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Changes in the frequency of record temperatures in Australia, 1957-2009

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The temporal distribution of record high and low temperatures in Australia during the 1957-2009 period has been investigated. Use has been made of two different data-sets: station data of daily maximum and minimum temperatures at stations drawn from the Australian high-quality daily temperature data-set, and area-averaged anomalies of monthly maximum and minimum temperature for the six Australian States and the Northern Territory.

For both data-sets, there is a marked tendency for low temperature records to outnumber high temperature records in the early part of the period, and for high temperature records to outnumber low temperature records in the later part of the period, with the ratio of high to low temperature records mostly being below 0.5 to 1 in the 1957-66 decade and above 2 to 1 in the 1997-2009 period. Time series of the difference between the numbers of high and low temperature records show positive trends significant at the five per cent level for all cases examined.

An examination of the frequency of record-setting in area-averaged data, detrended using the observed trends in mean annual Australian maximum and minimum temperatures, suggest that the frequency of record-setting is broadly consistent with the mean annual temperature trend for maximum temperatures, but for minimum temperatures changes in the frequency of record-setting are somewhat smaller than would be expected given the mean annual temperature trend.

Introduction

There has been a well-established warming trend (Cai et al. 2007) in Australia over the last 50 years, alongside similar warming trends which have been observed globally (Solomon et al. 2007). Over the period from 1957 to 2009, mean daily maximum and minimum temperatures in Australia have warmed by approximately 0.7-0.8°C (http://www.bom.gov.au/cgi-bin/climate/change/timeseries.cgi, viewed 26 April 2010).

Extreme temperature events have long been of particular interest in the assessment of climate change, because of their potential high impacts, the southeast Australian heatwave (Bureau of Meteorology, 2009) and associated bushfires of January-February 2009 being a particularly striking example. There have been a number of analyses of trends in extreme high and low temperatures in Australia since the 1950s (e.g. Collins et al. 2000; Trewin 2001; Alexander et al. 2007; Cai et al. 2007). These have found that, in general, the frequency of extreme high temperatures (both maximum and minimum) has increased in Australia and the frequency of extreme low temperatures has decreased, although there are regional variations and the signal for extreme high maximum temperatures is relatively weak.

A gap in analyses of temperature extremes, both those carried out in Australia and more globally (e.g. Alexander et al. 2006; Alexander et al. 2007), is that they generally cover relatively moderate extremes – most commonly the occurrence of days above the 90th or 95th percentile, or below the 10th or 5th percentile. There has been very limited attention given to trends in the most extreme events, although some studies have reported on trends in annual maxima and/or minima for temperature (e.g. Choi et al. 2009) or other elements (e.g. Kundzewicz et al. 2005). This is largely because they are, by definition, rare, and it is therefore very difficult to adequately identify changes in their occurrence

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through time at any individual location. Benestad (2003) notes that, while studies of the frequency of record-setting are numerous in the statistical literature, they are scarce in the climatological literature.

The temporal occurrence of record high and low temperatures has been chosen as the focus of this paper, partly to address that gap, and partly because record temperatures at a location are the subject of widespread public interest. In order to improve the signal-to-noise ratio, rather than use results from individual stations, the records have been aggregated across the Australian continent, and across the twelve calendar months of the year.

The approach taken is to compare the relative frequency of record high and low temperatures. This is a broadly similar approach to that carried out in a parallel study for the United States by Meehl et al. (2009).

This is a somewhat different approach from that taken by authors such as Benestad (2003, 2004), Fawcett et al. (2005) and Vogel et al. (2001), who have sought to determine whether the number of record events, counted sequentially from the start of a time series, differs significantly from the number that would be expected given a null hypothesis of a stationary underlying time series. A major challenge in such analyses has been assessing the significance of any changes, given the serial and spatial correlation of many climatological time series (Robert Fawcett, personal communication). A further type of study that has appeared in the literature is the assessment of the estimated return period of a specific extreme, or sequence of extremes, under a current or climate-change scenario (e.g. van Oldenborgh et al. 2006).

Data and methods

There were two complementary parts to this study. The first part involved Australian daily station data, while the second involved monthly area-averaged anomalies for the Australian States and the Northern Territory, which are drawn from gridded analyses of data from the Australian high-quality temperature daily temperature data-set (Trewin 2001).

Station-based analyses

The candidate stations for this study were drawn from the 103 stations of the Australian high-quality temperature daily temperature data-set (Trewin 2001). Most, although not all, of these stations have daily maximum and minimum temperature data from at least 1957 to 2009. The year 1957 was chosen as the start year for the present analysis because the daily temperature data from many Australian observing sites prior to 1957 remain undigitised (Jones and Trewin 2002).

The stations were then evaluated for missing data, with maximum and minimum temperatures being considered separately. An individual month was considered to be missing if there were ten or more missing days during that month. For each of the twelve calendar months, the month was used in the analysis only if it was missing in no more than one of the years in each of the ten-year periods 1957-66, 1967-76, 1977-86, 1987-96 and the thirteen-year period 1997-2009. If four or more of the twelve months were excluded under these criteria, the station was not used at all.

A major issue in the assessment of changes in observed temperatures is that of data homogeneity, as inhomogeneities can occur for numerous reasons, most commonly site moves or changes in the local site environment. The Australian high-quality daily temperature data-set includes adjustments to data to take these inhomogeneities into account. However, in this particular study, as record values are normally reported in the context of raw (not adjusted) historical data, it was decided to use unadjusted data, while excluding stations which were considered to be inhomogeneous.

For each station, annual mean maximum and minimum temperature anomalies were compared with the mean anomalies for the State in which they were located, as determined from the Australian annual temperature data-set (Della-Marta et al. 2004). The difference series was then examined, as well as any potential inhomogeneities identified from metadata (e.g. a documented site move). In general a station was excluded if one or more inhomogeneities of 0.4°C or greater were identified during the period 1957-2009. Minimum temperatures from the major urban centres (Sydney, Melbourne, Adelaide and Perth) were also excluded at this point because of potential urban heat island impacts, although it should be noted that at Sydney a comparison between local and State-wide minimum temperatures indicates no evidence of a anomalous local warming trend in the 1957-2009 period (possibly suggesting that any local urban heat island was already fully developed by 1957).

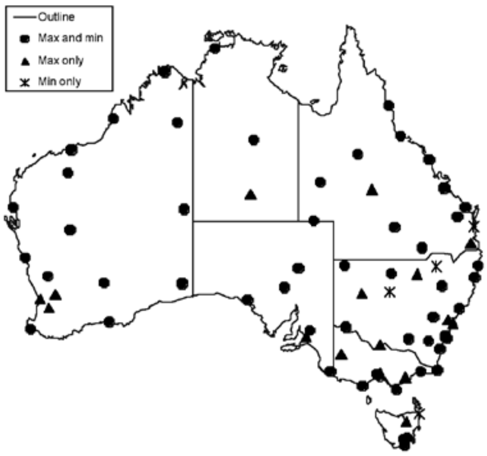
After the implementation of these selection criteria, 68 stations were used for maximum temperatures, and 56 for minimum temperatures; at nine of these stations one or more months were excluded because of missing data (a total of thirteen months for maxima and sixteen for minima). The locations of these stations are shown in Fig. 1. They are distributed across the Australian continent but are most heavily concentrated in the southeast.

For each of the stations used in the study, and for maximum and minimum temperatures separately, the year in which the highest and lowest temperature in the 53-year period 1957-2009 occurred for each of the twelve calendar months was identified.

In the event of a highest or lowest value being recorded on two or more occasions, these were attributed to years on a *pro rata* basis (e.g. if the highest value was recorded on two occasions, in 1975 and equalled in 1999, 0.5 of a record was attributed to 1975 and 0.5 of a record to 1999)[1]. A site with a complete daily maximum temperature time series over the 51-year period would therefore contribute exactly

1 Equal records were particularly common prior to metrication in 1972, when many stations reported to the nearest whole or half degree Fahrenheit most or all of the time. For example, Boulia (Queensland) has equalled its March record of 42.8°C (109.0°F) on six occasions, five of them between 1957 and 1972.

Fig. 1 Location of stations used in this study.



twelve highs and twelve lows to the total data count. In practice, missing data as described above resulted in total counts of 803 out of a maximum possible 816 (=12×68) for maximum temperature, and 656 out of a maximum possible 672 (=12×56) for minimum temperature.

The daily maximum and minimum temperature data-set contains a number of observations representing multi-day periods (for example, where the weekend observations are missing and the Monday observation is the maximum/minimum for a three-day period). For the purposes of high maximum and low minimum temperatures, these observations were still, in general, considered, as a record set at some point during a multi-day period is still a record (with the minor caveat that in a few cases the multi-day period may include parts of two calendar months). However, accumulated observations which followed a period of five or more consecutive days without observations were not considered. Such multi-day accumulated observations obviously do not yield usable values of low maximum and high minimum temperatures.

A further issue which affects a small part of the data-set is that of the time of observations for maximum and minimum temperatures. The current standard is for maximum and minimum temperatures to be measured for the 24 hours ending at 0900 local time, with the maximum being attributed to the previous day. However, in 1963 and earlier years, Bureau-staffed stations (and some others) used a period ending at midnight. Whilst the effect of this change on mean temperatures is small, in some parts of southern Australia a midnight observation time results in a markedly lower frequency of extreme high minimum temperatures in the warmer months, as unusually hot nights typically occur on the last night before a frontal passage and with a midnight observation time the minimum will normally reflect post-frontal conditions at or close to midnight the following evening (Trewin 2001). In the context of this paper, this may have resulted in a small number of record high minimum temperatures in southern Australia being missed in the 1957-63 period, although only about twenty per cent of the total network is likely to have been affected.

Area-averaged monthly analyses

The second part of the analysis was carried out using the time series of monthly area-averaged temperature anomalies (Jones et al. 2004) for the six Australian States and the Northern Territory, for maximum and minimum temperatures separately for each of the twelve months. This generated 84 data-points for maximum and minimum temperatures. While the Bureau of Meteorology's high-quality monthly analyses commence in 1950, in this study the period under consideration was limited to 1957-2009, to maintain comparability with the station-based results.

Results and discussion

Station-based daily analyses

The total number of records set in each year across the network was then calculated, for each of highest and lowest maximum temperature, and highest and lowest minimum temperature. These results are shown in Figs 2 and 3, whilst decadal mean values are shown in Table 1.

An increase is apparent over the 1957-2009 period in the number of record high maximum and minimum temperatures, and a decrease in the number of record low

Fig. 2 Frequency of record high (red) and low (blue) maximum temperatures in Australia, 1957-2007 (dashed line is 11-year running mean).

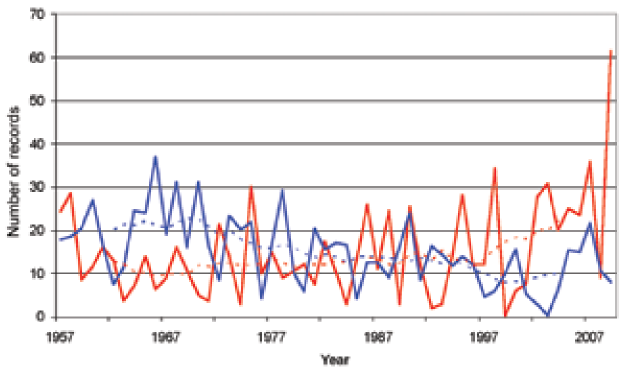


Fig. 3 Frequency of record high (red) and low (blue) minimum temperatures in Australia, 1957-2007 (dashed line is 11-year running mean).

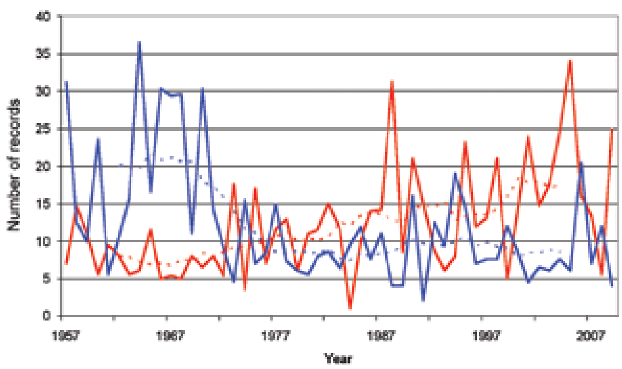


Table 1. Decadal mean frequency of high and low station daily temperature records for Australia. Highest ratios are denoted with bold type, while lowest ratios are underlined. Units are records per year.

Decade	*Maximum temperature*			*Minimum temperature*		
	High	*Low*	*Ratio*	*High*	*Low*	*Ratio*
1957-66	13.3	20.4	0.65	8.3	19.2	<u>0.43</u>
1967-76	12.2	19.1	<u>0.64</u>	8.3	15.9	0.52
1977-86	12.3	14.8	0.83	10.4	8.5	1.22
1987-96	13.5	13.9	0.97	14.8	9.9	1.49
1997-2006	18.7	8.1	2.31	18.3	8.6	**2.13**
1997-2009	22.5	9.3	**2.42**	17.5	8.4	2.08

maximum and minimum temperatures. The trends (slopes from linear regression, 95 per cent confidence intervals determined using a bootstrap procedure on the year/value pairs) are 0.24 (0.01-0.50) records per year for record high maximum temperatures, 0.23 (0.13-0.35) for record high minima, –0.26 (–0.38 - –0.14) for record low maxima and –0.25 (–0.41 - –0.11) for record low minima. The nature of the changes has varied somewhat between the elements. Record high maximum temperatures showed little change in the 1957-1996 period but increased strongly in frequency after 1996 (and particularly from 2002 onwards), record low minimum temperatures decreased sharply in frequency during the 1970s but have stayed relatively stable thereafter, whilst record high minima and low maxima have shown more even trends over the period. The large number of extreme high maxima from 2002 onwards coincides with very high mean annual maximum temperatures, which had a six-year national anomaly for 2002-09 of +0.80°C (reaching as high as +1.14°C for New South Wales), whilst the stability of the frequency of extreme low minimum temperatures post-1980 matches the weak trend in national mean minimum temperatures over the post-1980 period.

As an indicator of the imbalances between record high and low temperatures at the start and end of the period under discussion, in the decade 1957-66 record low temperatures outnumbered record high temperatures by ratios of 1.5 to 1 for maxima and 2.3 to 1 for minima, while in 1997-2009 record highs outnumbered record lows by ratios of 2.4 to 1 for maxima and 2.1 to 1 for minima.

Time series of the value of (number of high records – number of low records) were also calculated for each year for maximum and minimum temperatures (Fig. 4). These show trends of 0.49 (95 per cent confidence interval 0.22-0.77) records/year, and 0.49 (0.27-0.71) records/year, respectively, indicating a significant tendency over time for high temperature records to outnumber low temperature records for both maximum and minimum temperatures.

The time series also show considerable interannual variability, especially for record high maximum temperatures, where no monthly records were set at any stations in the network in 1999, whereas in 2009 61.5 records were set. It is worth noting that some extreme temperature events can show considerable spatial coherence over large areas, and can consequently lead to the setting of a large number of records in a single event. A good example of this is the exceptional cold spell of June 2007 in tropical Australia (Bureau of Meteorology 2007), which resulted in record low June maximum temperatures at twelve of the 68 stations in the network (Fig. 5). The very high 2009 value for record high maximum temperatures largely resulted from three exceptional events of this type, with seventeen records set

Fig. 4 Difference between numbers of high and low records for daily station data for maximum (red) and minimum (blue) temperatures, with lines of best fit (dashed). Note that the lines of best fit for the two time series are virtually identical.

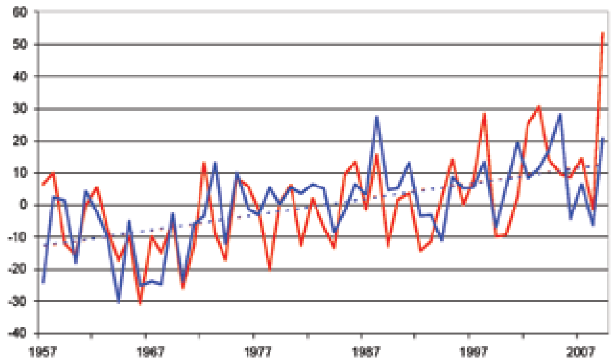


Fig. 5 The extent of record low June maximum temperatures on 20 June 2007 (from Bureau of Meteorology, 2007).

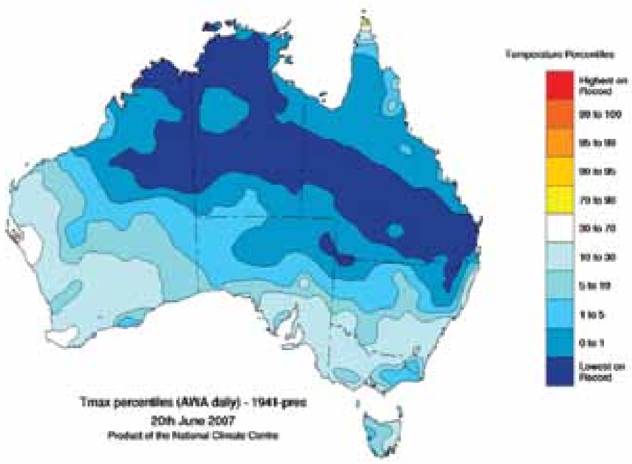


Table 2(a). Decadal mean annual frequency of high and low station daily maximum temperature records, by season. Bold/underlining as per Table 1. Units are records per year.

Decade	*Spring*			*Summer*			*Autumn*			*Winter*		
	High	*Low*	*Ratio*	*High*	*Low*	*Ratio*	*High*	*Low*	*Ratio*	*High*	*Low*	*Ratio*
1957-66	4.4	4.4	0.99	1.9	6.0	<u>0.32</u>	2.9	3.9	0.75	4.0	6.1	0.66
1967-76	1.9	6.0	<u>0.32</u>	4.2	4.5	0.95	2.1	4.8	<u>0.44</u>	4.0	3.9	1.03
1977-86	2.6	4.3	0.60	2.9	1.7	1.66	4.9	4.5	1.09	2.0	4.2	<u>0.47</u>
1987-96	3.7	3.4	1.08	2.9	3.7	0.80	2.9	3.5	0.83	4.0	3.3	1.22
1997-2006	5.7	1.5	3.65	4.6	2.4	1.91	5.1	2.7	1.87	3.3	1.4	**2.36**
1997-2009	5.9	1.4	**4.12**	6.1	3.0	**2.03**	5.7	2.7	**2.13**	4.9	2.2	2.24

Table 2(b). Decadal mean annual frequency of high and low station daily minimum temperature records, by season. Bold/underlining as per Table 1. Units are records per year.

Decade	*Spring*			*Summer*			*Autumn*			*Winter*		
	High	*Low*	*Ratio*	*High*	*Low*	*Ratio*	*High*	*Low*	*Ratio*	*High*	*Low*	*Ratio*
1957-66	1.9	5.0	<u>0.37</u>	2.4	4.8	<u>0.50</u>	2.1	4.4	0.46	2.1	5.0	<u>0.41</u>
1967-76	2.1	3.0	0.70	2.5	3.3	0.75	1.5	4.4	<u>0.34</u>	2.2	5.1	0.43
1977-86	2.7	2.5	1.05	2.3	2.0	1.17	3.3	1.5	**2.23**	2.1	2.5	0.85
1987-96	3.6	2.7	1.32	2.5	4.0	0.63	3.8	1.9	2.02	4.9	1.3	**3.64**
1997-2006	4.5	2.5	1.75	5.3	1.5	3.44	4.5	2.7	1.69	4.1	1.9	2.21
1997-2009	4.5	2.1	**2.10**	4.8	1.3	**3.80**	4.3	3.2	1.33	3.9	1.8	2.16

in late January and early February in southeastern Australia, 16.5 set in August (mostly in Queensland and northern New South Wales), and 13.5 set in November across southern and central Australia. The January-February and August 2009 events each saw more records set in a single event than the mean number for an entire year.

Results broken down by season are shown in Table 2. These show the same general patterns as those for the year as a whole, although there is more decade-to-decade volatility, as might be expected given the smaller number of events involved. For all seasons and for both maximum and minimum temperature, high temperature records outnumber low temperature records in the 1997-2009 period (by a ratio of between 1.3 and 4.1 to 1), while low temperature records outnumber high temperature records in the 1957-66 decade for all cases, although only just so for spring maximum temperatures (where 1957-66 had a large number of both high and low records).

A regional[2] breakdown is shown in Table 3. As for the seasonal breakdown, all four regions show similar general patterns to the national total, but with somewhat more volatility. There are few clear, consistent differences between the four regions, although the lack of extreme low maxima in the southeast in the last ten years is particularly marked, and the post-1997 increase in the frequency of extreme high maxima is more pronounced in southern Australia than it is in the north.

[2] For the purposes of this study, 'northwest' is defined as the Northern Territory and Western Australia north of 27°S (11 stations), 'northeast' as Queensland (13 stations), 'southwest' as South Australia and Western Australia south of 27°S (15 stations), and 'southeast' as New South Wales, Victoria and Tasmania (33 stations).

Across Tables 1, 2 and 3, the periods with the highest ratios of high to lowest ratios are indicated in bold type, with the lowest ratios underlined. Of the eighteen ratios given in the tables, fifteen of the highest ratios occur in either 1997-2006 or 1997-2009, with three in 1987-96. None of these highest ratios occur in the first three decades. For the lowest ratios, ten occur in the first decade, with six in the second decade. None of them occur in the post-1987 period.

Area-averaged monthly analyses

The number of records set by the area-averaged monthly analyses in each year from 1957 to 2009 was calculated. Decadal mean results are shown in Table 4. With only 84 data points, the total number of values is much smaller than is the case for station-based data.

As for station-based daily data, the monthly area averages show a dominance of low records over high records in the early part of the data-set, especially in the 1957-66 decade where the ratios are 2.1 to 1 for maxima and 4.3 to 1 for minima, and a comparable dominance of high records over low records in the 1997-2009 period with ratios of 2.6 to 1 and 3.3 to 1 respectively.

Annual time series of the difference between the number of high and low records (hereafter referred to as the 'difference time series'), as was done for the station-based data, were also calculated (Fig. 6). These show trends of 0.084 (0.034-0.137) records/year for maxima, and 0.098 (0.052-0.143) records/year for minima, again indicating a significant tendency over time for high temperature records to outnumber low temperature records for both maximum and minimum temperatures.

Table 3(a). Decadal mean annual frequency of high and low station daily maximum temperature records, by region. Bold/underlining as per Table 1. Units are records per year.

Decade	*NE*			*NW*			*SE*			*SW*		
	High	*Low*	*Ratio*	*High*	*Low*	*Ratio*	*High*	*Low*	*Ratio*	*High*	*Low*	*Ratio*
1957-66	2.7	3.9	0.69	1.9	2.3	0.80	6.1	9.8	0.63	2.6	4.3	<u>0.59</u>
1967-76	2.3	2.7	0.87	1.9	3.1	<u>0.60</u>	4.9	9.2	<u>0.53</u>	2.8	4.2	0.68
1977-86	1.0	3.4	<u>0.30</u>	1.9	2.0	0.95	6.9	6.9	0.99	2.3	2.3	1.00
1987-96	3.1	2.1	1.45	2.5	1.8	1.40	5.5	5.9	0.95	2.4	4.0	0.60
1997-2006	2.9	1.3	2.23	3.1	2.1	**1.48**	8.2	2.8	2.99	4.2	1.9	2.16
1997-2009	3.9	1.6	**2.38**	3.7	2.7	1.38	9.3	2.9	**3.28**	5.5	2.2	**2.53**

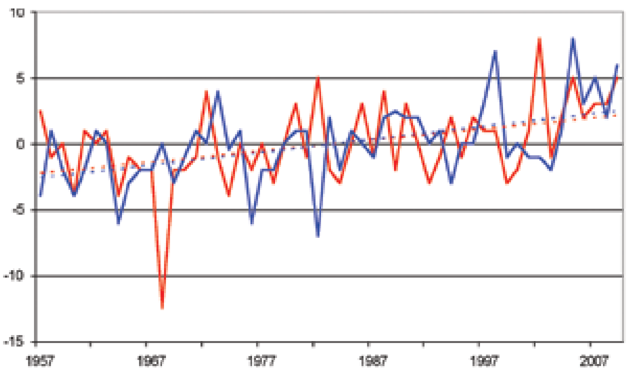
Table 3(b). Decadal mean annual frequency of high and low station daily minimum temperature records, by region. Bold/underlining as per Table 1. Units are records per year.

Decade	*NE*			*NW*			*SE*			*SW*		
	High	*Low*	*Ratio*	*High*	*Low*	*Ratio*	*High*	*Low*	*Ratio*	*High*	*Low*	*Ratio*
1957-66	1.9	4.0	<u>0.47</u>	1.1	3.3	<u>0.33</u>	3.7	7.3	<u>0.50</u>	1.7	4.5	<u>0.38</u>
1967-76	1.1	2.2	0.53	1.9	2.8	0.68	3.9	7.3	0.53	1.3	3.4	0.40
1977-86	1.3	1.4	0.91	2.3	1.8	1.24	4.7	4.1	1.16	2.1	1.2	1.82
1987-96	3.2	1.6	**1.98**	2.9	2.0	1.46	5.5	4.1	1.35	3.1	2.2	1.41
1997-2006	3.3	1.8	1.83	2.8	1.1	2.67	8.2	4.5	**1.85**	3.9	1.3	**3.04**
1997-2009	3.2	1.9	1.68	2.7	1.0	**2.71**	7.8	4.2	**1.85**	3.7	1.2	2.97

Table 4. Decadal mean frequency of high and low temperature monthly area-averaged temperature records for Australia. Highest ratios are denoted with bold type, while lowest ratios are underlined. Units are records per year.

Decade	*Maximum temperature*			*Minimum temperature*		
	High	*Low*	*Ratio*	*High*	*Low*	*Ratio*
1957-66	0.7	1.45	0.48	0.6	2.6	<u>0.23</u>
1967-76	0.9	3.05	<u>0.30</u>	1.25	1.9	0.66
1977-86	1.6	1.4	1.14	0.7	1.6	0.44
1987-96	1.2	0.9	1.33	1.55	1.0	1.55
1997-2006	2.6	1.2	2.17	2.9	1.2	2.42
1997-2009	3.15	1.23	**2.56**	3.3	1.0	**3.30**

Fig. 6 Difference between numbers of high and low records for monthly area-averaged data for maximum (red) and minimum (blue) temperatures, with lines of best fit (dashed).

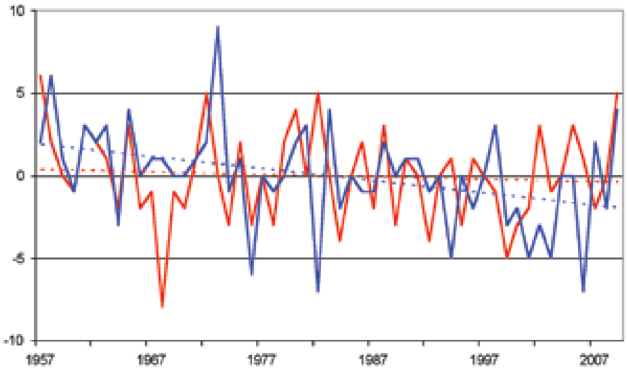


This part of the analysis was then repeated with detrended data, using the observed trends in Australian annual mean maximum and minimum temperatures over the 1957-2009 period (obtained from http://www.bom.gov.au/cgi-bin/climate/change /timeseries.cgi, viewed 26 April 2010). These trends are 0.156°C/decade (0.082-0.232) for maxima, and 0.163°C/decade (0.107-0.217) for minima. The detrending was carried out by subtracting [*Tr* (*y* – 1957)] from each data point, where *Tr* is the national trend value, per year, as stated above (0.0156°C for maxima, 0.0163°C for minima) and *y* is the year of the observation. The purpose of this was to determine whether the observed change in the frequency of extreme mean monthly values was consistent with observed trends in the mean, which equates to a null hypothesis of no trend in the difference time series using the detrended data.

The difference time series for the detrended data are shown in Fig. 7. These indicate that there is no significant trend for maxima (–0.015 (–0.063 – 0.037) records/year), but there is a significant negative trend for minima (–0.074 (–0.129 – –0.021) records/year), suggesting that the changes in the frequency of extreme area-averaged monthly minima have been less than would be consistent with the warming trend in mean minimum temperatures. Such a result would be consistent with a decrease in the variance of area-averaged mean monthly minimum temperatures.

To investigate this further, the analysis was repeated for minimum temperatures, imposing a range of trends on the monthly data and determining the effect on the difference time series. A value of 0.089°C/decade was found to generate a zero trend in the difference time series, while the range

Fig. 7 Difference between numbers of high and low records for detrended monthly area-averaged data for maximum (red) and minimum (blue) temperatures, with lines of best fit (dashed).



of imposed mean trend values which generated a difference time series whose trend did not differ significantly from zero at the 95 per cent level was from 0.051 to 0.135°C/decade. Whilst the upper bound of this range is within the 95 per cent confidence interval for the observed trend in mean minimum temperatures, it nevertheless suggests the possibility that extremes of mean monthly minimum temperature are warming more slowly than overall mean minimum temperatures. In this context, it is interesting to note that the frequency of record low minimum temperatures, unlike the frequency of the other three types of records, has not changed sharply post-1997. This has been a period of long-term drought over much of southern Australia. The post-1997 rainfall decline has been especially acute in autumn, a season which has seen a post-1997 increase in the frequency of record low minimum temperatures (Table 2(b)).

A high frequency of clear nights is a plausible mechanism for the lack of recent changes in record low minima, while feedbacks from low soil moisture may also have an influence. Such potential mechanisms require further investigation.

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