Climate Extremes

Indicators for State of the Environment Monitoring

By N Nicholls, B Trewin and M Haylock

AUSTRALIA: STATE OF THE ENVIRONMENT
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Series No. 2

Paper 1 | **The Atmosphere**

Environment Australia
Department of the Environment and Heritage

STATE OF THE
ENVIRONMENT
REPORTING

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By N Nicholls, B Trewin and M Haylock

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Preface

The national State of the Environment Reporting System is a program for regular, systematic analysis and evaluation of Australia's environment. The first major product of the system, *Australia: State of the Environment 1996*, was released in September 1996. Production of a State of the Environment Report covering the Australian jurisdiction is now a legislative requirement under the *Environment Protection and Biodiversity Conservation Act 1999*, the next report must be prepared by December 2001.

Since the publication of *Australia: State of the Environment 1996* a set of environmental indicators has been developed by technical and scientific experts for each of the seven reporting themes: Human Settlements; Biodiversity; The Atmosphere; The Land; Inland Waters; Estuaries and the Sea (now Coasts and Oceans); and Natural and Cultural Heritage.

This work culminated the world leading research documented in the Environmental Indicators Series for National State of the Environment Reporting. The theoretical framework and sets of environmental indicators documented in these reports provide the fundamental basis for the collection and analysis of data that will be used for the 2001 Australian State of the Environment Report and beyond.

The 2001 Australian State of the Environment Report will concentrate on trends and changes since the 1996 report, cover new and emerging issues, and will pioneer the use of the environmental indicators on a continental scale.

In conjunction with the second reporting cycle, a new technical paper series has been initiated. The papers in this second series were commissioned to contribute to the preparation of the next national State of the Environment Report. The scope of the second series of technical papers includes analysis of trends in environmental indicator data, case studies, and reviews of particular issues. All papers in the second technical paper series have been peer reviewed externally.

A list of national State of the Environment Reporting products and details on how to obtain them is provided at the back of this paper.

Acknowledgments

This paper was produced with support from the Australian State of the Environment Section of Environment Australia. Comments from Tahl Kestin were greatly appreciated.

Abstract

Various indices for monitoring variations in Australian climate extremes have been developed and calculated. Considerable efforts have been expended to ensure that the data used to construct the indices were not affected by inhomogeneities likely to result in biased trends. It is feasible to calculate the annual values of these indices each year. The indices selected provide a good overview of variations in extreme weather conditions relevant to many sectors of Australian society.

Most of the trends in the various indices of climate extremes investigated were relatively weak and lacked statistical significance. The main exceptions were trends in rainfall extremes in south-western Australia and trends in temperatures over the entire Australian region especially overnight minimum temperatures, where stronger warming trends were evident. At least in the case of annual temperature, however, the strong trend simply reflected a shift in the mean, with little evidence of changes in the frequency distribution about the mean. Overall, the results presented here do not provide strong evidence of a climate becoming more extreme or variable. However, it must be stressed that, while countrywide indices may show no trend, significant changes could possibly have occurred at the regional level. Also, while the indices examined in this paper provide a good selection of indicators of extremes, they are in no way comprehensive and the possibility of changing climate variability cannot be discounted on the basis of this paper.

Summary

Various indices for monitoring variations in Australian climate extremes have been developed and calculated. Considerable efforts have been expended to ensure that the data used to construct the indices were not affected by inhomogeneities likely to result in biased trends. The indices are:

- Number of tropical cyclones in various intensity categories;
- Annual-average windiness in Bass Strait;
- Average intensity of precipitation falling on very wet days, the number of very wet days, and the proportion of total rainfall falling on very wet days;
- Percentage of the country in drought (lowest 10% of annual rainfall) or wet conditions (highest 10% of annual rainfall);
- Percentage of the country very hot (mean annual temperature in highest 10% on record) or very cold (lowest 10%); and
- Areal-average frequency of cold or warm nights and days (temperatures in lowest 10% or in highest 10% of historical daily temperatures).

It is feasible to calculate the annual values of these indices each year. The indices selected provide a good overview of variations in extreme weather conditions relevant to many sectors of Australian society.

Examination of time series of these indices indicates that:

- The number of weak and moderate tropical cyclones observed has decreased since 1969 which, although consistent with changes in the Southern Oscillation Index, may be partly caused by changes in the observational network;
- The number of intense tropical cyclones has increased slightly since 1969;
- Windiness in the eastern Bass Strait has fallen, while it has increased slightly in the western Bass Strait, since the early 1960s;
- There has been a strong decrease, since 1910, in the intensity of rain falling on very wet days, and in the number of very wet days, in the south-west of the continent;
- There has been a strong increase in the proportion of annual rainfall falling on very wet days in the north-east;
- No clear trend has emerged in the percentage of the country in extreme rainfall (drought or wet) conditions, since 1910;
- There is a downward trend in frequency of cool nights, with some evidence of an upward shift in frequency of warm nights (since 1957);
- There is some suggestion of an increase in frequency of warm days since the mid-1970s; and
- No clear trend exists in the frequency of cool days.

Background

A workshop on indicators for the atmosphere for state of the environment (SoE) monitoring held in Melbourne on 21-22 January 1997 recommended that research be carried out to develop climate extremes indicators for SoE monitoring. The Australian State of the Environment Section of Environment Australia funded the Bureau of Meteorology Research Centre (BMRC) to carry out this research.

An international Workshop on Indices and Indicators for Climate Extremes, held in Asheville, North Carolina, USA, 3-6 June 1997 (Karl *et al.*, 1998) proposed a group of indices for monitoring climate extremes. Plummer *et al.* (1998) summarise other recent work documenting trends in climate extremes for Australia and New Zealand.

Climate extremes indices

As a result of the deliberations of the Asheville Workshop, it was decided that calculation of time-series of several climate extremes indices for Australia would provide a useful summary of temporal variations in extremes. The indices are listed below, and the methods and results of the calculation of these indices are described.

Storms

1. Number of tropical cyclones in various intensity categories.

Here we examine trends in tropical cyclone activity in the Australian region (south of the equator; 105-160°E), including both cyclones that formed in the region and cyclones that moved into the region after forming elsewhere. Improvements to the observational network have led to an increase in the number of cyclones observed. The largest increase occurred when satellite observations began in 1969/70. We therefore follow Holland's (1981) suggestion by considering only observations from this season onwards. Still, changes in the network since this date have meant that previously some systems may have been identified as cyclones when the observational evidence was incomplete, leading to an artificial decline in numbers. Adding to this decline is an increased understanding of cyclone structure which has enabled observers to more readily distinguish cyclones from types of systems not possessing the traditional tropical cyclone inner-core structure, which previously would have been identified as cyclones.

Time-series of the total number of tropical cyclones, along with the number with minimum pressures higher than 990hPa ("weak" cyclones), the number with minimum pressures less than 970hPa ("intense" cyclones), and the number between 970 and 990hPa ("moderate" cyclones), in each year since the 1969/70 season, are shown in Fig. 1. The total number of cyclones shows a significant downward trend. The correlation with the year was -0.43, significant at 95%. The number of weak and moderate cyclones also declined (correlations with year were -0.35 for weak cyclones and -0.56 for moderate cyclones). However, the number of intense cyclones increased, although the correlation with year (0.17) was weak and not significant.

Fig. 1a: Time series of the number of tropical cyclones in the Australian region.

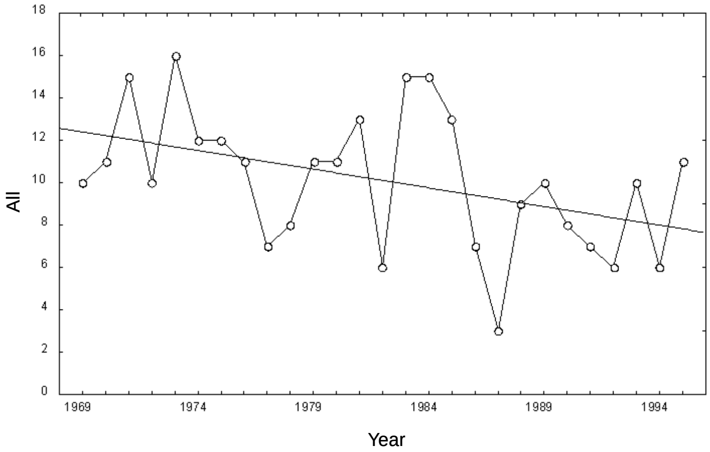


Fig. 1b: Time series of the number of weak tropical cyclones (those with minimum pressures greater than 990 hPa) in the Australian region.

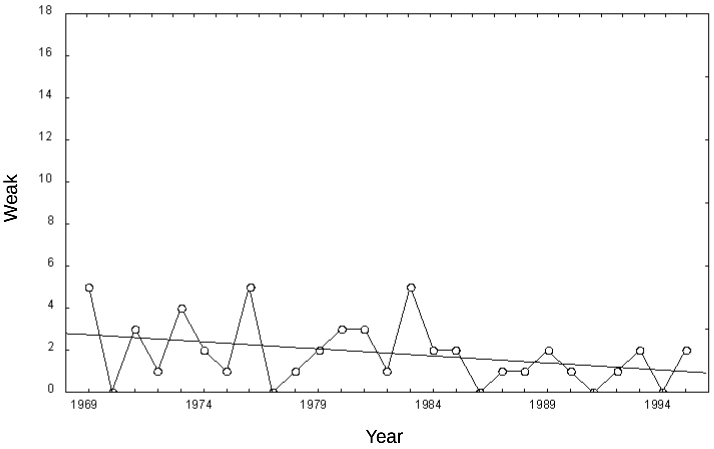


Fig. 1c: Time series of the number of moderate tropical cyclones (those with minimum pressures between 990 and 970 hPa) in the Australian region.

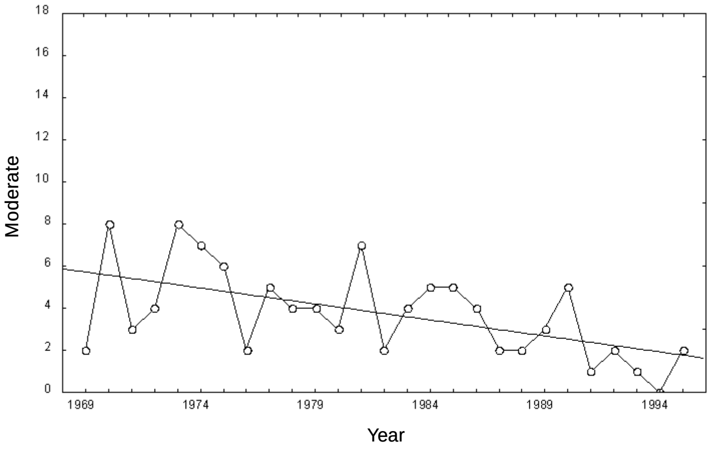


Fig. 1d: Time series of the number of strong tropical cyclones (those with minimum pressures less than 970 hPa) in the Australian region.

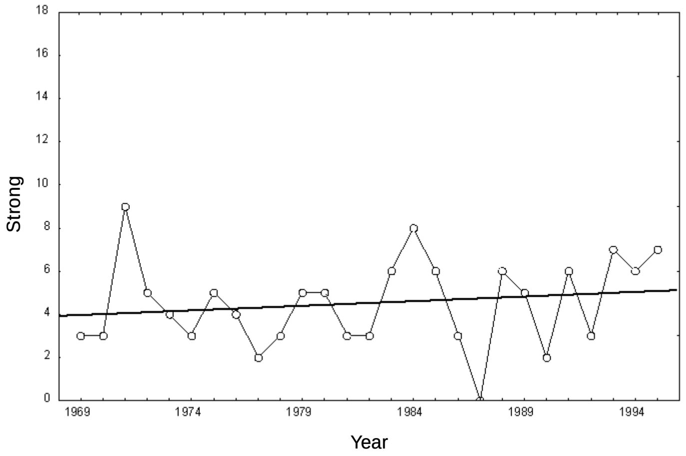
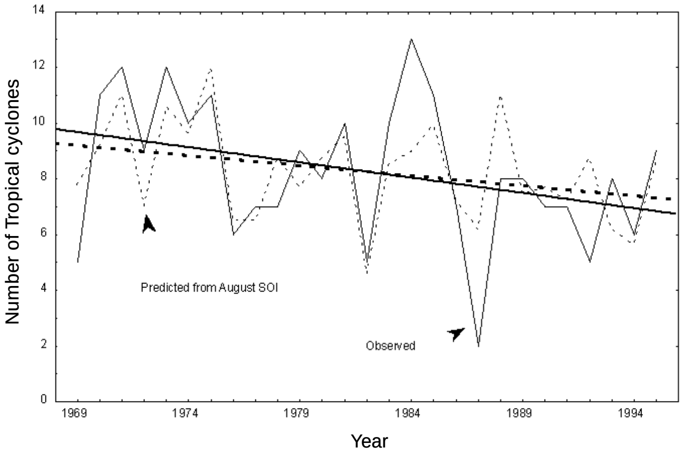


Fig. 2: Observed and predicted numbers of tropical cyclones with minimum pressures less than 990 hPa, in the Australian region. Prediction is from August SOI.



Much of the decline in the number of weak cyclones occurred abruptly, in the mid-1980s. Before and after 1985 there is little evidence of trends. The mean number of weak cyclones between 1969/70 and 1984/85 was 2.4; the mean number since the 1985/86 season has been 1.1; a difference significant at the 5% level. The abrupt nature of this decline suggests that the drop may be artificial, reflecting the changes in the understanding (and naming) of tropical cyclones as noted above.

The decline in the number of moderate cyclones can be attributed to changes in the El Niño – Southern Oscillation. The relationship between cyclone numbers and the Southern Oscillation Index (SOI), noted by Nicholls (1992), can be used to predict cyclone activity. Low values of the SOI during the Southern Hemisphere spring, typically associated with an El Niño, usually indicate that the ensuing cyclone season will have fewer than normal cyclones. Since the mid-1980s, there has been a decrease in the number of tropical cyclones predicted by the SOI values. This is shown in Fig. 2 which presents the number of tropical cyclones with minimum pressures less than 990hPa, along with the number of cyclones "predicted" by linear regression from the August SOI. The similarity in the linear trends of both series indicates that the SOI trend is the "cause" of much of the trend in cyclone numbers. That is, tropical cyclone activity in the Australian region has declined in recent years because of the tendency for a bias in the behaviour of the El Niño – Southern Oscillation relative to earlier years. Trenberth and Hoar (1996) point out that the recent behaviour of the El Niño – Southern Oscillation has been unusual, and biased toward more frequent, extended, or more intense El Niño episodes than previously. Since El Niño events (when the SOI is strongly negative) are usually associated with lower than normal tropical cyclone activity around Australia, the bias or trend noted by Trenberth and Hoar should have been accompanied by a trend towards fewer cyclones, as has been the case. More information can be found in Nicholls *et al*. (1998).

The weak increase in the number of more intense tropical cyclones has been more gradual and sustained over the period examined. The threshold of 970hPa for intense tropical cyclones equates, in the Australian region, to tropical cyclones with an eye identifiable from satellite imagery. Therefore the number of intense tropical cyclones is less likely to have been affected by changes in interpretation or observation networks since the advent of routinely available satellite images. However an artificial cause for the upward trend in intense cyclones cannot be entirely discounted.

2. Annual-average windiness, estimated from atmospheric pressure-gradient variations.

Trends in wind speed are an important aspect of climate change and variability. These trends are difficult to determine directly, as records of wind speed at any given station are highly sensitive to changes in the local environment (e.g., buildings erected in the vicinity) as well as to systematic changes arising from altered instrument types. Wind speed can also vary greatly over short intervals in both space and time. This makes it difficult to verify the validity of any given observation at a station. The field of sea-level atmospheric pressure is much more coherent in space and time, and is more suited to validity checks. This study therefore uses pressure gradients as a surrogate for windiness. The pressure gradient is the major influence on the large-scale wind field.

Only locations in Bass Strait could be used for this index, because of the specific data needs. The windiness index seemed most appropriate for coastal regions, but a network of stations recording pressure is needed to estimate windiness. Bass Strait was one ocean situation where sufficient data were readily available to allow the appropriate calculations.

There are eight stations in or bordering Bass Strait with daily pressure records over most of the last 40 years. The starting point of this study was 1957, as it is the starting point of daily data in digital form at the majority of stations.

The pressure data were subjected to the following quality control procedures:

1. The mean monthly sea-level pressure at each station for each month in the record was compared with the mean pressure of the three nearest neighbouring sites. The differences in the pressures between the station and the neighbouring sites were tested for inhomogeneities. Where inhomogeneities were detected, the data from before the inhomogeneity were adjusted to be consistent with the most recent data.
2. Each individual observation was checked against the observations at the same time from its nearest neighbours, and against observations immediately preceding and following it at the same station. Observations flagged through this process were checked using synoptic charts for the day and set to missing if they were suspect.

The observed wind speeds at Flinders and King Islands were compared with the pressure gradients in the vicinity of these stations, to check that the pressure gradients provided a useful index of wind speed. In order to compute the pressure gradient it is necessary

Fig. 3: Ratio of wind speed to pressure gradient at Flinders Island.

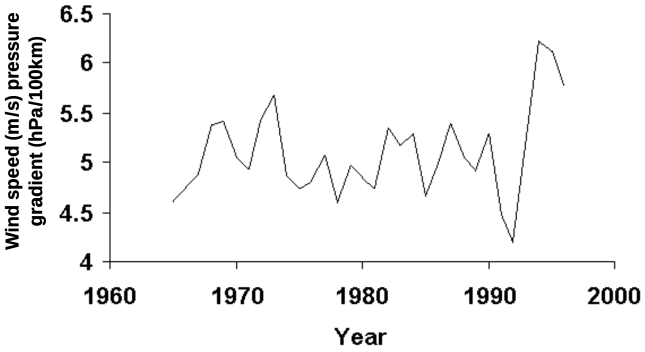


Fig. 4a: Pressure gradient in central Bass Strait.

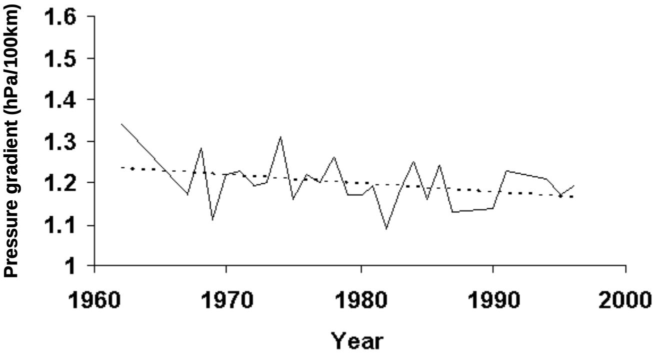


Fig. 4b: Pressure gradient in eastern Bass Strait.

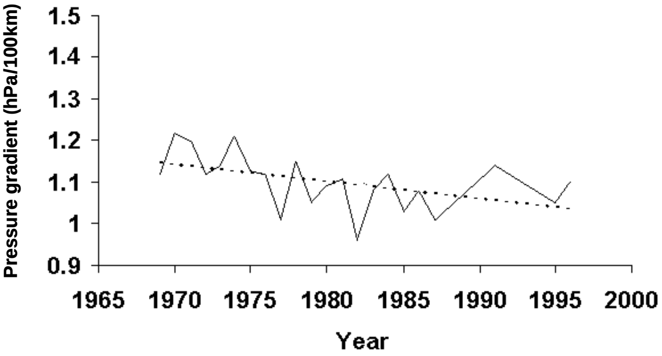
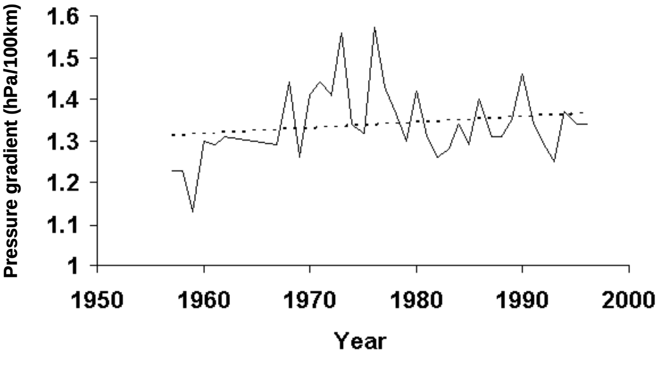


Fig. 4c: Pressure gradient in north-west Bass Strait.



to use two pairs of stations, preferably located such that the lines linking each pair intersect at an angle as close to 90∞ as possible. It is also necessary that the observations be simultaneous, thereby precluding the use of observations when Victoria and Tasmania are in different time zones. Correlations between the wind speed and pressure gradients as observed at 0900 each day suggest that the pressure gradients quite accurately reflect wind speeds near the centre of the area enclosed by the stations, even if one of the stations is quite distant from that centre (e.g., using Gabo Island pressure in a correlation with Flinders Island winds).

Figure 3 shows the ratio (mean wind speed)/(mean of daily pressure gradients) at Flinders Island. The ratio is quite stable except for a jump in 1991-92. This jump appears to have been caused by a change in instrument type, underlining the potential problems in using daily wind speed data to calculate trends in wind speed directly.

The eight stations were used to define eight regions for which pressure gradients were calculated. For each of the pressure gradient series, a mean monthly value was calculated from the magnitude of the daily pressure gradients. Three of these time series are plotted in Fig. 4. There has been a marked fall in pressure gradient (and thus in wind speed) over eastern Bass Strait, offset to some extent by a slight rise in the west.

This is more marked in summer than winter. While the questionable quality of the wind data means that trends in these data should be interpreted with caution, the trends in the direct wind measurements at Flinders Island and at King Island support the trends in pressure gradients in the eastern and western Bass Strait.

The observed fall in pressure gradient over eastern Bass Strait, coupled with the observed rise over western Bass Strait, suggests the possibility of circulation changes over the Bass Strait region. Leighton and Spark (1997) isolated several regions in south-eastern Australia which show a significant trend in anticyclonicity totals from 1965 to 1993.

Precipitation

3. Average intensity of precipitation falling on very wet days, the number of very wet days, and the proportion of total rainfall falling on very wet days.

Three indices of extreme rainfall were examined: the average intensity of rain falling in the highest 5% of 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 1mm of rain. Thresholds lower than 1mm can introduce trends in the number of raindays, associated with changes from imperial to metric units in 1974 (Hennessy *et al.*, 1999).

The extreme intensity describes changes in the upper percentiles and, unlike an analysis of a single percentile in isolation (e.g. Hennessy *et al.*, 1999), incorporates changes in all events above this percentile. The threshold for this index is the 95th percentile calculated from only raindays in order to maintain a fixed proportion of events. The index is calculated by averaging all events in the year with intensities equal to and above this threshold. 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 (e.g. Suppiah and Hennessy, 1998) will be influenced by the change in the number of raindays.

In calculating the *extreme frequency*, we elected to use a different cut-off for each station, rather than following the method of Karl *et al.* (1995b) involving a fixed threshold.

Fig. 5: Locations of 91 high quality rainfall stations and their division into three regions and one subregion.

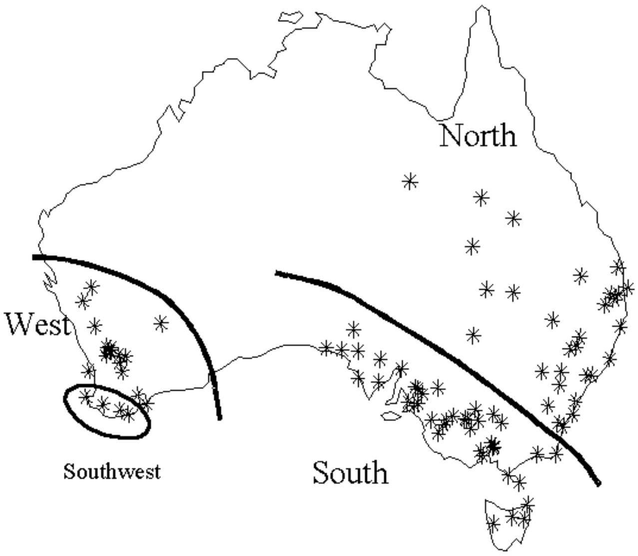


Table 1: Trends in total rainfall, the number of raindays and the three extreme indices for the four regions. Trends in bold are significant at the 5 percent level.

Region	Total mm/100yrs	Raindays days/100yrs	Extreme Intensity mm/100yrs	Extreme Percent %/100yrs	Extreme Frequency days/100yrs
north	87.33	**9.18**	2.17	**1.67**	0.56
south	50.17	6.39	-0.36	-0.38	0.30
west	-67.79	-6.55	-0.33	0.25	-0.68
south-west	**-185.07**	**-12.73**	**-3.36**	-0.21	**-2.63**

A fixed threshold is impractical for a country like Australia with a high spatial variation in rainfall intensity (the mean 95th percentile for the 91 stations varied from 14 to 48 mm/day). The index is calculated by counting the number of events in the year with intensities above this threshold. This approach is similar to that used by Karl and Knight (1998) who considered changes in frequencies of events above long-term percentiles in 5% groups over the US region.

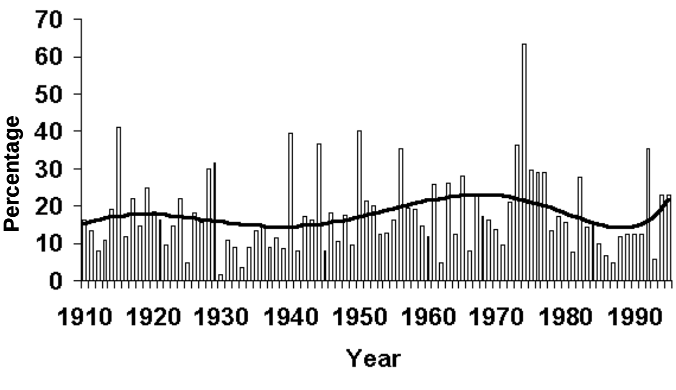
The *extreme percent* reflects changes in the upper portion of the distribution. The question of whether the rainfall distribution is becoming more "extreme" is complicated by changes in the number of raindays. The percentage of the total rainfall from the higher events is an indictor of changes in the shape of the rainfall distribution. This index is calculated for each year by dividing the year's total rainfall by the *extreme intensity*.

Ninety-one stations were selected from the Bureau's high-quality daily rainfall data set (Lavery *et al*., 1992) on the basis of having little missing data. They were divided into the three broad geographical regions: north, south, and west (Fig. 5), based on their location and annual rainfall cycle. All the stations in the south received more than 50 percent of their annual rainfall in the months May to October for the full record, while the stations in the northern group (except one) received less than 50 percent in these months. The stations in the west also received most of their annual rain from May to October. Four of the stations in the western group form the south-western subgroup and are of particular interest because rainfall in this region has decreased markedly since about 1960 (Allan and Haylock, 1992). These four stations are also included in the western group. The grouping corresponds closely with state boundaries: all the stations in the west are located in Western Australia, the stations in the south (except one) are located in Victoria, South Australia and Tasmania and all the stations in the north are located in New South Wales and Queensland.

Time series of the total rainfall, the number of raindays with at least 1mm rainfall, and the three extreme indices were calculated for each of the four regions for the period May 1910 to April 1998. In all cases the linear trend of the series appears to be a reasonable approximation to the long-term variations. A summary of the trends in these time series (Table 1) generally shows an increase in the northern and southern regions and a decrease in the western and south-western regions in all the variables. The exceptions were a decrease in the *extreme intensity* and *extreme percent* in the south and an increase in the *extreme percent* in the west, but none of these exceptions were significant.

Significant changes in the extreme indices were decreases in the south-west for the *extreme intensity* and *extreme frequency* and an increase in the *extreme percent* in the north. 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 decreasing above an extreme threshold, but the average intensity of the top 5% of events *taking into account the reduction in raindays* is also decreasing in the south-west. The significance of the increase in the extreme percent in the northern region, although only a small change of 1.6% per 100 years, reflects the low interannual variability in this index. This result shows

Fig. 6: Percentage of Australia with annual rainfall below decile 1 or above decile 9. Bold line shows 6th-order polynomial.



that although the average intensity of extreme events has been increasing insignificantly and the number of events above an extreme threshold has been increasing only marginally, the proportion of the total rain from the extreme events has been increasing significantly in the north-east.

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 *extreme 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, the insignificant positive correlations of the *extreme percent* suggest that the proportion of the total rainfall falling in the top 5% of events is not dependent on the total rainfall.

4. Percentage of country with annual precipitation below the 10th and above the 90th percentile (i.e. serious drought or wet conditions).

The index combines the amount of the country in drought (i.e. below 10th percentile) with that in wet conditions (i.e. above 90th percentile) and thereby shows how extreme, in terms of widespread precipitation, a particular year is. If Australia were tending to have more "droughts and floods" there would be a positive trend apparent in this index.

Using the high quality monthly rainfall data set as described in Lavery *et al*. (1997), annual total rainfall was calculated for each year of the period 1910-1995 at 379 stations around Australia. For each station, the 10th and 90th percentiles were calculated for the annual totals, then a weighting was determined for the station depending on the percentage of the country that this station occupied, with isolated stations having higher weights than stations in close proximity. Finally, for each year the weights were totalled for stations with annual totals below the 10th or above the 90th percentile.

A time series of this index, calculated for the country as a whole, is shown in Figure 6. One feature of note in this figure is the cluster of extreme years in the mid-1970s associated with widespread wet conditions. There is no obvious long-term trend. This index reflects only widespread extreme annual precipitation. If stations experienced floods and droughts independently of surrounding stations, one would expect the index to remain at around 20%. However, as can be seen in Figure 6, the large number of peaks corresponding to both wet years (e.g. 1915, 1950, 1974) as well as dry years (e.g. 1929, 1940, 1992) indicates that floods and

Fig. 7: Time-series of percentage of country warmer than 90th percentile and cooler than 10th percentile based on mean annual data. Bold line shows 6th-order polynomial.

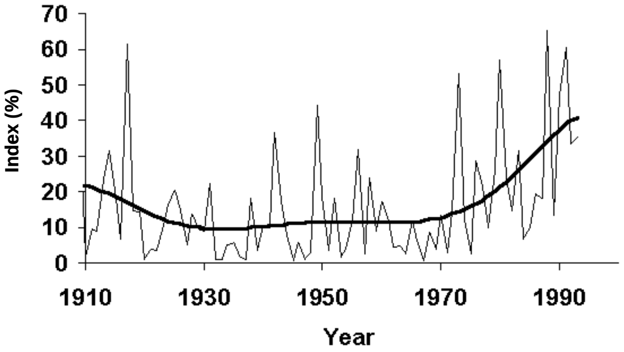


Fig. 8a: Time-series of percentage of country cooler than 10th percentile based on mean annual data. Bold line shows 6th-order polynomial.

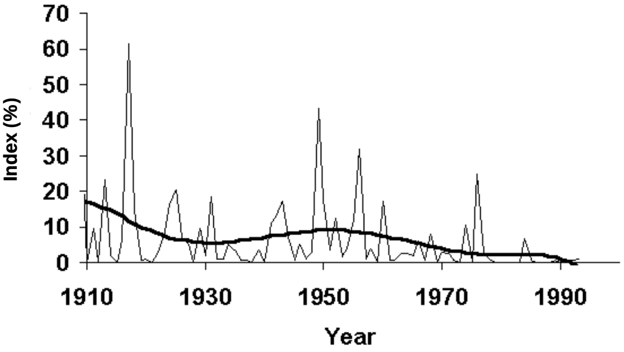


Fig. 8b: Time-series of percentage of country warmer than 90th percentile based on mean annual data. Bold line shows 6th-order polynomial.

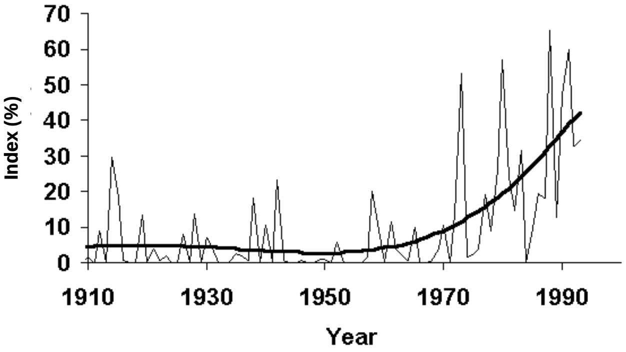


Fig. 9: Time-series of area-averaged temperature based on mean annual data. Bold line shows 6th-order polynomial.

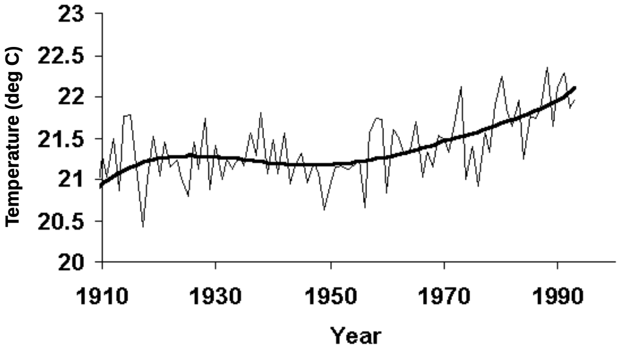


Fig. 10: Time-series of percentage of country warmer than 90th percentile and cooler than 10th percentile on detrended time series based on mean annual data. Bold line shows 6th-order polynomial.

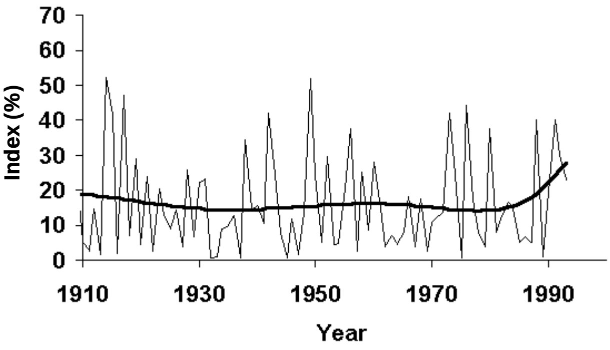


Fig. 11: Time-series of percentage of country warmer than 90th percentile and cooler than 10th percentile on detrended time series based on minimum annual data. Bold line shows 6th-order polynomial.

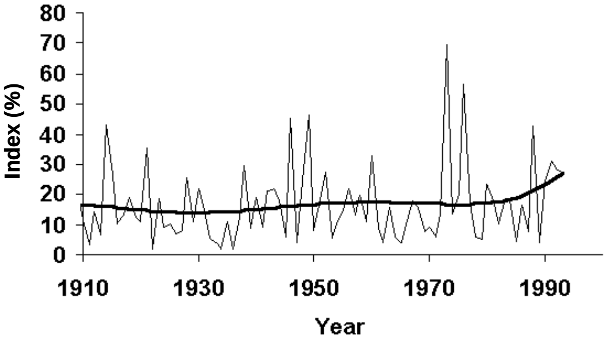


Fig. 12: Time-series of percentage of country warmer than 90th percentile and cooler than 10th percentile on detrended time series based on maximum annual data. Bold line shows 6th-order polynomial.

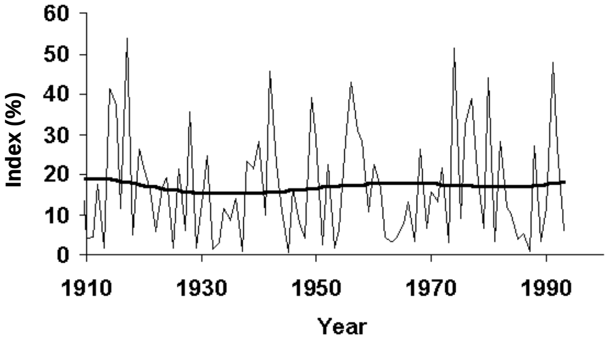
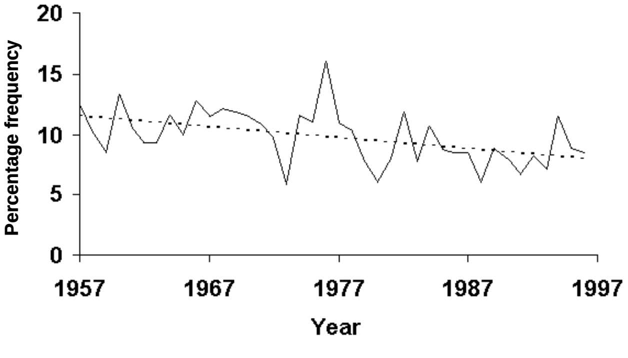


Fig. 13: Areal-average percentage of days with minimum temperatures below the 10th percentile.



droughts can occur over large areas. This observation is supported by our knowledge of the generally large-scale causes of these phenomena such as the Southern Oscillation (Nicholls and Kariko, 1992).

Temperature

5. Time-series of percentage of country warmer than 90th percentile and cooler than 10th percentile.

This index examines the changes in mean annual temperature over the country. A sharp drop in the number of available stations before 1910 restricts the time period for the analysis to after that year.

Annual mean temperature was calculated for each year of the period 1910-1993 at 224 stations around Australia. For each station the 10th and 90th percentiles were calculated for the annual temperature, then a weighting was determined for the station depending on the percentage of the area that this station represented, with isolated stations having higher weights than stations closely clustered. Finally, for each year the weights were totalled for stations with annual temperature below the 10th or above the 90th percentile.

At a single station under an unchanging climate, one would expect the 20 percent of years that fall outside the 10–90 percentile range to be regularly distributed. However, as Figure 7 shows, the decline from 1910 to 1930 then the steady rise after about 1970 indicates that there is a greater concentration of these 'extreme' years at either end of the record.

Whether this is due to an increase in the number of cooler or warmer years is answered by Figure 8, which shows both these series separately. The steady decline of cooler years as shown in Figure 8a and the sharp rise in warm years in Figure 8b suggest an overall warming of the continent this century. This warming is evident in Figure 9, which shows the areal-averaged mean annual temperature over Australia. Since this study is primarily interested in changes in climate variability, the trend is removed in order to overcome the effects of warming. Removing this trend from each station before calculating the index gives the series as shown in Figure 10.

With no significant trend, this series suggests that there has been no change in the distribution of relatively warmer and cooler years for the detrended temperature, but overriding this is a significant warming over the time period. This index illustrates only widespread extremes in annual temperature and

Fig. 14: Areal-average percentage of days with minimum temperatures above the 90th percentile.

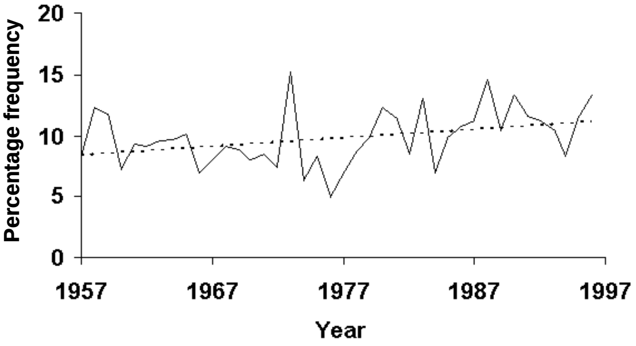


Fig. 15: Areal-average percentage of days with maximum temperatures above the 90th percentile.

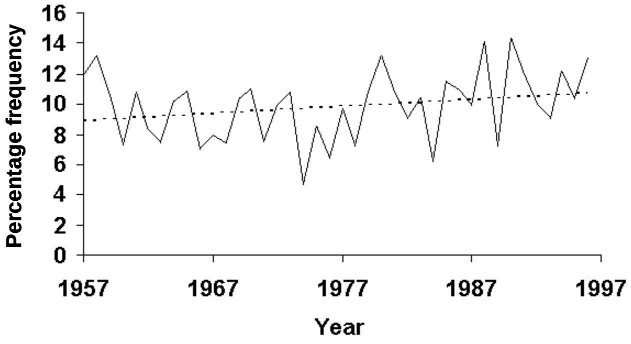
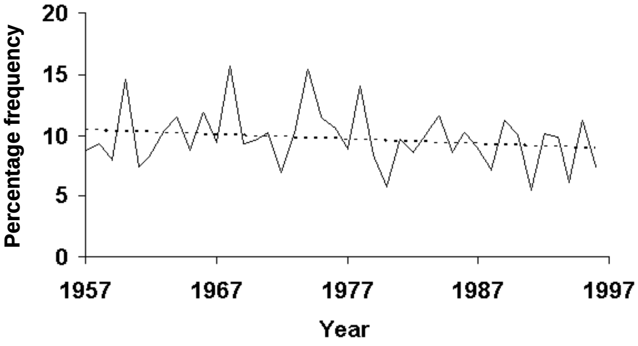


Fig. 16: Areal-average percentage of days with maximum temperatures below the 10th percentile.



any irregular distribution of extremely warm or cool temperatures at a single station would not be evident if most other stations were not experiencing such extremes. However, climate studies investigating temperature variation over Australia have shown that much of the variability is caused by large-scale phenomena, such as the Southern Oscillation, causing widespread changes in Australian temperatures (Coughlan, 1979).

A similar analysis was carried out using detrended minimum and maximum temperatures with the results shown in Figures 11 and 12. There is no significant trend in the results indicating that, although minimum and maximum temperatures have increased over the period 1910-1993, the variability has remained constant.

6. Areal average of percentage of very cold or warm days or nights (daily temperature in lowest 10% or highest 10% of historical temperatures).

Time-series of the areal average frequency of days with minimum temperatures below the 10th percentile and (separately) above the 90th percentile were calculated. These indices provide a guide to the area experiencing unusually frequent warm minimum temperatures or cool minimum temperatures. Percentile thresholds, rather than fixed temperature thresholds, were chosen because they are applicable to all parts of Australia in all seasons. To illustrate the difficulty in considering fixed thresholds, any analysis of interannual variability of the frequency of minimum temperatures below 0°C in Australia would be dominated by the five stations in the data set with more than 50 such nights per year; such an index would not consider conditions in the remainder of Australia, or outside of the winter period.

The number of days above the 90th percentile or below the 10th percentile was calculated on a high-quality 1957–1996 daily temperature data set. All data were checked and adjusted for inhomogeneities. The inhomogeneities were identified by the methods described in Torok and Nicholls (1997) and adjusted using the techniques described in Trewin and Trevitt (1996). Various methods were tested for calculating spatial averages. Little difference was found between the various analysis techniques. The results presented here are for the entire Australian region.

For Australia as a whole there has been a clear downward trend since 1957 in the areal-average frequency of days with cool minima (Figure 13). There has been an upward shift in the frequency of days with warm minima (Figure 14), although this shift appears to have occurred quite suddenly, around the mid-1970s.

The average area with maximum temperatures below the 10th percentile (cool days) and the average area with maximum temperatures above the 90th percentile (warm days) were calculated. The techniques and data used to calculate these are the same as for indices based on minimum temperatures. The time series for Australia as a whole are at Figures 15 and 16.

The trends in the maximum temperatures are less clear than was the case with the minimum temperatures. The average frequency of warm days (Figure 15) has been increasing since the mid-1970s, which was when the frequency of warm days reached its lowest value. The frequency of cool days (Figure 16) has not exhibited any clear trend.

Conclusions

Most of the trends in the various indices of climate extremes investigated here were relatively small and lacked statistical significance. The main exceptions to this were trends in rainfall extremes in south-western Australia and trends in temperatures over the entire Australian region—especially overnight minimum temperatures, where stronger warming trends were evident. At least in the case of annual temperature, however, the strong trend simply reflected a shift in the mean, with little evidence of change in the frequency distribution about the mean. Overall, the results presented here do not provide strong evidence of a climate becoming more extreme or variable. However, it must be stressed that, while countrywide indices may show no trend, significant changes could possibly have occurred at the regional level. Also, while the indices examined in this paper provide a good selection of indicators of extremes, they are in no way comprehensive and the possibility of changing climate variability cannot be discounted on the basis of this paper.

References

Allan, R. J., and Haylock, M. R. 1993, Circulation features associated with the winter rainfall decrease in southwestern Australia, *Journal Climate*, 7, 1356-1367.

Coughlan, M. J. 1979, Recent variations in annual-mean maximum temperatures over Australia, *Quarterly Journal R Meteorological Society*, 105, 707-719.

Hennessy, K. J., Suppiah, R. and Page, C. M. 1999. 'Australian rainfall changes, 1910-1995', *Australian Meteorological Magazine*, 48, 1-13.

Holland, G. J., 1981. On the quality of the Australian tropical cyclone data base. *Australian Meteorological Magazine*, 29, 169-181.

Karl, T. R., and Knight, R.W., 1998. Secular trends of precipitation amount, frequency, and intensity in the United States, *Bulletin of the American Meteorological Society*, 79, 231-241.

Karl, T. R., Knight, R. W., and Plummer, N., 1995. Trends in high-frequency climate variability in the twentieth century, *Nature*, 377, 217-220.

Karl, T., Nicholls, N., and Ghazi, A., 1998. CLIVAR/GCOS/WMO Workshop on Indices and Indicators for Climate Extremes, Asheville, North Carolina, 3-6 June 1997. *Climatic Change* (in press).

Lavery, B., Kariko, A., and Nicholls, N., 1992. A historical rainfall data set for Australia, Australian Meteorological Magazine, 40, 33-39.

Lavery, B., Joung, G., and Nicholls, N., 1997. An extended high-quality historical rainfall data set for Australia. *Australian Meteorological Magazine*, 46, 27-38.

Leighton, R.M., and Spark, E., 1997. Relationship between synoptic climatology and pollution events in Sydney. *International Journal Biometeorology*, 41, 76-89.

Nicholls, N., 1992. Recent performance of a method for forecasting Australian seasonal tropical cyclone activity. *Australian Meteorological Magazine*, 40, 105-110.

Nicholls, N., and Kariko, A., 1993. East Australian rainfall events: interannual variations, trends, and relationships with the southern oscillation, *Journal of Climate*, 6, 1141-1152.

Plummer, N., Salinger, M. J., Nicholls, N., Suppiah, R., Hennessy, K. J., Leighton, R. M., Trewin, B., and Lough, J. M., 1998. Twentieth century trends in climate extremes over the Australian region and New Zealand, *Climatic Change*. (in press).

Suppiah, R., and Hennessy, K. J., 1996. Trends in the intensity and frequency of heavy rainfall in tropical Australia and links with the Southern Oscillation, *Australian Meteorological Magazine*, 45, 1-17.

Suppiah R., and Hennessy, K. J., 1998. Trends in total rainfall, heavy-rain events and number of dry days in Australia, 1910-1990, *International Journal of Climatology*, 10, 1141-1164.

Torok, S. J., and Nicholls, N., 1996. A historical annual temperature data set for Australia. *Australian Meteorological Magazine*, 45, 251-260.

Trenberth, K. E., and Hoar, T. J., 1996. The 1990-1995 El Niño – Southern Oscillation event: Longest on record. *Geophysical Research Letters*, 23, 57-60.

Trewin,B.C., and Trevitt, A.C.F., 1996. The development of composite temperature records. *International Journal of Climatology*, 16, 1227-1242.

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