The changing nature of temperature extremes in Australia and New Zealand

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A dense network of stations in Australia and New Zealand, including urbanised sites, was analysed to assess urbanisation effects on indices of extreme temperature, type of distribution change observed, and relationships with key climate drivers (El Niño – Southern Oscillation (ENSO), sea-surface temperature (SST) and mean sea-level pressure (MSLP) patterns). A strong spatial and temporal coherence of trends in extreme temperature indices was notable across both rural and urban stations, except for diurnal temperature range which was strongly influenced by urbanisation and biased by data limitations. Increased mean maximum and mean minimum temperature, general increases in hot days and warm nights, and decreases in cool days and cold nights, persisted over three analysis periods (1931-2005, 1946-2005 and 1961-2005), with the proportion of significant trends increasing as analysis period lengthened for all indices except hot days. Rural stations had fewer significant increasing trends in warm extremes, while urbanised sites showed a greater number of significant hot day increases. Strong correlations were found between measures of mean temperature and temperature extremes, consistent across all three analysis periods and largely independent of urban status. The most common form of distributional change, for both maximum and minimum temperature, involved a significant shift in the mean and one or both extremes. However, the proportion of stations with this type of distribution shift reduced in the later period, with relatively more stations having no distribution change, or shifts in the mean (but not extremes) over 1961-2005, possibly due to a change in the relationship between ENSO and temperature and/or the effects of rapid population growth since the 1950s. This study indicates that measures of ENSO, such as NINO3.4 or our second MSLP pattern, have the potential to better predict temperature extremes over large areas of Australasia, especially eastern Australia, compared to other broadscale climate indices, such as near-global SST patterns.

Introduction

Several studies have examined trends in mean temperatures in the Australian (e.g. Coughlan 1979; Torok and Nicholls 1996), New Zealand (e.g. Salinger 1995) and southwest Pacific (e.g. Salinger 1995) regions. In recent years additional papers have also investigated temporal trends in temperature extremes and, in a few cases, temperature variability (e.g. Collins et al. 2000; Manton et al. 2001; Griffiths

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et al. 2005; Alexander et al. 2007). For example, Alexander et al. (2007) found that strong relationships exist between trends in mean and extreme temperatures in Australia, that absolute trends in the extremes were larger than those for mean temperature, and that cold minimum extremes were warming faster than warm minimum temperature extremes in all seasons. It was not determined whether these changes were significantly different from those which could be explained by a simple increase in the mean of the temperature distribution without any other distributional change (e.g. variance or skewness).

It is now well known that the relationship between changes in mean temperature and temperature extremes is highly non-linear (Mearns et al. 1984; Wigley 1988; Meehl et al. 2000) and that changes in the frequency of extreme events have a greater societal impact than changes in mean climate (Mitchell et al. 1990; Katz and Brown 1992; Griffiths et al. 2005), the effects of changing frequency of extreme events being felt in both urban and non-urban environments.

In the Australian and New Zealand region past studies of temperature extremes have generally restricted the analyses to high-quality non-urban temperature records (e.g. Salinger 1995; Collins et al. 2000), mainly to avoid potential warming biases associated with urbanisation. An exception was Griffiths et al. (2005) who investigated the use of changes in mean temperature as a predictor of changes in extreme temperature over the Asia-Pacific region. Although Griffiths et al. (2005) included some urbanised stations in their analyses, no highly urbanised sites from the Australia/New Zealand region were included. For the stations they considered, differences in the dominant temperature distribution changes between the urban and non-urban sites emerged, with non-urban sites more likely to exhibit changes in the mean, impacting on one or both extremes, with no change in standard deviation, while urban sites typically also included a change in variance (particularly for minimum temperature).

Broadscale environmental effects are known to influence mean temperature in the Australian and New Zealand region. For example, warmer temperatures in Australia are generally associated with El Niño episodes (Nicholls et al. 2005) and near-global patterns of sea-surface temperatures are used operationally by the Australian Bureau of Meteorology to provide seasonal (above and below median) temperature forecasts (Jones 1998). Some links have also been made in parts of the Australian and New Zealand region between climate extremes and the El Niño – Southern Oscillation (Trewin 2001; Nicholls et al. 2005).

This study extends previous temperature studies by: (a) investigating changes in the temperature distributions over time (maximum and minimum), including means, variance and extremes, for a large number of stations in Australia and New Zealand; (b) quantifying links between changes in the mean and extreme temperature; (c) assessing the impact of the length of the analysis period and the urban status of the station; and (d) determining links between broadscale environmental indicators (such as the El Niño – Southern Oscillation, mean sea-level pressure and sea-surface temperatures) and changes in extreme temperature indices. Unlike a number of other studies in the Australian and New Zealand region (e.g. Collins et al. 2000; Griffiths et al. 2005; Nicholls et al. 2005) stations with potential warming biases associated with urbanisation were included, as well as a considerably greater station density than other similar studies (e.g. Griffiths et al. 2005; Nicholls et al. 2005).

Data and analysis method

Climate station selection

High-quality daily temperature data series were obtained from the Australian Bureau of Meteorology and the New Zealand National Climate Database. Stations were selected that had a long period of record, including the standard reference period 1961 – 1990. Additional criteria included: less than 20 per cent of the daily values missing in each year; that the stations were well maintained; with documented metadata; and were preferably non-urban, single-site locations. Information obtained from the Australian Bureau of Statistics and Statistics New Zealand was used to classify the stations into highly urbanised (population greater than 300 000 with more than 300 people per km^2 in 2001), urbanised (either the population was greater than 300 000 or more than 300 people per km^2, but not both) or rural (less than 300 000 people and density less than 300 per km^2), using the criteria of Griffiths et al. (2005). It is acknowledged that the urban status of a station, based solely on 2001 status, is a simplification for ease of analysis and may not be entirely representative of the urban status of all stations over the entire analysis period. The locations of the stations are shown in Figs 1 and 2 and details given in the Appendix.

The criterion of less than 16 per cent daily values missing, i.e. a particular year having at least 308 days of data available, equates to a greater than 50 per cent probability that all four of the most extreme hot or cold events for that year would be included in the data-set (Haylock and Nicholls 2000). Three periods of analysis were used to investigate trends in the extremes, means, variance and diurnal temperature range, as well as the relationship between mean temperature and

Fig. 1 **Station location and data duration: 17 stations with 1931-2005 data (black stars), 36 stations with 1946-2005 data (white squares), and 65 stations with 1961-2005 data (grey circles). Note that, for example, all 118 stations with data present over the 1961-2005 period are used in the 1961-2005 analysis, and that similarly, 53 stations with data present over the 1946-2005 period are used in the 1946-2005 analysis.**

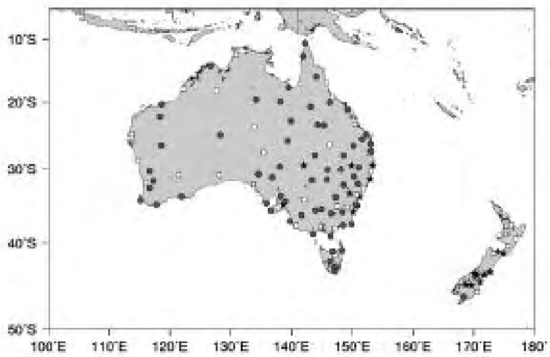
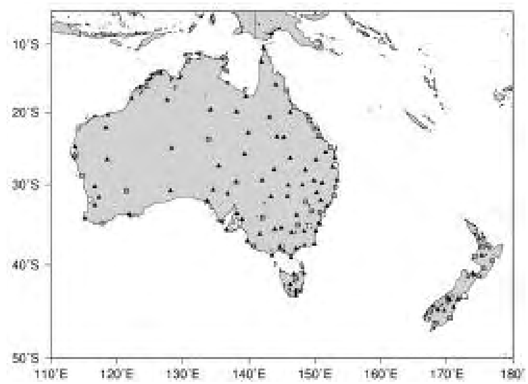


Fig. 2 **Urban status of the stations. Highly urban sites (population was greater than 300 000 with more than 300 people per km^2 in 2001) (circles), urban sites (either the population was greater than 300 000 or more than 300 people per km^2, but not both) (squares) and rural sites (less than 300 000 people and density less than 300 per km^2) (triangles).**



extremes. These were 1961-2005 (45 years; 118 stations), 1946-2005 (60 years; 53 stations) and 1931-2005 (75 years; 17 stations). These three periods were chosen to maximise available high-quality data, and for comparison with previous analyses of extreme temperature indices in the Australasian region.

A relatively even geographical data coverage was achieved for the periods 1961-2005 and 1946-2005. For the longer period 1931-2005, stations were restricted to the southeastern quadrant of Australia and predominantly the South Island of New Zealand due to a lack of high-quality, long-duration data elsewhere. Therefore, 1931-2005 results may reflect the differential spatial data coverage to some degree.

In addition, due to the limitations of available station data, the proportion of rural stations varies across the analysis periods (59 per cent in 1931-2005, 43 per cent in 1946-2005, 69 per cent in 1961-2005). Again, the results across the analysis periods may, to some degree, reflect the differential degree of urbanisation.

Additional climate variables

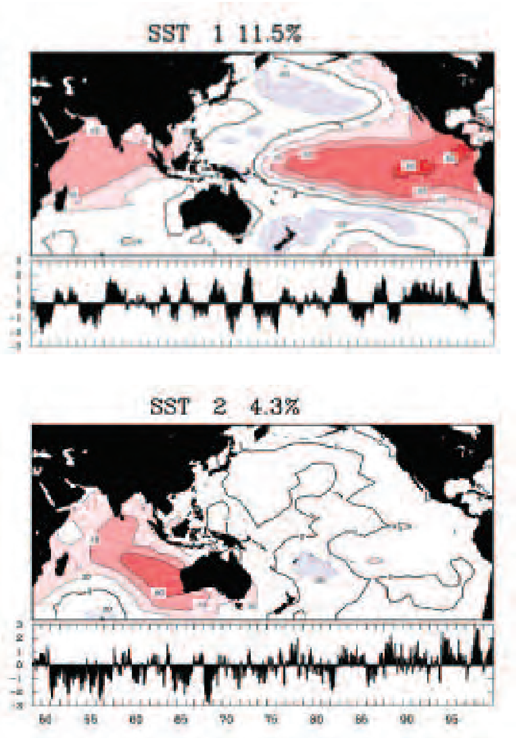
Australasian temperature variability has been shown to be influenced by broadscale environmental effects, including circulation changes, the Southern Oscillation and near-global sea-surface temperature (SST) (Jones 1998; Trewin 2001; Nicholls et al. 2005). Therefore, three broadscale indices were considered as potential drivers of temperature extremes in this study: NINO3.4, two near-global SST patterns and two near-global MSLP patterns.

A monthly index of NINO3.4 was obtained from the Climate Explorer website at http://climexp.knmi.nl. This index represents SST anomalies in the region 5ºS to 5ºN, 120ºW to 170ºW.

Near-global SST patterns were represented by the first two VARIMAX rotated principal components of the Indian/Pacific region (Drosdowsky and Chambers 2001). These monthly values were obtained from the National Climate Centre of the Bureau of Meteorology, where they are used operationally for Australian seasonal temperature outlooks. The first pattern, SST1 (explaining 11.5% of the variance), shows positive loadings in the tropical central and eastern Pacific (Fig. 3), surrounded by negative loadings in the subtropical north and south Pacific. The time series of this pattern clearly shows historical warm (El Niño) and cold (La Niña) events. The second SST pattern (SST2, explaining 4.3% of the variance) is largely confined to the Indian Ocean in a region that has been shown to be associated with large-scale circulation over Australia (Nicholls 1989; Simmonds and Rocha 1991).

The first two orthogonal (VARIMAX) rotated S-mode principal components of monthly values of mean sea-level pressure (MSLP), as described in Li et al. (2005) and Drosdowsky (1993), were used to represent the main near-global modes of MSLP variability. The NCEP-NCAR (National Centers for Environmental Prediction – National Center for Atmospheric Research) reanalysis data were restrict-

Fig. 3 **First two VARIMAX rotated principal components of near-global sea-surface temperature patterns together with the time series of their amplitudes, 1949 to 1999 (Drosdowsky and Chambers 2001).**



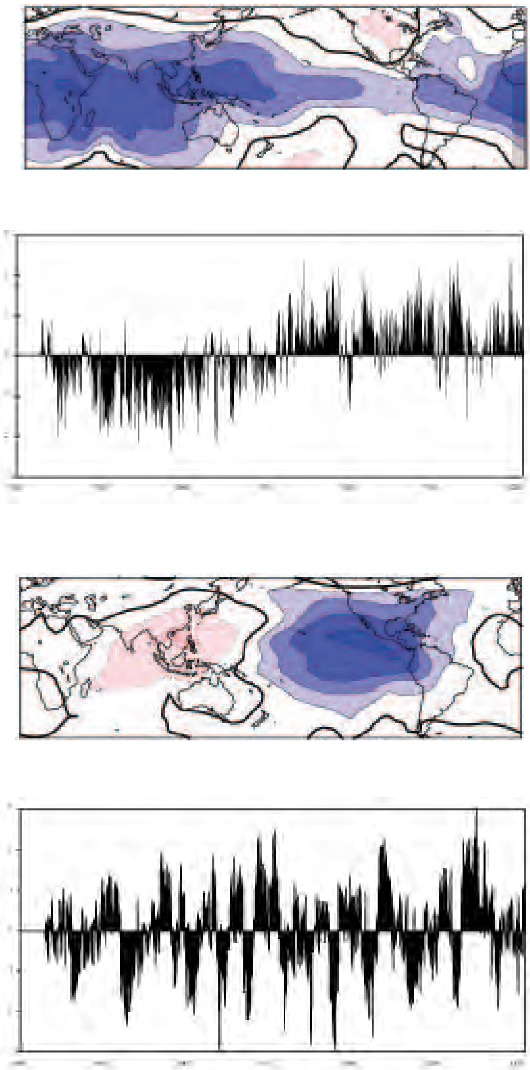
ed to the period 1948 to 2005 and the region 55°S to 66°N, due to known data issues south of 55° S prior to 1968 (Li et al. 2005). Together these patterns explain around 24% of the total variance. The first pattern (15.8% of the variance) extends over a large region of the tropics and subtropics (Fig. 4), but is particularly strong over the equatorial Indian Ocean. The time series of this pattern shows a tendency for negative values prior to the mid-1970s and positive values after this. The second principal component, accounting for 8.2% of the variance, is centred over the central and eastern Pacific. The first pattern is significantly correlated with Darwin MSLP ($r = 0.290$, $p < 0.001$; 1961-2005) and the second with Tahiti MSLP ($r = 0.458$, $p < 0.001$; 1961-2005).

Relationships between the broadscale indices are further explored in later sections.

Analysis methods

Extreme temperature indices in this study were based on percentiles calculated from daily data. The 1st and 99th percentiles in each calendar year were calculated

Fig. 4 **The first two rotated (VARIMAX) principal component patterns of mean sea-level pressure, using data from 1949 to 2005.**



for each of the variables described below using all non-missing days. The 1st percentile corresponded to the fourth lowest value and the 99th percentile to the fourth highest in each year. The indices used in this study are comparable with other studies using a subset of these data (Manton et al. 2001; Griffiths et al. 2005; Nicholls et al. 2005).

The following extreme indices were calculated for each year and for each analysis period (1931-2005, 1946-2005 and 1961-2005):

- hot days (HD): frequency of days with maximum temperature above the analysis period mean 99th percentile;
- cool days (CD): frequency of days with maximum temperature below the analysis period mean 1st percentile;
- warm nights (WN): frequency of days with minimum temperature above the analysis period mean 99th percentile; and
- cold nights (CN): frequency of days with minimum temperature below the analysis period mean 1st percentile.

Using the daily temperature time series, an annual average, as well as an annual standard deviation, for both maximum temperature and minimum temperature were calculated. The means and annual standard deviations were calculated from 365/366 data points, without removing the annual cycle, in order to represent changes in the shape of the distribution of annual daily temperatures. As a result of this approach, the standard deviation as defined here can inadvertently reflect changes due to a change in the mean (or a shift in the annual cycle), and at higher latitude locations, it will largely be a measure of seasonal temperature range. Mean annual diurnal temperature range was also calculated for each year.

These additional indices were denoted by:

- Tmin: the mean minimum temperature;
- Tmax: the mean maximum temperature;
- SD Tmin: the standard deviation of minimum temperature;
- SD Tmax: the standard deviation of maximum temperature;
- DTR: the mean annual diurnal temperature range; calculated by averaging the 365/366 daily DTR values for each year.

A modified version of the non-parametric Kendall tau test (Wang and Swail 2001) was used to assess the statistical significance of trends in the annual time series of the indices for each station and each of the three time periods, making no prior assumptions about the distributions of the indices. Correlation (Pearson) and graphical analysis were used to assess the statistical significance (at the five per cent level) of relationships between changes in the extremes, mean and standard deviation of the minimum and maximum temperature distributions. Because the correlations are based on series that were not detrended, changes in mean state, as well as interannual variability, are reflected in the correlations.

The monthly values of the broadscale climate indices (NINO3.4 anomalies, SST1 and SST2, and MSLP1 and MSLP2) were averaged for the austral winter period JJA (June to August) and summer period DJF (December to February) as well as over the calendar year (January to December). Correlations and graphical analyses were used to identify statistically significant relationships (at the five per cent level) between the seasonal/annual broadscale climate indices and the annual station temperature indices.

Spatial mapping of results was undertaken using GMT software (Wessel and Smith 2001). Correlation maps were produced using an adjustable tension continuous curvature surface gridding algorithm (Smith and Wessel 1990) to create a correlation surface based on point correlation data at the stations. Where appropriate, statistical significance of individual stations was plotted as an overlay on the correlation maps; no adjustment was made to account for field significance.

Results

Trends in temperature indices

Regardless of the period of analysis, around one-quarter of all stations showed a significant increase in the number of hot days over time, with less than ten per cent of stations experiencing a significant decrease in the number of hot days (Table 1(a)). No stations had significant increases in the number of cool days. The proportion of stations with significant decreases in the number of cool days increased as the length of the analysis period increased. The proportion of stations with significant increasing or decreasing trends in the number of warm nights also increased with increasing length of analysis period, the majority of the significant trends being towards more warm nights over time. Half to three-quarters of the stations had significant trends towards fewer cold nights over time (the proportion of stations increasing with increasing analysis period). Very few stations had significant increases in the number of cold nights.

Almost all stations had trends towards warmer maximum and minimum temperatures over time, the majority of which were statistically significant (at the five per cent level). Very few stations had significant increases in the standard deviation of maximum or minimum temperature and around 20–35 per cent of stations experienced statistically significant decreases in daily temperature variability over time. The significance of trends over time in the diurnal temperature range (DTR) was highly dependent on the analysis period used. For the analysis periods 1961-2005 and 1931-2005 there were similar proportions of stations with significant increases and decreases in DTR (slightly more significant decreases in the 1961-2005 period and slightly more increases in the 1931-2005 period). For the 1946-2005 period there were six times as many significant decreases in DTR than increases (Table 1(a)).

Table 1(a). Index trends observed over the three analysis periods (see Appendix for exact details). The number of stations in each category is given, with the percentage of the total number of stations given in brackets. Statistical significance was determined at the 5% level.

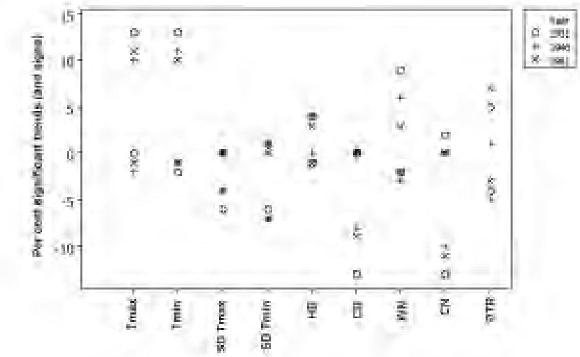
	Hot days (HD)	*Cool days (CD)*	*Warm nights (WN)*	*Cold nights (CN)*	*Tmax*	*Tmin*	*SD Tmax*	*SD Tmin*	*DTR*
1961-2005		(N = 118)							
Sig. increase	24 (20%)	0 (0%)	29 (25%)	2 (2%)	65 (55%)	74 (63%)	2 (2%)	3 (3%)	22 (19%)
Sig. decrease	10 (8%)	42 (36%)	7 (6%)	57 (48%)	5 (4%)	4 (3%)	23 (19%)	23 (19%)	28 (24%)
1946-2005		(N = 53)							
Sig. increase	13 (25%)	0 (0%)	26 (49%)	0 (0%)	33 (62%)	39 (74%)	0 (0%)	5 (9%)	3 (6%)
Sig. decrease	4 (8%)	30 (57%)	4 (8%)	29 (55%)	3 (6%)	1 (2%)	11 (21%)	14 (26%)	19 (36%)
1931-2005		(N = 17)							
Sig. increase	4 (24%)	0 (0%)	9 (53%)	2 (12%)	13 (76%)	13 (76%)	0 (0%)	1 (6%)	5 (29%)
Sig. decrease	1 (6%)	13 (76%)	2 (12%)	13 (76%)	0 (0%)	2 (12%)	6 (35%)	6 (35%)	4 (24%)

Table 1(b). Index trends observed over each period, differentiated by whether the site was rural or non-rural (either urban or highly urban), for the periods 1931-2005 (N=17), 1946-2005 (N=53) and 1961-2005 (N=118). HU = highly urbanised; UR = urbanised; RU = rural (definitions as in Appendix). The number of stations in each category is given, with the percentage of the total number of stations given in brackets. Statistical significance determined at the 5% level.

	Hot days (HD)	*Cool days (CD)*	*Warm nights (WN)*	*Cold nights (CN)*	*Tmax*	*Tmin*	*SD Tmax*	*SD Tmin*	*DTR*
1961-2005			(No. HU = 7; No. UR = 29; No. RU = 82)						
Sig. increase HU	0 (0%)	0 (0%)	2 (29%)	0 (0%)	5 (71%)	6 (86%)	0 (0%)	1 (14%)	1 (14%)
UR	11 (38%)	0 (0%)	12 (41%)	0 (0%)	16 (55%)	22 (76%)	1 (3%)	0 (0%)	1 (3%)
RU	13 (16%)	0 (0%)	15 (18%)	2 (2%)	44 (54%)	46 (56%)	1 (1%)	2 (2%)	20 (24%)
Sig. decrease HU	0 (0%)	3 (43%)	0 (0%)	6 (86%)	1 (14%)	0 (0%)	1 (14%)	1 (14%)	1 (14%)
UR	1 (3%)	14 (48%)	0 (0%)	19 (66%)	1 (3%)	0 (0%)	7 (24%)	8 (28%)	10 (34%)
RU	9 (11%)	25 (30%)	7 (9%)	32 (39%)	3 (4%)	4 (5%)	15 (18%)	14 (17%)	17 (21%)
1946-2005			(No. HU = 6; No. UR = 24; No. RU = 23)						
Sig. increase HU	0 (0%)	0 (0%)	6 (100%)	0 (0%)	6 (100%)	6 (100%)	0 (0%)	1 (17%)	0 (0%)
UR	8 (33%)	0 (0%)	15 (63%)	0 (0%)	15 (63%)	20 (83%)	0 (0%)	1 (4%)	0 (0%)
RU	5 (22%)	0 (0%)	5 (22%)	0 (0%)	12 (52%)	13 (57%)	0 (0%)	3 (13%)	3 (13%)
Sig. decrease HU	0 (0%)	3 (50%)	0 (0%)	5 (83%)	0 (0%)	0 (0%)	0 (0%)	1 (17%)	1 (17%)
UR	0 (0%)	13 (54%)	0 (0%)	16 (67%)	0 (0%)	0 (0%)	3 (13%)	7 (29%)	12 (50%)
RU	4 (17%)	14 (61%)	4 (17%)	8 (35%)	3 (13%)	1 (4%)	8 (35%)	7 (30%)	6 (26%)
1931-2005			(No. HU = 4; No. UR = 3; No. RU = 10)						
Sig. increase HU	1 (25%)	0 (0%)	3 (75%)	0 (0%)	4 (100%)	4 (100%)	0 (0%)	0 (0%)	1 (25%)
UR	1 (33%)	0 (0%)	2 (67%)	0 (0%)	2 (67%)	2 (67%)	0 (0%)	0 (0%)	0 (0%)
RU	2 (20%)	0 (0%)	4 (40%)	2 (20%)	7 (70%)	7 (70%)	0 (0%)	1 (10%)	4 (40%)
Sig. decrease HU	0 (0%)	4 (100%)	0 (0%)	4 (100%)	0 (0%)	0 (0%)	1 (25%)	0 (0%)	2 (50%)
UR	0 (0%)	2 (67%)	0 (0%)	2 (67%)	0 (0%)	0 (0%)	2 (67%)	1 (33%)	1 (33%)
RU	1 (10%)	7 (70%)	2 (20%)	7 (70%)	0 (0%)	2 (20%)	3 (30%)	5 (50%)	1 (10%)

A comparison of trend results for only the 17 stations common across all three analysis periods is given in Fig. 5. For the Tmax, Tmin, cool days (CD), warm nights (WN) and cold nights (CN) indices, the majority of the 'common station' trends are in the same direction, regardless of analysis period, and the percentage of significant trends increases with increasing period length (consistent with the influence that sample size has on statistical significance and test accuracy, if a real trend were present). The percentage of significant trends for the SD Tmax, SD Tmin, and hot days (HD) indices showed only a small range across the three analysis periods, but DTR showed a marked spread – consistent with the earlier finding that trends in DTR were highly dependent on the period analysed.

Fig. 5 Comparison of the percentage of significant trends (both positive and negative) in each of the extreme indices over the three analysis periods; 1931-2005 (circles), 1946-2005 (plus signs), 1961-2005 (crosses).



As was found in Griffiths et al. (2005), the percentage of significant increases in the mean (of both maximum and minimum temperature) was larger than the percentage of significant increases in the frequency of warm/hot extremes (hot days and warm nights) or decreases in cool/cold extremes (cool days and cold nights; the exception being cool days in the 1931-2005 analysis period).

Regardless of the urban status of the stations (highly urban, urban or rural) there was a tendency for Tmax, hot days, Tmin and warm nights to increase over time and for SD Tmax, cool days, SD Tmin and cold nights to decrease over time. However, there were some differences between urban and rural stations. Over the period 1961-2005, the rural stations had fewer significant increasing trends in Tmin (56% of stations compared to 76% for urban and 86% for highly urban); fewer significant increasing trends in warm nights (18% compared to 41% for urban and 29% for highly urban); and fewer decreasing trends in cold nights (39% compared to 66% for urban and 86% for highly urban) (Table 1(b)). More significant increasing trends in hot days were observed for urban stations than either highly urban or rural sites (38%, 0% and 16% respectively). These results held regardless of the analysis period (Table 1(b)).

Categorising stations by distribution changes

The summary section of Table 2 lists the number and percentage of stations in broad categories of change, and also by analysis period. Overall, the most com-

Table 2. Number of stations that fall into the 'significant change' (at the five per cent level) categories listed for the period 1931-2005 (N=17), 1946-2005 (N=53) and 1961-2005 (N=118). The percentage of the total number of sites is given in brackets, and a summary is given (lower table).

Significant changes	*1931 – 2005*		*1946 – 2005*		*1961 – 2005*	
	MaxT	*MinT*	*MaxT*	*MinT*	*MaxT*	*MinT*
No change in mean, extremes or SD	1 (5.9)	1 (5.9)	7 (13.2)	7 (13.2)	26 (22.0)	26 (22.0)
Mean, both extremes only	4 (23.5)	6 (35.3)	6 (11.3)	11 (20.8)	11 (9.3)	16 (13.6)
Mean, CD/CN only	4 (23.5)	2 (11.8)	12 (22.6)	5 (9.4)	14 (11.9)	17 (14.4)
Mean, HD/WN only	0 (0)	0 (0)	5 (9.4)	3 (5.7)	12 (10.2)	5 (4.2)
Mean, SD, CD/CN only	4 (23.5)	2 (11.8)	5 (9.4)	4 (7.5)	5 (4.2)	13 (11.0)
Mean only	1 (5.9)	1 (5.9)	6 (11.3)	4 (7.5)	22 (18.6)	19 (16.1)
All variables	0 (0)	4 (23.5)	0 (0)	8 (15.1)	1 (0.8)	6 (5.1)
Mean, SD, HD/WN only	0 (0)	0 (0)	2 (3.8)	5 (9.4)	4 (3.4)	1 (0.8)
HD/WN only	1 (5.9)	0 (0)	2 (3.8)	2 (3.8)	3 (2.5)	4 (3.4)
CD/CN only	0 (0)	0 (0)	4 (7.5)	0 (0)	4 (3.4)	4 (3.4)
SD, both extremes only	0 (0)	1 (5.9)	2 (3.8)	0 (0)	0 (0)	1 (0.8)
Mean, SD only	0 (0)	0 (0)	0 (0)	0 (0)	1 (0.8)	1 (0.8)
SD, HD/WN only	0 (0)	0 (0)	0 (0)	1 (1.9)	2 (1.7)	2 (1.7)
Extremes only (both)	0 (0)	0 (0)	0 (0)	1 (1.9)	1 (0.8)	1 (0.8)
SD, CD/CN only	1 (5.9)	0 (0)	1 (1.9)	0 (0)	6 (5.1)	1 (0.8)
SD only	1 (5.9)	0 (0)	1 (1.9)	2 (3.8)	6 (5.1)	1 (0.8)
Summary results (2-5 ignore variance changes):						
1. No change	1 (5.9)	1 (5.9)	7 (13.2)	7 (13.2)	26 (22.0)	26 (22.0)
2. Mean, not extremes	1 (5.9)	1 (5.9)	6 (11.3)	4 (7.5)	23 (19.5)	20 (16.9)
3. Extremes (1 or 2), not mean	2 (11.8)	1 (5.9)	9 (17.0)	4 (7.5)	16 (13.6)	13 (11.0)
4. Mean and both extremes	4 (23.5)	10 (58.8)	6 (11.3)	19 (35.8)	12 (10.2)	22 (18.6)
5. Mean and extremes (1 or 2)	12 (70.6)	14 (82.4)	30 (56.6)	36 (67.9)	47 (39.8)	58 (49.2)
6. Change in SD	6 (35.3)	7 (41.2)	11 (20.8)	20 (37.7)	25 (21.2)	26 (22.0)

Fig. 6 **Locations where a significant change (open circles) in the mean and (1 or 2) extremes over the period 1961 to 2005 was observed: (a) Tmax, (b) Tmin. All other station locations are also shown (solid dots).**

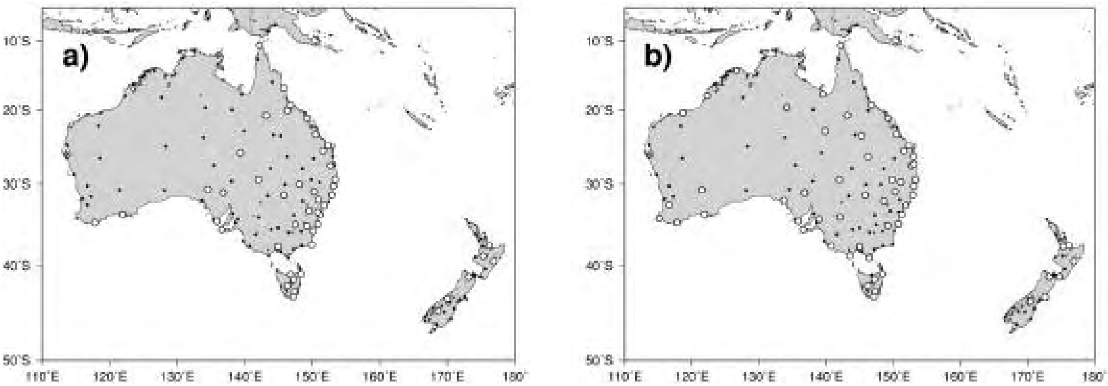
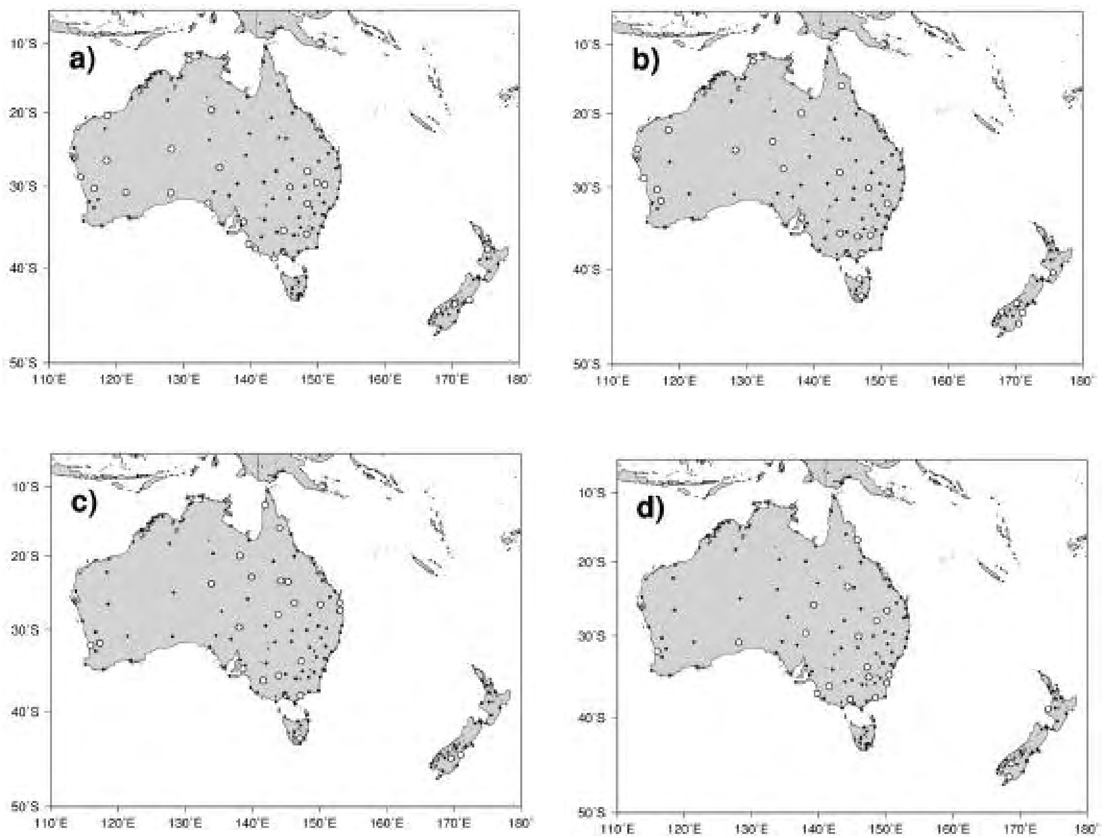


Fig. 7 **Locations where no distributional change was detected (open circles) over the period 1961-2005: (a) Tmax (b) Tmin; or there was a change in mean only: (c) Tmax, (d) Tmin. All other station locations are also shown (solid dots).**



mon form of distribution change, for both maximum and minimum temperature and regardless of the length of the analysis period, involved a significant shift in the mean and one or both extremes. The longer the analysis period the greater the proportion of stations exhibiting this distributional change (ranging from 40-71% for Tmax and from 49-82% for Tmin) – see Table 2, summary section 5. This type of change was particularly common for stations located on the eastern coast of Australia (Fig. 6).

The shortest analysis period differed from the others in that it contained a greater proportion of stations with no significant change in the mean, extremes or standard deviation (i.e. no distributional change) and of stations with changes only in the mean (Fig. 7). Most of the stations that experienced no significant shift in the mean, extremes or standard deviation were away from the coast; similarly for stations where only the mean temperature changed.

Stations with a significant change in temperature variability were predominantly coastal (Fig. 8).

Some differences in the distribution change between rural and non-rural stations were evident over the two most recent periods; the sample size for the 1931-2005 period was, in practicality, too small to draw any inference (Table 3). For both the 1946-2005 and 1961-2005 periods, rural stations showed a higher proportion of 'no change' stations than non-rural stations, for both minimum and maximum temperatures. However, when the results were broken down according to rural or non-rural status, in most cases the sample sizes remained too small to perform robust statistical tests for differences (Given the power of a test, or the ability of a test, to detect true differences of a particular size depends on the sample size, the size of the effect to be detected, the Type I error rate and sample variability; in our opinion, in most cases the sample sizes were too small to yield adequate power – see Table 3).

Correlations between mean temperature and frequency of extremes

There were large regions of consistently strong correlations between the measures of mean temperature and the extreme temperature indices over the three analysis periods. Over the period 1961-2005, correlations between the number of hot days and mean maximum temperature ranged between 0.09 and 0.82, with an average correlation of 0.51 across all stations. This relationship was particularly strong in eastern and central Australia, as well as in the North Island of New Zealand (Fig. 9(a)). As a comparison, the average HD/Tmax correlation was also 0.51 for both 1931-2005 and for 1946-2005.

Correlations between the number of cool days and mean maximum temperature ranged between -0.01 and -0.74 with an average correlation of -0.43 (1961-2005) across all stations. The strongest correlations were in the coastal regions, particularly in the north and east of Australia and in the South Island and eastern North Island of New Zealand (Fig. 9(b)).

Correlations between the number of warm nights and the mean minimum temperature ranged between 0.04 and 0.73 with an average correlation of 0.46 (1961-2005) across all stations. The regions with the strongest relationship between the mean minimum temperature and the number of warm nights were the central parts of Australia, particularly in the east, and much of New Zealand (Fig. 10(a)).

Fig. 8 Locations where a change in the standard deviation was detected (open circles) over the period 1961-2005: (a) Tmax, (b) Tmin. All other station locations are also shown (solid dots).

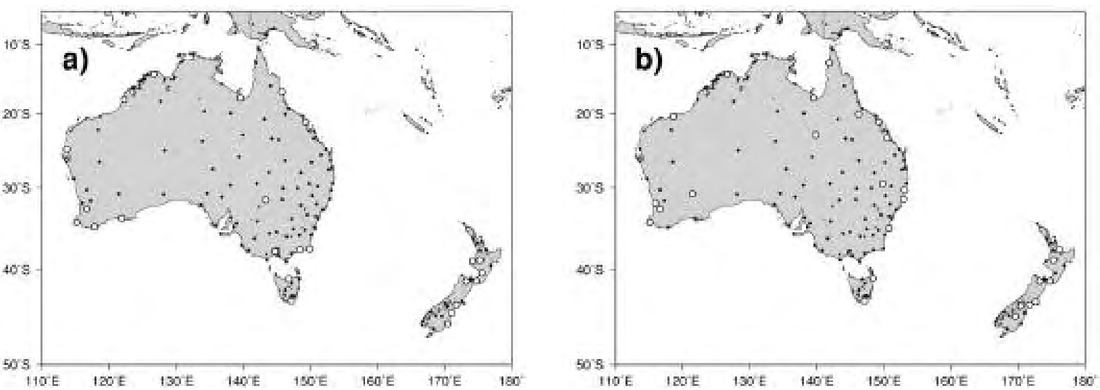
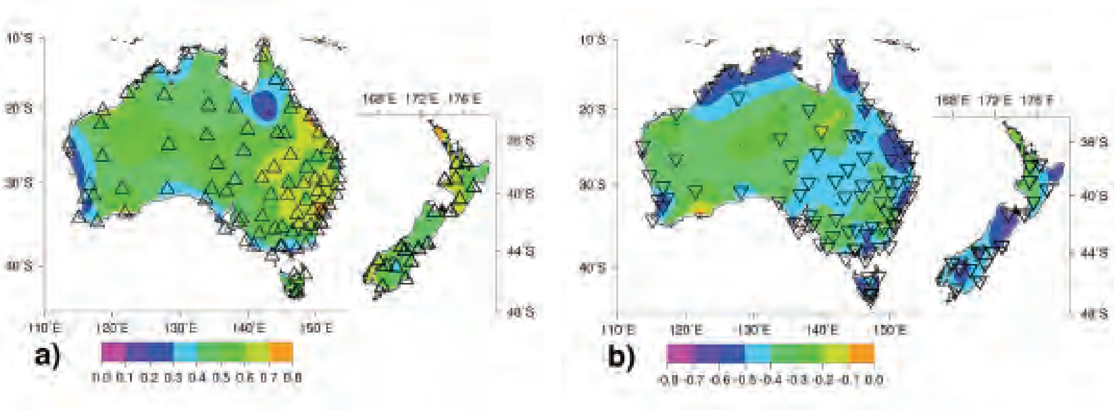


Table 3. Summary of the number of stations that fall into the 'significant change' (at the five per cent level) categories, differentiated by whether the site was rural or non-rural (either urban or highly urban), for the periods 1931-2005 (N=17; number rural = 10, non-rural = 7), 1946-2005 (N=53; number rural = 23, non-rural = 30) and 1961-2005 (N=118; number rural = 82; non-rural = 36) (definitions as in Appendix). The percentage of the total number of sites is given in brackets.

Significant changes	*1931 – 2005*		*1946 – 2005*		*1961 – 2005*	
	MaxT	*MinT*	*MaxT*	*MinT*	*MaxT*	*MinT*
Summary results (2-5 ignore variance changes): non-rural						
1. No change	0 (0)	1 (14)	3 (10)	2 (7)	7 (19)	5 (14)
2. Mean, not extremes	0 (0)	0 (0)	4 (13)	3 (10)	4 (11)	5 (14)
3. Extremes (1 or 2), not mean	0 (0)	0 (0)	5 (17)	2 (7)	3 (8)	3 (8)
4. Mean and both extremes	2 (29)	5 (71)	2 (7)	16 (53)	6 (17)	12 (33)
5. Mean and extremes (1 or 2)	6 (86)	6 (86)	17 (57)	23 (77)	19 (53)	23 (64)
6. Change in SD	2 (29)	1 (14)	3 (10)	10 (33)	9 (25)	10 (28)
Summary results (2-5 ignore variance changes): rural						
1. No change	1 (10)	0 (0)	4 (17)	5 (22)	19 (23)	21 (26)
2. Mean, not extremes	1 (10)	1 (10)	2 (9)	1 (4)	19 (23)	15 (18)
3. Extremes (1 or 2), not mean	2 (20)	1 (10)	4 (17)	2 (9)	12 (15)	10 (12)
4. Mean and both extremes	4 (40)	5 (50)	4 (17)	2 (9)	6 (7)	10 (12)
5. Mean and extremes (1 or 2)	6 (60)	8 (80)	13 (57)	13 (57)	28 (34)	35 (43)
6. Change in SD	3 (30)	6 (60)	8 (35)	10 (43)	16 (20)	16 (20)

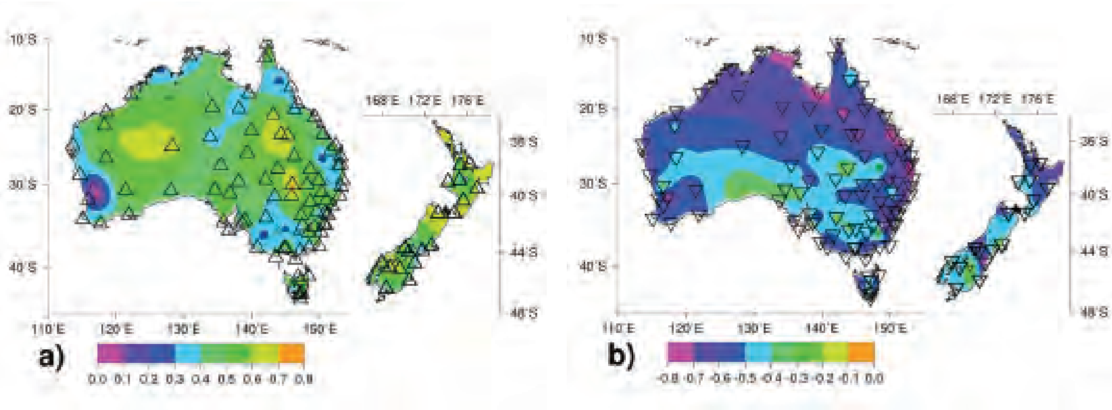
Fig. 9 Correlations with Tmax (a) hot days and (b) cool days, 1961-2005. Statistical significance (at the five per cent level) and the sign of the correlation at the individual stations is indicated by triangles – bold large triangles representing significant correlations, positive (negative) correlations represented by up (down) facing triangles.



Correlations between the number of cold nights and the mean minimum temperature ranged between -0.14 and -0.82, with an average correlation of -0.55 (1961-2005) across all stations. The strongest relationships between the number of cold nights and mean minimum temperature were over the north and east of Australia (Fig. 10(b)). As a comparison, the average CN/Tmin correlation was -0.58 for 1931-2005 and -0.57 for 1946-2005.

For the stations with data back to 1931 the correlations between the mean temperature and the extremes indices were of a similar strength for the 1931-2005 period as for the 1961 to 2005 period (not shown). Urban status resulted in no apparent difference in the relationships between mean temperatures and extremes indices, with urban and nearby rural stations displaying similar correlations (Figs 9-10 compared with Fig. 2). This was confirmed by calculating average correlations

Fig. 10 Correlations with Tmin (a) warm nights and (b) cold nights, 1961-2005. Statistical significance (at the 5% level) and the sign of the correlation at the individual stations is indicated by triangles – bold large triangles representing significant correlations, positive (negative) correlations represented by up (down) facing triangles.



for the rural sites for the three periods and comparing to the averages for the non-rural sites (not shown), with only one case (out of 12, i.e. 4 extremes variables, 3 periods) indicating that there may be a difference between the relationship between the means and extremes for rural and non-rural sites – cold nights and Tmin for the 1931-2005 period (rural sites: mean -0.433, standard error (s.e.) of mean 0.035; non-rural mean -0.541, s.e. of mean 0.044). The urbanised sites tend to be located in a narrow coastal strip on the eastern seaboard of Australia, as well as in the North Island of New Zealand – and yet, for example, there is a large area of high correlation (>0.6) between Tmax and the hot day index (Fig. 9(a)) along the Queensland and New South Wales coast, and extending 10 degrees of longitude inland i.e. covering both urban and rural sites.

Relationships to broadscale indices

Prior to correlating with the temperature indices, the broadscale indices were checked for persistence and inter-relationships, using data from 1961 to 2005. Most indices (SST1, NINO3.4, MSLP2) showed no persistence from year to year (either on the annual, DJF or JJA timescales). Only SST2 showed persistence on the annual and JJA timescales. MSLP1 showed persistence from year to year on all three timescales (though the relationship was weaker for DJF).

On the annual timescale a number of the large-scale indices were significantly (at the 5% level) positively correlated (SST1 and NINO3.4; SST1 and MSLP1; SST2 and MSLP1, NINO3.4 and MSLP1), while others were negatively correlated (SST1 and MSLP2; NINO3.4 and MSLP2) (significant at the 5% level). Many of these relationships also held when the data were averaged over the JJA timescale.

Since 1961, SST2 and MSLP1 have experienced strong trends towards higher values on all timescales. An increasing trend was also seen for SST1 on annual and DJF timescales.

The strength of the relationship between the temperature indices and the broadscale indices was assessed by tabulating the number of stations with statistically significant correlations (Table 4(a)). A number of relationships stood out as being beyond the possibility of chance, having at least five times as many stations with significant correlations than expected by chance alone at the 5% level. The number of significant relationships between the temperature indices and the broadscale indices was generally lower during the DJF period than in JJA or annually. For most of the temperature indices the use of MSLP1 (particularly in the same year as the temperature extremes and during JJA or annually) or SST2 (same year and JJA or annually) resulted in a greater number of significant correlations.

In most cases, there appeared to be a greater spatial coherence (as measured by the number of stations with significant correlations) when considering Tmin and Tmax and the broadscale circulation or SST indices than the other indices of extreme temperatures. There were generally fewer significant correlations between the broadscale indices and measures of change in standard deviation, warm nights or cool days (the exception being cool days and SST2 of the same year – JJA and annually). This was particularly evident during the DJF period.

Table 4(a). Number of significant (at the 5% level) correlations between variables using 1961 to 2005 period (118 stations). BOLD values = at least 25% of all stations, UNDERLINED = at least 50% of all stations. Prev = broadscale index values from the year prior to the temperature index; same refers to indices from the same year. The quoted figures include both positive and negative correlations.

	TMax	*SD Tmax*	*HD*	*CD*	*TMin*	*SD Tmin*	*WN*	*CN*	*DTR*
Annual									
MSLP1 (prev)	**34**	10	20	11	**<u>71</u>**	15	24	**51**	**32**
MSLP1 (same)	**46**	21	**33**	11	**55**	23	**33**	**32**	28
MSLP2 (prev)	13	6	6	6	15	19	18	10	2
MSLP2 (same)	22	7	13	5	**34**	18	19	11	**30**
NINO3.4 (prev)	18	4	2	8	28	23	16	17	0
NINO3.4 (same)	**44**	20	**32**	2	29	20	22	8	30
SST1 (prev)	19	11	3	10	**34**	27	13	23	7
SST1 (same)	**<u>59</u>**	19	**48**	7	**34**	15	**32**	7	27
SST2 (prev)	16	12	13	14	**41**	8	12	**30**	**31**
SST2 (same)	**50**	29	8	**49**	**58**	25	9	**43**	**36**
DJF									
MSLP1 (prev)	20	18	8	25	**54**	13	10	**43**	27
MSLP1 (same)	19	7	16	8	**<u>63</u>**	17	17	**40**	**39**
MSLP2 (prev)	3	2	3	2	4	2	2	1	4
MSLP2 (same)	19	27	10	4	18	7	18	8	4
NINO3.4 (prev)	1	2	5	0	0	1	1	1	3
NINO3.4 (same)	24	13	13	4	**32**	11	28	14	5
SST1 (prev)	3	16	9	1	6	1	0	6	5
SST1 (same)	**40**	13	28	10	**54**	13	**39**	21	6
SST2 (prev)	11	4	6	5	15	8	7	18	16
SST2 (same)	10	10	5	12	**47**	27	7	**31**	17
JJA									
MSLP1 (prev)	**49**	11	26	25	**<u>64</u>**	13	27	**46**	**31**
MSLP1 (same)	**57**	28	**43**	18	**53**	21	26	28	**32**
MSLP2 (prev)	12	6	10	4	25	24	20	13	2
MSLP2 (same)	22	6	10	5	**36**	24	14	20	**39**
NINO3.4 (prev)	22	4	5	6	27	24	22	14	3
NINO3.4 (same)	**34**	8	19	3	**32**	27	14	11	**41**
SST1 (prev)	13	17	3	10	24	29	11	21	7
SST1 (same)	**38**	10	**31**	1	24	15	14	11	21
SST2 (prev)	18	10	13	15	**36**	8	6	27	**33**
SST2 (same)	**53**	**57**	7	**<u>78</u>**	**45**	27	12	**50**	**34**

Given the strong trends in some of the broadscale indices, both the broadscale and extremes indices were linearly detrended and the correlations recalculated (Table 4(b)). The previously high numbers of significant correlations with MSLP1, SST1 and SST2 were no longer present when detrended data were used, indicating that the high correlations were most likely due to trends in the respective time series, rather than to a causal relationship. Relationships between the extreme indices and MSLP2 and NINO3.4, however, remained after the data were detrended indicating a possible causal relationship.

A subset of the correlation results was further investigated to identify regional patterns and potential links between various extreme temperature indices and lead periods. Initially, correlation patterns were compared using detrended values of the same broadscale index and the various components of the temperature distributions. Correlations between the index of mean maximum temperature (Tmax) and an annual index of NINO3.4 showed high spatial coherence, as seen in Fig. 11. High values of NINO3.4 generally corresponded to higher values of Tmax and more hot days, particularly in eastern Australia and lower values of Tmax and fewer hot days in New Zealand. As expected from Table 4, there was less spatial coherence when considering the relationship between NINO3.4 and other components of the maximum temperature distribution, such as the standard deviation or the number of cool days. The correlation pattern for Tmin indicated strong negative relationships between NINO3.4 and Tmin at stations to the southeast and northeast of Australia and over New Zealand. Correlations

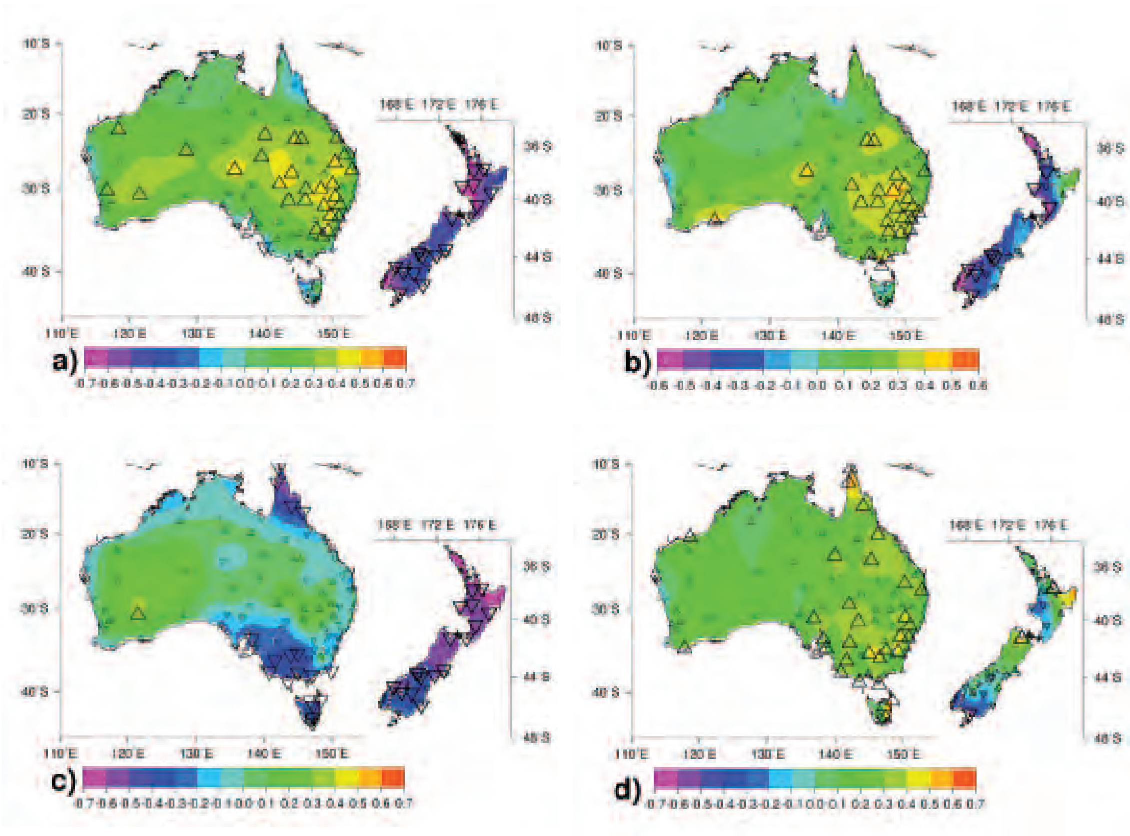
Table 4(b). Number of significant (at the 5% level) correlations between variables using 1961 to 2005 period – linearly detrended data (118 stations). BOLD values = at least 25% of all stations, UNDERLINED = at least 50% of all stations.

	TMax	*SD Tmax*	*HD*	*CD*	*TMin*	*SD Tmin*	*WN*	*CN*	*DTR*
Annual									
MSLP1 (prev)	2	2	6	3	7	1	2	3	11
MSLP1 (same)	17	23	20	7	7	6	8	1	11
MSLP2 (prev)	15	6	6	8	24	23	21	13	3
MSLP2 (same)	29	8	17	5	**33**	21	20	10	**32**
NINO3.4 (prev)	19	4	4	6	26	20	19	12	1
NINO3.4 (same)	**47**	20	**37**	4	**36**	21	25	13	**34**
SST1 (prev)	7	4	7	4	5	1	1	13	11
SST1 (same)	7	3	4	4	6	4	3	10	11
SST2 (prev)	10	5	7	1	9	1	4	13	10
SST2 (same)	11	5	9	5	5	2	4	12	18
DJF									
MSLP1 (prev)	1	2	3	4	3	2	1	4	7
MSLP1 (same)	6	4	2	12	19	4	2	7	19
MSLP2 (prev)	1	2	2	1	1	0	1	4	3
MSLP2 (same)	22	22	16	3	25	10	22	7	3
NINO3.4 (prev)	1	4	5	0	0	1	1	0	3
NINO3.4 (same)	25	18	15	4	**37**	11	**30**	14	4
SST1 (prev)	10	5	8	3	11	2	3	13	15
SST1 (same)	8	3	6	3	7	2	3	12	12
SST2 (prev)	10	5	9	3	12	2	4	13	13
SST2 (same)	8	3	7	3	10	2	3	13	16
JJA									
MSLP1 (prev)	3	6	6	6	3	2	3	1	8
MSLP1 (same)	12	21	16	3	3	8	4	3	8
MSLP2 (prev)	18	6	11	5	26	26	22	14	2
MSLP2 (same)	26	8	13	7	**42**	24	14	23	**44**
NINO3.4 (prev)	24	5	7	6	29	20	25	14	3
NINO3.4 (same)	**34**	9	19	3	**41**	28	14	17	**48**
SST1 (prev)	8	4	8	3	7	2	3	13	12
SST1 (same)	11	3	7	3	7	1	4	14	12
SST2 (prev)	9	5	8	2	11	2	4	13	13
SST2 (same)	9	7	8	4	9	3	3	14	14

were mainly positive between NINO3.4 and the DTR over most of Australia, with the strongest correlations tending to occur in eastern Australia, particularly in the south. Correlations between DTR and NINO3.4 were mixed and not often significant over New Zealand.

NINO3.4, Tmin and Tmax are used to illustrate how the relationship between the temperature indices and a broadscale index changed when considering different averaging periods (annual, DJF or JJA). For Tmin the spatial correlation pattern with NINO3.4 in JJA was fairly similar to that observed when using annual NINO3.4 values from the same year, the most noticeable difference being a greater number of significant correlations in northern Australia for the JJA period (compare Fig. 11(c) and Fig. 12(a)). Using DJF values of NINO3.4 (Fig. 12(b)) strengthened the correlations over much of northeastern Australia, but weakened the correlations in southern Australia and New Zealand. The number of cold nights in eastern Australia was positively correlated with NINO3.4 during JJA (not shown), particularly over southeastern Queensland, while for hot days the strongest (negative) correlations with NINO3.4 in JJA were in New Zealand (not shown). NINO3.4 in JJA was strongly correlated with DTR over much of eastern Australia (positive) and New Zealand (mostly negative) (not shown). For Tmax the strength and spatial coherence of the correlation patterns were similar when using JJA values of NINO3.4 in the same year to the use of annual NINO3.4 values (compare Fig. 11(a) with Fig. 12(c)). Higher DJF values of NINO3.4 also tended to correspond to a greater number of warm nights in eastern Australia (Fig. 12(d)).

Fig. 11 **Detrended annual NINO3.4 index (same year), correlated with detrended (a) Tmax, (b) HD, (c) Tmin and (d) DTR. Statistical significance (at the 5% level) and the sign of the correlation at the individual stations is indicated by triangles – bold large triangles representing significant correlations, positive (negative) correlations represented by up (down) facing triangles.**



In broad terms, the correlation patterns for MSLP2 and NINO3.4 were very similar across various seasons and for many of the extreme indices, though of a different sign and greater spatial coherence over eastern Australia for NINO3.4. In comparison, the corresponding patterns for detrended MSLP1 correlations were generally much weaker and less coherent. SST patterns 1 and 2 showed very little spatial coherence in their correlation patterns for most extremes indices, as illustrated in Table 4(b).

Urban status did not appear to affect the correlations between the temperature and broadscale indices; with nearby urban and rural stations displaying similar correlations (for example, Fig. 11(a), where urban records on the Queensland and New South Wales coast and in New Zealand show similar correlations to rural sites located in nearby coastal and inland sites).

Illustrative cases

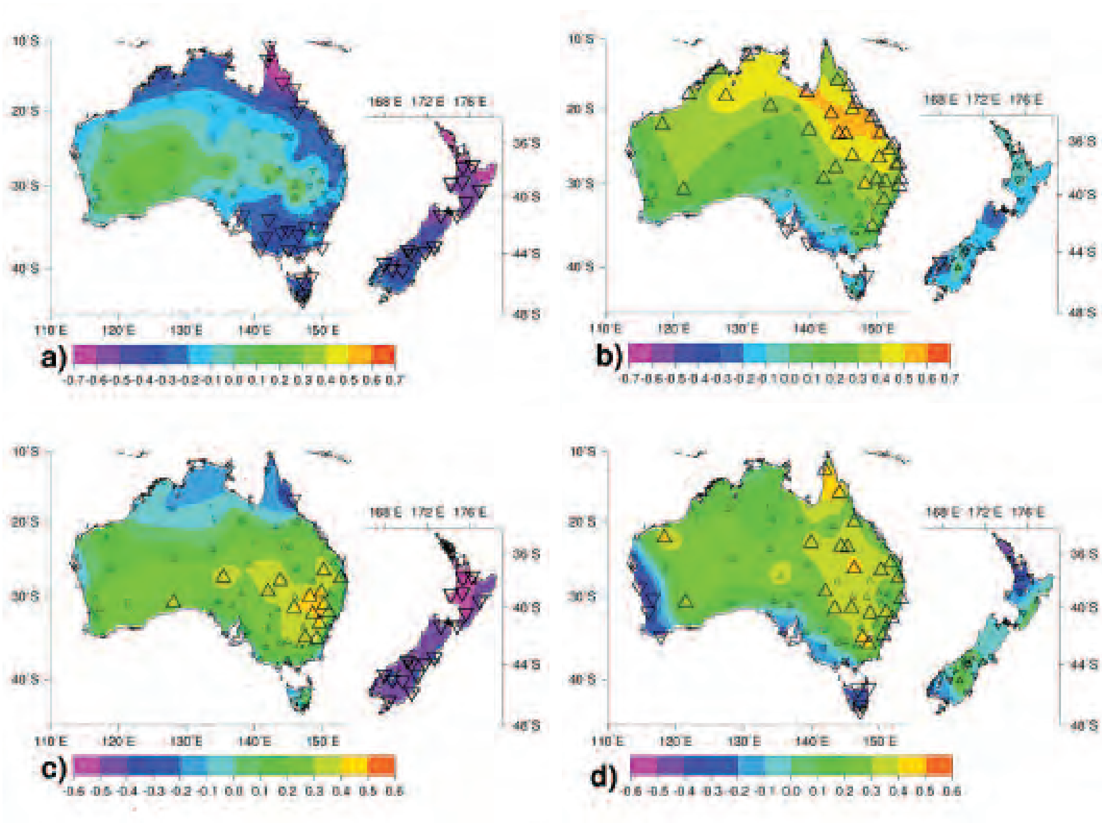
Changes in mean minimum temperature and extremes, with variability change

A change in mean minimum temperature and at least one extreme, together with a change in temperature variability, was typical for a number of stations, particularly those which had data over the period 1931-2005. For example, Port Macquarie in eastern Australia (an urban site), over the period 1931 to 2005, had an increase in mean minimum temperature and the number of warm nights as well as a decreased variability in minimum temperatures and fewer cold nights. The resultant temperature distribution change is shown in Fig. 13.

Reduction in maximum temperature variability, fewer extremes

Carnarvon, Australia, is one of a number of coastal

Fig. 12 Correlations between (a) detrended JJA NINO3.4 index (same year) and detrended Tmin, (b) detrended DJF NINO3.4 (same year) and detrended Tmin, (c) detrended JJA NINO3.4 (same year) and detrended Tmax and (d) detrended DJF NINO3.4 (same year) and WN. Statistical significance (at the 5% level) and the sign of the correlation at the individual stations is indicated by triangles – bold large triangles representing significant correlations, positive (negative) correlations represented by up (down) facing triangles.

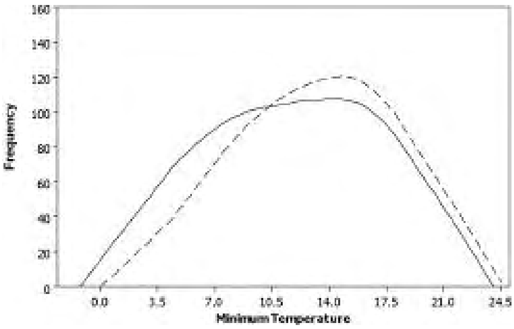


sites in northern and western Australia where a reduction in the variability of maximum temperature, but no change in mean climate, corresponded to a reduction in extremes (Fig. 14(a)). These reductions in the standard deviation and both extremes were significant at Carnarvon, corresponding to 'SD, both extremes only' in Table 2. The decrease in both hot days and cool days can be clearly seen (Fig. 14(b)), although both series are noisy. There was no significant trend in Tmax. The other station that demonstrated this type of behaviour in maximum temperatures over the 1946-2005 period was Halls Creek. (Both Carnarvon and Halls Creek were rated as rural stations.) For minimum temperature, similar distributional changes were seen for Ashburton (1961-2005 period) and Moruya (1931-2005 period). Both Ashburton and Moruya were classified as rural sites.

Discussion and conclusions

Many recent studies have found a general trend towards increased mean temperatures, a marked reduction in cold extremes and an indication of an increase in hot extremes, both globally (e.g. Easterling et al. 1997; Alexander et al. 2006) and regionally (e.g. Manton et al. 2001; Griffiths et al. 2005; Alexander et al. 2007). Griffiths et al. (2005) extended the Manton et al. (2001) study by covering a longer analysis period (five additional years) and using two more stations in the New Zealand region (as well as other station differences outside the Australia/New Zealand region), taking the Australian station total to 15 and the New Zealand total to four. In the current study, over the 1961 to 2005 period – comparable to Griffiths et al. (2005), 118 stations were considered – 100 for Australia and 18 for New Zealand, offering improved

Fig. 13 Daily minimum temperature distribution at Port Macquarie; 1931 to 1941 (black line) compared to 1991 to 2005 (dashed line) (Lowess smoothed probability density functions with 0.2 degrees of smoothing).

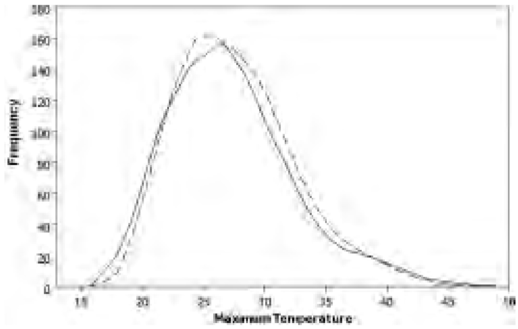


spatial data coverage and the inclusion of urbanised records, in order to undertake a preliminary investigation on the effects of urbanisation on indices of extreme temperature and the type of distribution change observed. In addition, a longer period of data (1931-2005) was analysed in the current study, and correlations between indices of extreme temperature and indices of key climatological variables (such as SST and MSLP patterns) were calculated.

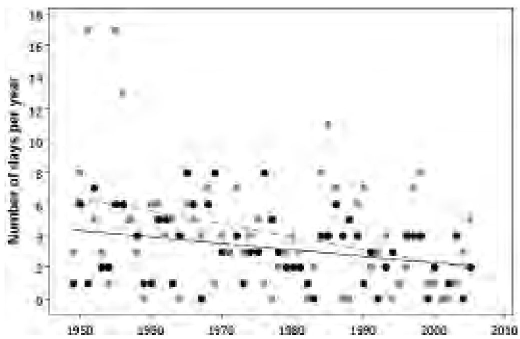
Urbanisation affects local temperatures primarily through increased minimum temperatures, a reduction in the diurnal temperature range and, to a lesser extent, increased maximum temperatures (Coughlan 1979; Karl et al. 1988; Kim and Baik 2004; Griffiths et al. 2005). The urban heat island effect has also been associated with decreased temperature variability and changes to climatic trends (Li et al. 2004; Griffiths et al. 2005). The impact of urbanisation on temperature can vary by location, due to differences between countries and regions in the environmental conditions around the observing sites within the city and the geographic location of the city (Kim and Baik 2004; Li et al. 2004). Coastal cities generally exhibit less of an urbanisation effect than inland cities, regardless of the city size (Kim and Baik 2004), possibly related to influences of the land/sea circulation. Due mainly to the open geometry (layout) of Australian and New Zealand cities, the difference between rural and urban temperatures is expected to be smaller in Australia and New Zealand than for similar sized cities in Europe and North America (Torok et al. 2001). For temperature extremes, the most rapid increases (for both high maximum and minimum temperatures) tend to occur at urban stations (DeGaetano and Allen 2002).

Fig. 14 (a) Daily maximum temperature distribution at Carnarvon, 1951 to 1961 (black line) compared to 1991 to 2001 (dashed line) (Lowess smoothed probability density functions with 0.2 degrees of smoothing) and (b) number of hot days per year with fitted trend line (black dots) and number of cold days per year with fitted trend line (grey squares).

(a)



(b)



The population of Australia has increased over the period 1931-2005 from approximately five million to just over 20 million (Australian Bureau of Statistics, 2007), while the population of New Zealand increased at a slightly slower rate, from around 1.5 million in the 1930s to just over four million people 75 years later (Treasury Internal Database 2007). Time series of total population for both countries show a marked increase in population (often called 'the baby boom') which occurred immediately after World War II. The so-called 'baby boom' is most obvious in the Australian data, but New Zealand also shows increased population and a steeper rate of population increase since the late 1940s.

Against a backdrop of rapid population increase since the late 1940s, significant increases in mean annual temperature from about 1950 (roughly coincident with the population increase), a shift towards higher pressures over Australia and the Tasman Sea, and warmer Indian Ocean SSTs, Australian and New Zealand maximum and minimum temperature distributions have altered as described below.

Spatial coherence of trends in extreme temperatures, suggested by Griffiths et al. (2005) and Alexander et al. (2007), was confirmed by the use of the higher station density of this study, all studies finding not only a general trend towards warmer mean maximum and mean minimum temperatures over Australia/New Zealand but also general increases in the number of hot days and warm nights and decreases in the number of cool days and cold nights. The strongest signal was for cool days and cold nights.

The proportion of stations with significant increases in warm nights, or significant decreases in cold nights or cool days, increased as analysis period lengthened (consistent with the influence that sample size has on statistical significance and test accuracy, if a real trend were present). The notable exception was hot days – the proportion of stations with an increase in hot days remained at about 25 per cent, regardless of analysis period.

The majority of stations did not experience statistically significant changes in temperature variability over time. For the few that did, the majority were towards reduced variability over time; a result consistent with Griffiths et al. (2005). Trends in diurnal temperature range depended on the analysis period, and will be discussed more fully below. Diurnal temperature range was not considered by Griffiths et al. (2005).

The most common form of distributional change, for both maximum and minimum temperature, involved a significant shift in the mean and one or both extremes. This is comparable with the Griffiths et al. (2005) results, based on non-urbanised Australian and New Zealand sites. Although they used a small number of stations, their analysis indicated that this type of distribution change was more likely in eastern Australia, particularly for maximum temperature, a result which held with the denser station network of this study. Mean maximum and minimum temperatures in eastern Australia are known to be influenced by the Southern Oscillation (Jones and Trewin 2000), with El Niño events producing more significant impacts on the extremes than the mean (Salinger and Lefale 2005) which may, at least partially, explain this result.

The majority of stations with significant changes in temperature variability were coastal, a result also consistent with the Australian stations in Griffiths et al. (2005) and included a relatively even mix of both rural and non-rural sites. Strong correlations were found between the measures of mean temperature and temperature extremes, consistent with other analyses (e.g. Griffiths et al. 2005; Alexander et al. 2007). Although the indices of Alexander et al. generally reflected less extreme temperatures than those used in this study, broadly similar spatial patterns of correlations emerged. Trends in Tmax and Tmin were most significant in the east of Australia, as were trends in the extreme indices, although increases in warm nights and decreases in cold nights were also significant along the southern coast of the continent. The largest correlations between means and extremes were most often found in the east of Australia (except for warm nights with Tmin) and significant correlations between possible drivers of underlying climate variability, e.g. detrended annual NINO3.4, and indices of temperature extremity (Tmax, hot days and DTR) were also located in the east. These correlations appeared consistently strong across all three analysis periods and appeared largely independent of urban status. Regions with significantly high correlations suggest that changes in mean temperature may have the potential to be used to predict changes in extreme temperature.

Influence of analysis period

A similar spatial coverage of stations was achieved for the 1946-2005 and 1961-2005 periods. However, for 1931-2005 available station data were restricted to the eastern regions of Australia, particularly towards the south, and mainly to the South Island of New Zealand. In addition, the proportion of rural sites was comparable for the 1931-2005 and 1961-2005 periods, but much lower (43 per cent) for the 1946-2005 analysis. Despite the differences in station coverage and degree of urbanisation, very similar levels of significant trends in the extremes indices were seen, regardless of the time period considered. Comparison of the effect of different time periods on a subset of the stations, those which had data for all three time periods, reinforced these results and provided further information (Fig. 5). In particular, as the length of the analysis period was increased (backward in time) the number of significant positive trends in mean minimum temperature, warm nights, and to a lesser extent cold nights and minimum temperature variability, increased. In contrast, the number of cool days decreased with increasing length of analysis period. Previous global studies have remarked that maximum temperatures have not increased as fast as minimum temperatures (e.g. Alexander et al. 2006; Easterling et al. 1997), though on the regional level some differences have been seen, for example, in parts of New Zealand (Easterling et al. 1997). This study adds further to this finding, with a greater number of trends towards warmer minimum temperatures over time and no clear trend over time in the number of significant increasing trends for maximum temperature (Fig. 5).

Many regions of the globe have experienced a narrowing of the diurnal temperature range over time (Easterling et al. 1997). Considering the Australia-New Zealand region as a whole, this result only held over the 1946-2005 period (most of the significant trends in DTR were negative) while the other two analysis periods had a fairly even split between increased and decreased DTR over time. This probably reflects both the rapid population growth/urbanisation seen over the 1946-2005 period in particular, and the much lower proportion of rural sites analysed in the period 1946-2005.

As mentioned earlier, most of the stations exhibiting change in the 'mean, extremes (1 or 2)' were in eastern Australia and potentially influenced by ENSO. During the early 1970s it appears that the relationship between ENSO and Australian temperatures may have changed, with the correlation between temperature and SOI weakening in more recent decades (Nicholls et al. 1996), possibly contributing to the reduction seen in the number of stations with this type of distributional change as the analysis period shortens, as may changes in population of many of the cities (see below).

Urban status

While acknowledging that the urban status of a station defined in this paper, based solely on 2001 status, is a simplification for ease of analysis, and that urbanisation 'drift' may have occurred at some sites over time, a number of interesting results emerged.

The rural stations had fewer significant increasing trends in Tmin, warm nights and cold nights, and so the 'typical' urbanisation effects of increased minimum temperatures, and reduced minimum temperature variability, appear to be present in the urbanised (or highly urbanised) station data. In addition, urbanised sites showed a higher proportion of significant increase in the hot days index, consistent with other studies which showed the most rapid increases in temperature extremes occur at urban locations.

The significance of trends over time in the diurnal temperature range was highly dependent on the analysis period used, with the period 1946-2005 showing the largest percentage of significant decreases in DTR. This most likely reflected the relatively high proportion (~57%) of urban stations analysed over this period as compared with the other two periods, and is, again, consistent with the known effects of urbanisation.

For both the 1946-2005 and 1961-2005 periods, rural stations showed a relatively higher proportion of 'no change' stations, for both minimum and maximum temperatures, while non-rural stations showed a relatively lower proportion. In addition, for both minimum and maximum temperature, the proportion of 1961-2005 urban stations with a 'mean, 1 or 2 extremes' type of distribution change was relatively reduced. The first result is consistent with the effects of urbanisation – i.e. that the urban heat island effect increases mean temperature and decreases temperature variability – but it is notable that it is seen so clearly in the maximum temperature distribution.

Relationships between temperature indices and broadscale indices

Primary modes of large-scale circulation and SST variability over Australasia, as represented by principal components, have altered since 1949. MSLP1, a tropical/subtropical pattern which is particularly strong over the equatorial Indian Ocean, has shown a shift to more positive loadings, corresponding to generally higher MSLP values over the Australian region, since the mid-1970s as have SST1 (a pattern related to the tropical central and eastern Pacific, clearly showing ENSO events) and SST2 (an Indian Ocean pattern). The net impact of these pattern changes has been an increase in SSTs since 1949 in the Indian Ocean and around the northern, western and southern coasts of Australia.

Major climatic features, such as El Niño, are known to influence mean Australian and New Zealand climate. ENSO is a significant source of seasonal and year-to-year climate variability in New Zealand and Australia (e.g. Mullan 1995; Jones and Trewin 2000). Nicholls et al. (2005) also identified that ENSO impacted on temperature extremes in the Asia-Pacific region, namely that more hot days tend to occur in the year following the onset of an El Niño event, and that the relationship between detrended NINO3.4 and the hot days index was, in fact, stronger than the relationship with Tmin. Table 4(a) showed strong relationships (sometimes lagged) between particular pairings of circulation or SST patterns, and indices of temperature extremity, however, many of these strong relationships disappeared for MSLP1 and for both SST patterns when linear trends in the time series were removed. Although the correlations between Tmax or Tmin and a broadscale pattern (such as MSLP2 or NINO3.4) are very strong and often cover a large geographical area, there are equally strong relationships between various measures of extremity (hot days, cool days, warm nights, cold nights) which are sometimes quite regional in nature, for example, broadscale circulation represented by the

NINO3.4 index appeared to influence eastern Australia and New Zealand in different ways for many of the extremes indices (resulting in correlations of opposite signs, e.g. Figs 11(a) and 11(b)). This is consistent with the results of Nicholls et al. (2005) (compare their Fig. 1), Nicholls et al. (1996) (El Niño results in generally higher temperatures for Australia) and Salinger and Lefale (2005) (El Niño results in generally cooler temperatures for New Zealand). At least in Australia, the relationship between the Southern Oscillation and temperature is said to be largely due to Southern Oscillation driven variations in radiative and latent heat fluxes (Jones and Trewin 2000). Relationships between annual and seasonal values of NINO3.4 and Tmax were generally consistent and strong over eastern Australia and New Zealand, while there was a marked difference in the relationship between minimum temperature and NINO3.4 in DJF and JJA consistent with Jones and Trewin (2000). Nevertheless, although beyond the scope of this paper, these relationships need further investigation (in particular to see if the relationships are static over time), as there is potential for the prediction of regional temperature extremes.

Implications of results

There was a high coherence of results both spatially and temporally, although urbanisation does impact on DTR and possibly the type of distributional change observed. Although urbanisation is evident in the observational record (in that we see the rural and urban stations showing differing proportions of change in indices of extremity such as hot days, cold nights, etc), extremes are also influenced by broadscale climate, such as NINO3.4 and MSLP2.

A strong spatial consistency of trends for many indices of temperature extremity in Australia and New Zealand (except DTR which appears to be strongly influenced by urbanisation) is notable when using data from both rural and urban stations, and adds weight to the indices methodology employed here. The observed temporal pattern in trends (except for DTR) when analysed over differing analysis periods is consistent with the underlying climatic background (namely, an increase in mean temperatures since about 1950, coincident with rapid urbanisation; and a shift towards generally warmer SSTs). The most common form of distributional change for Australian and New Zealand stations, for both maximum and minimum temperature, involved a significant shift in the mean and one or both extremes. However, the proportion of stations with this type of distribution shift reduced in the later analysis period, with relatively more stations having no distribution change, or shifts in the mean (but not extremes) in the 1961-2005 period, possibly due to a change in the relationship between ENSO and temperature and/or the effects of urbanisation.

This study indicates that some measures of ENSO, such as NINO3.4 or MSLP2, have the potential to provide better predictors of many of the temperature extremes over large areas of the Australian (particularly eastern Australia) and New Zealand region, than other broadscale indices, such as SSTs.

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Appendix

List of stations, their location and period of record. The data used for analysis were in most cases shorter, bounded by the analysis periods of 1931-2005, 1946-2005 and 1961-2005 and, in some cases, limited by incomplete annual records. The longest analysis period is listed. Also listed is the urban category used for each station using the criteria of Griffiths et al. (2005). HU = highly urbanised (population greater than 300 000 with more than 300 people per km^2 in 2001); UR = urbanised (either the population greater than 300 000 or more than 300 per km^2, but not both); RU = rural (less than 300 000 people and density less than 300 per km^2). Australian sites are listed in order of their Bureau of Meteorology Station number.

Country	*Station*	*Latitude (decimal)*	*Longitude (decimal)*	*Temperature (available)*	*Analysis period*	*Urban status*
Australia	Kalumburu	14.30°S	126.64°E	1957-2005	1961-2005	RU
	Halls Creek	18.23°S	127.66°E	1944-2005	1946-2005	RU
	Broome	17.95°S	122.23°E	1939-2005	1946-2005	RU
	Port Hedland	20.37°S	118.63°E	1948-2005	1961-2005	RU
	Wittenoom	22.24°S	118.34°E	1958-2005	1961-2005	RU
	Carnarvon	24.88°S	113.67°E	1945-2005	1946-2005	RU
	Meekatharra	26.61°S	118.54°E	1950-2005	1961-2005	RU
	Dalwallinu	30.28°S	116.66°E	1957-2005	1961-2005	RU
	Geraldton	28.80°S	114.70°E	1941-2005	1946-2005	UR
	Perth	31.93°S	115.98°E	1944-2005	1946-2005	HU
	Cape Leeuwin	34.37°S	115.13°E	1957-2005	1961-2005	RU
	Albany	34.94°S	117.80°E	1949-2005	1961-2005	UR
	Esperance	33.83°S	121.89°E	1957-2005	1961-2005	RU
	Cunderdin	31.66°S	117.25°E	1957-2005	1961-2005	RU
	Wandering	32.67°S	116.67°E	1957-2003	1961-2005	RU
	Forrest	30.83°S	128.11°E	1946-2005	1946-2005	RU
	Kalgoorlie	30.79°S	121.45°E	1939-2005	1946-2005	UR
	Giles	25.04°S	128.29°E	1956-2005	1961-2005	RU
	Darwin	12.42°S	130.88°E	1941-2005	1946-2005	UR
	Tennant Creek	19.64°S	134.18°E	1957-2005	1961-2005	RU
	Alice Springs	23.80°S	133.89°E	1941-2005	1946-2005	UR
	Woomera	31.16°S	136.80°E	1949-2005	1961-2005	RU
	Tarcoola	30.71°S	134.57°E	1962-1999	1961-2005	RU
	Marree	29.65°S	138.06°E	1957-2005	1961-2005	RU
	Oodnadatta	27.54°S	135.44°E	1940-1997	1946-2005	RU
	Ceduna	32.13°S	133.71°E	1939-2005	1946-2005	RU
	Port Lincoln	34.72°S	135.86°E	1957-2002	1961-2005	RU
	Snowtown	33.78°S	138.21°E	1958-2001	1961-2005	RU
	Cape Borda	35.75°S	136.59°E	1957-2005	1961-2005	RU
	Adelaide	34.92°S	138.62°E	1887-2005	1931-2005	HU
	Nuriootpa	34.48°S	139.00°E	1957-1999	1961-2005	RU
	Mount Gambier	37.75°S	140.79°E	1942-2005	1946-2005	UR
	Robe	37.16°S	139.76°E	1957-2005	1961-2005	RU
	Thursday Island	10.59°S	142.21°E	1950-1993	1961-2005	RU
	Weipa	12.68°S	141.92°E	1959-2005	1961-2005	RU
	Palmerville	16.00°S	144.08°E	1957-2005	1961-2005	RU
	Burketown	17.74°S	139.55°E	1957-2005	1961-2005	RU
	Richmond (Qld)	20.73°S	143.14°E	1957-2005	1961-2005	RU
	Cairns	16.87°S	145.75°E	1942-2005	1946-2005	UR
	Townsville	19.25°S	146.77°E	1940-2005	1946-2005	UR
	Mackay	21.12°S	149.22°E	1959-2005	1961-2005	UR
	Charters Towers	20.04°S	146.27°E	1957-2005	1961-2005	RU
	Barcaldine	23.55°S	145.29°E	1957-2005	1961-2005	RU
	Longreach	23.44°S	144.28°E	1957-2005	1961-2005	RU
	Camooweal	19.92°S	138.12°E	1957-2005	1961-2005	RU
	Birdsville	25.90°S	139.35°E	1957-2005	1961-2005	RU

Country	*Station*	*Latitude (decimal)*	*Longitude (decimal)*	*Temperature (available)*	*Analysis period*	*Urban status*
	Boulia	22.91ºS	139.90ºE	1948-2005	1961-2005	RU
	Gayndah	25.63ºS	151.61ºE	1957-2005	1961-2005	RU
	Rockhampton	23.38ºS	150.48ºE	1939-2005	1946-2005	UR
	Bundaberg	24.91ºS	152.32ºE	1957-2005	1961-2005	UR
	Amberley	27.63ºS	152.71ºE	1941-2005	1946-2005	RU
	Brisbane	27.42ºS	153.11ºE	1949-2000	1961-2005	HU
	Tewantin	26.39ºS	153.04ºE	1957-1996	1961-2005	RU
	Miles	26.66ºS	150.18ºE	1957-2005	1961-2005	RU
	St George	28.04ºS	148.58ºE	1962-1997	1961-2005	RU
	Charleville	26.41ºS	146.26ºE	1942-2005	1946-2005	RU
	Thargomindah	28.00ºS	143.82ºE	1957-2005	1961-2005	RU
	Tibooburra	29.44ºS	142.01ºE	1921-2005	1931-2005	RU
	Wilcannia	31.56ºS	143.37ºE	1957-2005	1961-2005	RU
	Bourke	30.09ºS	145.83ºE	1957-1996	1961-2005	RU
	Cobar	31.49ºS	145.83ºE	1957-2005	1961-2005	RU
	Walgett	30.04ºS	148.12ºE	1957-2005	1961-2005	RU
	Moree	29.48ºS	149.84ºE	1879-1998	1931-2005	RU
	Gunnedah	31.03ºS	150.27ºE	1959-2005	1961-2005	RU
	Inverell	29.78ºS	151.11ºE	1957-1997	1961-2005	RU
	Yamba	29.43ºS	153.36ºE	1921-2005	1931-2005	RU
	Coffs Harbour	30.31ºS	153.12ºE	1943-2005	1946-2005	UR
	Port Macquarie	31.43ºS	152.92ºE	1921-2003	1931-2005	UR
	Williamtown	32.79ºS	151.84ºE	1942-2005	1946-2005	RU
	Scone	32.06ºS	150.93ºE	1959-2005	1961-2005	RU
	Bathurst	33.43ºS	149.56ºE	1921-2005	1931-2005	UR
	Dubbo	32.21ºS	148.57ºE	1957-1999	1961-2005	UR
	Sydney	33.86ºS	151.21ºE	1859-2005	1931-2005	HU
	Richmond (NSW)	33.60ºS	150.78ºE	1939-2005	1946-2005	UR
	Jervis	35.09ºS	150.80ºE	1957-2004	1961-2005	RU
	Nowra	34.94ºS	150.55ºE	1955-2000	1961-2005	RU
	Moruya	35.91ºS	150.15ºE	1921-2005	1931-2005	RU
	Canberra	35.30ºS	149.20ºE	1939-2005	1946-2005	HU
	Cabramurra	35.94ºS	148.38ºE	1962-1999	1961-2005	RU
	Wagga Wagga	35.16ºS	147.46ºE	1942-2005	1946-2005	UR
	Wyalong	33.93ºS	147.24ºE	1959-2005	1961-2005	RU
	Deniliquin	35.55ºS	144.95ºE	1957-2003	1961-2005	RU
	Mildura	34.23ºS	142.08ºE	1946-2005	1946-2005	UR
	Nhill	36.34ºS	141.64ºE	1951-2005	1961-2005	RU
	Kerang	35.73ºS	143.92ºE	1962-2005	1961-2005	RU
	Rutherglen	36.11ºS	146.51ºE	1957-2005	1961-2005	RU
	Gabo Island	37.57ºS	149.91ºE	1957-2005	1961-2005	RU
	Orbost	37.69ºS	148.46ºE	1957-2005	1961-2005	RU
	Sale	38.11ºS	147.13ºE	1945-2005	1946-2005	RU
	Wilsons Promontory	39.13ºS	146.42ºE	1957-2005	1961-2005	RU
	Melbourne	37.81ºS	144.97ºE	1855-2005	1931-2005	HU
	Laverton	37.86ºS	144.75ºE	1943-2005	1946-2005	RU
	Cape Otway	38.86ºS	143.51ºE	1957-2005	1961-2005	RU
	Low Head	41.06ºS	146.79ºE	1957-2001	1961-2005	RU
	Launceston	41.54ºS	147.20ºE	1939-2005	1946-2005	UR
	Eddystone	40.99ºS	148.35ºE	1957-2005	1961-2005	RU
	Cape Bruny	43.49ºS	147.14ºE	1957-2005	1961-2005	RU
	Hobart	42.89ºS	147.33ºE	1944-2005	1946-2005	UR
	Grove	42.99ºS	147.08ºE	1957-2005	1961-2005	RU
	Butlers Gorge	42.28ºS	146.27ºE	1957-1993	1961-2005	RU
New Zealand	Ruakura	37.78ºS	175.31ºE	1940-2003	1946-2005	UR
	Invercargill	46.42ºS	168.33ºE	1948-2005	1961-2005	UR
	Ophir	45.11ºS	169.61ºE	1924-2005	1931-2005	RU
	Tekapo	44.00ºS	170.44ºE	1928-2005	1931-2005	RU

Country	*Station*	*Latitude (decimal)*	*Longitude (decimal)*	*Temperature (available)*	*Analysis period*	*Urban status*
	Napier	39.50ºS	176.91ºE	1940-2005	1946-2005	UR
	Kelburn (Wellington)	41.29ºS	174.77ºE	1931-2005	1931-2005	UR
	Musselburgh (Dunedin)	45.90ºS	170.51ºE	1947-2005	1946-2005	UR
	Queenstown	45.04ºS	168.66ºE	1930-2005	1931-2005	RU
	New Plymouth	39.01ºS	174.18ºE	1944-2005	1946-2005	UR
	Waimate	44.74ºS	171.04ºE	1908-2005	1931-2005	RU
	Nelson	41.30ºS	173.23ºE	1943-2005	1946-2005	UR
	Mt Cook	43.74ºS	170.09ºE	1929-2005	1931-2005	RU
	Milford Sound	44.67ºS	167.92ºE	1934-2005	1946-2005	RU
	Taumarunui	38.89ºS	175.26ºE	1947-2005	1946-2005	RU
	Palmerston North	40.38ºS	175.61ºE	1940-2005	1946-2005	UR
	Tauranga	37.67ºS	176.20ºE	1941-2005	1946-2005	UR
	Ashburton	43.90ºS	171.75ºE	1928-2005	1931-2005	RU
	Christchurch Gardens	43.53ºS	172.62ºE	1905-2005	1931-2005	HU