Annual climate summary 1998: Australia's warmest year on record

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A high-quality dataset developed to monitor long-term temperature trends in Australia has been updated. The annual mean time-series indicates that in 1998 Australia recorded its highest ever annual mean temperature since the start of the high-quality record in 1910. The largest contribution to the record temperature came from much higher than usual minimum temperatures throughout the northern half of the continent. High-quality rainfall and cloud cover datasets have also been updated. Greater than average cloud cover during 1998 contributed to milder overnight temperatures and generally wetter than average conditions through most of the country. The result of a warm, wet and cloudy year during 1998 is unusual in the instrumental record for Australia as studies of interannual climate variations indicate that mean temperature is generally out of phase with both rainfall and cloud cover. However, these apparent inconsistencies support the suggestion made by previous studies that the relationship between Australian temperature and rainfall changed abruptly during the early 1970s.

Introduction

Any change in site location, exposure, instrumentation or observational practice has the potential to result in a significant inhomogeneity in the climate record of an observing station. These artificial discontinuities can be as large as natural climate variations and make it difficult to detect any real trends in the climate. Increasing concern about potential climate change associated with the enhanced greenhouse effect has made it critical that any station data used to examine such change has been adjusted for inhomogeneities.

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Procedures to identify and adjust for inhomogeneities in a climate record generally involve analysis of historical station information, visual examination of data, neighbour checks and statistical tests. A number of studies (e.g. Torok and Nicholls 1996; Lavery et al. 1992, 1997) have used these techniques to develop Australian high-quality datasets which are used operationally by the Bureau of Meteorology's National Climate Centre for long-term climate monitoring.

Annual mean temperature

Torok and Nicholls (1996) developed a set of Australian high-quality historical temperature records using available station documentation, graphical checks and statistical tests. Station records were corrected for discontinuities in annual mean temperature, generally over the period 1910 to 1993. One of the major problems identified by Torok and Nicholls was the poor documentation of changes in instrument shelters to the current Stevenson screen. Generally this occurred throughout Australia in the early 1900s (Nicholls et al. 1996a) and to avoid the associated complications they concentrated on the post-1910 period. 224 temperature records were reconstructed to an acceptable standard, 181 of which were identified as being non-urban.

The non-urban temperature records of Torok and Nicholls (1996) are used operationally to compute Australia's annual mean temperature, with the corrected temperature records of Giles (25.0°S, 128.3°E) and Woomera (31.2°S, 136.8°E) having been added to the original network to improve inland sampling. Urban stations are not included to avoid the artificial warming associated with increasing population. Torok and Nicholls examined the homogeneity of the temperature records up to and including 1993. A thorough homogeneity analysis of the post-1993 records has not yet been undertaken. However, this is not expected to have a significant impact on the spatially averaged temperature values for recent years.

In recent years, for any observing site move that is likely to involve a significant discontinuity in the station's climate record, the Bureau of Meteorology has generally assigned a new site number to the station. Only data corresponding to the original station numbers of Torok and Nicholls (1996) have been used in this study and consequently large discontinuities associated with significant site moves should have been avoided. Also, as the sites used are designated as non-urban, the effects of urbanisation since 1993 should be minimal. The main sources of inhomogeneity since 1993 are likely to come from changes in site exposure and instrumental drift. However, all sites should have regular inspection and maintenance programs to minimise these influences. Also, the impacts of these changes on individual station records is likely to be random (some will involve a positive bias while others experience a negative bias) so the overall bias to the network should be minimal.

Initially, annual mean maximum and minimum temperature anomalies were calculated for every available station in the high-quality temperature network. These anomalies were calculated from the averages of each station's 12 monthly mean anomalies, which were determined relative to the long-term averages over the period 1961 to 1990. In order to calculate an annual mean maximum or minimum temperature for any given station, all monthly mean values must have been available. A monthly mean value was considered missing if more than ten, or more than five consecutive, daily temperature values were missing during the month. These criteria are less strict than the World Meteorological Organization criteria which recommend no more than three consecutive missing daily values and no more than five missing daily values in total in order for a monthly mean to be considered valid (WMO 1989). For stations with up to three missing monthly mean maximum or minimum temperature values during the year, the values were interpolated using the objective analysis scheme of Mills et al. (1997). Stations with more than three missing months of maximum or minimum temperature data were not included in the analysis.

Since the initial work by Torok and Nicholls (1996) some of the high-quality stations have closed. Also, data losses resulted in some of the remaining stations being unable to meet the criteria for data availability and consequently they were unable to be included in the analysis for some years. In recent years about 130 non-urban stations from the original 181 have had enough data to be included in the annual analysis, with 129 included in the 1998 analysis. Any further closures of high-quality temperature sites may jeopardise the integrity of the network and lead to unreliable spatial averages of mean temperature. However, some of the high-quality temperature station closures may actually involve station relocations in which the station has continued at a new location with a different site number. A thorough homogeneity assessment of the network may enable the original high-quality records of some 'closed' sites to be matched onto the record of a new site, effectively increasing the number of high-quality temperature stations still open.

Once annual mean maximum and minimum temperature anomalies were determined for all available stations, the Theissen Polygon weighting scheme of Lavery et al. (1997) was used to determine all-Australian mean maximum and minimum temperature anomalies. This scheme divides the area for which a spatial average is required into polygons, one for each station in the network. The spatial average is then computed by weighting each station according to the fraction of the total landmass that its polygon represents. The Australian annual mean temperature anomaly was then determined from the average of the Australian annual mean maximum and minimum temperature anomalies.

All-Australian averages of temperature anomalies were calculated, rather than averages of temperatures, due to the much greater spatial coherence of temperature anomalies. The effects of topography and other local influences can result in significant differences between temperature values at relatively close stations. However, station temperature anomalies calculated relative to some common reference period, will often have much greater agreement. Consequently a more appropriate method to calculate a spatial average of temperature is to average a network of station temperature anomalies, rather than temperatures (Jones et al. 1986). In this study, the standard reference period of 1961 to 1990 was used to calculate station anomalies.

The Australian mean temperature anomaly for 1998 was found to be +0.73°C. This departure is greater than the previous highest recorded departure of +0.66°C set in 1988. The mean minimum temperature anomaly for 1998 was greater than that for mean maximum temperature, consistent with the decreasing trend in diurnal temperature range observed in recent decades (Plummer et al. 1995). The mean minimum temperature anomaly was +1.03°C, well above the previous highest of +0.85°C set in 1973. However, the mean maximum temperature was only 0.42°C above average, less than the greatest anomaly of +0.83°C recorded in 1991.

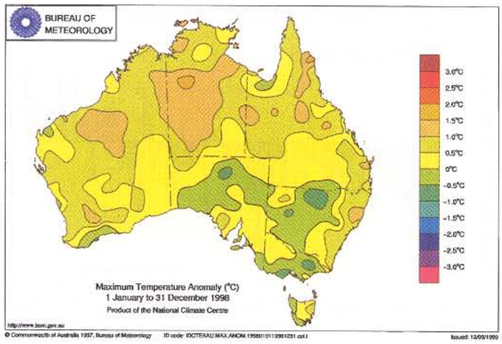
As in any year, considerable spatial variation exists in the 1998 mean temperature anomalies. The largest mean maximum temperature anomalies were reported in the north, with much of inland Northern Territory and northern Western Australia reporting annual mean anomalies greater than 1°C, relative to their 1961 to 1990 averages (Fig. 1(a)). Some southern parts actually recorded cooler than average maxima during 1998. Above average minimum temperatures were also concentrated in the northern half of the country, with areas of greatest departure in subtropical regions (Fig. 1(b)). Generally above average minimum temperature anomalies were greater than those for maxima.

The greater contribution of minimum temperatures to the record Australian mean is also reflected in seasonal temperature anomalies (not shown). Analyses of seasonal minimum temperature during 1998 consistently showed warm anomalies throughout the country, apart from some far southern parts (Mullen 1998; Courtney 1998; Collins 1999; and Beard 1999). Seasonal maximum temperature anomalies were far more mixed than those for minima, although summer 1997/98 and autumn 1998 generally showed greater than average maxima throughout Australia. A series of heat waves in late summer and early autumn produced well above average maximum temperatures in central and southern Western Australia, including a new state record of 50.5°C at Mardie (21.2°S, 116.0°E) on 19 February 1998.

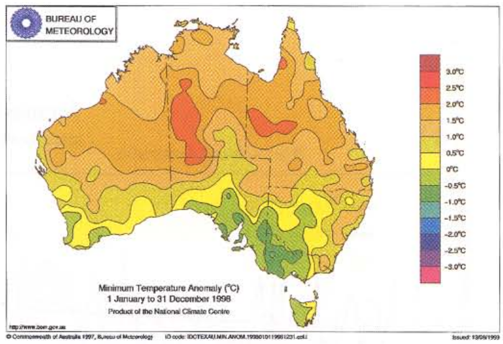
The time-series of Australian annual mean temperature values (Fig. 2) was re-calculated from 1910 based on the network used for the 1998 analysis.

Fig. 1 Annual mean (a) maximum and (b) minimum temperature anomalies throughout Australia during 1998. Anomalies represent departures from the average over the 1961 to 1990 reference period.

(a)



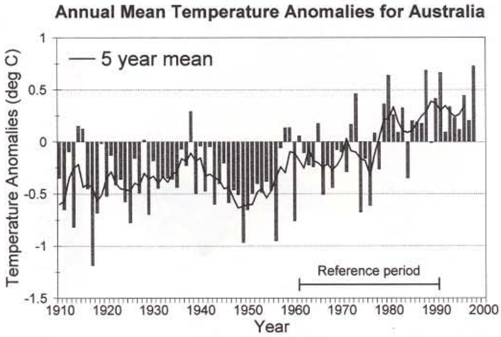
(b)



Starting from 1910, the station weights used in the spatial averaging scheme were re-calculated each time a new station was introduced into the network, with the first full year of data being considered as a station's start year. This technique produced slightly different annual mean values to those published in previous studies. If any station in the network did not have enough data to be included in the analysis for any particular year it was given zero weighting in the all-Australian average and its Theissen polygon was considered as a 'hole' in the Australian landmass for that year.

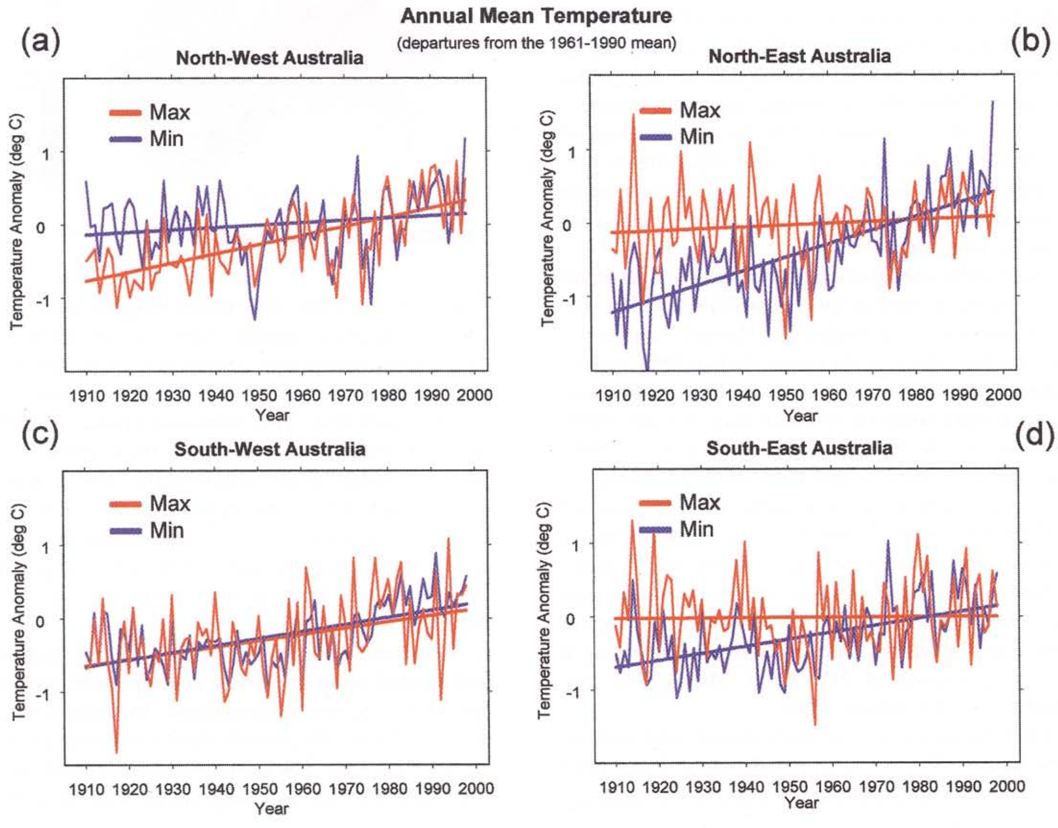
Torok and Nicholls (1996) found that generally both annual mean maximum and minimum temperatures have increased throughout Australia over the period 1910 to 1993, mainly due to an abrupt increase during the 1970s. The post-1993 annual mean values have supported an increasing trend, with all of them

Fig. 2 Time-series of annual mean temperature anomalies for Australia. Anomalies are calculated with respect to the 1961 to 1990 reference period.



being greater than the 1961 to 1990 average. Linear regression applied to the 1910 to 1998 mean temperature anomalies reveals a trend of 0.83°C/century, with trends of 0.61°C/century and 1.05°C/century for mean maximum and minimum temperatures, respectively. Torok and Nicholls (1996) calculated slightly weaker trends of 0.54°C/century and 0.98°C/century for annual mean maxima and minima based on 1910 to 1993 data. Torok and Nicholls found the warming trend in minimum temperatures to be largest in the north, particularly the northeast, while the largest increases in maximum temperatures were found in the west of the country. The 1910 to 1998 data support these findings with the northwest quadrant showing the strongest increase in maximum temperatures (Fig. 3(a)) and the northeast quadrant (Fig. 3(b)) showing the strongest increase in minimum temperatures.

Fig. 3 Time-series of annual mean temperature anomalies for the four quadrants of Australia divided by the lines 135°E and 26°S. Linear regression lines are also shown.



Annual mean rainfall

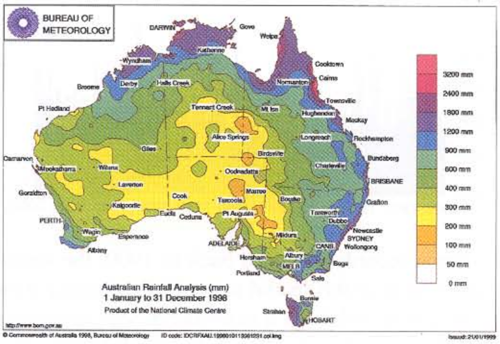
Lavery et al. (1992) used available station history information and a variety of graphical and statistical tests to select 191 high-quality rainfall stations for monitoring long-term changes in Australian rainfall. However, considering the high spatial variability of rainfall, the network did not provide sufficient coverage of the country to allow the calculation of reliable spatial averages. Consequently, additional stations were introduced to the network, most of which were composites of two or more highly correlated neighbouring stations (Lavery et al. 1997). This resulted in a total of 379 high-quality rainfall records, 339 of which started during or before 1910. The number of high-quality stations gradually increased up to 1970 and was stable until 1992. From 1993 onwards station closures have resulted in a gradual decline in available stations.

The high-quality rainfall dataset of Lavery et al. (1997) was updated from 1992 to 1998 for this summary. Initially annual rainfall totals were calculated for every available station in the network, based on each station's 12 monthly rainfall totals. For stations with up to three missing monthly rainfall totals the missing values were interpolated using the same objective analysis scheme as that used to interpolate monthly mean temperatures (Mills et al. 1997). A monthly rainfall total was considered missing if no monthly rainfall total was available from the National Climate Centre's climate database, indicating that a monthly rainfall record sheet was not received from the station for that particular month. Due to data losses and station closures, only 311 stations from the original 379 high-quality stations were able to be included in the analysis for 1998. If missing monthly rainfall totals were not interpolated only 283 stations would have been available. The area-weighted averaging scheme used to calculate an Australian annual mean temperature was also used to calculate an all-Australian annual mean rainfall total.

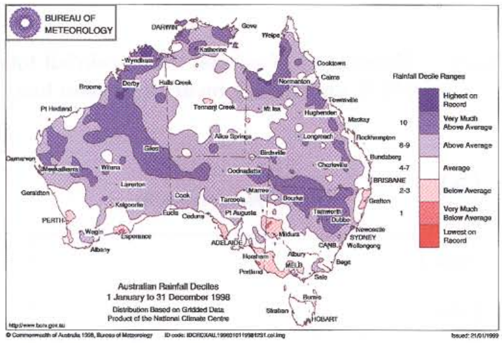
The Australian annual mean rainfall for 1998 was found to be 567 mm, making 1998 the 13th wettest year since 1900. The 1998 value was greater than the 1961 to 1990 average of 487 mm but well short of the highest on record of 801 mm recorded in 1974. The areas of greatest annual rainfall during the year were in the far north, along parts of the east coast and in western Tasmania where totals of more than 1200 mm were reported (Fig. 4(a)). In comparison with climatology, 1998 was a wet year with most of the country reporting annual rainfall greater than the 80th percentile (Fig. 4(b)). Most of the rain contributing to the higher than average annual rainfall fell during winter and spring. Rainfall decile patterns during summer

Fig. 4 Annual rainfall (a) totals and (b) deciles throughout Australia during 1998. Decile values are determined from gridded rainfall analyses since 1900.

(a)



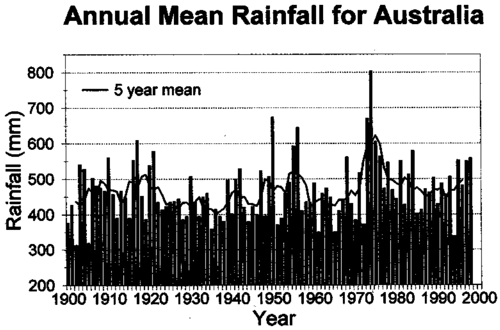
(b)



1997/98 (Mullen, 1998) and autumn 1998 (Courtney, 1998) were mixed, although some very heavy falls were reported in far northern parts during January with major flooding experienced around Townsville and Katherine. Winter (Collins 1999) was very wet through vast areas of the continent, largely due to enhanced northwest cloudband activity. During June two low pressure systems dramatically turned drought to flood in eastern Victoria while in August a low pressure trough along the southern New South Wales coast resulted in major flooding and landslides in the Wollongong area. Spring was also generally very wet throughout the continent, largely due to tropical-extratropical cloudbands and early northern wet season activity (Beard 1999).

The time-series of Australian annual mean rainfall (Fig. 5) was re-calculated from 1900 based on the network used for the 1998 analysis. However, since not

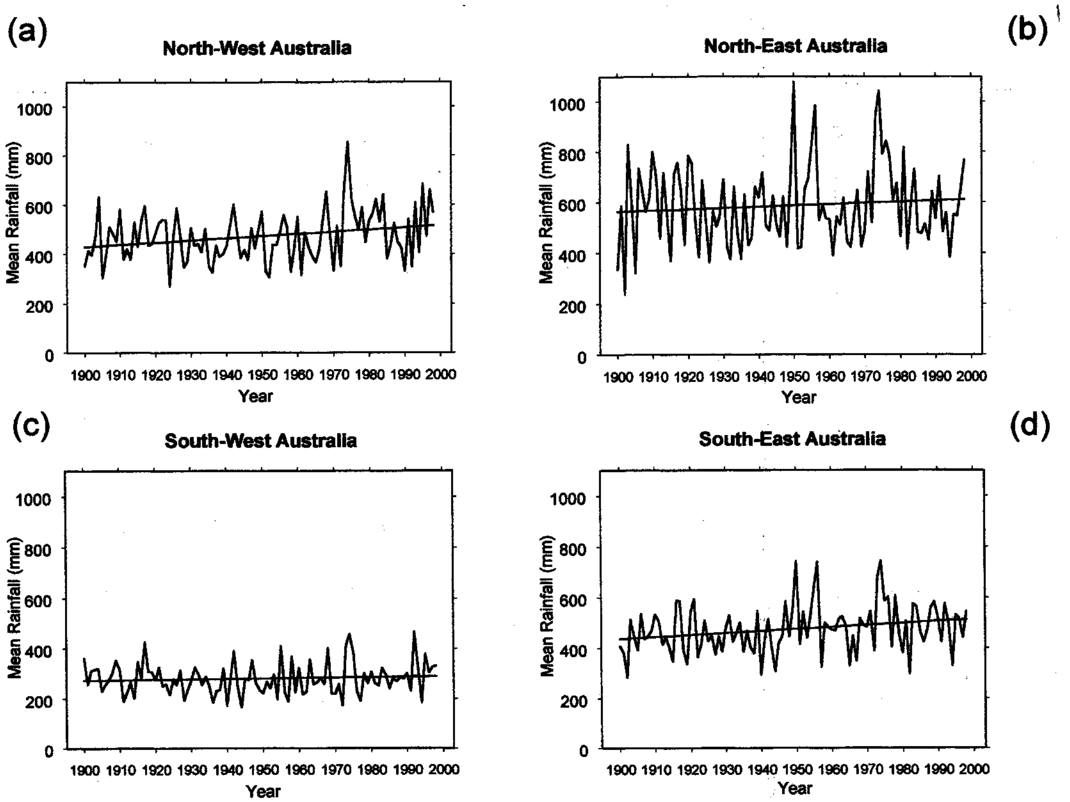
Fig. 5 Time-series of annual mean rainfall totals for Australia. Five-year mean values are also shown.



all station records extended back to 1900, the station weights used in the spatial averaging technique were re-calculated each time a new station was introduced to the network. This produced slightly different annual mean values to those published previously. If a station did not have enough data for the calculation of an annual rainfall total for any year it was given zero weighting in the all-Australian average for that year and the area it represented was not considered part of the total Australian area. Applying linear regression to the annual mean series gives a trend of 65 mm/century over the period 1900 to 1998, largely due to several very wet years during the mid-1970s. The five-year mean rainfall (Fig. 5) also shows a weak upward trend although high interannual rainfall variability dominates any long-term trends.

Lavery et al. (1997) determined a smaller trend value of 5 mm increase per century over the period 1890 to 1992. Several wet years during 1890 to 1900 result in a much weaker upward trend than if only post-1900 data is considered and hence the smaller trend value. It was decided not use pre-1900 data in this study as the network was relatively unstable during this period and Australian annual mean rainfall values were found to be highly dependent on the type of station weighting procedure used. Hennessy et al. (1999) also found an increase in Australian mean rainfall over the period 1910 to 1995.

Fig. 6 Time-series of annual mean rainfall totals for the four quadrants of Australia divided by the lines 135°E and 26°S. Linear regression lines are also shown.



The time-series of annual mean rainfall for the four quadrants of Australia (Fig. 6) indicate that most of the increase in all-Australian mean rainfall has been in the northwest (Fig. 6(a)) and southeast quadrants (Fig. 6(d)). The northeast (Fig. 6(b)) and southwest (Fig. 6(c)) quadrants show little or no trend since 1900. The southwest quadrant has the lowest mean annual rainfall while the northeast displays the largest interannual variability. Studies of Australian seasonal rainfall trends (e.g. Hennessy et al. 1999; Nicholls and Lavery 1992) have determined decreasing trends in winter rainfall in southwest Australia and increasing trends in summer rainfall in eastern Australia.

Annual mean cloud amount

Jones and Henderson-Sellers (1992) used monthly mean cloud data to show increased cloudiness over Australia during the period 1910 to 1989. A later study by Plummer et al. (1997) used daily 9am and 3pm observations of total cloud to examine changes in mean cloud cover and the frequency of occurrence of cloudy and clear days. However, due to the lack of pre-1957 digitised daily data this work was confined to the period 1957 to 1996. The data was adjusted for inconsistent observation practices and time of observation bias due to the introduction of daylight savings. An Australian high-quality cloud dataset has been based on this work and updated to include 1997 and 1998.

The original cloud network used by Plummer et al. (1997) included 172 observing stations, 160 of which were available for inclusion in the analysis for 1998. Again the area-weighted averaging scheme used by Lavery et al. (1997) was used to calculate an all-Australian average. The weights applied to each station in the spatial averaging were not re-calculated for 1997 and 1998 due to the relative stability of the network since 1957. The 12 stations from the original network that were unavailable for the 1998 analysis were simply given zero weighting in the overall average. Probably the greatest risk to this high-quality cloud network comes from the trend toward 'stand-alone' automatic weather stations (AWSs) at which no manual observation input is made. AWSs are currently unable to provide measurements of cloud amount in a format consistent with conventional observational practices. With an enhanced hydrological cycle believed to be an indicator of global warming, it is important that a reliable cloud observation network is maintained.

The annual mean cloud amount for Australia during 1998 was calculated to be 3.44 oktas. This is higher than the 1961 to 1990 average of 3.23 oktas and consistent with the above average annual mean rainfall. The time-series of Australian annual mean cloud cover (Fig. 7) generally shows a rise up to the mid-1970s, consistent with the high annual mean rainfall totals during these years. A decrease from the early 1980s may be associated with the increased number of El Niño events during the 1980s and 1990s.

El Niño-Southern Oscillation

1998 was a transition year in the development of the El Niño-Southern Oscillation. The series of monthly Southern Oscillation Index (SOI) values during 1998 (Fig. 8) clearly show that the strong El Niño event that developed during autumn 1997 began to break-down in autumn of 1998 before a transition to weak La Niña conditions by the end of 1998. This development is described in seasonal climate summaries of the southern hemisphere by Mullen (1998), Courtney (1998), Collins (1999) and Beard (1999).

The development of Pacific sea-surface temperatures (SSTs) during 1998 (not shown) also reflects a year of transition. Early in the year the remnants of the warm tongue associated with the declining El Niño event were still evident in the far eastern tropical Pacific. During winter, significantly warmer than average waters in the western Pacific and cool anomalies along the central equatorial Pacific suggested the transition toward a Pacific cool event. Warm SST anomalies in the western Pacific and eastern Indian Ocean persisted throughout the remainder of the year, resulting in the Asian region being surrounded by significantly warmer than average ocean temperatures.

Fig. 7 Time-series of annual mean cloud cover over Australia.

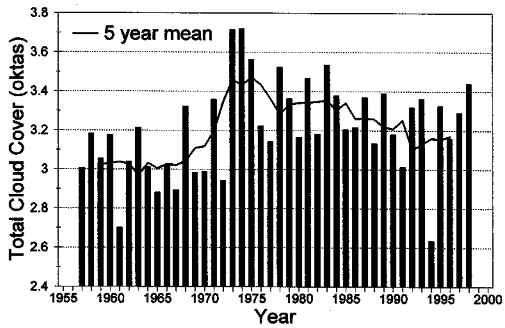
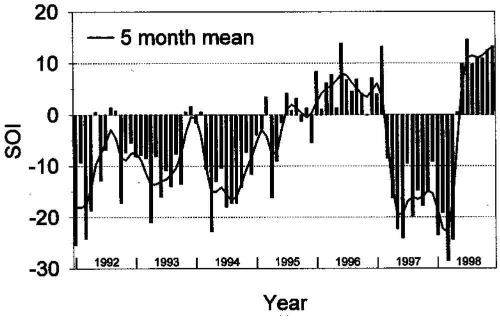


Fig. 8 Time-series of monthly Southern Oscillation Index values over the period 1992 to 1998.



Discussion

The linear trends calculated from the annual mean time-series used in this study are summarised in Table 1. Generally these trends show similar values to those quoted in previous studies. Confidence bounds were also calculated for each linear regression trend at the 95 per cent level using the parametric technique of Seber (1977). These confidence bounds indicate that, apart from the trend for the annual mean cloud cover time-series, all trends are significant at the 95 per cent level. Significance of the trends was also tested using the non-parametric Kendall-tau method (Press et al. 1996) which gave the same results as the parametric method at the 95 per cent confidence level.

The positive trend in Australian annual mean temperature is consistent with the global mean temperature trend which also shows an increase over the 20th century (Jones et al. 1999). The study by Jones et al. indicates that, as for Australia, the global mean temperature during the 1998 was also the highest ever recorded. The record global mean temperature may have been boosted by warm SSTs associated with the declining phase of the 1998/99 El Niño event. Nevertheless, the short-term warming associated with the El Niño event was superimposed on a background trend of gradually increasing global temperatures. In the global mean temperature time-series since 1856, 10 of the 12 warmest years have occurred since 1987 (Jones et al. 1999).

The increasing Australian mean minimum temperature trend is larger than that for maximum temperature and consequently a decreasing trend is evident in the diurnal temperature range (DTR). The DTR time-series used was actually the anomaly of Australian annual mean DTR, calculated by subtracting the annual mean minimum temperature anomaly values from the annual mean maximum temperature anomaly values. This decreasing trend is studied in greater detail for different regions of Australia by Plummer et al. (1995) and Torok and Nicholls (1996). A decreasing trend in DTR has also been observed over many other land areas of the globe (Karl et al. 1993).

The positive rainfall trend value determined in this study is larger than that found in previous studies, primarily because of the decision not to use pre-1900 values which include a number of relatively wet years. The high interannual variability of Australian mean rainfall results in large 95 per cent confidence bounds, indicating that the calculated trend is only just significant at the 95 per cent level. The non-parametric Kendall-tau method also indicated only marginal significance in the rainfall trend at this confidence level. The 95 per cent confidence bounds for the cloud series were also large, resulting in a non-significant trend. Due to the shorter time period and general shape of the cloud data distribution (a rise to a peak in the mid-1970s followed by a weak decline), a linear fit to this data is not appropriate. However, a linear trend value is included for the cloud series in Table 1 for completeness.

Table 1. Linear trend values for annual mean time-series from updated high-quality datasets.

	Trend (per century)	*95% confidence bounds*	*Period*
Max T (°C)	0.61	±0.31	1910-1998
Min T (°C)	1.05	±0.28	1910-1998
Mean T (°C)	0.83	±0.26	1910-1998
DTR (°C)	-0.43	±0.28	1910-1998
Rain (mm)	65	±57	1900-1998
Cloud (oktas)	0.57	±0.60	1957-1998

The increasing trends in all-Australian mean surface temperature and rainfall and decreasing trend in DTR are consistent with the results of an enhanced greenhouse climate simulation by Power et al. (1998a). The study used a coupled atmosphere/ ocean/sea-ice model to compare simulations of the Australian climate before and after a three-fold increase in atmospheric carbon dioxide. The observed increase in atmospheric carbon dioxide throughout the 20th century is considerably less than a factor of three. Nevertheless, the similarities between observed and modelled changes suggest that greenhouse warming may account for some of the changes. However, it remains possible that such changes are simply due to natural variability.

Correlations between the detrended annual mean time-series used in this study are shown in Table 2. These correlations were applied over the period 1910 to 1998, except for correlations involving cloud data, which were calculated over the period 1957 to 1998. The time-series were detrended by subtracting the linear regression values from the annual mean values for each year.

Both mean maximum and minimum temperatures were higher than average in 1998, consistent with the positive correlation (0.54) between their annual mean time-series. However, the combination of higher than average maximum temperature and greater than average rainfall during 1998 appears to be unusual in the instrumental record, as suggested by the negative correlation (-0.63) between the annual mean time-series of maximum temperature and rainfall. Nicholls et al. (1996b) also found a strong negative correlation between maximum temperature and rainfall using earlier versions of the high-quality datasets used in this study. However, the mean values for 1998 are not necessarily inconsistent with more recent behaviour of the Australian climate. Nicholls et al. (1996b) demonstrated abrupt changes in the relationships between some Australian mean climate parameters during the early 1970s. One of the main changes identified was an increase in maximum temperature relative to rainfall. The mean maximum temperature of 1998 was increased so greatly with respect to rainfall that both were higher than average during the year. The other identified change since 1970 was an increase in Australian rainfall relative to SOI.

Intuitively, greater than average rainfall associated with above average cloud cover during 1998 is consistent with milder overnight temperatures. However, this is not reflected in the long-term correlation (0.05) between the annual mean values of minimum temperature and rainfall. Nicholls et al. (1996b) also found no correlation between annual mean minimum temperature and rainfall in the observational record. However, Nicholls et al. (1997) found that the close correlation between maximum and minimum temperature masks a relationship between minimum temperature and rainfall. Removing the variability associated with maximum temperatures, the partial correlation between minimum temperature and rainfall was found to be strongly positive, reflecting a tendency for wet years to also have higher than average minimum temperatures. The results for 1998 are consistent with this relationship. The positive correlation between minimum temperature and rainfall is also reflected in the correlation between DTR and rainfall being a stronger negative correlation (-0.74) than that between maximum temperature and rainfall (-0.63).

Reflecting the strong correlation of maximum temperature with rainfall, Power et al. (1998b) found a tendency for annual mean DTR and mean temperature to be out of phase with rainfall in the observational record. These relationships were also evident in output from an atmospheric general circulation model forced with observed sea-surface temperatures.

Table 2. Correlations between annual mean time-series. Note that correlations involving cloud are calculated over the period 1957 to 1998 while all other correlation are calculated over the period 1910 to 1998. Asterisks denote correlations that are significant at the 95% level using the Kendall-tau method.

	Cloud	Rain	DTR	Mean T	Min T
Max T	-0.57*	-0.63*	0.56*	0.88*	0.54*
Min T	0.21	0.05	-0.39*	0.83*	
Mean T	-0.24	-0.36*	0.12		
DTR	-0.80*	-0.74*			
Rain	0.84*				

Consequently, the result of a negative annual mean DTR anomaly (-0.61°C) for 1998 is consistent with these findings. The positive mean temperature anomaly in 1998 appears to be uncommon for a wetter than average year. However, this does not seem to be as rare as higher than average maximum temperature during a wet year, as the correlation between mean temperature and rainfall (-0.36) is weaker than that for maximum temperature and rainfall (-0.63).

Greater than average cloud cover for Australia in 1998 is consistent with wetter than average conditions through most of the country. This relationship is common in the instrumental record, as demonstrated by the high positive correlation (0.84) between annual mean rainfall and cloud cover. Power et al. (1998b) also found Australian mean cloud cover to be generally in phase with rainfall in output from an atmospheric general circulation model. The strong relationship between cloud and rainfall is reflected in the correlations between cloud and temperature being of similar values to the equivalent correlations between rainfall and temperature. In particular, there is a strong tendency for annual mean cloud cover and maximum temperature to be out of phase, resulting in a correlation of -0.57. Again, the results of 1998 appear anomalous with this long-term relationship.

Conclusions

Correlations between the annual mean time-series derived from the updated high-quality datasets used in this study indicate that a warm, wet and cloudy year in 1998 is unusual in the instrumental record. However, several previous studies (e.g. Nicholls et al. 1996b; Power et al. 1998b) have noted that the long-term relationships between rainfall and temperature appear to have changed since the early 1970s. The annual mean values of key climate variables in 1998 appear to be consistent with relationships established since the change, although it is also possible that the apparently anomalous results of 1998 could have simply occurred by chance.

The changes in relationships between parameters are unlikely to be due to changes in instruments or observation practice (Nicholls and Kariko 1993; Torok and Nicholls 1996). Nicholls et al. (1996b) suggested that these changes could be associated with climate change involving increasing temperature with minimal change in rainfall. Power et al. (1998b) suggested that the changes may be due to naturally occurring interdecadal climate variability, predictable modes of decadal variability or greenhouse warming. Whatever the underlying reason, such changes would have serious implications for applications such as seasonal climate prediction. This highlights the importance of maintaining long-term climate monitoring in order to better understand potential changes in Australia's climate.

Acknowledgments

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