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An assessment of recent trends in Australian rainfall

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Trends in Australian rainfall over the period 1901 to 2002 are analysed with the aim of evaluating and assessing long-term trends. In particular, this study examines long-term trends in Australian rainfall with the aim of identifying any continental-scale patterns that could be described as 'unusual'. All-Australia annual average rainfall and all-Australia average decile time series indicate a positive long-term trend over the full period. Trend maps indicate that much of this trend is the result of increases in summer half-year rainfall over western, northern and central Australia that have occurred over the latter part of the record 1952-2002. While significant negative trends in winter half-year rainfall over southwest Western Australia are evident, there is little evidence that they are part of any continental-scale trends, at least not on 100 or 50-year time-scales. Empirical Orthogonal Teleconnection patterns (EOTs) of annual rainfall provide a means for delineating independent spatial modes. These indicate that much of the variance in all-Australian rainfall can be attributed to the first two modes that cover much of central eastern Australia and central western Australia. In addition, the pattern of positive trends comprises at least two modes, which, being linearly independent, indicate that the large-scale pattern of increases is itself unusual in a historical context.

Introduction

Studies over the last decade into Australian rainfall have often noted the presence of long-term and short-term trends but have rarely identified any statistically significant trends, mainly because the data are characterised by high interannual variability. The only exception is the southwest region of Western Australia (SWWA) where a relatively sudden decrease in winter season (and annual) rainfall of about 20 per cent occurred around the 1970s.

Reliable long-term trend analyses have been made possible because of the application of extensive quality-control procedures and the identification of high-quality station records (Lavery et al. 1992) and composite records (Lavery et al.1997) that go back as far as the beginning of the twentieth century. Many individual records extend further back in time. Nicholls and Lavery (1992) analysed 191 high-quality station records and confirmed the results of earlier studies that identified long-term decreases in winter rainfall over southwest Western Australia and increases in summer rainfall over parts of eastern Australia. They noted the relatively poor geographical coverage of Western Australia and also noted that trends since 1900 needed to be assessed against evidence that conditions during the late twentieth century may have been similar to those of the late nineteenth century.

Suppiah and Hennessy (1996) looked at trends in a number of rainfall statistics over the period 1910 to 1989 using daily data from 53 stations. Following the study by Nicholls and Lavery (1992), Suppiah and

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Hennessy (1998) were able to extend their previous results by looking at daily data from 125 stations spanning the period 1910 to 1990. The pattern of trends confirmed previous studies but also indicated decreases in winter half-year rainfall over inland Queensland. Lavery et al. (1997) identified a total of 379 long-term and composite records and, using a weighted average based on a Thiessen polygon technique, calculated that all-Australia average annual rainfall had increased at a rate of 5 mm per 100 years between 1890 to 1992. Hennessy et al. (1999) also studied changes in rainfall statistics based on the new set of stations and found that, over the 85-year period 1910 to 1995, all-Australia rainfall had increased by a much greater rate of about 32 mm per 100 years but, in both cases, these trends were not judged to be statistically significant.

In a recent report, Manins et al. (2001) noted that all-Australia rainfall over the period 1900 to 1999 exhibited a weak upwards trend but, because of high interannual variability, was not unusual and simply reflected several wet years during the 1970s. Collins and Della-Marta (2002) show the all-Australian annual average rainfall time series of Lavery et al. (1997) updated to the year 2000 and again noted that the long-term positive trend was characterised by high year-to-year variability.

The impetus for updating trend analyses stems mainly from the fact that it is now recognised that our climate is not static and may be changing in response to increases in anthropogenic gases in the atmosphere. Pittock (1983) postulated that trends in district mean rainfall over the period 1913 to 1978 could be partly attributed to enhanced greenhouse gases (EGG) since this was also a period of warming in the southern hemisphere. A scenario of future rainfall due to EGG was first put forward by Pittock and Salinger (1982) who suggested: ‘increased rainfall north of about 30°S, and possibly as far south as 37°S, with a possible decrease in southern Australia, especially in the south-west.’

Since then, increases in global and Australian temperatures have continued and it is now more widely accepted that the observed warming can be partly attributed to EGG. Temperature records show that Australian mean temperature has increased by about 0.9°C since 1910. Australia’s warmest year on record was 1998 while 2002 was its fifth warmest year on record (Della-Marta et al. 2003). Globally, data collected and analysed by the Hadley Centre in collaboration with the Climatic Research Unit of the University of East Anglia suggest that average near-surface surface temperature has risen by about 0.7°C since 1900 (www.met-office.gov.uk/research/hadleycentre/CR_data/Annual/HadCRUG.gif). More recently, the results of climate models that attempt to simulate the effect of EGG have become available, and suggest a range of significant rainfall changes for Australia by the year 2030 (CSIRO 2001) – less than 30 years away. Even more recently, interest in rainfall trends has become more intense because of the widespread drought of 2002 and an ongoing sequence of years of below average rainfall over parts of southeast Australia.

The present study looks more closely at long-term trends in Australian rainfall with the aim of identifying any patterns that could be described as unusual. The term ‘unusual’ is used here to describes trends that are unlikely to be the result of internal variability within the atmosphere-ocean system, the implication being that they may be the result of external factors and therefore deserving of close scrutiny. The study deals with trends on a point-by-point basis that satisfy conventional significance testing, and also patterns of trends that are unlikely to occur given some knowledge of the spatial degrees of freedom within the data.

All-Australia rainfall

Stations that have provided daily rainfall observations to the Bureau of Meteorology are indicated in Fig. 1 and, while the number of operational stations does change over time, it serves to illustrate the difference in station density between the densely populated coastal regions compared with the interior. Jeffrey et al. (2001) describe an archive of Australian rainfall and climate data based on the careful interpolation of daily data amassed by the Bureau and managed by the National Climate Centre. The rainfall data exist on a 0.05° grid, and the result of calculating a time series of area-weighted all-Australia annual average rainfall 1901 to 2002 is shown in Fig. 2(a). This time series is essentially identical to that shown by Collins and Della-Marta (2002), which is based on just the high-quality rainfall sites and the spatial averaging technique of Lavery et al. (1997). This similarity indicates that the two methods for generating gridded rainfall are consistent. The Jeffrey et al. (2001) dataset forms the basis of this study.

According to the data, 1974 was the wettest year on record followed by 2000 and 1950. It also indicates that 2002 was the third driest year and certainly the driest year in almost 100 years. The Bureau of Meteorology’s Annual Climate Summary 2002 states that this was the fourth driest with 1902, 1905 and 1961 all drier. The last three years are therefore notable because they include the second highest (2000) and near lowest (2002) totals on record. The strong influence of El Niño/La Niña events on

Fig. 1 **Location of stations that have reported daily rainfall observations to the Bureau of Meteorology at some time (source: Dean Collins, Bureau of Meteorology).**

Australian rainfall is indicated by the correlation (r = +0.50) with the annual mean Southern Oscillation Index (SOI). Another feature of the time series is the existence of a trend of +73 mm per 100 years (equivalent to an increase of 16 per cent per 100 years), which accounts for about 7 per cent of the total variability (see Table 1). Thus, while 2002 was one of the driest years, the long-term trend suggests Australia has become wetter.

Previous studies that have noted a long-term increase have typically not placed a great deal of weight upon this finding, possibly because it was deemed to reflect a single wet period 1973-1975. Because of high interannual variability (standard deviation = 83 mm according to Table 1), previously derived trends have not been regarded as statistically significant. However, the fact that 2000 was the second wettest year on record suggests that this trend may now deserve closer attention.

Before assessing the statistical significance of the trend, some account needs to be taken of the degrees of freedom within the data. The annual values exhibit persistence due to the fact that 1 January falls within the monsoon season and, for those regions affect-

Table 1. Features of all-Australia annual average rainfall time series.

	Area averaged total	*Area averaged decile*
Mean (std)	461 (83) mm	5.0
Trend (1901-2002)*	+73 mm per 100 years (r =0.26) (dof =55)	+1.25 per 100 years (r =0.244) (dof =73)
Trend (1901-1951)	+5 mm per 100 years (r =+.001) (dof =47)	-.08 per 100 years (r =-.09) (dof =47)
Trend (1952-2002)	+102 mm per 100 years (r =+.16) (dof =25)	+2.4 per 100 years (r =+.22) (dof =38)
5 'wettest' years**	1974 (1974) 2000 (2000) 1950 (1973) 1956 (1950) 1955 (1956)	1974 1973 2000 1975 1917
5 'driest' years**	1902 (1902) 1905 (1905) 2002 (1961) 1961 (2002) 1994 (1994)	1905 1928 1961 1994 2002
Correlation with annual mean SOI	+0.50	+0.44

* 'r' represents the correlation coefficient associated with the trend line of best fit
'dof' refers to the estimated degrees of freedom within the time series

** The bracketed years represent rankings according to the Bureau of Meteorology Annual Australian Climate Summary 2002.

ed, can mean that a good/poor season can span two years. This implies that the degrees of freedom are likely to be far fewer than 102 years. Based on the lag-1 autocorrelation between the annual values, the effective degrees of freedom are estimated to be about 55 (Mitchell et al. 1966). Consequently, the overall trend (with trend correlation coefficient r = +0.26) is estimated just to be significant at the 5 per cent confidence level.

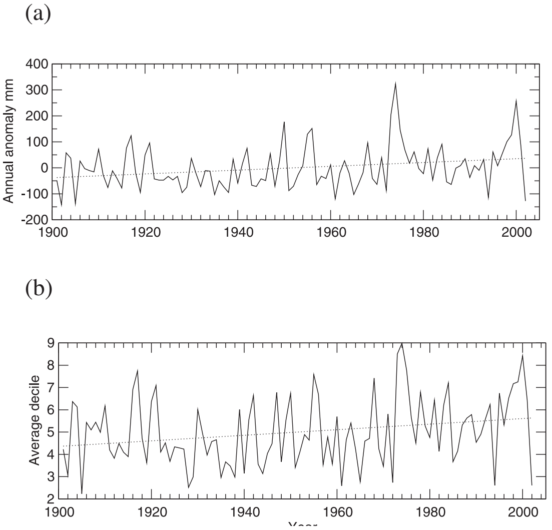
If we consider the first half of the period, 1901 to 1951, the trend is +5 mm per 100 years (r = +0.001) which is not statistically significant. Over the second half, 1952 to 2002, it is a relatively large +102 mm per 100 years (r = +0.16) but is still not statistically significant, i.e. the last 51 years are not particularly unusual unless seen in the context of the full record.

The all-Australia average values represent an estimate of the total amount of water falling on the continent in each year. This is a useful hydrological indicator but it needs to be remembered that the data upon which it is calculated are based on the interpolation of non-uniformly spaced station records. Over relatively large, data-sparse regions, Fig. 1 suggests that the contribution to the continental average could possibly unduly reflect the influence of a relatively few stations. Despite the number of high quality records that have been identified, this is an issue over much of central Western Australia (Lavery et al. 1992). If these regions are relatively dry, or the rainfall is uniform over large distances, then this is less likely to be a problem. Otherwise, in analysing trends or variability, the influence of these regions needs to be considered.

A second issue arises from the fact that annual rainfall totals vary considerably across the continent. Totals of less than 400 mm occur over most inland areas increasing to more than 1000 mm over relatively small coastal regions around the north, east, southeast and southwest of the continent. Totals exceeding 4000 mm occur over the east-facing slopes of northeast Queensland and the west-facing slopes of Tasmania. It is unclear whether the peaks and troughs in the time series represent variability of rainfall from the high rainfall areas (mainly in the north), or whether they represent variability of rainfall over relatively drier, but more extensive, regions elsewhere.

An alternative to averaging the raw totals across all the grid-points is to transform the values into deciles (the Bureau of Meteorology regularly publishes decile maps on monthly, seasonal, and longer time-scales). All-Australia area-averaged decile values (values determined from the full record) provide an alternative index of rainfall conditions since all grid-points contribute to the index on an equal basis, thereby removing the bias towards the high rainfall regions. A time series of this index is shown in Fig. 2(b) and is very similar to the raw time series, the major differences being the relative ranking given to different years. Both time series rank 1974 and 2000 as amongst the five wettest years on record and 1905, 1961, 1994 and 2002 as amongst the five driest years on record. However, 1950 is the third wettest according to raw totals but is ranked 15th according the decile values. Similarly, 1902 is the driest according to the raw values but is ranked 11th driest according to the decile values. Otherwise, the fact that both time series are similar indicates that the all-Australia average time series represents more than just variability of the wettest regions. Both time series can only be similar if they reflect rainfall fluctuations on the large scale.

Fig. 2 **All-Australian annual rainfall indices derived from: (a) area-averaged total; (b) area-averaged mean decile value.**



Like the total time series, the decile time series exhibits a positive trend over the full period. There is less persistence in the decile values and the estimated degrees of freedom (73) are greater than in the raw totals because there is no bias towards the wet, monsoon-dominated regions. Consequently, the trend correlation coefficient (r = +0.244) is also estimated to be significant at the 5 per cent level. The existence of nominally significant trends in both time series implies large-scale pattern(s) of increases over the full period. This is investigated by inspection of trend maps.

Trend maps

A trend map is constructed by using linear regression to define a linear trend at each grid-point, and then forming a contour map of either the regression or correlation (r) coefficients. While both maps will be qualitatively similar in terms of identifying the location of positive or negative trends, for this study the trend correlation maps are preferred since the values are not biased towards the wetter regions (where the magnitude of any trends is likely to be greater than those elsewhere).

Figure 3(a) shows the trend map for annual totals over the full period 1901 to 2002. The colour coding is such that positive values are represented by shades of blue, negative values by shades of red and values within +0.1 and -0.1 are represented by white fill. The somewhat remarkable feature of this map is the fact that most of the continent has experienced increases, with the strongest increases (r values in excess of +0.3) occurring over the central, western and northern portions of the continent. These increases contrast with the well-known decreases that have occurred in the relatively small southwest region of Western Australia (SWWA) (r values less than -0.3).

The comparable trend maps for the first half and second halves of the record are shown in Figs 3(b) and 3(c). Over the first half, the pattern of trends tends to be incoherent with positive trends interspersed with negative trends. These are features that could be expected due to natural variability within the data, taking account of the fact that there exists some degree of spatial dependence within Australian rainfall data. The results for the second half present a very different picture (Fig. 3(c)). In this case, the central, western and northern portions all exhibit positive trends while negative trends are confined to SWWA, the eastern and southeastern regions. An indicator of the differences between the maps is the percentage area of the entire continent covered by r values that exceed 0.3 in magnitude. Over the first half the percentage exceedance is 4 per cent, with about 2 per cent representing negative trends and 2 per cent representing positive trends. Over the second half, the comparable numbers are 22 per cent exceedance, comprising 3 per cent negative trends and 19 per cent positive trends.

The trend map for winter (May to October) half-year rainfall is shown in Fig. 4(a). Increases throughout the northern, central and southeastern regions, and the decline over the SWWA region, stand out clearly as components of Fig. 3(a). The trend maps for the two halves of the record are shown in Figs 4(b) and 4(c). These illustrate that only the decreases over SWWA are a recent feature of the data. The other trends in the full record appear to be early features of the data. In fact, the pattern of trends in winter rainfall over the recent period appears far less unusual than the earlier trends, mainly because the

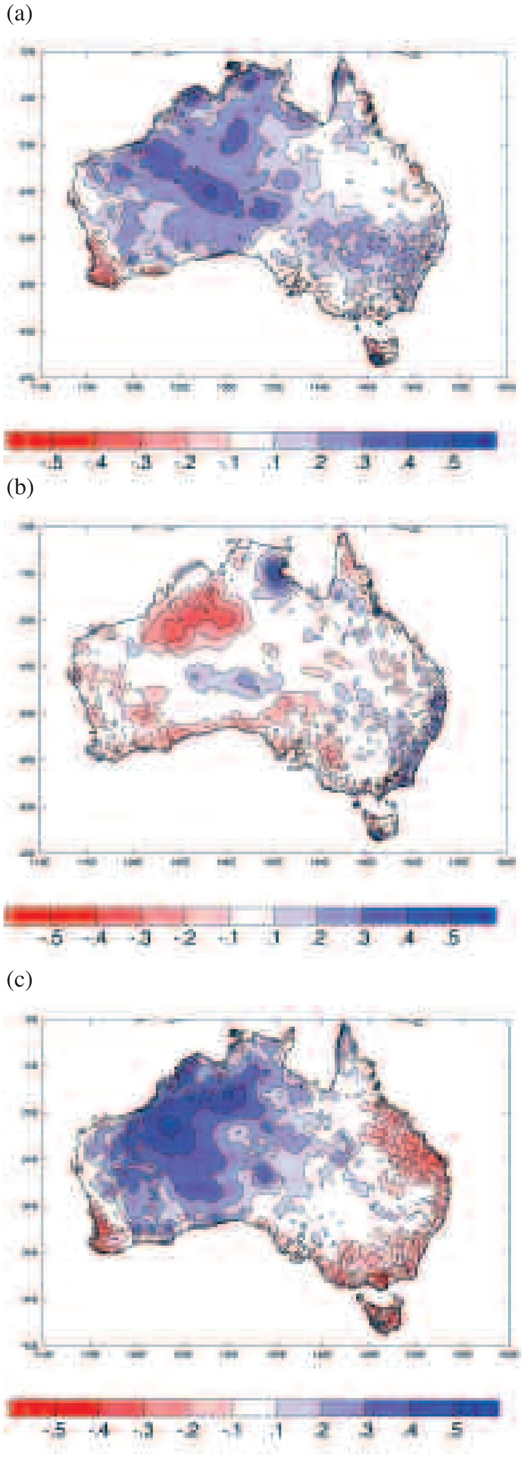


Fig. 3 **Trends in annual average rainfall expressed in terms of the correlation coefficient of a linear fit to the data at each grid-point: (a) 1901 to 2002; (b) 1901 to 1951; and (c) 1952 to 2002.**

trends are not particularly large and appear incoherent. Six per cent of r values exceed 0.3 in magnitude for the first half (representing approximately 4 per cent negative and 2 per cent positive trends) compared to only 1.7 per cent for or the second half (1.1 per cent negative and 0.6 per cent positive). While Figs 4(a) and 4(c) capture the significant decreases over SWWA that are known to have occurred during the 1970s, they do not indicate whether they are part of any larger scale pattern. Figure 4(c) also indicates the presence of negative trends over the far southeast region, but there is no indication that these are significant or unusual, at least on the 50-year and 100-year time-scales considered here.

The trend map for summer (November to April) half-year rainfall is shown in Fig. 5(a). In this case the first summer (1901) includes November 1900 and the last summer (2002) includes April 2002. This map is also remarkable since it appears that increases dominate the trends almost everywhere and obviously dominate the annual trends in Fig. 3(a). The breakdown into two halves (Figs 5(b) and 5(c)) indicates that the majority of the increases, covering much of western, northern and central Australia, have occurred over recent time. Six per cent of the r values exceed 0.3 for the first half of the century (representing 3 per cent negative and 3 per cent positive trends) compared to 29 per cent for the second half (representing 3 per cent negative and 26 per cent positive trends). It is therefore apparent that annual rainfall has increased over much of the continent since 1901 and that the majority of the increases have occurred during the summer half of the year and over the last 51 years.

A major reason for describing the trends in annual and summer half-year rainfall as unusual is the fact that the strength and pattern of increases are relatively extensive and coherent. This involves a degree of subjective judgement and the question remains as to whether the pattern of trends really does exhibit ‘field significance’. It could be argued that this may not be the case if it only involved a single mode of variability as opposed to a consistent positive trend across several independent modes. This argument would imply that the number of independent spatial degrees of freedom over the relevant region was relatively small, in which case any trend would, by definition, cover a large area. Techniques for testing for field significance must take into account spatial interdependence of the data (Livezey and Chen 1983). One method for dealing with this interdependence or estimating independent spatial degrees of freedom is to perform an orthogonal function analysis of the data. The following section describes the application of one such technique, Empirical Orthogonal Teleconnections (EOTs), to this problem.

Fig. 4 **As for Fig. 3 except for Australian average May to October rainfall.**

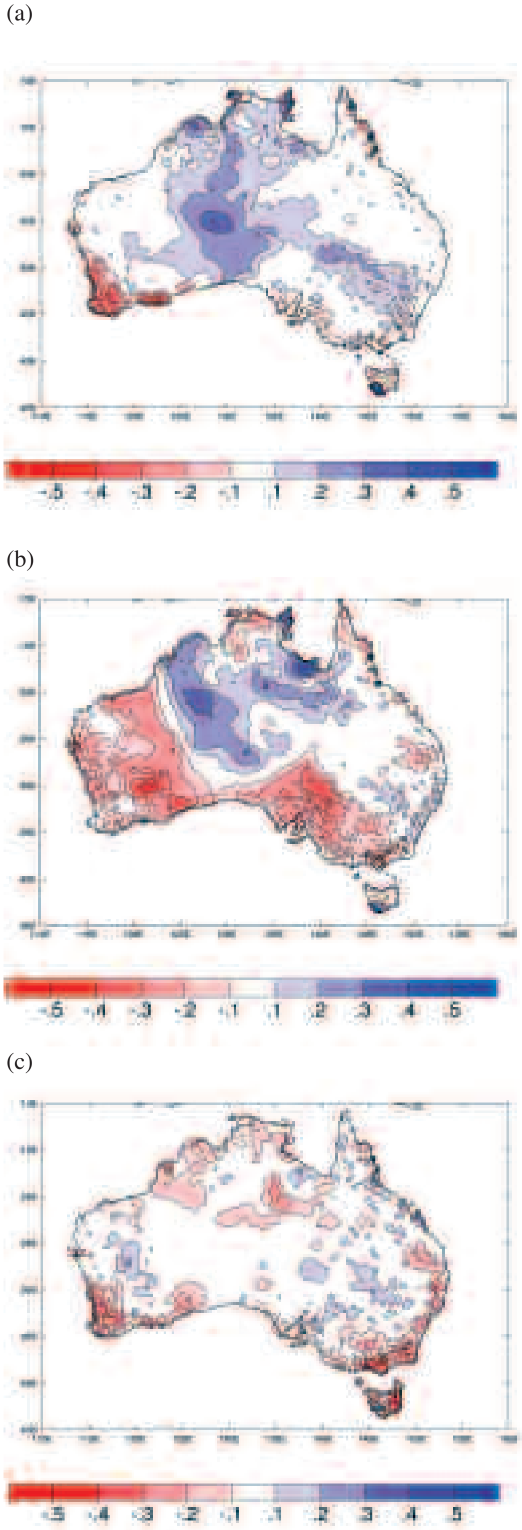
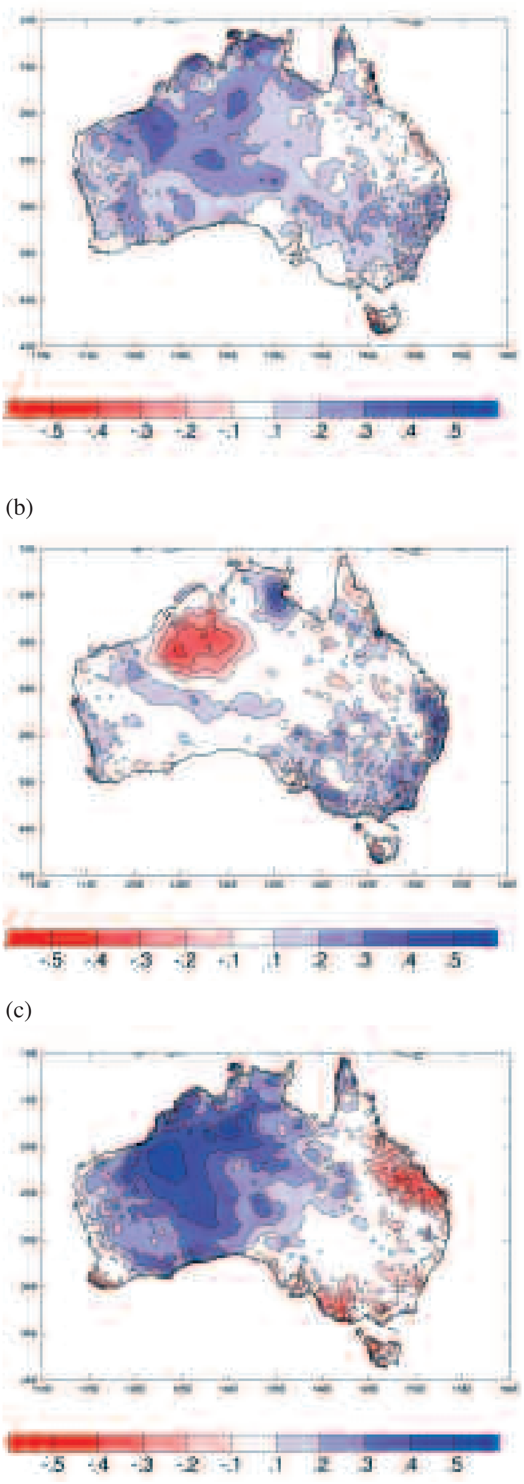


Fig. 5 As for Fig. 3 except for Australian average November to April rainfall .


(a)

(b)

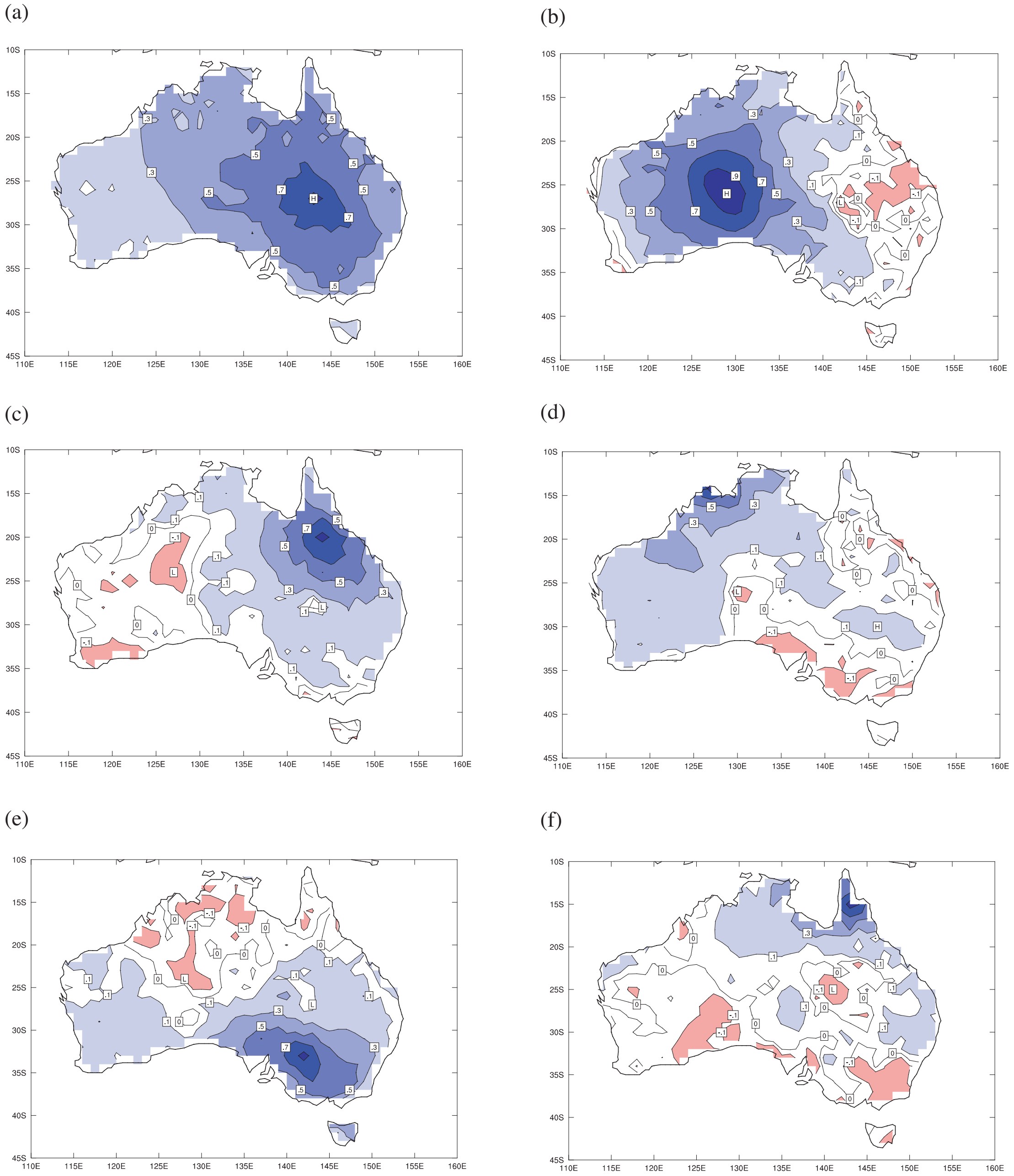
(c)

Empirical Orthogonal Teleconnection patterns

When considering the variability of data distributed in space and time, a standard technique to employ is Empirical Orthogonal Function (EOF) analysis. An alternative to EOF analysis, described as Empirical Orthogonal Teleconnection (EOT) analysis, is described by van den Dool et al. (2000) and, while not particularly new, offers several advantages over conventional EOF analysis. EOTs are constrained to be orthogonal in just one direction (time) rather than (as EOFs are constrained) two directions (space and time). As a result, EOTs appear to provide a straightforward interpretation of patterns within data with a minimum of computation. van den Dool et al. (2000) analysed some commonly used datasets and found the leading EOT patterns looked very much like the corresponding rotated EOFs, but were achieved far more efficiently. Secondly, EOFs are designed to provide a concise description of global variance and, in the case of rainfall data, this is not necessarily desirable. Global variance involves the sum (over the area of interest) of the anomalies squared. As discussed previously, the largest rainfall anomalies will tend to be those associated with the largest totals (typically the tropical regions). This bias is amplified if global variance, comprising the square of the anomalies, is used as a descriptor of the data. A less biased approach is simply to use the global integral (or annual average) as a descriptor. In other words the all-Australian rainfall time series, while still biased, provides a more natural descriptor of the data than would the equivalent time series that measures global variance. It also readily lends itself to EOT analysis which, amongst a number of advantages, provides a means of identifying effective spatial degrees of freedom (or nodes).

In adopting an EOT approach to Australian annual rainfall data, the first step is to find that grid-point whose time series (called T1) most closely matches the global integral as represented by the all-Australian annual mean rainfall time series shown in Fig. 2(a). The second step is to perform a linear regression of T1 with all grid-point time series and generate a map of correlation coefficients. This map (with r = +1.0 centred on the selected grid-point) is the first spatial mode (S1) or teleconnection pattern. Figure 6(a) shows S1 while the time series (of annual rainfall recorded at the grid-point located at 27°S, 143°E) T1 is shown in Fig. 7(a). S1 could be described as a 'central east' mode since correlations exceed 0.5 over much of the eastern half of the continent. An alternative description is the 'Winton' mode since this is the name of the station closest to the centre of this pattern (N.Nicholls, personal communication, 2003).

Fig. 6 Australia annual average teleconnection patterns: (a) 'central east' or 'Winton' mode (S1) which explains 60% of the variability in the time series shown in in Fig.1(a); (b) 'central-west' mode (S2) which explains a further 15%; (c) 'north-east' mode (S3) which explains a further 9.5%; (d) 'north-west' mode (S4) which explains a further 3.5%; (e) 'south-east' mode (S5) which explains a further 2.9%; (f) 'Cape York' mode (S6) which explains a further 2.2%.



S1 explains 60 per cent of the variability in the all-Australia time series and, over the full period, exhibits an increase over time equivalent to 58 mm per 100 years (or 25 per cent of the long-term mean per 100 years) (Table 2). The trend correlation coefficient (r = +0.13) is not statistically significant. T1 is significantly correlated (r = +0.43) with the annual mean SOI and, not surprisingly, S1 resembles the pattern obtained when the annual mean SOI is regressed against rainfall.

Table 2. Australian annual rainfall teleconnection modes.

	T1	*T2*	*T3*	*T4*	*T5*	*T6*
Description	central east (‘Winton’)	central west	north-east	north-west	south-east	Cape York
Variance explained	60%	15%	9.5%	3.5%	2.9%	2.2%
Trend (1901-2002) (mm per 100 years)	+58	+120	+30	+160	+7	-12
(% per 100 years)	+25%	+109%	+8%	+20%	+5%	-1.5%
	(r =+0.13, dof = 69)	(r =+0.34, dof = 54)	(r =+0.04, dof = 93)	(r =+0.20, dof = 79)	(r =+0.003, dof = 97)	(r =-0.02, dof = 87)
Correlation with annual mean SOI	0.43	0.01	0.22	0.05	0.05	0.09

Given T1, the next step in the analysis is to remove its influence upon the rainfall data set, prior to repeating the whole procedure. This is done by using the results of linear regression of T1 on each individual grid point time series, and subtracting out that proportion of the rainfall signal explained by T1. Having removed the influence of T1 from the data, the all-Australia area-weighted total is re-calculated and the analysis continues by finding that grid-point whose time series most closely matches the resultant residual time series. The resultant spatial pattern S2 is shown in Fig. 6(b) while the time series (T2) (26°S , 129°E) is shown in Fig. 7(b).

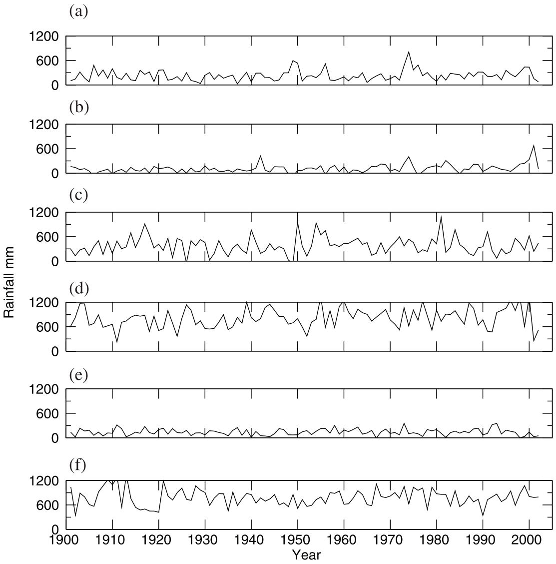
S2 represents variability over the central west region of the continent and explains a further 15 per cent of the original variance (Table 2). T2 exhibits a strong increase over time (109 per cent per 100 years) and the associated trend correlation coefficient (r = +0.34) is statistically significant despite the relatively low effective degrees of freedom (54). A word of caution is required since Fig. 6(b) suggests that S2 represents variability over that portion of the continent where rainfall stations are most sparse. It is apparent from Fig. 1 that S2 may be dominated by the relatively small number of stations whose effect has been interpolated over large distances. While it cannot be ignored, it should be realised that a proportion of all-Australia rainfall apparently reflects observations from this data-sparse region.

Continuing the process of removing the effect of each selected grid-point time series from each residual time series leads to a succession of EOTs (S3, T3), (S4, T4), (S5, T5) etc., each one linearly independent, and each explaining a diminishing amount of the original variability. The third mode (S3 (Fig. 6(c)) and T3 (Fig.7(c)) explains a further 9.5 per cent and represents rainfall in the northeast of the continent. This also exhibits a weak trend of +8 per cent per 100 years but is not statistically significant. The fourth mode (S4 (Fig. 6(d)) and T4 (Fig. 7(d))) explains 3.5 per cent and represents rainfall in the northwest. This mode exhibits a trend of +20 per cent per 100 years, which is also significant according to r (= +0.20) and the effective degrees of freedom (= 79). S5 (southeast mode) and S6 (Cape York mode) explain a further 2.9 per cent and 2.2 per cent respectively but neither exhibits any significant trends. Lower order modes are not considered any further here. Note that S3, S4 and S6 represent high rainfall regions with relatively high variability yet they contribute a relatively small portion of the original variability. This reflects the relative area of these regions, and therefore their overall contribution, compared to S1 and S2.

The leading three modes explain 85 per cent of the original variance, which confirms the implication that the all-Australian time series reflect rainfall fluctuations on the large scale and are not biased towards the high/summer rainfall regions to the north. The first five modes exhibit increases over the full period, the largest and most significant being S2 and S4. Therefore the region of the continent where the strongest positive trends are evident is not represented by a single mode but by at least two independent modes.

Based on the estimated degrees of freedom, the trends in these two modes are conservatively estimated to be significant at or near the five per cent level. All modes are linearly independent (in time) since the effect of each time series is removed by linear regression. With regard to statistical significance, a question that can be asked is ‘What are the

Fig. 7 **Australian annual average rainfall teleconnection time series corresponding to the spatial patterns shown in Fig. 6: (a) T1; (b) T2; (c) T3; (d) T4; (e) T5; and (f) T6.**



chances of two out of randomly selected (i.e. independent) six items passing a test at the five per cent level or better?' (see Livezey and Chen 1983). The actual chances are estimated to be less than one per cent indicating that the trends in the data are unlikely to be due to coincidence.

Discussion and conclusions

In discussing Australian rainfall data a number of issues usually arise including the quality of station records that are used to form databases, the presence of any apparent fluctuations in the data, the significance of any such fluctuations and how representative these are of the large scale. The last issue can be important if interpolation of observations is performed over relatively data-sparse regions. Finally, assuming that any fluctuations that have been identified are real, unusual and extensive enough to be warrant attention, the issue of attribution becomes relevant. Importantly, the results of climate model simulations of the 20th century could then be examined to determine if they reproduce the observed variability.

In this study it is assumed that the gridded rainfall data provides a reasonable representation of Australia's actual rainfall over the period 1901 to 2002. With that caveat in mind, the analysis reveals that all-Australia annual mean rainfall and all-Australia annual mean rainfall deciles exhibit increases over the period 1901 to 2002. While a long-term positive trend has been noted in previous studies, it now no longer can be seen solely as the result of the anomalously wet period 1973-1975, but now also reflects the relatively wet year 2000.

The observed decrease in winter rainfall over southwest Western Australia since the 1970s has long been regarded as unusual and, according to a recent report (IOCI 2002) the most likely explanation is that it represents the accumulated effect of several factors including EGG. At this stage, it appears that the trend maps, in isolation, do not reveal anything unusual about the continent-scale pattern of trends in winter half-year rainfall, at least not on the 50 to 100-year time-scales dealt with here. That being said, it is still possible that the changes affecting SWWA may be part of large-scale changes in rainfall over the oceans to the south (where there are obviously no rain gauges). Some modelling studies (e.g. Thompson and Solomon 2002) suggest that the impact of EGG is likely to be decreases in high latitude and increases in mid-latitude mean sea-level pressure, changes that have already been observed over recent decades. Increases in mean sea-level pressure accompany SWWA wintertime rainfall decreases (Smith et al. 2000) and so the observed decreases, while covering a relatively small area, may reflect changes taking place further south.

Unlike SWWA, decreases in winter half-year rainfall over southeast Australia over recent decades, while serious, do not appear unusual considering the full record. This picture could alter if relatively dry conditions were to persist for a few more years.

It is apparent that trends in summer half-year rainfall over the period 1952-2002 dominate the trends in annual rainfall over the full period 1901-2002. The trend pattern is dominated by increases over much of western, northern and central Australia.

In attempting to assess the 'field significance' of trends in annual rainfall we have used the results of EOT analysis that provides a means of revealing spatial modes within the data. The major findings from this analysis are:

- The dominant mode represents rainfall over the central-east region of the continent, explains 60 per cent of the original variance, and is strongly linked to the SOI.
- The second mode represents rainfall over the central-west of the continent and explains 15 per cent of the original variance. It is also apparent that this mode represents the region of the continent where observations are most sparse. This needs to be kept

in mind when analysing continent-scale totals and indices.

- The third, fourth and sixth modes represent rainfall over the relatively wet northeast, northwest, and Cape York regions of the continent and explain 9.5, 3.5 and 2.2 per cent of the original variance respectively.
- The fifth mode represents the southeast of the continent and explains 2.9 per cent.

Variations in all-Australia annual rainfall totals are therefore dominated by rainfall over the extensive inland areas of Australia and not by those over the relatively smaller, high rainfall regions. The central west (S2) and northwest (S4) modes are linearly independent, cover a substantial fraction of the continent, yet exhibit positive trends that are judged to be significant at or near the 5 per cent level. This indicates that the long-term increases in rainfall over this part of the continent could be described as unusual in a historical context. Note that this analysis does not prove that the increases are unusual, they may well dissipate after a few more years, but at this point in time the probabilities suggest they deserve close scrutiny.

While the factors affecting winter half-year rainfall are still open to question, the increase in summer half-year and annual rainfall over the western half of the continent coincides with warming of the continent itself and also with that of the Indian Ocean. An investigation of the links between these changes, particularly with climate models, may therefore be insightful.

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