decadal-scale decrease in annual rainfall has NOT been accompanied by a decrease in high-intensity rainfall (Yu and Neil, 1993).

- Long-term variations in rainfall reflect changes in the anticyclone over the continent and the Indian Ocean, and to cyclonic/frontal behaviour to the south (Allan and Haylock, 1993).

- The long-term variations in rainfall have occurred over the same period in which there have been long-term changes in Indian Ocean sea surface temperatures, SSTs, (Ansell *et al*., 1999; Smith *et al*., 1999), raising the possibility that it is these SST changes that are driving the rainfall decline.

- Rainfall variations are associated with the El Niño - Southern Oscillation (Wright, 1974), although the relationship is weaker than is the case for the eastern states (McBride and Nicholls, 1983).

There is a perception that the Southern Oscillation Index (SOI), until recently the basis for operational seasonal rainfall forecasting in Australia, is less effective in prediction for the south-west, relative to the eastern states. Nicholls (1989) identified a mode of variability of Indian Ocean SST that appeared to be related to rainfall in the south and south-east of the continent, somewhat distinct from the El Niño - Southern Oscillation mode affecting the eastern states. As a result, Drosdowsky and Chambers (1998) developed a new system for seasonal rainfall forecasting, now operationally implemented in the Bureau of Meteorology's National Climate Centre, using Indian and Pacific Ocean SST patterns as predictors (replacing the earlier system which used just the SOI as a single predictor). The new method provides a longer lead time for the predictions, is more stable, and exhibits somewhat increased skill. However, skill in the new system is still greater in the east and north of the country. Figure 2 shows the skill expected from a system just using the SOI as a predictor. Figure 3 shows the skill using the first two Principal Component Patterns of Indian and

Pacific Ocean SSTs as predictors. Both figures show cross-validated LEPS scores. More detail on this is available in Drosdowsky and Chambers (1998). For here it suffices to say that the shaded areas delineate the regions where skill could be expected on independent data. Heavier shading indicates greater expected skill. Although the new SST-based system is generally more skilful than the SOI-based scheme, nevertheless, not a great deal of skill is apparent for the south-west.

Thus, two major problems are apparent with regard to rainfall in the south-west:

- What is the cause of the observed, decadal-scale decrease in rainfall in south-west Western Australia (and can we predict whether it will continue)?

- Can we develop useful methods for seasonal climate prediction for south-west Western Australia?

This report discusses BMRC work regarding these two problems, carried out through 1998 and early 1999 as part of the IOCI. The focus has been on May-October rainfall, because of the marked decline in rainfall during this part of the year. Rainfall at Manjimup has been used to illustrate the behaviour across the south-west.

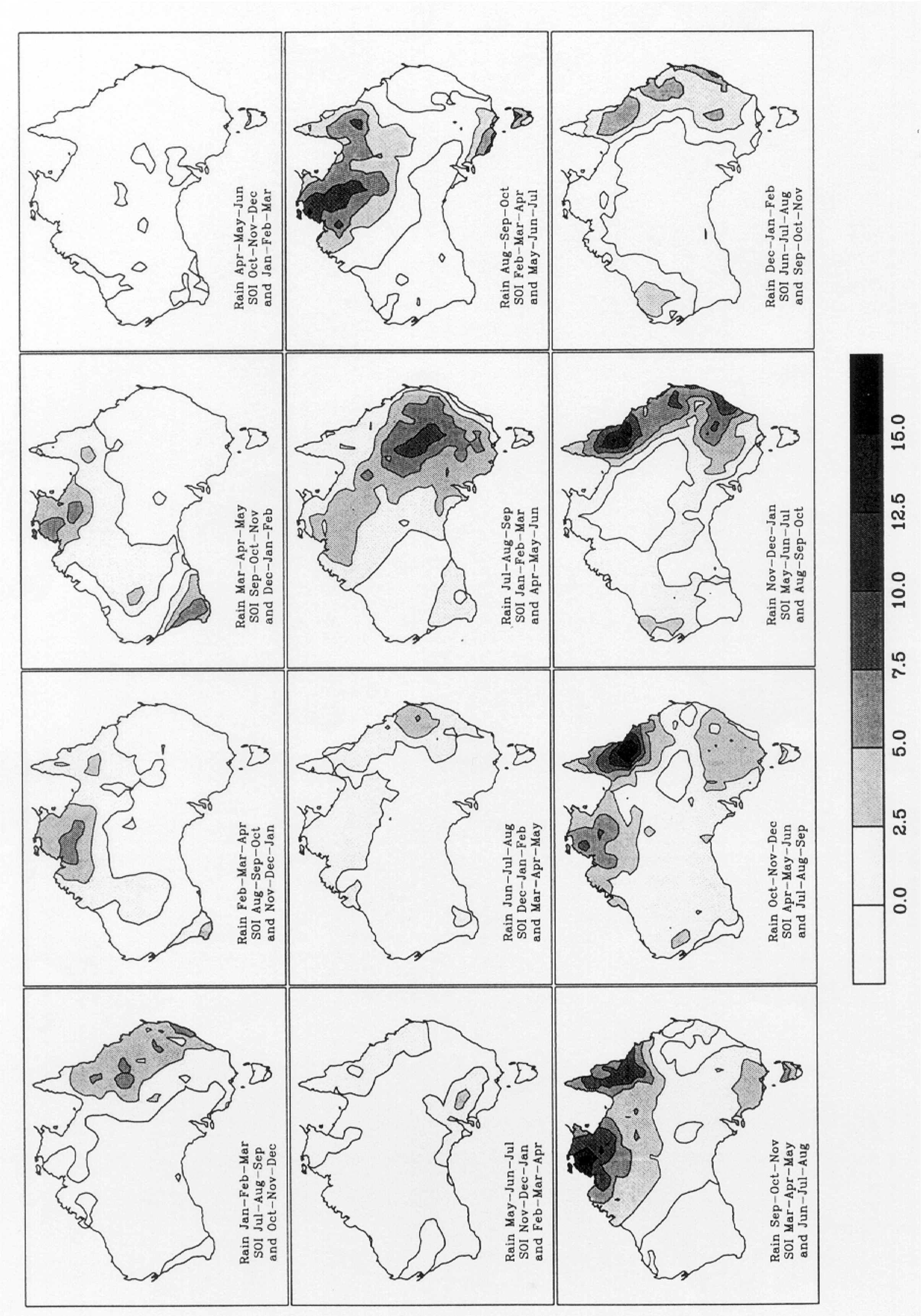


Figure 2 Cross-validated skill of seasonal rainfall predictions with past two seasons SOI as predictor. Zero lead.

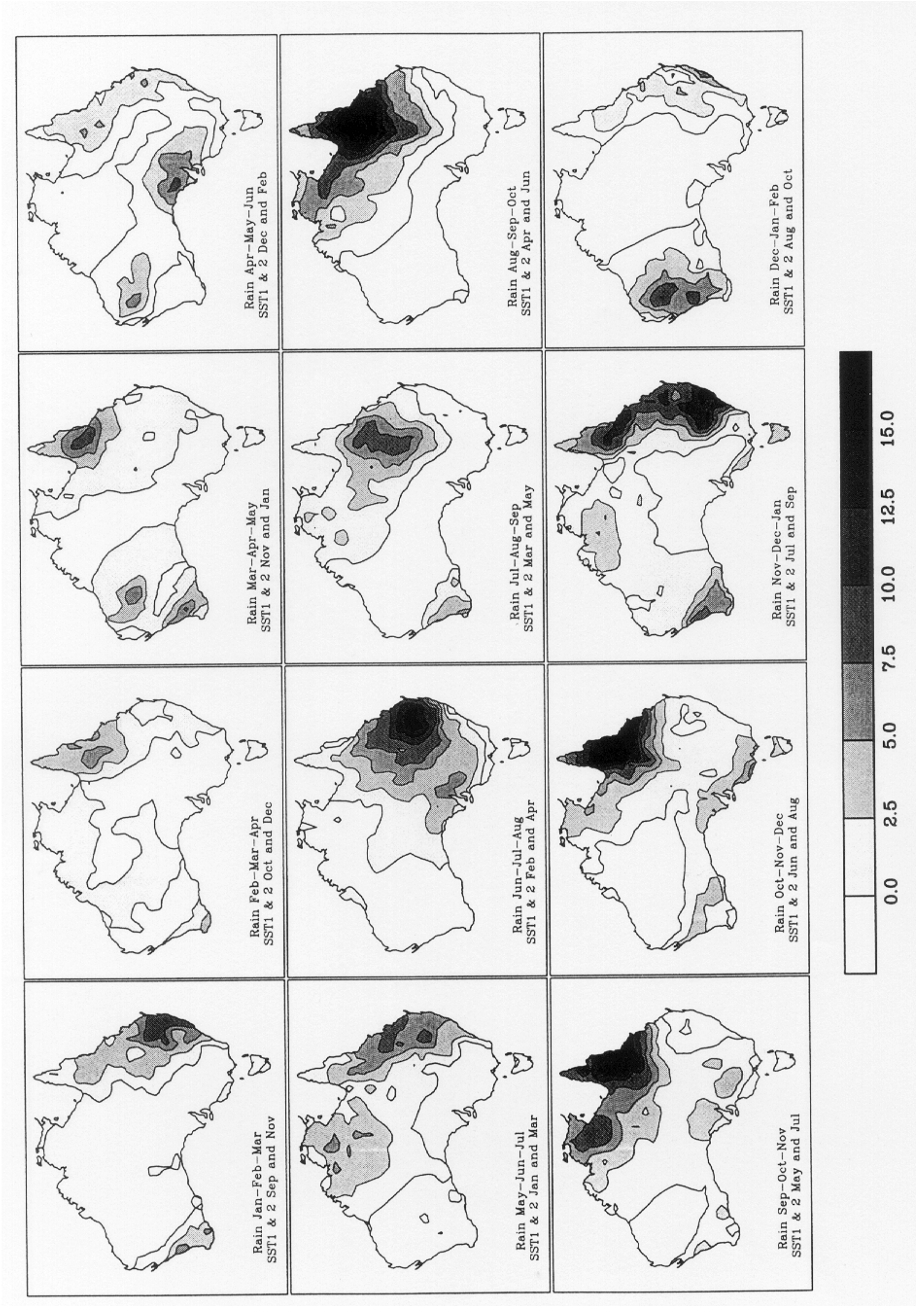
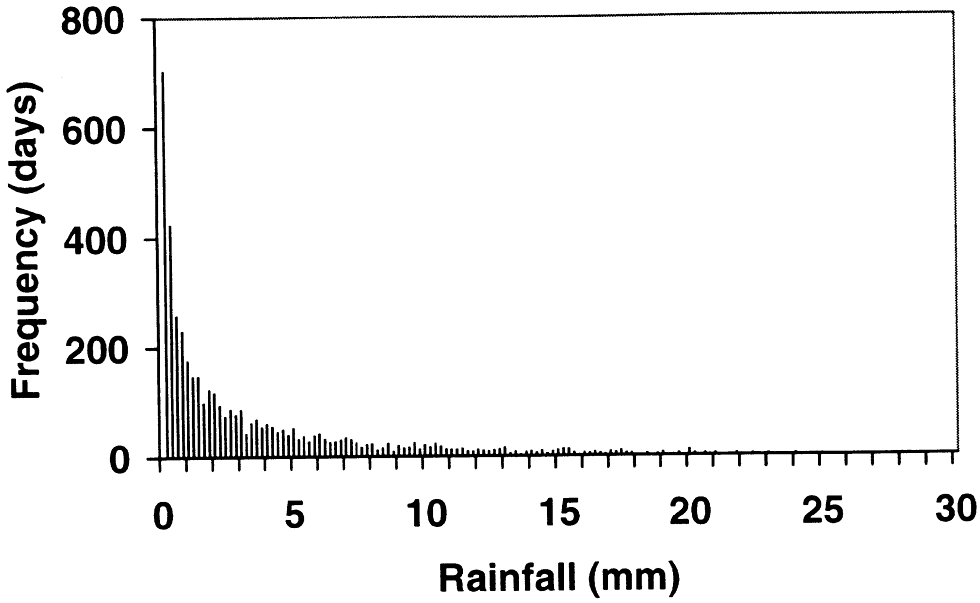


Figure 3 Cross-validated skill with first two patterns of Indian and Pacific Ocean SSTs as predictors. One month lead.

2. SELECTION OF HIGH-QUALITY CLIMATE DATA FOR THE SOUTH-WEST

Lavery *et al*. (1992) describe the techniques used to select a high-quality set of rainfall stations for Australia, and provide details of the 191 stations finally chosen as the best for examining rainfall trends and variations. These techniques included an exhaustive search through station documentation. Stations with adverse comments in their documentation regarding exposure, observer accuracy, or instrumentation were excluded. Only stations that have been recording continuously since at least 1910, and continue to record at present, were considered. Only data from 1910 were considered because useful documentation about observing stations prior to this is almost nonexistent. Station history documentation since 1910 is, however, not always complete. So other approaches were also needed. Statistical tests were applied to the daily rainfall data to check the long-term reliability of station records. Lavery *et al*. (1992) describe these tests. They included calculation of the "bias statistic" (Craddock, 1981) and the inspection of frequency histograms of daily rainfall readings for irregularities indicating observer neglect. Stations likely to have been affected by urbanisation, or with major site relocations likely to introduce biases, were also excluded. The records from stations with smaller site relocations were examined carefully to ensure these had not introduced spurious rainfall changes.

The potential problems in dealing with daily rainfall data are illustrated in Figure 4, which shows frequency distributions at two stations. The frequency distribution at one station, shown in the lower part of the figure, is clearly affected by observers “rounding” measurements to the nearest millimetre. This can be compared with the smoother distribution for the neighbouring station shown in the top part of the figure. The statistical tests applied to the station data were used to identify stations where rounding was not too severe. Because of the scarceness of such stations, data from stations exhibiting some problems were used, at least for analysis on monthly or seasonal rainfall. Rounding and other problems are likely to be less of a problem on these longer time scales, relative to the problems they cause when using daily data.



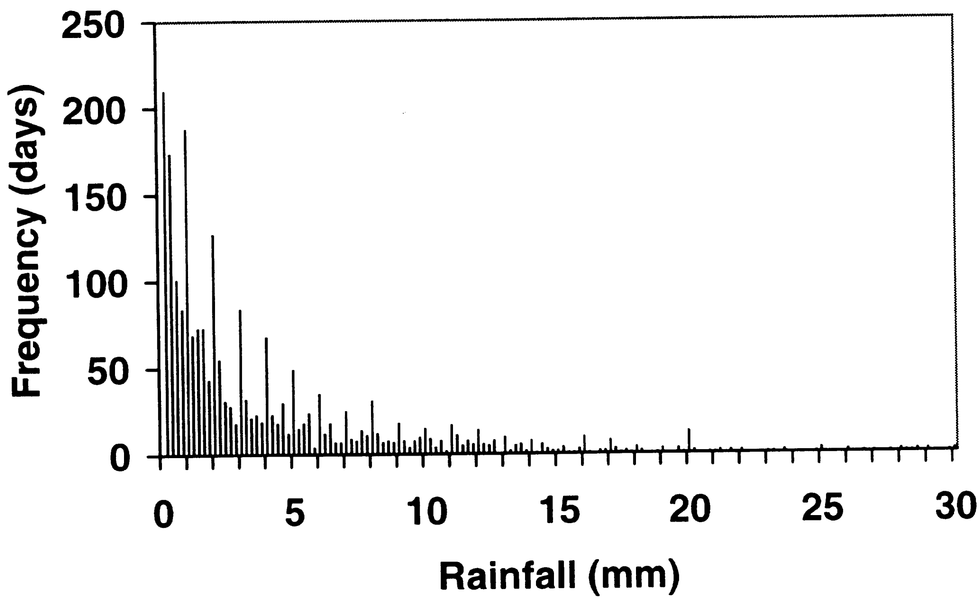


Figure 4 Frequency distributions of daily rainfall at Albany (009564) and Arthur River (010505)

Lavery *et al*. (1997) extended the data set produced by Lavery *et al*. (1992), to improve the spatial distribution across the country. Higher-quality composited monthly rainfall records (from two or more neighbouring stations) and some records of shorter duration were added. This produced a final data set of 379 stations with high-quality monthly rainfall records which can reliably monitor rainfall trends for most of Australia. The high-quality daily rainfall stations (selected from Lavery *et al*., 1992) used in the current study are shown in Figure 5 (upper part) and listed in Table 1.

Torok and Nicholls (1996) prepared a high-quality annual temperature data set for Australia. Only stations with long continuous records were selected (except where shorter records from two or more stations could be composited). Rigorous statistical techniques and careful searching of station documentation were used to adjust for discontinuities due to changes in instrumentation, location, observer practices, and in the local environment (e.g. vegetation growth, urbanisation). This produced a data set with 224 stations across the country. For this study, all stations within the area south of 27ºS and west of 122ºE that were identified by Torok and Nicholls (1996) as having high quality temperature records were used. The locations of these stations with high-quality daily data are shown in Figure 5 (lower portion), and listed in Table 2. There are fewer stations available for the analysis of daily temperatures than is the case for daily rainfall.

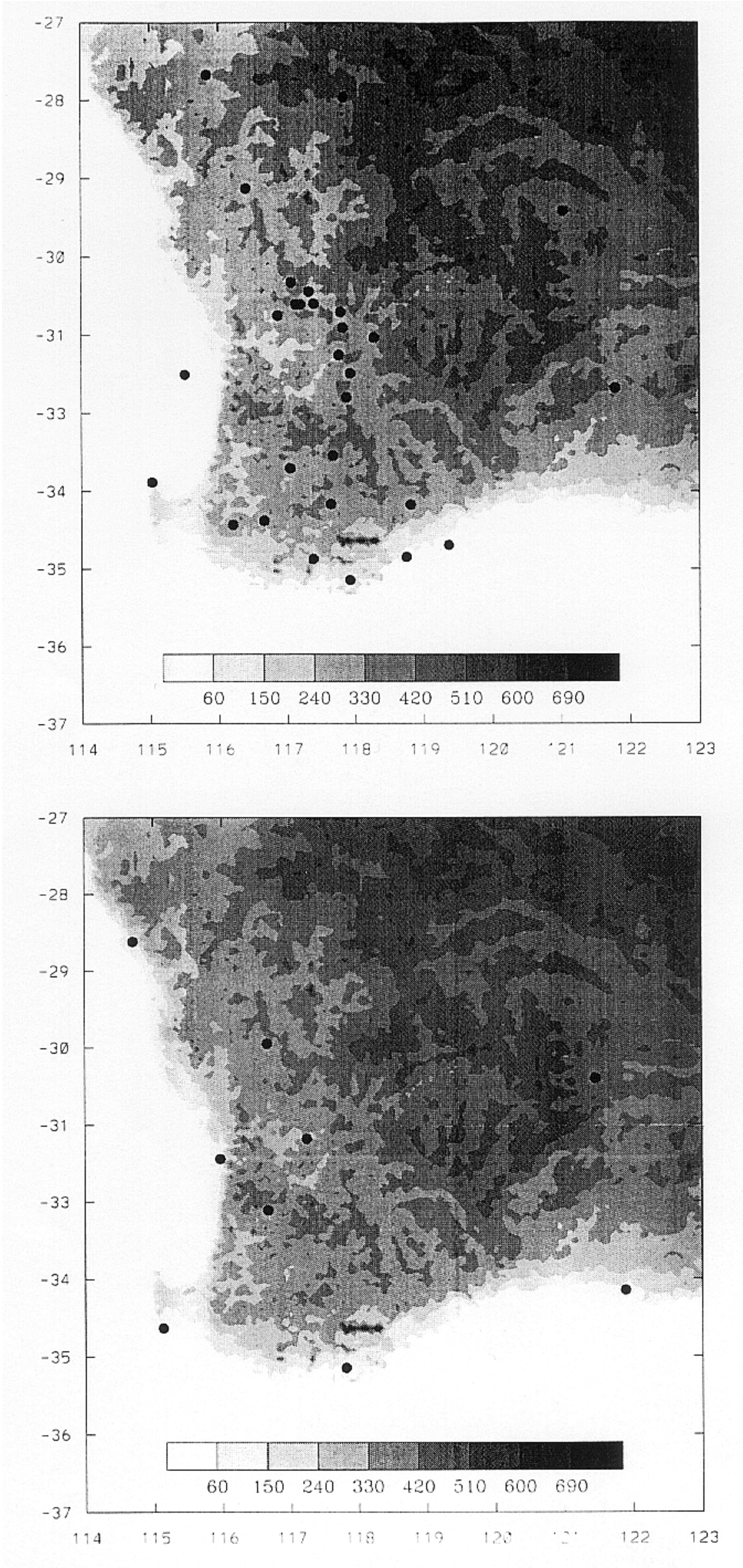


Figure 5 Location of high-quality rainfall stations (top) and temperature stations (bottom). Elevation shown shaded.

Table 1 Rainfall stations with little missing data were selected from the high-quality daily rainfall data set (Lavery *et al.*, 1992) maintained by the Bureau of Meteorology. Rainfall records contain days where data is either missing or is a value accumulated over several days. To avoid problems introduced by missing and accumulated readings, all accumulations were set to missing and stations were selected from the high-quality set if they contained less than 10% of days missing (36 days) for at least 90% of the years from 1910 to 1992. The resulting 29 stations in the south-west (Table 1) provide good coverage west of 119°E and south of 30°S. These stations were updated to 1998 from the Bureau's records.

STATION	LATITUDE	LONGITUDE	START YEAR	END YEAR
06055	-27.75	115.83	1904	1998
07057	-28.07	117.84	1895	1997
08066	-30.70	117.06	1907	1998
08106	-29.37	116.40	1910	1998
09038	-32.01	115.50	1881	1995
09519	-33.54	115.02	1907	1998
09520	-34.61	118.75	1897	1997
09564	-34.94	117.92	1907	1998
09591	-34.64	117.38	1907	1998
09594	-34.44	119.36	1907	1997
09616	-34.09	116.66	1907	1990
09619	-34.15	116.20	1903	1998
10024	-31.17	116.86	1910	1997
10032	-31.00	117.39	1907	1998
10037	-31.73	117.76	1889	1998
10039	-31.01	117.20	1907	1998
10045	-31.01	117.13	1907	1998
10092	-31.48	118.28	1904	1998
10123	-31.99	117.93	1910	1998
10126	-31.12	117.79	1910	1998
10133	-30.83	117.32	1909	1998
10149	-31.34	117.82	1902	1998
10505	-33.34	117.04	1891	1998
10525	-33.85	117.64	1891	1998
10536	-32.33	117.87	1910	1998
10541	-33.86	118.81	1907	1998
10636	-33.16	117.67	1907	1998
12052	-29.69	121.03	1898	1998
12065	-32.20	121.78	1898	1998

Table 2 Nine temperature stations were selected from the Bureau of Meteorology's high-quality daily temperature data set (Trewin and Trevitt, 1996). These records were subjected to rigorous quality control, applied to both monthly means and daily observations, to ensure continuity in both time and space. Table 2 lists the nine stations from this data set located in the south-west region.

STATION	LATITUDE	LONGITUDE	START YEAR	END YEAR
08039	-30.28	116.66	1955	1997
08051	-28.80	114.70	1950	1997
09021	-31.94	115.97	1950	1997
09518	-34.37	115.13	1950	1997
09741	-34.94	117.80	1960	1997
09789	-33.83	121.89	1957	1997
10035	-31.66	117.25	1950	1997
10648	-32.68	116.67	1950	1997
12038	-30.79	121.45	1950	1997

3. HOW SURPRISING IS THE DECREASE IN RAINFALL?

We have fitted statistical models to station rainfall and estimated the likely frequency of the observed runs of dry years in recent decades. We used a modified version of the approach of Trenberth and Hoar (1996), who looked at the unusualness of the length of the 1990-1995 El Niño – Southern Oscillation event. Since the period from May to October, hereafter referred to as winter, is most important for rainfall in south-western Australia, winter rainfall only was analysed. Using the entire period of rainfall records for each station, winter rainfall anomalies were calculated by subtracting the mean from the winter rainfall total and dividing by the standard error.

A preliminary investigation of the time series of the winter rainfall anomalies for a number of stations indicated that a decrease in mean rainfall had occurred from around the mid-1970's. For this reason the station data was divided into two parts, pre-1975 and post-1975. This provided up to 96 years of data in the first (pre-1975) data set, since the first station records occur in 1880. The same year for dividing the data was chosen for all stations to simplify computations.

A time series model was then fitted to the pre-1975 (test period) data. Auto-regressive moving average (ARMA) models were used with the order of the model selected by iterative fittings using S-PLUS software until the model with the lowest Akaike's Information Criterion (AIC) was obtained. The AIC invokes a performance and penalty function related to the number of parameters in the model.

The resulting model was then used to generate 101,000 years of synthetic record. The first 1000 years were discarded because of possible spin-up problems and the remainder used to estimate the probability of runs of dry years such as those recently observed. This was done by counting the length of runs in the observed and simulated data sets. The results are shown in Table 3. Many of the recent runs of drier than normal years are very unusual, in the historical context.

Table 3 Subset of "unusualness" of run results. The column headed "EXP. YRS" indicates the estimated number of years between runs of dry years of the length experienced at the station (indicated in column headed "RUN YEARS")

RAINFALL STATION	NUMBER	LAT., LON.	RUN YEARS	EXP. YRS
Perenjori (Perangery)	08106	-29.37,116.42	1976-1983	885
Mount Barker (Kendenup P.O.)	09561	-34.49, 117.63	1974-1987	3571
Mount Barker (Pardelup)	09591	-34.64, 117.38	1978-1987	5556
Manjimup (Wilgarrup)	09619	-34.15, 116.20	1975-1987	847
Meckering P.O.	10091	-31.63, 117.01	1984-1990	94
Arthur River Comp.	10505	-33.35,117.03	1975-1982 1989-1994	455 90
Corrigin P.O.	10536	-32.33, 117.87	1984-1994	571
Cranbrook P.O.	10537	-34.30, 117.57	1978-1987	3448
Norseman P.O.	12065	-32.20, 121.87	1975-1983	465

We have also estimated breakpoints in the rainfall data series, where there is a sudden change in mean rainfall, and looked for spatial consistency. Statistical analyses of 'winter' and 'summer' temperature and rainfall data were carried out to look for potential changes or breaks in the mean level. Initially the method of Hubert (1997) was used. Hubert's method was devised to segment a time series yielding an optimal partition (from a least squares point of view) of the original series into as many sub-series as possible, all differences between two contiguous means remaining simultaneously significant, which was ensured using the Scheffe test of contrasts. The method uses the Bayesian procedure defined by Lee and Heghinian (1977) which supposes the *a priori* existence of a change of the mean somewhere in the series and yields at each time step an *a posteriori* probability of mean change. Hubert modified this procedure to locate all possible singularities within a time series. Each optimal segmentation is ranked by ascending segmentation order. This is followed by the display of the optimal objective function value (being the sum of the squares of deviations from the local mean). Each segment is described by an indicator of the beginning and end of the segment, the length, mean and standard deviation. A test of independence of residuals (Wald-Wolfowitz) is applied to the final optimal segmentation with the result of the test being indicated by an integer. In the analyses rainfall and temperature data are not anomalies but are quality-controlled six-monthly values. This method is useful for finding changes in the mean level and is a useful test for stationarity of the time series. However, there are a number of drawbacks. The procedure can be sensitive to outliers, and only finds changes in mean level and not changes in slope. Work is currently being undertaken to look for change-points that involve changes in slope.

An example, for Mount Barker (Pardelup) May-October rainfall, of the results of the breakpoint analysis, is shown in Figure 6. Figure 7 shows a map of the years (indicated by last two digits) of breakpoints in May-October rainfall in south-west Western Australia. Considerable spatial consistency is evident, in the sense that most of the stations showing downward changes/breaks are clustered in the south-west of the region, while further to the northeast stations either exhibited upward changes or no breaks were found.

Seven of the nine temperature stations had general increases in the mean levels for minimum winter temperature (the other two had fairly constant mean levels). Few stations had mean level changes when looking at winter maximum temperatures.

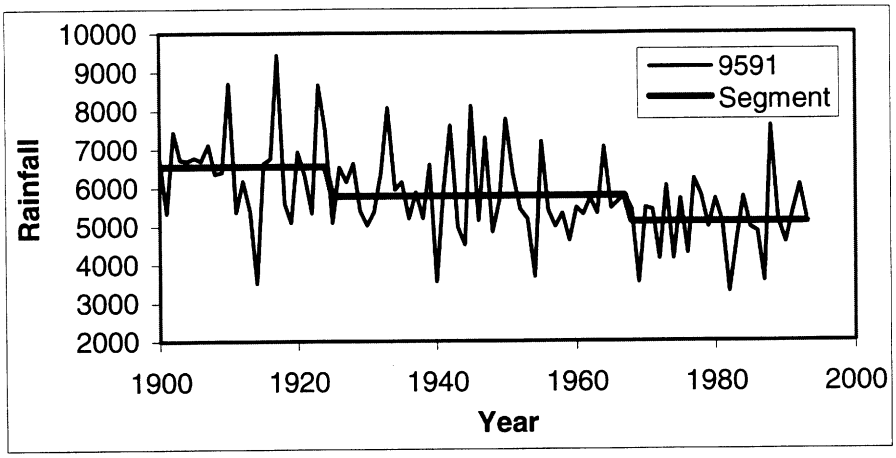


Figure 6 Breakpoint example, Mount Barker (Pardelup) May-October Rainfall (10ths of mm)

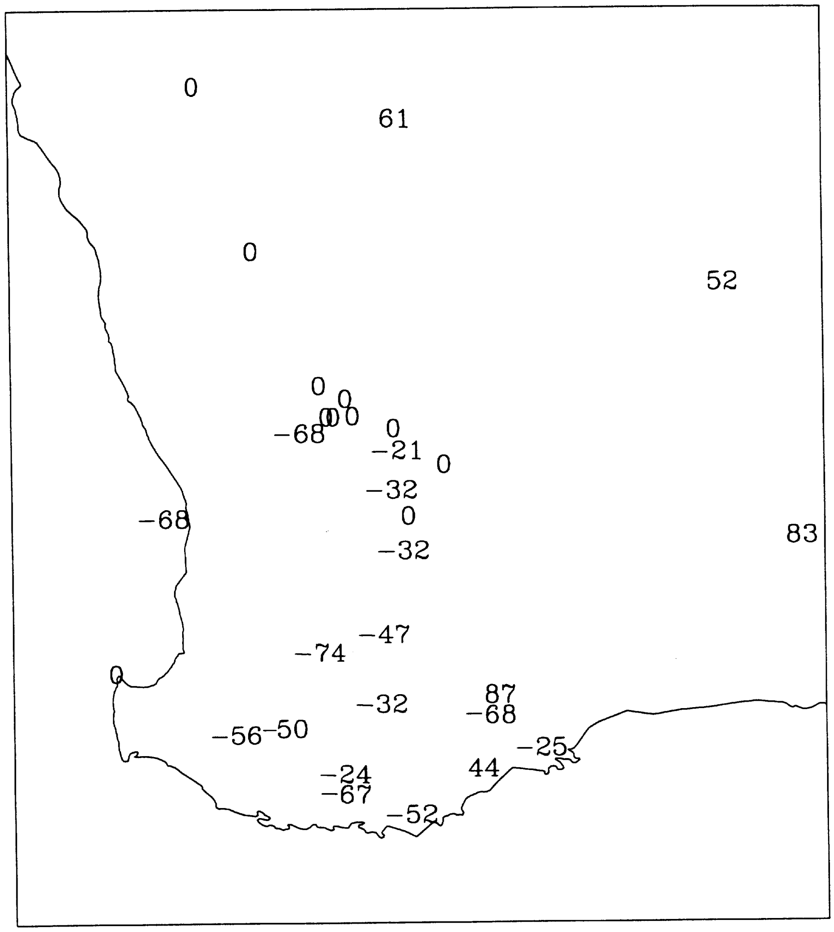


Figure 7 Rainfall Breakpoint Summary. The numbers indicate the last two digits of the year in which there was a significant change in the mean. The negative sign indicates that the change was toward lower mean rainfall. A zero indicates a station at which there was no significant break-point.

4. HAS EXTREME RAINFALL DECLINED AS WELL AS TOTAL RAINFALL?

We have examined how changes in the numbers of days of rain, and the amount of rain falling in extreme events, have contributed to the trends in total rainfall. Figure 8 shows Manjimup May-October rainfall, and the number of days recording rainfall above 1 mm in each year. Some of the decline in rainfall may be attributable to a decline in the number of rain days, although the decline in rain days has not been as marked. Nor does it exactly parallel the decline in total rainfall. Around 1980, for instance, the number of rain days was relatively high, yet rainfall was quite low. Figure 9 shows the Manjimup May-October rainfall and the total rainfall on days each year receiving rainfall above the long-term 99th percentile of daily rainfall (i.e. heavy rain days). As with the rain days, this heavy rainfall index matches the variations in rainfall to a degree. In this case, however, the decline in heavy rainfall was more marked than the decline in total rainfall. Around 1950 Manjimup received typically about 150 mm from heavy rain days, while by the 1970s it was only receiving about 50 mm.

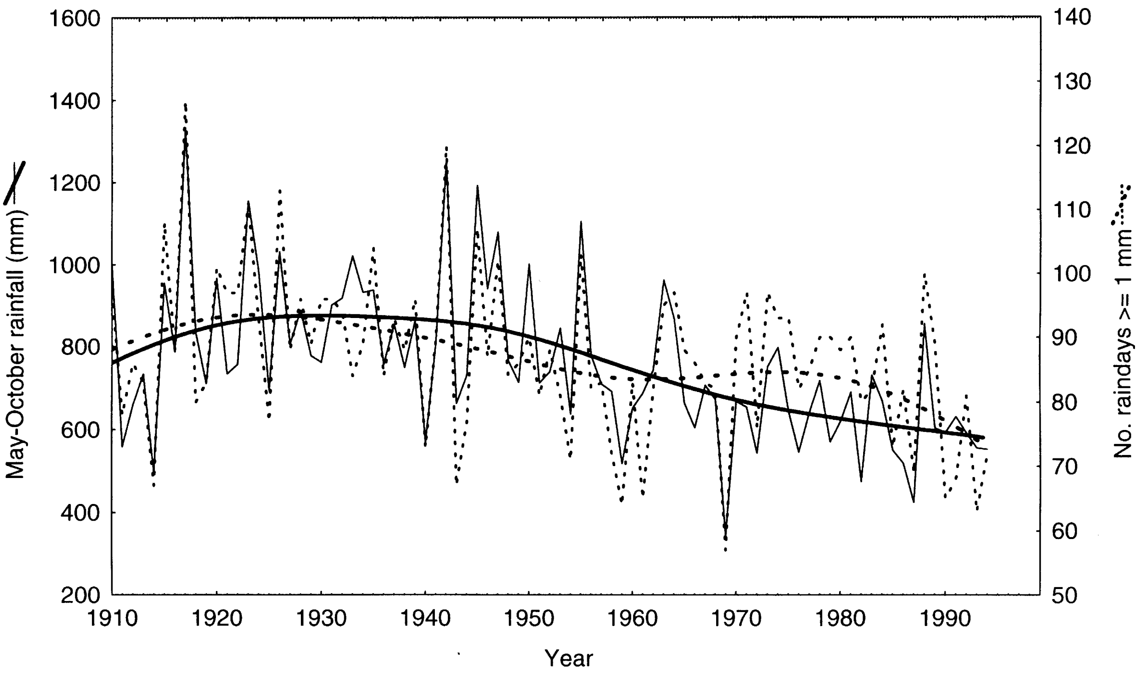


Figure 8 Manjimup May-October rainfall

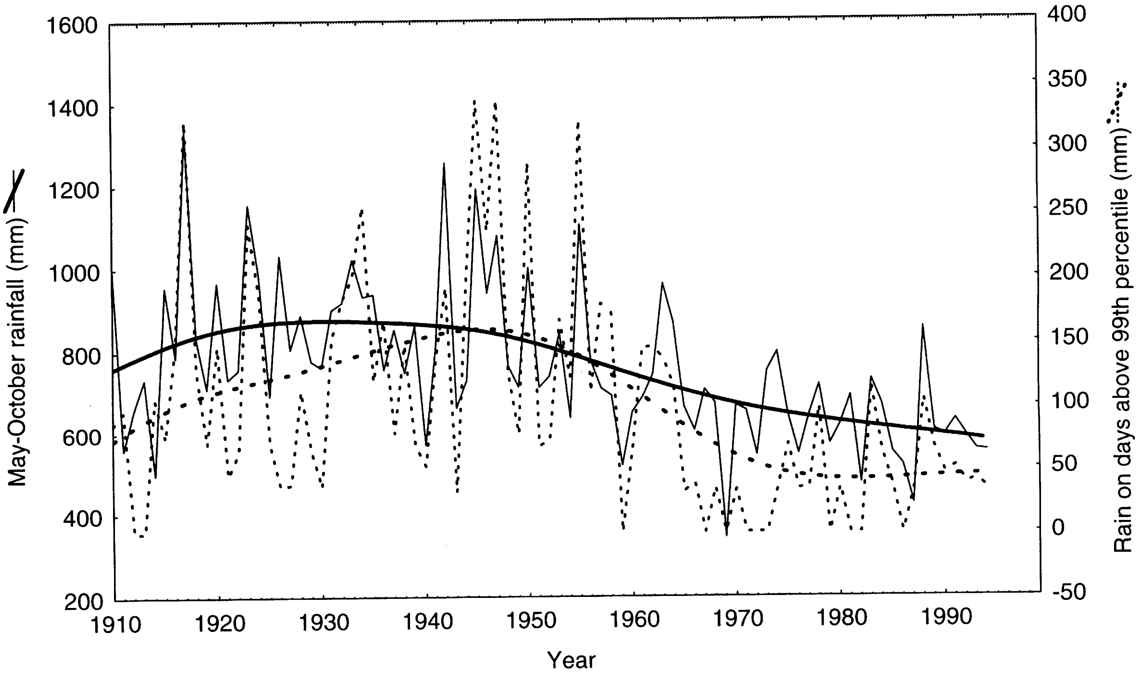


Figure 9 Manjimup May-October rainfall

Figures 8 and 9 do indicate that much of the decline in rainfall in the south-west could be attributable to a decline in the number of days with rain, and a decline in the amount of rain falling in heavy rainfall events. The total rainfall at Manjimup is correlated at 0.80 with the number of rain days, and at 0.75 with the amount of rainfall falling on heavy rain days (both correlations calculated from 85 years of data). Together, the number of rain days and the amount of rain falling on heavy rain days account for 86% of the variance in total May-October rainfall. Figure 10 shows the observed May-October rainfall, and rainfall predicted from a multiple linear regression with the number of rain days and the amount of rain falling on heavy rainfall days as predictors. Most of the short and long term variations in observed rainfall are reproduced by the "predicted" rainfall, indicating that these two simple rain indices account for most of the variations. The "predicted" rainfall is slightly higher than observed during the 1970s and 1980s, but otherwise the fit is excellent.

The fact that the fit between observed and "predicted" in Figure 10 is not quite perfect indicates that other changes are occurring in the frequency distribution of rainfall. Figure 11 shows the frequency distributions of Manjimup daily rainfall in the period 1910-1953 and in the period 1954-1997. Apart from the very low rainfall amounts, all the other categories, from light rain to heavy rain, show a marked decrease in the second half of the record. This analysis indicates that, to explain the decline in rainfall in the south-west, we need to explain why the number of rain events has declined, and why heavy rainfall events have become less heavy.

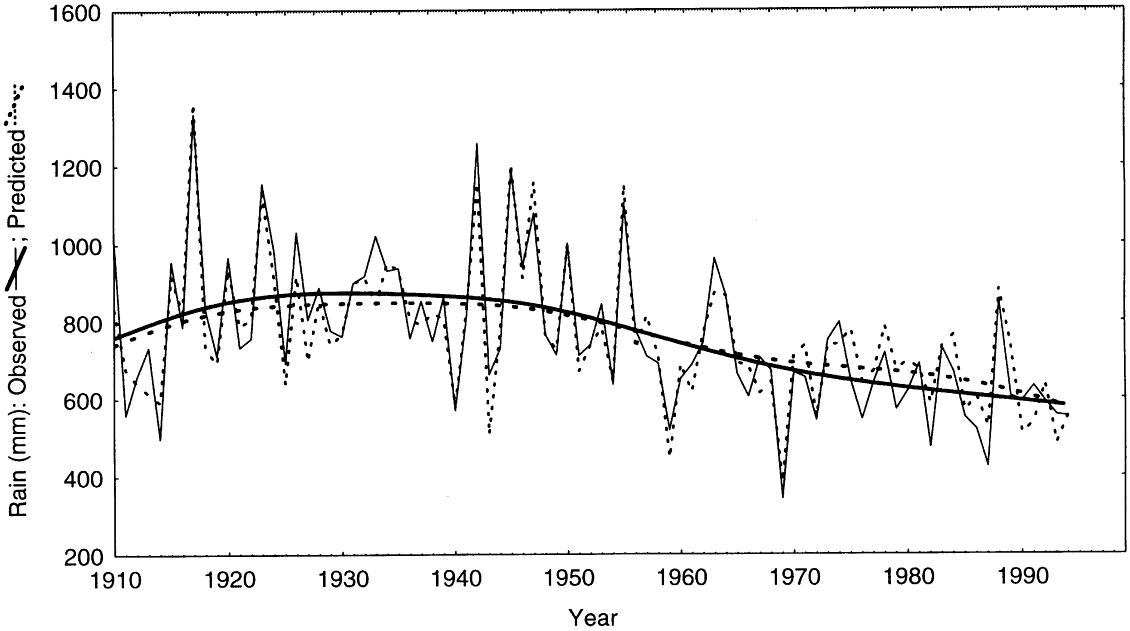


Figure 10 Manjimup May-October rainfall predicted from no. raindays & amount of rain falling on days with heavy rain (99th percentile)

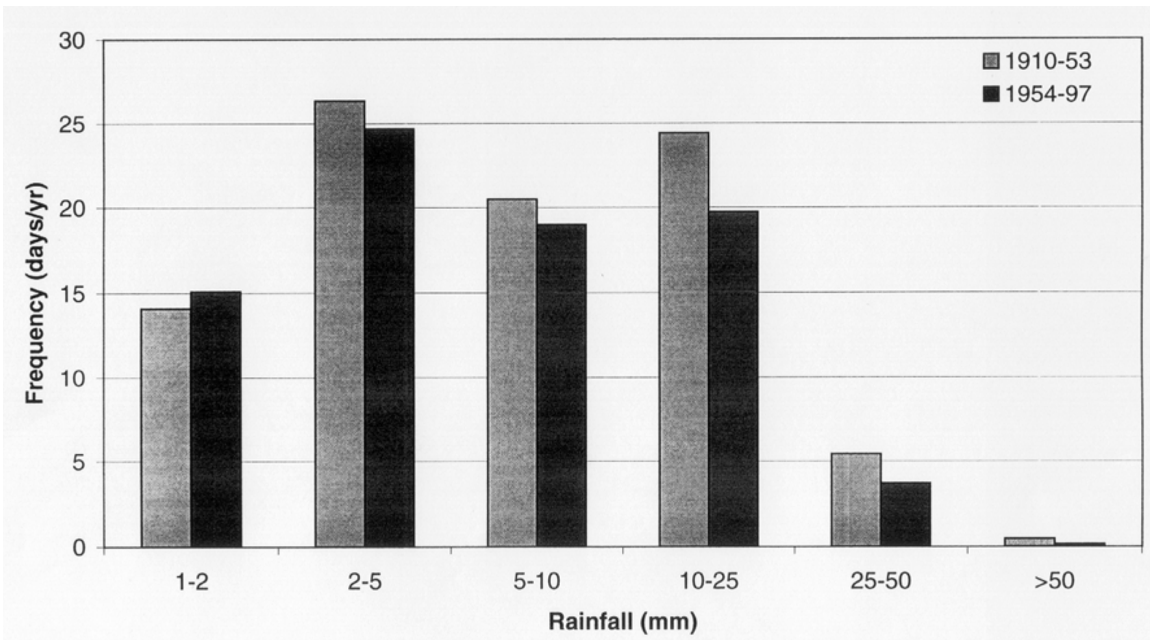


Figure 11 Daily rainfall frequencies, Manjimup May-October

Several new indices have been designed to better represent how extreme rainfalls are changing in SWWA. We use four very high-quality daily rainfall stations to confirm and elaborate on the conclusion that the amount of rain falling in extreme events has contributed to the decline in rainfall. The aim was to use an accurate and consistent data set using a fixed number of stations with minimal artefacts. Therefore, any accumulations of rainfall over more than one day were set to missing and stations were selected only if they had less than 10 days missing for at least 80 years in the 88 year period (1910-1998). A year's record with 10 days missing is equivalent to there being more than a 10% chance of having at least one missing value in the top four events. For a selected station this will occur in less than 10% of the years. Only four stations (Busselton, Albany, Mount Barker, and Manjimup) in the south-west passed these rigorous quality control checks. We believe that averaging the various indices across these stations will provide a guide to the regional long-term variations in extreme rainfalls. We examine annual rainfall in this section, rather than May-October rainfall.

Three indices of extreme rainfall were examined: the average intensity of rain falling in the highest 5% of rain events (calculated using only raindays) and hereafter referred to as the *extreme intensity;* the number of events above the long-term mean 95th percentile (calculated using only raindays), referred to as the *extreme frequency;* and the proportion of total rainfall falling in the highest 5% of raindays, referred to as the *extreme percent*. Raindays are defined as days with at least 1 mm of rain. Thresholds lower than 1 mm can introduce trends in the number of raindays, associated with changes from imperial to metric units in 1974.

The *extreme intensity* describes changes in the upper percentiles and, unlike an analysis of a single percentile in isolation, incorporates changes in all events above this percentile. The threshold for this index is the 95th percentile calculated only from raindays in order to maintain a fixed proportion of days. At a station where the number of raindays changes equally over all intensities, the *extreme intensity* will not change, whereas a percentile calculated from all days will be influenced by the change in the number of raindays.

In calculating the *extreme frequency*, we elected to use a different cutoff for each station. A fixed threshold is impractical for a country like Australia with a high spatial variation in rainfall intensity (the mean 95th percentile for 91 high quality stations varied from 14 to 48 mm/day).

The *extreme percent* reflects changes in the upper portion of the distribution but normalised with regards the entire distribution. The question of whether rainfall distribution is becoming more “extreme” is complicated by changes in the number of raindays. The percentage of the total rainfall from the higher events is an indicator of changes in the shape of the rainfall distribution.

Time series of these three indices for the south-west are shown in Figure 12. Significant decreases are observed for the *extreme intensity* and *extreme frequency*. Decreases in heavy rainfall intensity and frequency in the south-west have been noted by Suppiah and Hennessy (1998), however their measure of intensity did not take into account the strong reduction in the number of raindays. The results of this study show that not only is the number of events above an extreme threshold decreasing, but the average intensity of the top 5% of events *taking into account the reduction in raindays* is also decreasing.

Correlations with total rainfall for the number of raindays and the three extreme indices were calculated. Highly significant correlations for raindays and the *extreme frequency* and *intensity* suggest that years with high rainfall receive rain on more days and with a higher average intensity in the top 5% of events and a larger number of events above an extreme threshold. However, insignificant positive correlations of the *extreme percent* suggest that the proportion of the total rainfall falling in the top 5% of events is largely independent of the total rainfall.

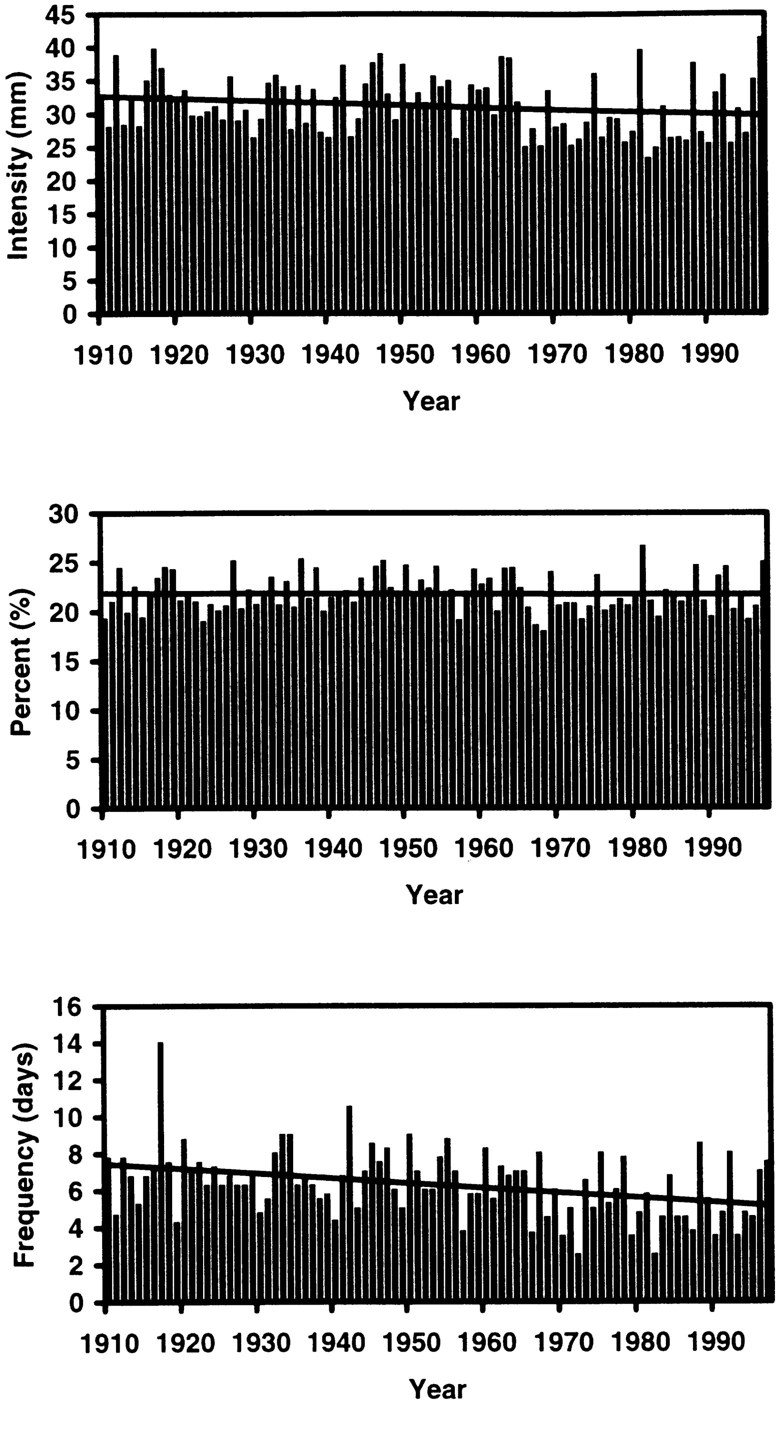


Figure 12 Time series of extreme rainfall indices for the southwest of Western Australia annual rainfall

5. IS THE RAINFALL DECREASE DUE TO CHANGES IN ATMOSPHERIC CIRCULATION?

Allan and Haylock (1993) noted that rainfall in the south-west was strongly correlated with mean sea level pressure (MSLP) over the continent and over the ocean to the west and south. They noted that Perth MSLP and south-west June-August rainfall was correlated at –0.80. They suggested that changes in frontal activity would be involved in this relationship, and that long-term rainfall variations may be reflecting long-term modulations of mid-latitude frontal activity. Support for this hypothesis was provided by Ansell *et al*. (1999) and Smith *et al*. (1999). The latter paper demonstrates that the number of mid-latitude depressions just to the south of south-west Western Australia has declined in recent decades (see also Plummer *et al*., 1999).

Figure 13a shows Manjimup May-October rainfall with Perth MSL pressure (scale reversed). The close, although not perfect, relationship between the two variables is clear. The relationship is even clearer in Figure 13b which is a scatter diagram showing the changes from year-to-year in the two variables. Calculating year-to-year changes ("first differences") is used to remove the influence of the longer-term variations, and to focus on short term (inter-annual behaviour). The correlation between the first differences of the two variables is –0.75 (n=84); when MSLP at Perth increases, south-west rainfall decreases. The regression line in Figure 13b can be used to estimate how much rainfall is likely to decline with a certain increase in pressure. MSLP increased about 1 hPa between about 1950 and about 1990 (Figure 13a). The regression (Figure 13b) indicates this would likely produce a decrease in Manjimup rainfall of about 100 mm. This is about half the decrease in rainfall observed at Manjimup.

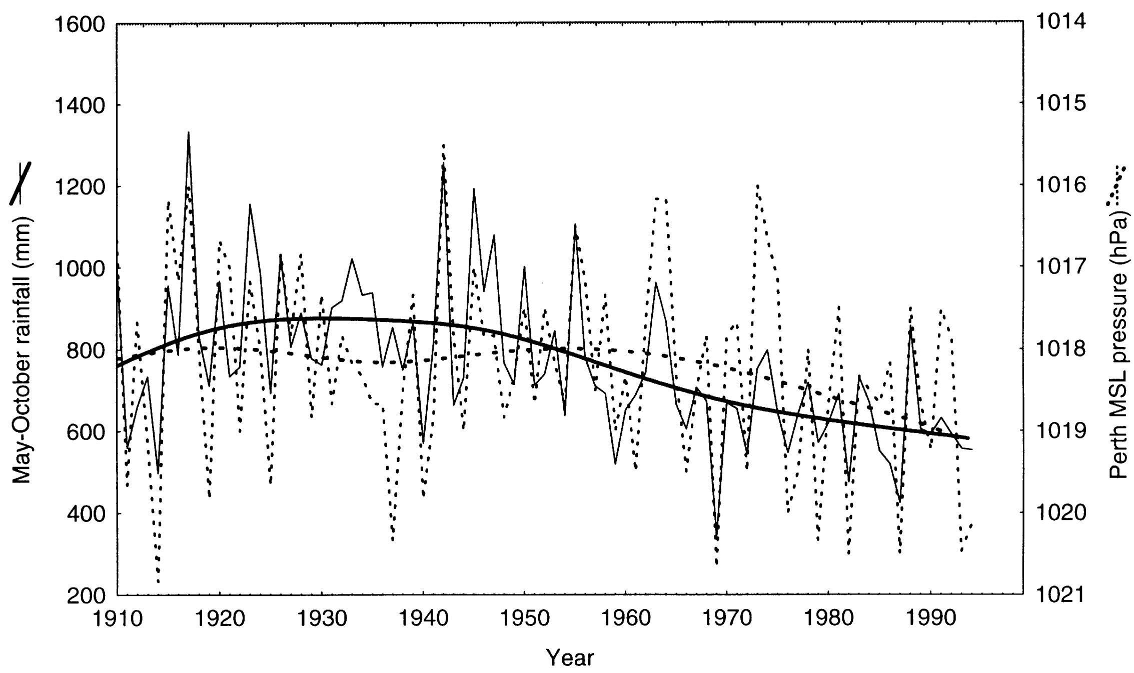


Figure 13a Manjimup May-October rainfall

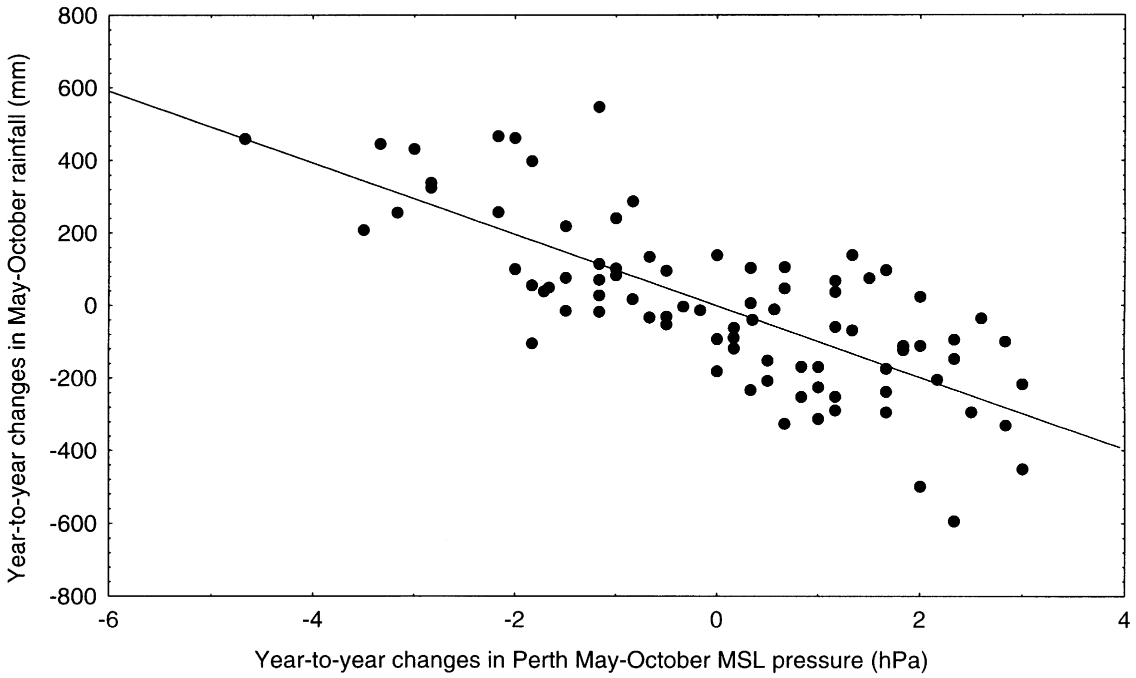


Figure 13b Manjimup May-October rainfall

About 50% of the decline in rainfall could NOT be attributed to the increase in atmospheric pressure (and thus the change in atmospheric circulation). Part of this unexplained decrease represents a change in the relationship between atmospheric pressure and rainfall. Figure 14 shows a scatter diagram of Manjimup rainfall against Perth MSLP, for two sets of years: those before 1955 and those from 1955 to present. The earlier years generally received greater rainfall for any value of Perth MSLP than was the case in the latter part of the century. The difference in the relationships in the two sets of years is sufficient to account for the "unexplained" 50% of the decrease in rainfall since mid-century. Clearly, a secular change in the relationship between the atmospheric circulation and rainfall in the south-west occurred sometime during the 1950s.

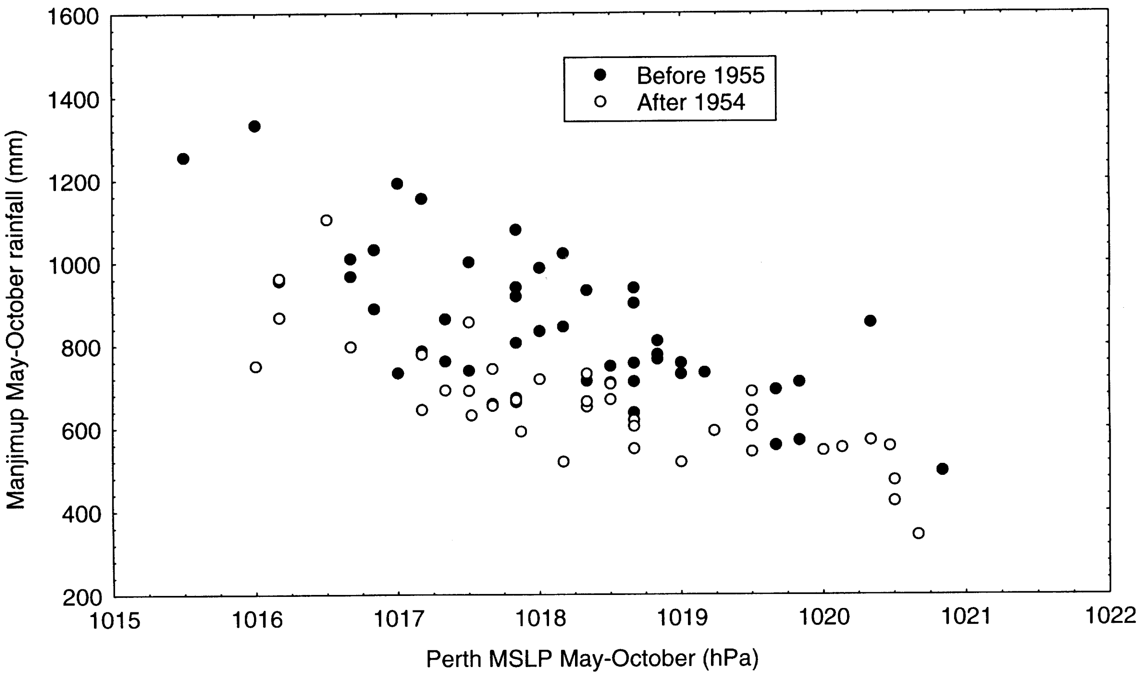


Figure 14 Manjimup May-October rainfall

The possible cause of this apparent secular change in circulation and rainfall relationship will be addressed later in this report. For the moment we focus on finding an explanation of the change in pressure at Perth, since this can account for about half the decrease in rainfall in the south-west. Figure 15 shows time series of Perth MSLP and the SOI for May-October. The close relationship between the two variables is obvious ($r = -0.51$, $n = 85$). The relationship between the year-to-year changes in the variables (Figure 16) is even closer ($r = -0.64$), indicating that long-term variations are reducing the correlation on interannual time-scales. This is shown in Figure 15 by the fact that prior to the mid-1970s, the smoothed graphs of the two time-series are offset, whereas in recent decades the two smooth graph are not offset. The recent increase in Perth pressure has been larger than would be expected if Perth MSL pressure was *only* caused by variations in the SOI. This is also shown in Figure 17, which shows the observed MSLP at Perth, plus Perth MSLP "predicted" from observed values of the SOI and the linear relationship between the two variables. Again, the SOI "under predicts" the increase in pressure since about 1970.

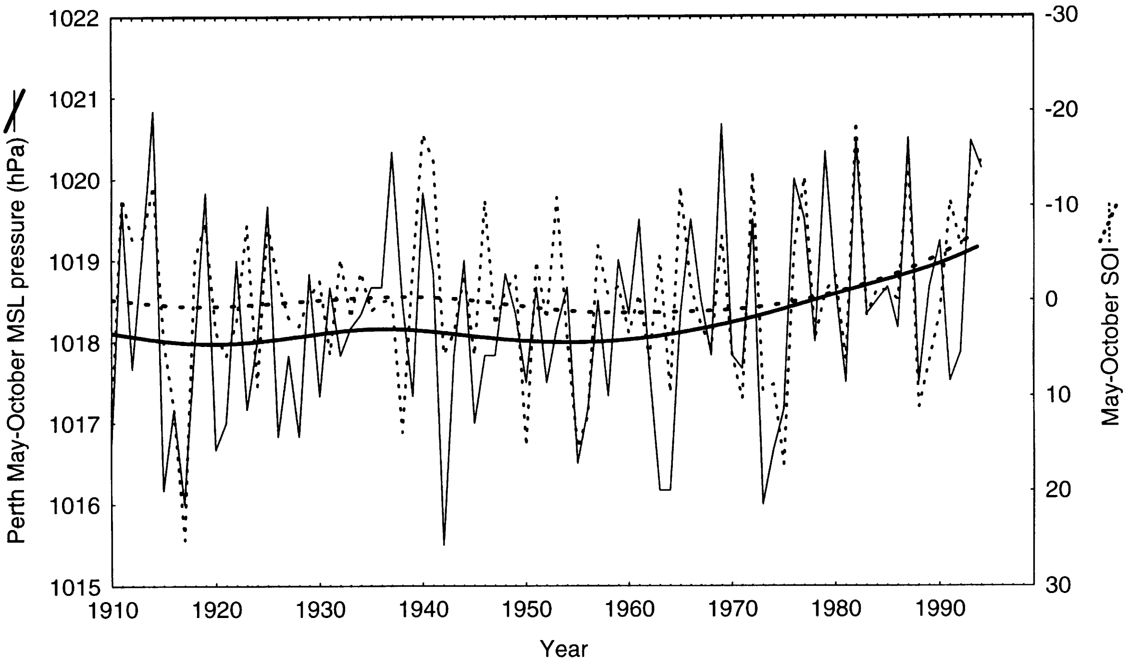


Figure 15 Perth May-October MSL pressure

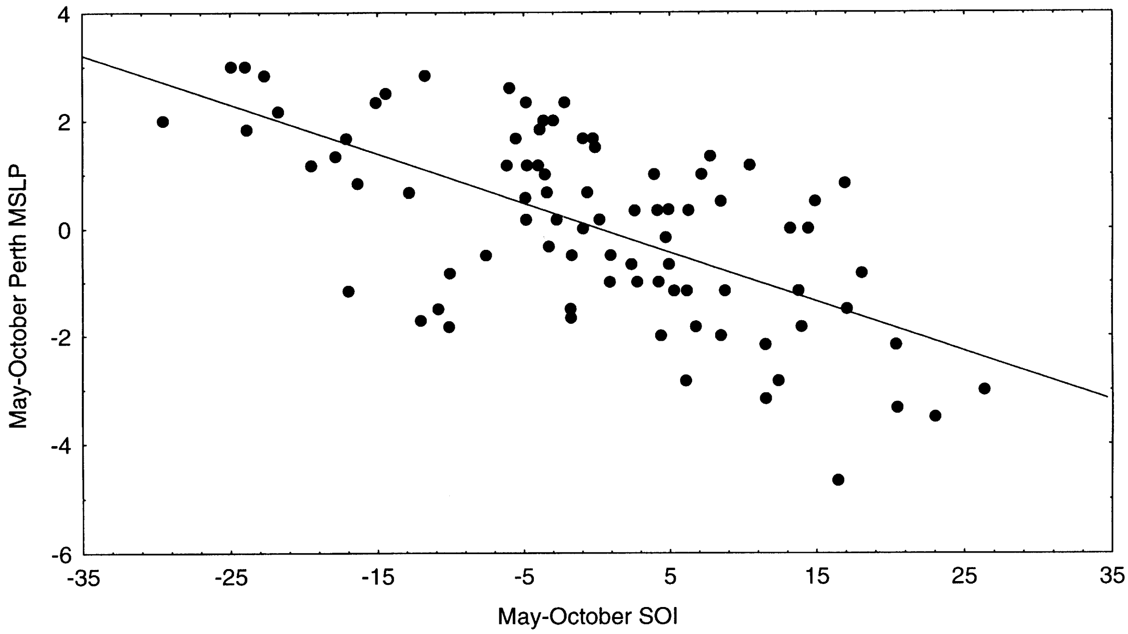


Figure 16 Perth May-October MSL pressure Year-to-year changes

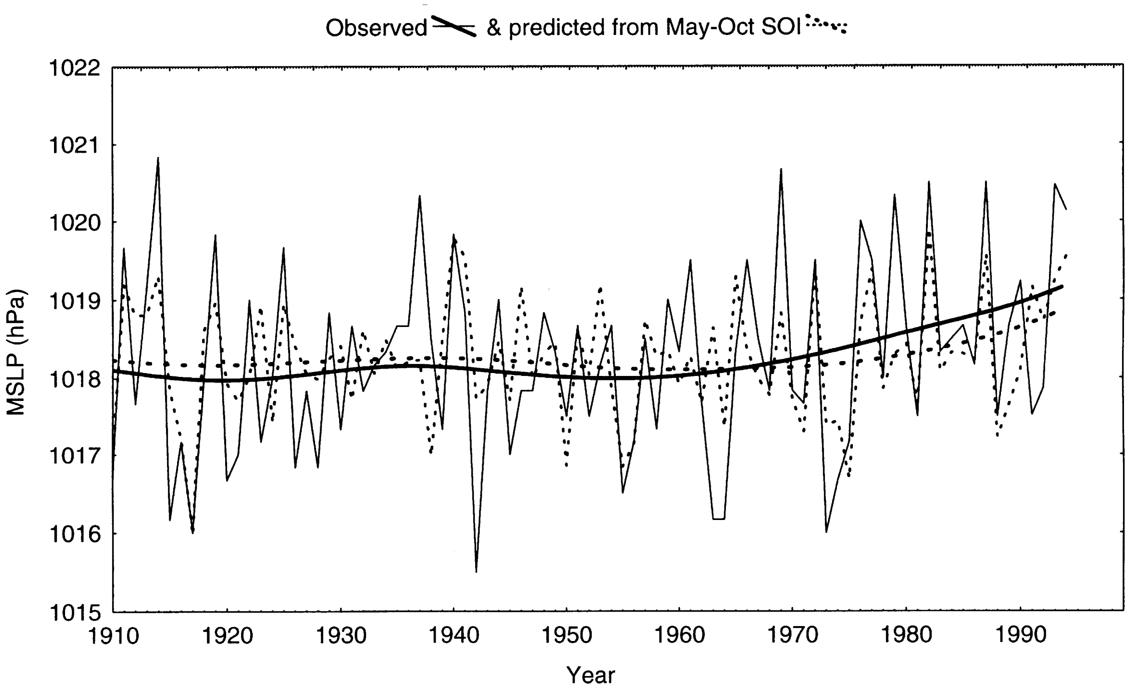


Figure 17 Perth May-October MSLP

Despite this recent "under prediction", the change in the SOI does account for some of the increase in Perth MSL pressure. Thus, since Perth pressure changes account for some of the decrease in south-west rainfall it is of interest to see whether the relationship between the SOI and south-west rainfall can account for some of the decrease in rainfall. Figure 18 shows that the interannual variations of Manjimup rainfall and the SOI are closely related, but the longer term variations are largely separate – thus the SOI long-term trend only falls towards the end of the period. If changes in the SOI were to explain the long term variations in rainfall, the SOI smoothed graph would parallel the smoothed rainfall graph. The inter-annual variations are closely related (Figure 19; $r = 0.55$, $n=85$). Figure 20a shows the observed Manjimup rainfall, plus rainfall "predicted" from the observed SOI. Although the interannual variations are well-predicted, the long-term decline in rainfall is not predicted. The "predicted" rainfall curve shows only a small decline and this decline starts much later than the observed decline. Clearly, much of the decline in rainfall is NOT due to the observed long-term changes in the SOI.

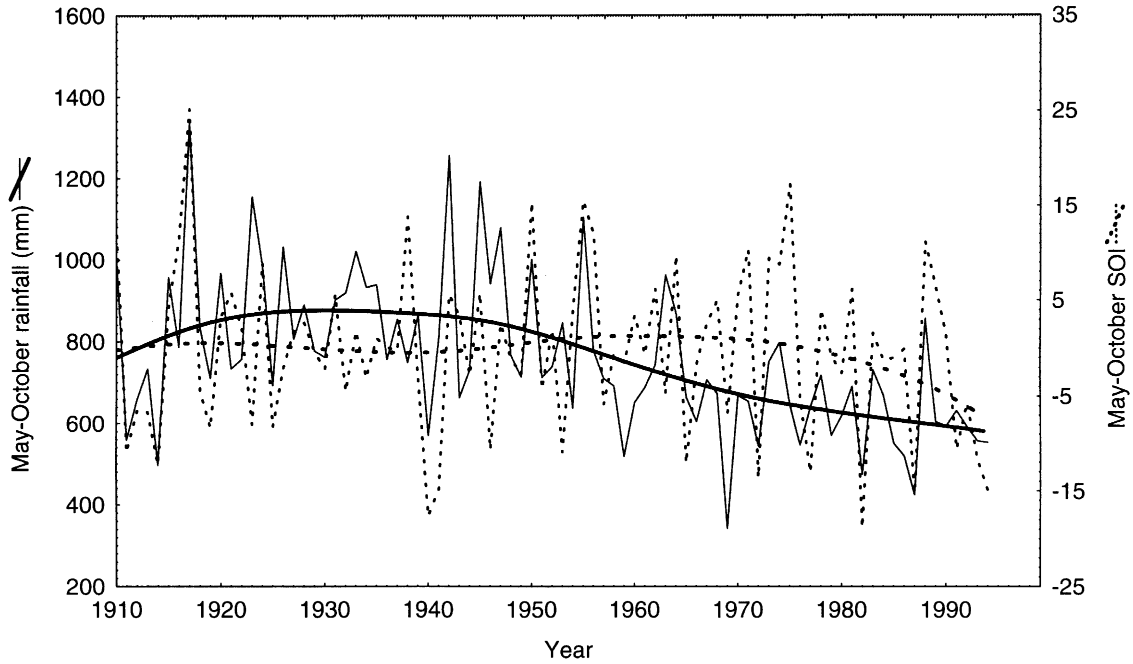


Figure 18 Manjimup May-October rainfall

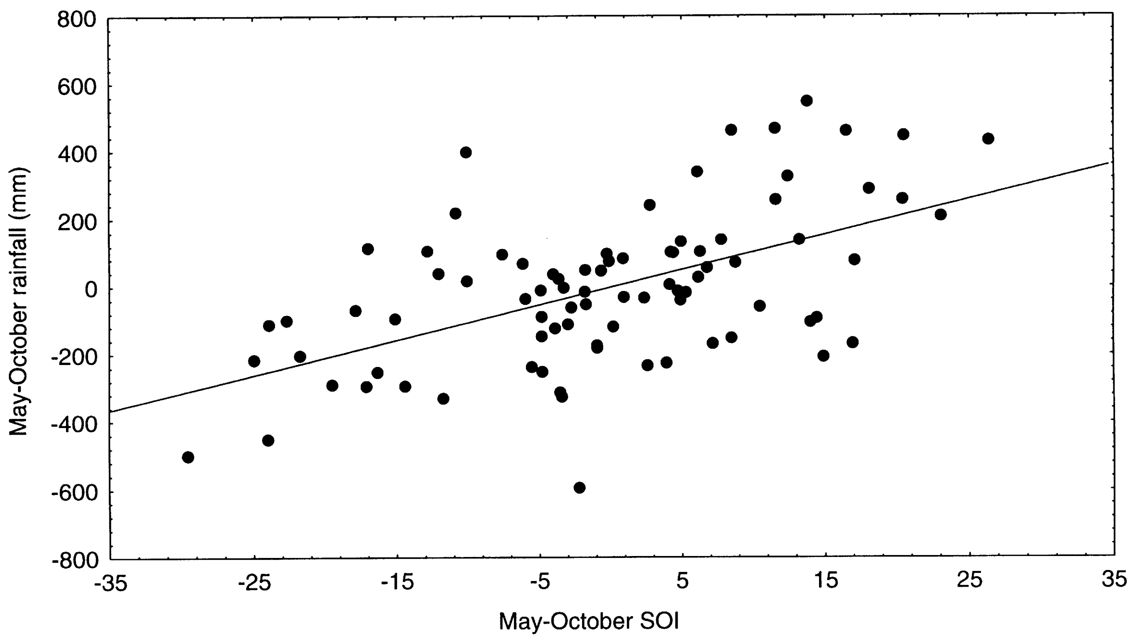


Figure 19 Manjimup May-October rainfall Year-to-year changes

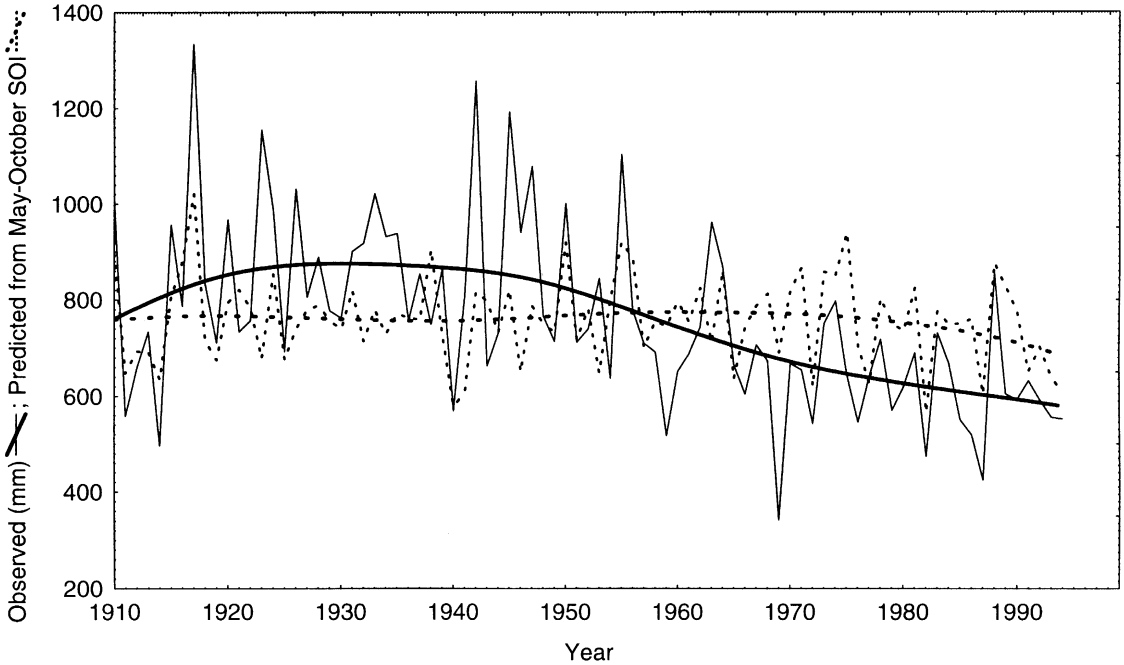


Figure 20a Manjimup May-October rainfall

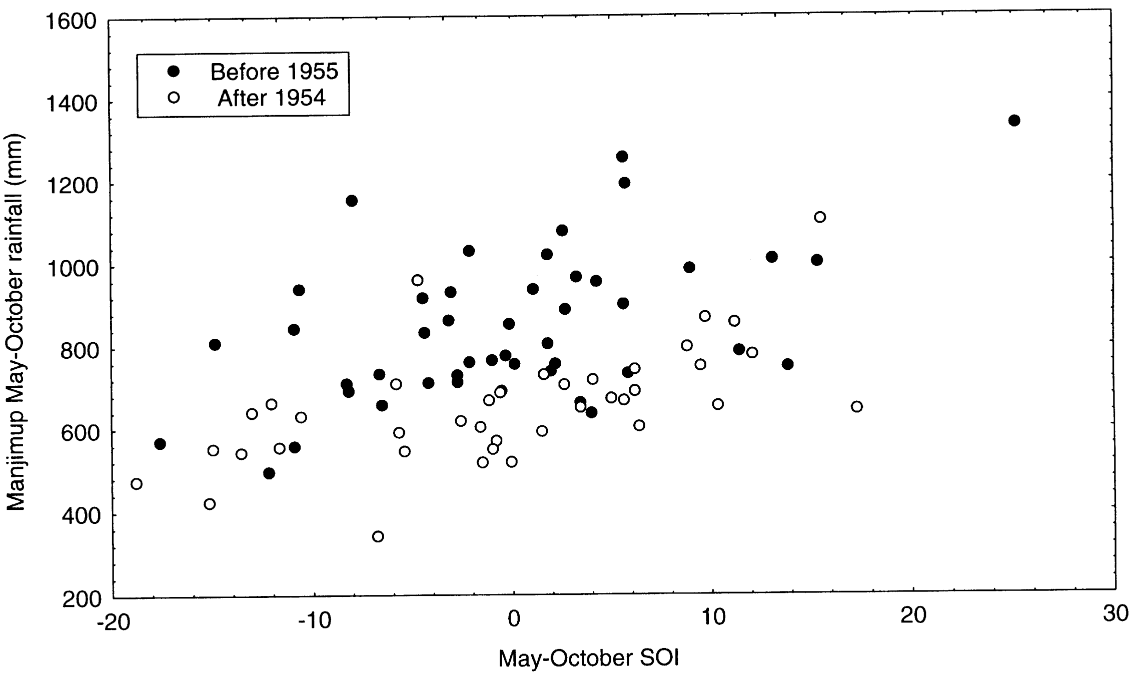


Figure 20b Manjimup May-October rainfall

This means there has been a secular change in the relationship between the SOI and south-west rainfall. This change is illustrated in Figure 20b, which shows a scatter diagram of May-October Manjimup rainfall versus the SOI, with the data separated into two sets, prior to and after the mid-1950s (analogous to Figure 14). Before the mid-1950s, rainfall at Manjimup was greater, for a particular value of the SOI, than was the case after the mid-1950s. In the two subsets (before and after the mid-1950s) the relationship between the SOI and rainfall is quite strong, but the relationship after the mid-1950s is clearly offset, relative to the earlier relationship. Nicholls *et al*. (1996, 1997) showed that secular changes had occurred in the relationships between Australian climate variables and the El Niño - Southern Oscillation, although the changes appeared to have taken place in the early 1970s, rather than the mid-1950s. Nicholls (1992) showed that a secular change in the relationship between the SOI and Australian region tropical cyclone activity had occurred in the mid-1980s, although Nicholls *et al*. (1998) showed that this change appeared to be artificial, resulting from changes in the way weak tropical cyclones are analysed. Nicholls (1992) pointed out that, whatever the cause of the change in the relationship, better predictions were obtainable by relating changes in the SOI from year-to-year to changes in tropical cyclone numbers. This approach can cope with such secular changes in relationship as are observed between the SOI and south-west rainfall. We return to this point later.

6. IS THE RAINFALL DECREASE ATTRIBUTABLE TO CHANGES IN INDIAN OCEAN SSTS?

If changes in the SOI (and thus the El Niño - Southern Oscillation) cannot be blamed for (much of) the decreased rainfall in the south-west in recent decades, perhaps changes in Indian Ocean SSTs are to blame? Nicholls (1989) demonstrated that winter rainfall over central and south-east Australia was related to a pattern of variation in Indian Ocean SSTs. Ansell *et al*. (1999) and Smith *et al*. (1999) suggest that Indian Ocean SST patterns are related to rainfall in the south-west. It therefore seems reasonable to investigate the nature of this relationship, to determine whether Indian Ocean SSTs could be related to the decline in rainfall.

Figure 21 shows the spatial patterns of the first two principal components (PCs) of Indian Ocean SSTs for the period May-October. PC1 essentially represents an in-phase variation in SST across the basin; PC2 has a dipole pattern, with variations at middle and low latitudes tending to occur out of phase. Figure 21 also shows time-series of the two PCs. Both PCs exhibit long-term variations, with PC1 exhibiting a secular trend over the period in which rainfall has declined. The correlation of PC1 and Manjimup rainfall is –0.46 (n = 43). This suggests that the decline in rainfall may be related to the observed long-term increase in Indian Ocean SSTs.

If this was correct, one may expect that interannual variations in PC1 were also related to interannual variations in south-west rainfall. However, the correlation between first differences of PC1 and Manjimup rainfall is only –0.20 and is not statistically significant. Thus much of the apparent relationship between rainfall and PC1 simply reflects the long-term changes in both variables. This could easily be just a coincidence, since the degrees of freedom in the long-term trends are so few. If the coincidence of the long-term trends does represent a physical mechanism, it is not obvious how this could operate at decadal time-scales when clearly the rainfall and PC1 are only very weakly related at interannual time-scales.

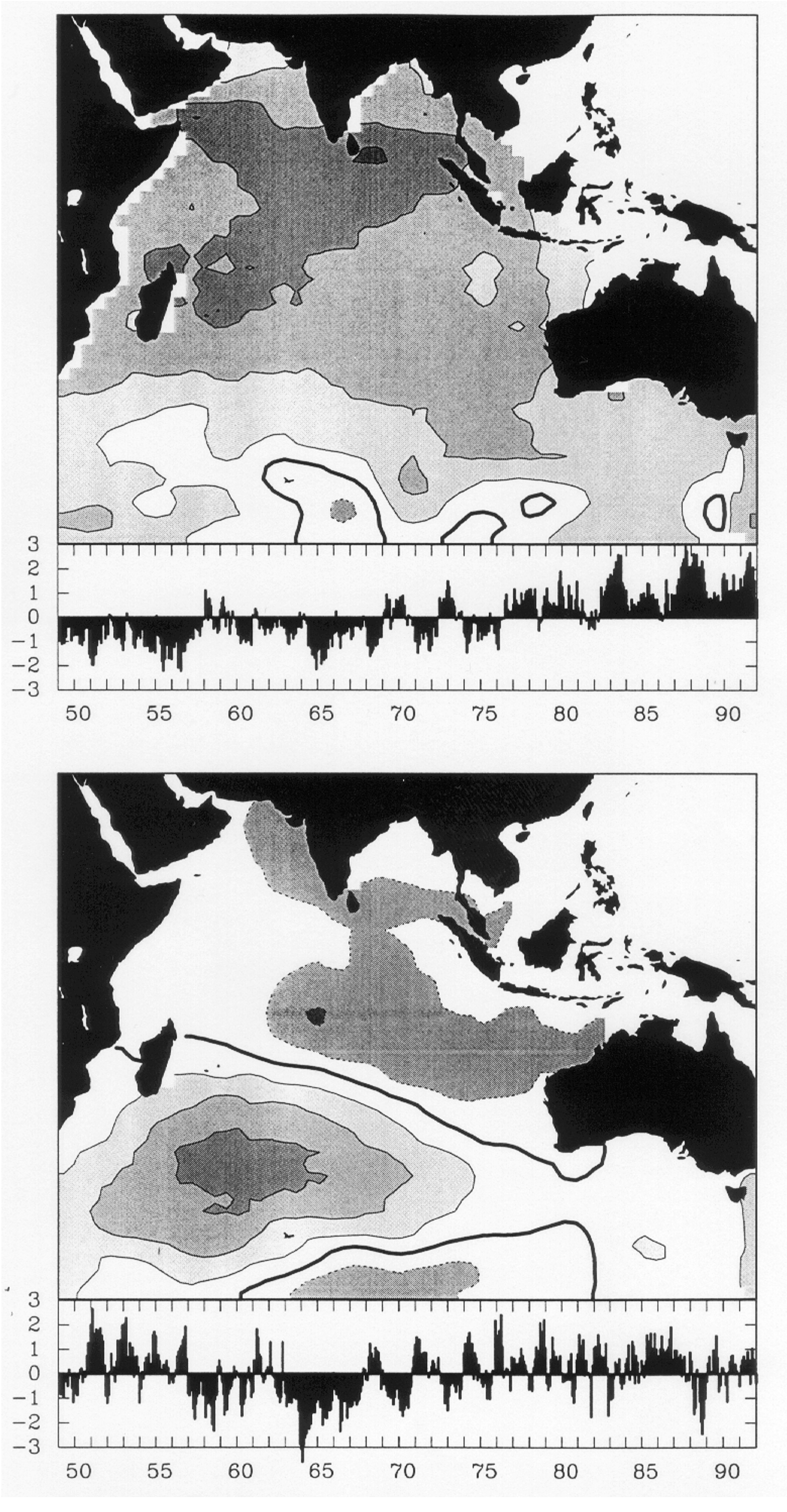


Figure 21 The first two principal components of Indian Ocean SST

The second PC of Indian Ocean SST (PC2) is only weakly related to Manjimup rainfall ($r = -0.11$). It is slightly more strongly, but still not significantly, correlated with rainfall when first differences of both variables are correlated ($r = -0.19$).

Figure 22 shows the correlation between Manjimup June-August rainfall and June-August SSTs, to further explore the spatial nature of the relationship, and to check whether the effects noted with May-October rainfall also apply to the "traditional" winter period. The top panel shows the correlations using the unfiltered data. Manjimup rainfall is correlated with an El Niño–like pattern in the Pacific, but is also correlated with Indian Ocean SSTs. The bottom three panels use different methods to remove the long-term trend. The second panel de-trends using a linear trend, the third panel shows the results of calculating first differences of the SSTs and rainfall, and the bottom panel shows the correlations calculated on residuals from a ten-year moving average. The results are similar, whatever method of de-trending is used: the correlations with the Pacific El Niño–like pattern remain, while the correlations with Indian Ocean SSTs are reduced, although the correlation with SSTs in the southern-most part of the ocean remains. This reduction in the strength of the correlation tends to support the earlier result calculated on PC1 and PC2, namely that interannual variations in rainfall and Indian Ocean SSTs are not strongly correlated.

Although most of the correlation between Indian Ocean SSTs and Manjimup rainfall arises from decadal time-scales, there is still a weak relationship at interannual time-scales. We have explored the source of this relationship further, using path analysis. Path analysis allows us to investigate the underlying correlation structure in situations where there are several inter-related predictor variables all correlated with one or more predictand or response variables. This technique appears not to have been used in the study of relationships between SSTs and climate variables. It is used here to decompose the correlation between Indian Ocean SSTs and south-west rainfall into the contribution arising from the unique effect of Indian Ocean SSTs on rainfall, and the contribution arising from the common relationship of Pacific Ocean and Indian Ocean SSTs with rainfall (through the El Niño - Southern Oscillation). The SOI is used as a measure of the El Niño - Southern Oscillation.

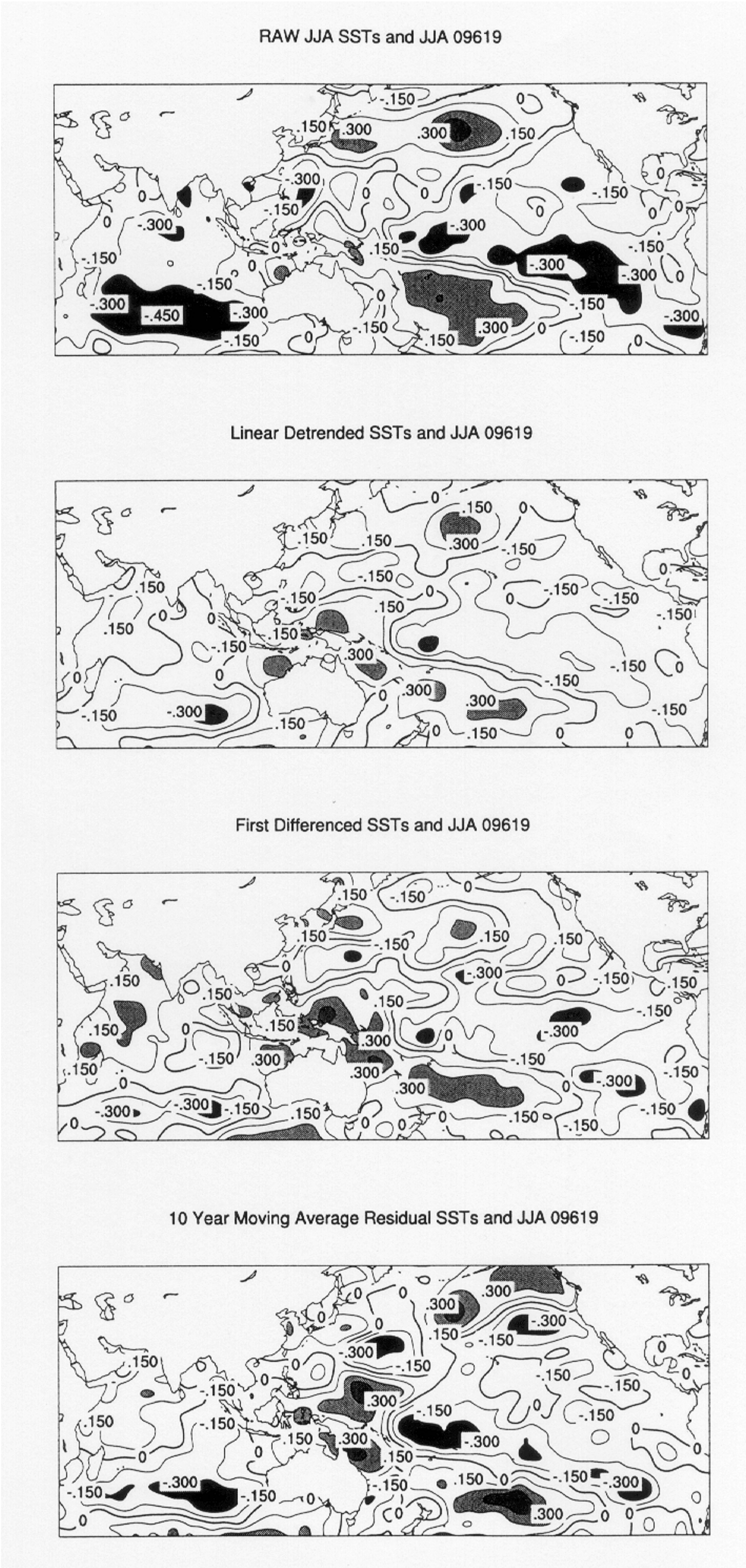


Figure 22 Correlation between Manjimup June-August rainfall and SSTs

A path diagram for this analysis is shown in Figure 23. The diagram indicates, with double-headed arrows, that PC1, PC2, and the SOI are inter-related, with the correlations between first differences of these variables indicated. It is postulated and shown in the path diagram, that all three of these variables may affect Manjimup rainfall. All three are correlated with Manjimup rainfall, as is also indicated in the diagram. Also shown in the diagram are β values or path coefficients. These are the standardised (mean zero, standard deviation one) regression coefficients in a multiple regression with all three independent variables. With these values, the correlations between each of the independent variables (PC1, PC2, SOI) and Manjimup rainfall can be decomposed into unique and common effects, as shown in Figure 23.

$$\Delta SOI, \Delta RAIN \quad r = 0.56 = \underbrace{0.56}_{\text{direct}} + \underbrace{\overbrace{(-.48 \times .01)}^{0}}_{\text{common } \Delta PC1} + \underbrace{\overbrace{(-.07 \times -.14)}^{-.01}}_{\text{common } \Delta PC2}$$

$$\Delta PC1, \Delta RAIN \quad r = -.20 = \underbrace{.01}_{\text{direct}} + \underbrace{\overbrace{(-.40 \times -.14)}^{0.06}}_{\text{common } \Delta PC2} + \underbrace{\overbrace{(-.48 \times .56)}^{-.27}}_{\text{common } \Delta SOI}$$

$$\Delta PC2, \Delta RAIN \quad r = -.19 = \underbrace{-.14}_{\text{direct}} + \underbrace{\overbrace{(-.40 \times .01)}^{0}}_{\text{common } \Delta PC1} + \underbrace{\overbrace{(-.07 \times .56)}^{-.04}}_{\text{common } \Delta SOI}$$

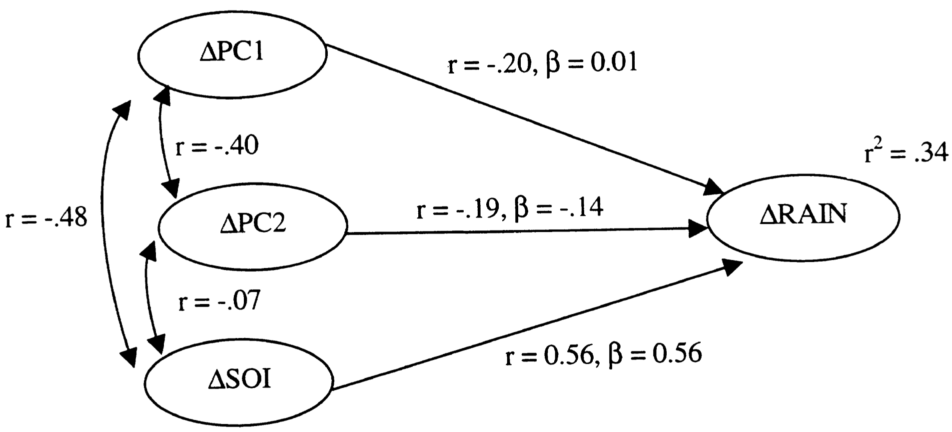


Figure 23 Decomposed correlations (top) and path diagram for the relationships between Indian Ocean principal components of SST (PC1 and PC2), the SOI, and Manjimup rainfall (RAIN). All variables expressed as first differences.

The correlation (r = -20) between year-to-year changes in PC1 and Manjimup rainfall is due to the common effect with the SOI. That is, the correlation arises because PC1 is correlated with the SOI (r = -0.48) which in turn is correlated with rainfall (r = 0.56). In the equation decomposing the correlation between PC1 and rainfall, this common effect is calculated in the standard way, by multiplying the correlation between the SOI and PC1 (-0.48) and the standardised regression coefficient between the SOI and rain (0.56). There is essentially NO direct, unique effect of year-to-year changes in PC1 on year-to-year changes in rainfall separate from the effect in common with the SOI (β = 0.01). PC2 has a very weak and non-significant direct (unique) effect, whereas the SOI has a strong and statistically significant unique effect (β = 0.56).

In summary, the second principal component of Indian Ocean SST (PC2) is NOT significantly related to Manjimup rainfall (and thus almost certainly rainfall generally through the south-west) during May-October. The first principal component of Indian Ocean SST (PC1) IS significantly correlated, but this relationship is mainly due to long term trends in both time-series. The changes from year-to-year in the two variables are only weakly related and this weak relationship simply reflects the fact that both variables are influenced by the El Niño - Southern Oscillation. There thus appears to be no independent effect of Indian Ocean SST PC1 on south-west rainfall at interannual time-scales.

7. CAN WE DEVELOP BETTER METHODS FOR SEASONAL PREDICTION IN THE SOUTH-WEST?

As was noted above, Nicholls (1992) suggested that in a situation where secular changes had tended to weaken correlations potentially useful for seasonal prediction, use of the relationships between interannual changes in the variables can lead to more robust forecast methods. Tapp (1997) has demonstrated that examining the SOI in the current winter and the previous winter, can provide some information regarding winter rainfall, implying that changes in the SOI from one year to the next may provide some skill in winter rainfall prediction for the south-west. For example, the linear regression between year-to-year changes in the May-October SOI and Manjimup rainfall (with the intercept set to zero) is:

Change in rainfall = 10.4 Change in the SOI

If the change in the SOI from last year to this year was predictable (perhaps with a coupled ocean-atmosphere model), this equation could be used to predict the change in Manjimup rainfall expected to accompany this change in the SOI. Then, since last year's Manjimup rainfall is known, we could use this approach to predict this year's Manjimup rainfall.

The May-October rainfall can, however, be predicted quite early in the winter, using this approach and observed values of the change in the SOI. Thus, the change in the May-October rainfall at Manjimup from year-to-year is plotted in Figure 24 against the change in the June SOI from year-to-year. The correlation is 0.51 (n =84), and the regression is:

Change in May-October rainfall (mm) = 7.8 Change in June SOI

So, at the end of June, the total May-October rainfall can be predicted with considerable skill. This indicates that rainfall over part of this period (e.g. late winter or early spring) may be predictable, in advance, simply by adopting the strategy of relating changes in the SOI to changes in rainfall. Further work is needed to confirm this.

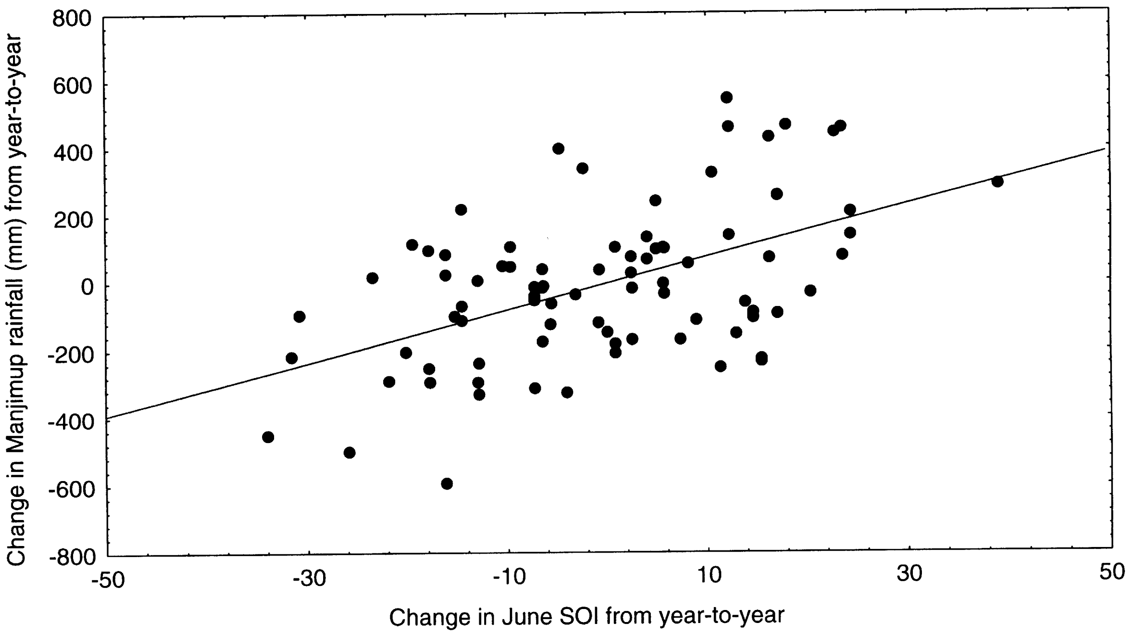


Figure 24 Manjimup May-October rainfall and June SOI Year-to-year changes

8. HOW DOES THE EL NIÑO - SOUTHERN OSCILLATION AFFECT SOUTH-WEST RAINFALL?

The discussion above demonstrates that the SOI does have a substantial influence on south-west rainfall, although this influence is confounded by a secular change in the relationship between the SOI and rainfall. Since it was shown earlier that regional atmospheric circulation changes, as measured by MSLP at Perth, were closely related to south-west rainfall, it is of interest to examine the mechanism by which the El Niño - Southern Oscillation (measured by the SOI) influences south-west rainfall. Does this occur just through influencing Perth MSLP which in turn influences rainfall, or does the SOI have a separate effect distinct from its influence via the regional circulation changes measured by Perth MSLP?

Figure 25 shows the path diagram for the relationships between Perth MSLP, the SOI, and Manjimup rainfall. The SOI is significantly correlated with rainfall, but the direct, unique effect is weak and not significant. Most of the SOI-rainfall correlation is due to the common effect due to Perth MSLP and Manjimup rainfall being correlated with the SOI. Thus, the SOI essentially affects rainfall, on interannual time-scales, through changing the atmospheric circulation (as measured by Perth MSLP).

$$\Delta\text{SOI}, \Delta\text{RAIN} \quad r = 0.55 = \underbrace{0.12}_{\text{direct}} + \overbrace{\underbrace{(-.64 \times -.67)}_{\substack{\text{indirect} \\ \Delta\text{MSLP}}}}^{0.43}$$

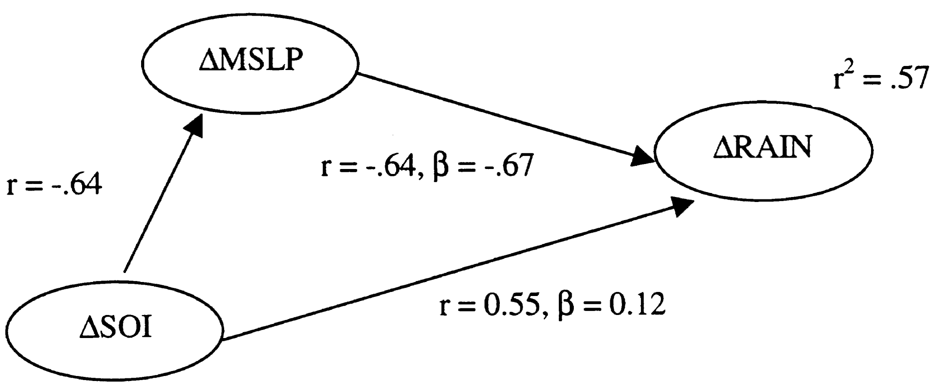


Figure 25 Decomposed correlations (top) and path diagram (bottom) for the relationships between SOI, Perth MSLP (MSLP) and Manjimup rainfall (RAIN). All variables expressed as first differences.

9. CAN CLIMATE MODELS HELP US IN SEASONAL PREDICTION IN THE SOUTH-WEST?

Figure 26 shows time-series of observed rainfall averaged over the south-west and rainfall simulated by the BMRC climate model forced by observed SSTs. The model resolution was 9 levels, and R31, and the results are from an ensemble of six model simulations, each started with slightly different initial conditions. Rainfall series are shown separately for the periods May-October and November-April. The model exhibits little skill in reproducing the observed rainfall. In particular, it fails to reproduce the observed decline in May-October rainfall. The model, in fact, produces an increasing rainfall trend, instead of the decline observed. The inability of the model to reproduce the observed trend in rainfall supports the argument that this trend is NOT due to changes in SSTs.

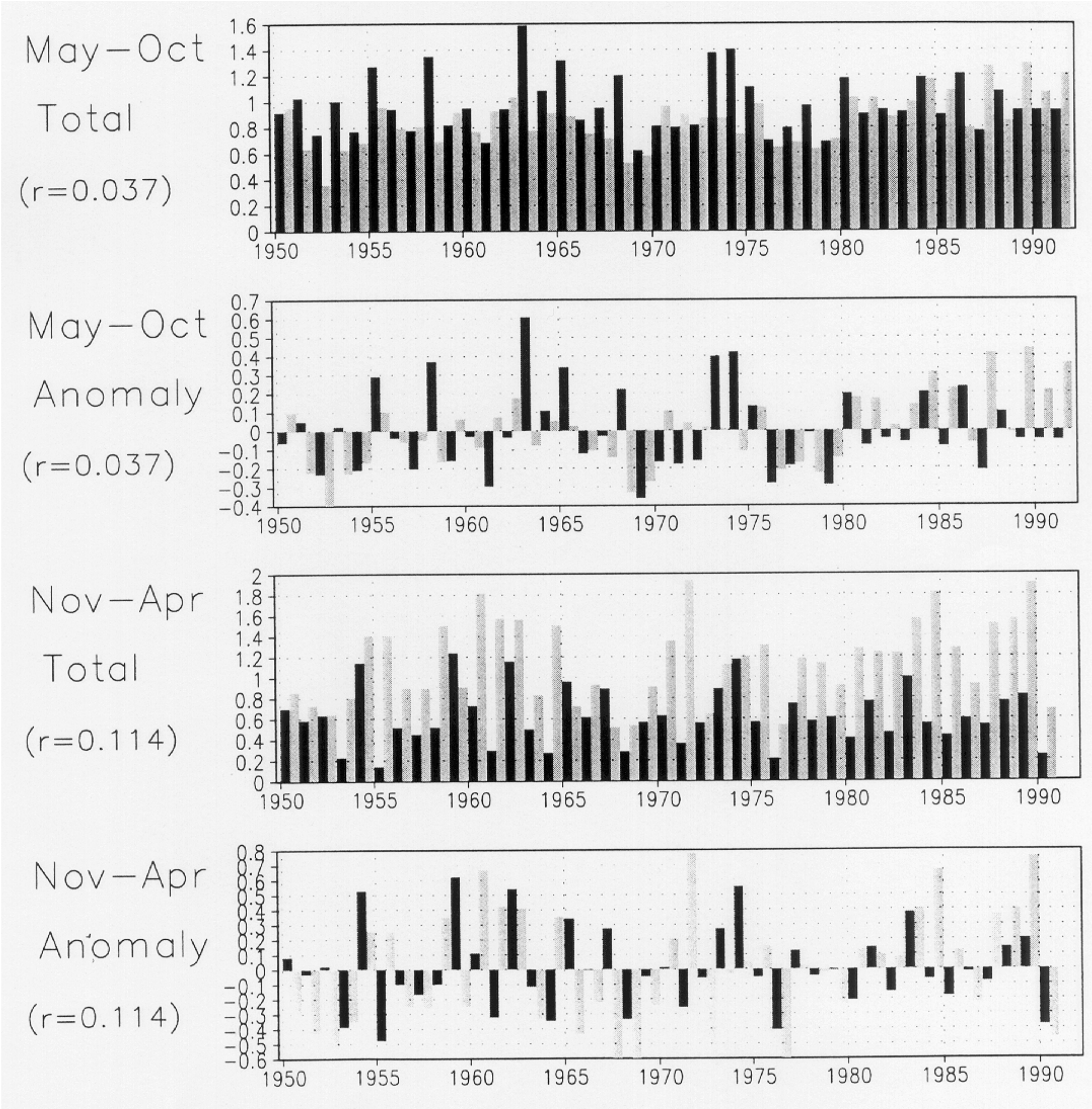


Figure 26 Interannual variations SW WA Rainfall
Observed vs Modelled (mm/day)

10. CONCLUSIONS AND FURTHER WORK

- We have selected stations with high-quality daily/monthly rainfall, and daily temperature data over a long period, for analysis. These data sets can be made available to others interested in using high-quality climate data for the south-west.

- We have fitted statistical models to station rainfall and estimated the likely frequency of the observed runs of dry years in recent decades. They are unusual. We also have estimated breakpoints in the rainfall data series, where there is a sudden change in mean rainfall. The dates of these breakpoints show considerable spatial consistency.

- Changes in the numbers of days of rain, and the amount of rain falling in extreme events, have contributed to the trends in total rainfall.

- About half of the observed decline in rainfall is related to changes in regional atmospheric circulation, as represented by Perth atmospheric pressure. Part of the observed increase in Perth pressure represents changes in the El Niño - Southern Oscillation, as measured by the SOI. However, little of the observed rainfall decline is attributable to long-term changes in the El Niño - Southern Oscillation.

- Interannual variations in Indian Ocean SSTs appear to be only weakly related to south-west rainfall, and even this weak relationship seems to mainly represent the effect of the El Niño - Southern Oscillation on both Indian Ocean SSTs and south-west rainfall, rather than an independent effect of the SSTs on rainfall. Since the interannual variations appear to be unrelated, it seems unlikely that the long-term changes in both Indian Ocean SSTs and south-west rainfall are causally related. This conclusion is supported by the inability of climate models, when forced with observed SSTs over the 20th century to reproduce the observed decline in south-west rainfall.

- Secular changes have confounded the interannual relationships between the SOI and south-west rainfall, disguising some of the predictability achievable through the use of the SOI. An approach using year-to-year differences in the SOI has been proposed to overcome this confounding effect.

Future work planned for the next phase of the IOCI builds on the BMRC work completed in phase one, and includes:

- Development of specific seasonal forecasts for south-west Western Australia
- Further investigation of possible causes of the decadal decline in rainfall in south-west Western Australia
- Development of system for prediction of tropical cyclone activity in Western Australian region

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APPENDIX: LIST OF ACRONYMS

BMRC	Bureau of Meteorology Research Centre
IOCI	Indian Ocean Climate Initiative
SST	Sea Surface Temperature
SOI	Southern Oscillation Index
NCC	National Climate Centre (of the Bureau of Meteorology)
LEPS	Linear Error in Probability Space
MSLP	Mean Sea Level Pressure