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Trends in Australia's climate means and extremes: a global context

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Using a standard set of annual and seasonal climate extremes indices derived from daily temperature and precipitation data, relationships between mean and extremes trends across Australia and the globe are analysed. Extremes indices are calculated using station data from Australian high-quality daily temperature and precipitation datasets and pre-existing high-quality datasets of climate extremes for the globe. Spatial correlations are calculated between the trends in means and extremes both annually and seasonally for maximum and minimum temperature and precipitation across Australia, and annually for precipitation across the rest of the globe. In Australia, trends in extremes of both temperature and precipitation are very highly correlated with mean trends. Annually, the spatial correlation between trends in extremes and trends in the mean is stronger for maximum temperature than for minimum temperature. However, this relationship is reversed in winter, when minimum temperatures show the stronger correlations. Analysis of the rate of change of extremes and means across Australia as a whole shows most stations have greater absolute trends in extremes than means. There is also some evidence that the trends of the most extreme events of both temperature and precipitation are changing more rapidly in relation to corresponding mean trends than are the trends for more moderate extreme events. The annual relationships between means and extremes of precipitation in Australia are consistent with all other global regions studied.

Introduction

Australia, described in Dorothea Mackellar's 1904 poem *My Country* as the country of 'drought and flooding rains', may be better placed than most to adapt to changes in climate extremes. However, climate change might shift extremes towards conditions that will stress vulnerable systems such as Australia's unique ecosystems (Pittock et al. 2001). There is growing evidence that the global changes in extremes that have been observed in recent decades (e.g.,

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Kiktev et al. 2003) can only be accounted for if anthropogenic, as well as natural, factors are considered, and under enhanced greenhouse gas forcing the frequency of some of these extreme events is likely to change (e.g., Hegerl et al. 2004; Tebaldi et al. 2006). Folland et al. (2001) stated that in some regions both temperature and precipitation extremes have already shown amplified responses to changes in means. This tendency might result in more dramatic shifts than have been seen up to now.

Trends in Australian temperature and precipitation extremes have been examined extensively; e.g., Hennessy et al. (1999), Plummer et al. (1999), Collins et al. (2000), Haylock and Nicholls (2000), Manton et al. (2001) and Griffiths et al. (2005). These studies reported widespread increases in warm temperature extremes and decreases in cold temperature extremes, while trends in rainfall extremes show more regionally dependent variations. The relationships between means and extremes of temperature have been examined across Australia by Trewin (2001) and Griffiths et al. (2005). Griffiths et al. (2005) found changes in mean temperatures between 1961 and 2003 to be a good indicator for changes in a range of temperature extremes. That analysis extended across South East Asia, Australia and the South Pacific, but the spatial distribution across Australia was relatively sparse. Trewin (2001) used a larger selection of stations and found that the lower (cold) tails of both the minimum and maximum temperature distributions were warming faster than the upper (warm) tails.

Most studies, however, have focused on the analysis of temperature and precipitation extremes separately. Assessing trends in precipitation and temperature concurrently allows statements to be made about the drivers of some of these trends, given the high correlation between the two across much of Australia. For most of Australia, the correlation between mean temperature and precipitation is negative and statistically significant (Power et al. 1998). This correlation is strongly dictated by maximum daily temperatures. Correlations between rainfall and minimum temperature vary regionally – in many places there is no statistically significant correlation; in the southern half of the continent statistically significant correlations are positive, while in the north they are negative. However, partial correlations between precipitation and minimum temperature, after the relationship between minimum and maximum temperature has been removed, reveal statistically significant positive correlations across most of Australia south of about 20°S. Correlations between the Australia-wide average annual precipitation and temperature are consistent with the widespread spatial responses described above (Nicholls et al. 1997; Power et al. 1998).

The breadth of Australian observational studies was made possible by the availability of high-quality daily datasets that have undergone extensive checks for temporal inconsistencies. This study aims to use these datasets in order to assess simple measures of the relationship between means and extremes of temperature and precipitation at all the stations across Australia. Variations in this signature on the regional and seasonal scale will be assessed. Extremes are selected from the standardised set used in Alexander et al. (2006) to allow a comparison of the annual relationship between means and extremes across Australia with the rest of the globe.

We start by describing the data and methods used, followed by a discussion of the results and conclusions.

Data and methods

While inland Australia has a relatively sparse geographical coverage of climate recording stations, for the data that are available there has been a long history of assessing data quality and subsequent homogenisation to minimise the effect of changes in exposure or observing practices (Lavery et al. 1992; Torok and Nicholls 1996; Trewin 2001; Della-Marta et al. 2004). Two sources of readily available Australian data were used in this study. These are the Bureau of Meteorology's National Climate Centre (NCC) interpolated grids of monthly temperature and precipitation and a subset of station data used in the calculation of these grids, which also contain information on daily time-scales. For global analysis, precipitation stations used by Alexander et al. (2006) that have sufficient non-missing data are used.

Gridded fields

The 0.25° × 0.25° gridded fields of monthly maximum and minimum temperature and precipitation were obtained from the NCC. The gridded data are based on station data, interpolated using a two-dimensional Barnes analysis. For precipitation we used a gridded dataset based on the homogeneous rainfall series described in Lavery et al. (1997), while Jones (1998) provides details about the temperature grids. The gridded data were used to create maps to describe the coarse spatial variability in the seasonal trends to allow an easy visual comparison with trends in the extreme indices at station locations. The daily datasets are available at http://www.bom.gov.au/climate/change/datasets/datasets.shtml, while analyses based on the homogeneous monthly datasets are available at http://www.bom.gov.au/climate/change/.

Station data

For Australian station records, temperature data have been adjusted for inhomogeneities at the daily time-scale from 1957 onwards by taking account of the magnitude of discontinuities for different parts of the distribution (Trewin 2001). Stations used in this study are updated from the high-quality list used by Trewin (2001), although three stations (Nhill, Sale and Wilcannia) have been removed from the analysis since they are known to have inhomogeneities at or around 1996, after which no homogeneity adjustments have been applied. Prior to 1957, the amount of digitised daily temperature data is limited and most of the digital data that do exist have only become available recently. For stations that do have pre-1957 data, flat monthly homogeneity adjustments have been made prior to 1957 due to a lack of digitised daily comparison data, thereby increasing the potential for undetected inhomogeneities to exist in the extremes. Australian precipitation data came from a high-quality precipitation dataset (Haylock and Nicholls 2000). Subsequent studies have shown that multi-day rainfall in some instances has been incorrectly recorded as daily values, particularly just after the weekend (Viney and Bates 2004). However, analysis of the extremes in rainfall for a subset of stations has not shown any significant trend differences between rainfall gathered during the whole week and rainfall gathered between Tuesday and Friday (Dörte Jakob, personal communication). Therefore we did not reject any stations from the analysis for this reason. For global stations we use the high-quality indices dataset that was developed on behalf of the World Meteorological Organization Commission of Climatology and the Climate Variability and Predictability Project (ETCCDMI). The dataset includes 27 indices derived from daily data for 2223 temperature and 5948 precipitation-observing stations across the globe. Details of the indices can be found at http://cccma.seos.uvic.ca/ETCCDMI/.

Extremes indices calculation

Extremes indices for Australia have already been calculated from these daily station data for the global study of Alexander et al. (2006), but have been updated here using all available data up to 2005. Indices are calculated using standard software produced on behalf of the ETCCDMI by the Climate Research Branch of the Meteorological Service of Canada. Two versions of the software are available, FClimDex written in FORTRAN and RClimDex written in the statistical software package R, which produce identical results. The use of a standardised methodology to calculate climate indices allows the results to be compared directly with other regional analyses (e.g., Aguilar et al. 2005; Zhang et al. 2005; Vincent et al. 2005; Haylock et al. 2006; Klein Tank et al. 2006; and New et al. 2006), which in turn can be fitted seamlessly into a global analysis. Although the indices for Australia have already been used in the global study of Alexander et al. (2006), because of the uneven distribution of global stations, the results in that study were gridded onto a 3.50° longitude × 2.75° latitude grid. This makes it difficult to pinpoint small regional shifts, such as in the southwest corner of Australia where there are strong gradients in mean rainfall. For this reason we revisit and update the analysis of Australian climate indices to 2005 at individual stations. Table 1 lists the indices that have been used in this study. It should be noted that some of the indices recommended by ETCCDMI are not relevant for the Australian climate (see Collins et al. (2000)). Thus we do not analyse growing season length and annual occurrences of days where maximum temperature is less than 0°C. In addition, a precipitation index measuring the number of days greater than a user-defined amount of rainfall was not considered since the indices R10mm (days above 10 mm) and R20mm (days above 20 mm) were deemed sufficient for our study. For temperature, all indices except occurrence of frost (FD), cold and warm spell duration (CSDI and WSDI), tropical nights (TR) and summer days (SU) can be calculated seasonally as well as annually. For precipitation, only the maximum one-day and five-day precipitation totals indices (RX1day and RX5day) are calculated on a monthly basis.

The indices have been chosen to measure the extreme ends (and in some cases the mean or total, e.g., PRCPTOT) of the temperature and precipitation distributions, but are not so extreme that they are unreliable due to the data quality or the length of record.

Missing data

Missing station data are accounted for using the ETCCDMI-recommended standard criteria (see Appendix C of the RClimDex user manual on the ETCCDMI website at http://cccma.seos.uvic.ca/ETCCDMI/RClimDex/RClimDexUserManual.doc). Briefly, monthly indices are calculated if no more than three days are missing in the month, and annual values if no more than 15 days are missing in the year. However an annual value will also not be calculated if any month's data are missing. For percentile threshold indices, e.g., TX10p, TN90p, and duration indices, e.g., CSDI and WSDI (see Table 1), additional criteria are applied as described in the RClimDex manual.

Table 1. The extreme temperature and precipitation indices used in this study as recommended by the ETCCDMI. The full list of all recommended indices and precise definitions is given at http://cccma.seos.uvic.ca/ETCCDMI/list_27_indices.html. For spell duration indicators (marked with a *), a spell can continue into the next year and is counted against the year in which the spell ends. Precipitation indices for Australia are calculated using stations from Haylock and Nicholls (2000) and temperature indices using stations from Trewin (2001).

ID	*Indicator name*	*Indicator definitions*	*Units*
TXx	Max Tmax	Monthly maximum value of daily maximum temperature	ºC
TNx	Max Tmin	Monthly maximum value of daily minimum temperature	ºC
TXn	Min Tmax	Monthly minimum value of daily maximum temperature	ºC
TNn	Min Tmin	Monthly minimum value of daily minimum temperature	ºC
TN10p	Cool nights	Percentage of time when daily minimum temperature < 10th percentile	%
TX10p	Cool days	Percentage of time when daily maximum temperature < 10th percentile	%
TN50p	Warm nights	Percentage of time when daily minimum temperature > 50th percentile	%
TX50p	Warm days	Percentage of time when daily maximum temperature > 50th percentile	%
TN90p	Warm nights	Percentage of time when daily minimum temperature > 90th percentile	%
TX90p	Warm days	Percentage of time when daily maximum temperature > 90th percentile	%
DTR	Diurnal temperature range	Monthly mean difference between daily maximum and minimum temperature	ºC
FD0	Frost days	Annual count when daily minimum temperature < 0°C	days
SU25	Summer days	Annual count when daily maximum temperature > 25°C	days
TR20	Tropical nights	Annual count when daily minimum temperature > 20°C	days
WSDI*	Warm spell duration indicator	Annual count when at least 6 consecutive days of maximum temperature > 90th percentile	days
CSDI*	Cold spell duration indicator	Annual count when at least 6 consecutive days of minimum temperature < 10th percentile	days
RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
RX5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
SDII	Simple daily intensity index	The ratio of total annual precipitation to the number of wet days (≥ 1 mm)	mm/day
R10mm	Number of heavy precipitation days	Annual count when precipitation > 10 mm	days
R20mm	Number of very heavy precipitation days	Annual count when precipitation > 20 mm	days
CDD*	Consecutive dry days	Maximum number of consecutive days when precipitation < 1 mm	days
CWD*	Consecutive wet days	Maximum number of consecutive days when precipitation ≥ 1 mm	days
R95p	Very wet days	Annual total precipitation from days > 95th percentile	mm
R99p	Extremely wet days	Annual total precipitation from days > 99th percentile	mm
PRCPTOT	Annual total wet-day precipitation	Annual total precipitation from days ≥ 1 mm	mm

Trend and correlation calculation

As stated in the introduction, there are statistically significant correlations between mean temperature and precipitation across much of Australia. Therefore, before analysing the relationships between means and extremes of the individual variables, correlations (using a simple Pearson product-moment correlation unless otherwise stated) were calculated for area-averaged values over Australia between annual, summer (December–February, or DJF in tables) and winter (June–August, or JJA in tables) mean maximum and mean minimum temperatures and mean rainfall for 1957-2005, using the high-quality gridded datasets outlined above.

Using the gridded monthly interpolated fields and monthly station data described above, we also calculated linear trends for annual (January–December, or Ann in tables) and seasonal (December–February, March-May, June–August and September–November, or DJF, MAM, JJA and SON in tables) mean maximum and mean minimum temperature and precipitation. Because of the rainfall variability across Australia, percentage trends were additionally calculated to make the trends consistent across the country, i.e., the values in a time series were divided by the mean over the period of record prior to the trend calculation at each grid-point or station in order to represent the trends as a percentage of average. For temperature, the period 1957–2005 (49 years) was analysed to cover the period of homogeneous record, and for precipitation, because of its much longer record, two periods were chosen: 1910–2005 (96 years) and 1951–2005 (55 years). For the analysis of trends in the station data, at least 80 per cent of available data had to be available over the periods studied. Seasonal data had to have at least two of the three months present otherwise the value for that year was regarded as missing. While this is probably more appropriate for temperature data, the two-month threshold was also used for precipitation data to provide sufficient temporal and spatial coverage for analysis. The magnitude of the trends is calculated using a nonparametric trend estimator and statistical significance is measured at the five per cent level throughout.

To determine how well the trends in extremes are spatially correlated with trends in means across Australia, we calculate linear trends in the means of precipitation and maximum and minimum temperature, and in the extremes indices (Table 1), over the period of interest for all the stations in our study. Linear trends are calculated using a modified version of the non-parametric Kendall tau test (Wang and Swail 2001) since prior assumptions do not have to be made about the distribution of the indices time series. In addition, the method is robust to the effect of outliers in the series. The linear trends in means are calculated as the annual or seasonal trends in either precipitation or mean maximum or minimum temperature. To represent a measure of the spatial correlation between trends in means and extremes, rather than a temporal correlation at each station, mean trends are correlated with the linear trends for each extreme index across all stations.

Although these correlations provide information about the relationship between two variables (i.e., the mean and the extreme index) they do not indicate the magnitude or rate of change of one variable in relation to the other. In the case of the absolute-threshold temperature indices, i.e., TXx, TNn, TXn and TNx (see Table 1), it makes sense to compare trends in the mean directly with trends in the maximum or minimum values since both are measured in the same units (i.e., °C per year). In all other cases trends are presented here as a percentage trend of the average (described above). The indices trends are then plotted against the mean trends to not only show how the trends in the means and extremes vary at each station point but also how they vary across the country as a whole. Each scatter plot (Figs 5 to 8) is fitted with a line of best fit using total least-squares regression. This method is recommended when there are likely to be 'errors' in the data corresponding to the horizontal and vertical coordinates of the plotted points, since it minimises the distance of each point perpendicular to the fitted line, rather than just the difference in the vertical, as would be the case with ordinary least-squares regression. From the slope of the line of best fit we can determine if trends in extremes across Australia as a whole are the same as trends in the mean, e.g., if the slope of the line was equal to −1.0 or 1.0, where comparable units are being used, then the absolute trends in extremes would be of the same magnitude as trends in means.

For a global perspective on the Australian results, similar measures are calculated for comparison. Although we do not have access to the mean maximum and minimum temperatures for the global stations with extreme indices, the PRCPTOT precipitation indicator does give a measure of total mean precipitation at each station with which to compare the other indices. Because PRCPTOT is an annual indicator, only annual changes are considered for each index. The period 1951–2003 is used for comparison since this is when most global stations have sufficient data. Only stations that have at least 40 years of precipitation data during this period are used. Again linear trends are calculated as a percentage of the average for each precipitation index in Table 1. The percentage trends for the precipitation indices are then plotted against the percentage trends in PRCPTOT to determine the relationship between the means and extremes of rainfall. In addition to a global analysis, five non-overlapping latitude bands are chosen to compare with Australian results.

The relationship between means and extremes of temperature and precipitation in Australia

There are strong relationships between temperature and rainfall in Australia that we need to bear in mind when looking at trends in the means and extremes of both. There is a strong negative correlation between spatially averaged Australia-wide rainfall and maximum temperature in all seasons (summer and winter are shown in Table 2). A statistically significant correlation between rainfall and minimum temperature is only evident in winter, when there is a strong positive relationship. These results hold true even if the linear trends are removed prior to the correlation calculation, although the significant correlations are slightly stronger using the detrended data.

To gain an appreciation for the spatial variability of climate trends across Australia, maps of the trends in the gridded mean fields were plotted and overlaid with a triangle at each station location to represent the magnitude and statistical significance of the trend for each extremes index (Figs 1 to 4). Only statistically significant trends in mean temperature or precipitation are shown in colour.

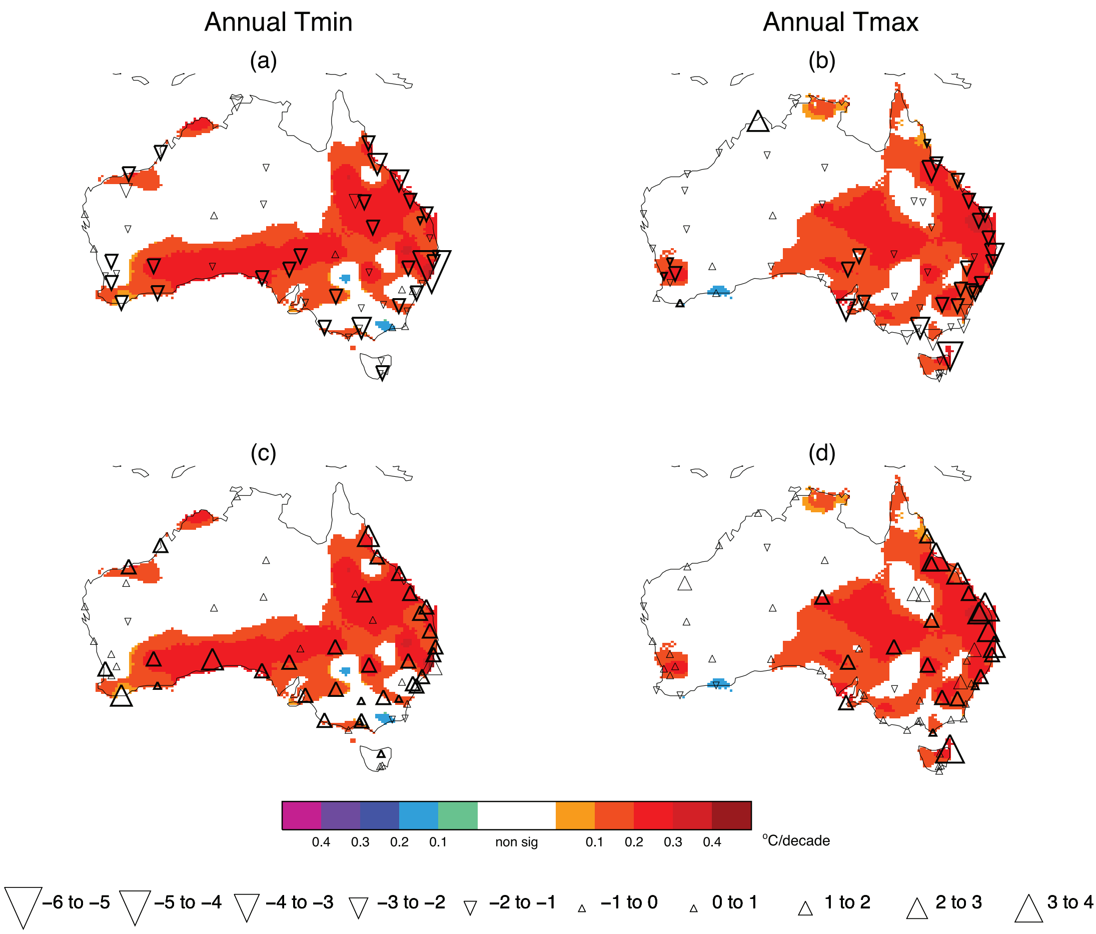
Table 2. Left-hand side: correlations (using a Kendall tau test) between mean rainfall, averaged over Australia, and mean maximum and minimum temperatures for 1957–2005. Right-hand side as for left-hand side but for detrended values. Correlations significant at the five per cent level are marked in bold.

	With trend			*Detrended*		
	DJF	*JJA*	*Ann*	*DJF*	*JJA*	*Ann*
Tmax	**-0.63**	**-0.48**	**-0.59**	**-0.67**	**-0.52**	**-0.72**
Tmin	0.14	**0.66**	0.07	0.08	**0.67**	0.03

Maps – temperature

Annually averaged mean maximum and minimum temperatures are increasing across most of Australia with an associated statistically significant decrease in the annual occurrence of cold nights (Fig. 1(a)) and cold days (Fig. 1(b)). All the other temperature indices show similar spatially coherent trends commensurate with warming: reductions in frost days and cold spells and an associated significant increase in all the other temperature indices, particularly the annual occurrence of warm nights (Fig. 1(c)) and warm days (Fig. 1(d)). These results agree well with Collins et al. (2000) who studied changes in annual extreme temperature trends up to 1996 and other stud-

Fig. 1 Annual trends (°C/decade) in mean minimum temperature ((a), (c)) and mean maximum temperature ((b), (d)) for 1957–2005. Only statistically significant trends are shown in colour. Maps are overlaid with annual trends (per cent/decade) at each station location with sufficient high-quality data represented by upward (downward) triangles for increasing (decreasing) trends for (a) cold nights (TN10p), (b) cold days (TX10p), (c) warm nights (TN90p) and (d) warm days (TX90p) (Table 1). The size of the triangle reflects the magnitude of the trend. Bold indicates statistically significant change.



ies such as Tryhorn and Risbey (2006) who found a general increase in heat waves across Australia in recent decades. At a particular location, the trends in the mean minimum temperature and cool nights (Fig. 1(a)) are generally slightly larger than the trends in mean maximum temperature and cool days (Fig. 1(b)) respectively. Spatially, the trends in mean maximum and minimum temperatures are mostly statistically significant in the east of the continent and are up to 0.4°C per decade, an increase of approximately 2°C since 1957. In the southeast, the trend in cool nights is stronger than the underlying warming of mean minimum temperature. Within the southeast region there are small areas where the mean minimum temperature has been decreasing, particularly in east Gippsland and the Australian Alps and a small part of northwest New South Wales. Mean maximum temperature has significantly decreased along part of the southern coastline of Western Australia. There are also non-significant decreases in temperature in the northwest of the continent (not shown) along with small increases in the number of cool days and nights. The majority of stations, however, exhibit statistically significant increases in the annual occurrence of warm nights, even in some places where mean minimum temperature has been decreasing (Fig. 1(c)). Warm day temperature trends (Fig. 1(d)) are bigger than warm night temperature trends along the east coast, although in other regions the converse is true.

Annual results can mask significant seasonal changes so mean minimum (Figs 2(a), 2(c), 2(e) and 2(g)) and mean maximum (Figs 2(b), 2(d), 2(f) and 2(h)) temperatures were analysed for summer (December–February), autumn (March–May), winter (June–August) and spring (September–November) respectively, with trends in cool nights (left) and cool days (right) superimposed. Corresponding seasonal results are also shown in Fig. 3 with trends in warm nights (left) and warm days (right). Figure 2 shows that decreases in annual mean maximum temperature in northwest Australia and the southern coast of southwest Australia are mostly a result of a significant decrease in daytime temperature in summer. Cold days are increasing in these regions (Fig. 2(b)) and warm days are decreasing (Fig. 3(b)). Mean minimum temperatures are also decreasing, although not statistically significantly so, in parts of the northwest in all seasons except spring, generally with an associated decrease in warm nights (Figs 3(a), 3(c), 3(e) and 3(g)).

Maps – precipitation

Figure 4 shows seasonal trends in mean precipitation for two periods, 1910–2005 and 1951–2005, overlaid with seasonal trends in maximum one-day precipitation. The trends vary throughout the seasons, highlighting the importance of examining each season rather than just the annual average. The spatial variability in precipitation is much greater than for temperature and it is clear that there is much less statistical significance in the precipitation trends. Where long-term trends in mean precipitation are significant, they tend to be positive outside southwest Western Australia for the September to March period (Figs 4(g), 4(a), 4(c)) and mixed for winter (Fig. 4(e)). However, in recent decades, a pattern of statistically significant decreases in both the means and extremes has emerged in the eastern half of the country for the December to August period (Figs 4(b), 4(d) and 4(f)). In the west, the most striking feature of recent trends in mean precipitation is the statistically significant moistening in the northwest in summer (Fig. 4(b)). There are, unfortunately, no high-quality daily stations in this region to indicate how the extremes are behaving. As suggested in Nicholls et al. (1997) and Power et al. (1998), this increase is associated with a decrease in maximum temperature (Fig. 2(b)). The driver behind this feature is not clear, and is the topic of on-going studies (Dörte Jakob, personal communication). One suggestion is that the continental warming further south is driving an enhancement of the Australian monsoon (Wardle and Smith 2004).

For trends in precipitation extremes there is a mixed pattern throughout the seasons but more recent decades generally show larger absolute trends. In general, the directions of the trends in the extremes follow the mean trends but there are a few occasions when a significant decrease in the mean is associated with a significant increase in the extremes or vice versa e.g. southwestern Western Australia in spring (Fig. 4(g)). One-day maximal precipitation trends in summer are increasing at most sampled locations over the period 1910–2005 (Fig. 4(a)), although relatively few of them are statistically significant. The more recent trend (Fig. 4(b)) shows a very mixed signal, with larger increases in the southwest and general decreases along the east coast compared to the longer term period. While the long-term trend in autumn shows small and mostly non-significant trends in extreme precipitation (Fig. 4(c)), probably the most striking feature in recent decades is the decrease in both means and extremes across Tasmania and the southern coastline of South Australia and Victoria (Fig. 4(d)). This feature can also be seen in maximum five-day precipitation totals (not shown). In winter the decline in mean rainfall in the southwest is evident, and the most extreme daily totals are also declining over the last 100 years (Fig. 4(e)); however there is a mixed response more recently (Fig. 4(f)). Over the last 50 years mean rainfall decreases are evident along the east coast, and the extremes show some

Fig. 2 **Seasonal trends (°C/decade) in mean minimum temperature (left-hand side) and mean maximum temperature (right-hand side) for 1957–2005. Only statistically significant trends are shown in colour. Maps are overlaid with annual trends (per cent/decade) at each station location with sufficient high-quality data represented by upward (downward) triangles for increasing (decreasing) trends for (a), (c), (e) and (g) cold nights (TN10p) and (b), (d), (f) and (h) cold days (TX10p). The size of the triangle reflects the magnitude of the trend. Bold indicates statistically significant change. Key as per Fig. 1.**

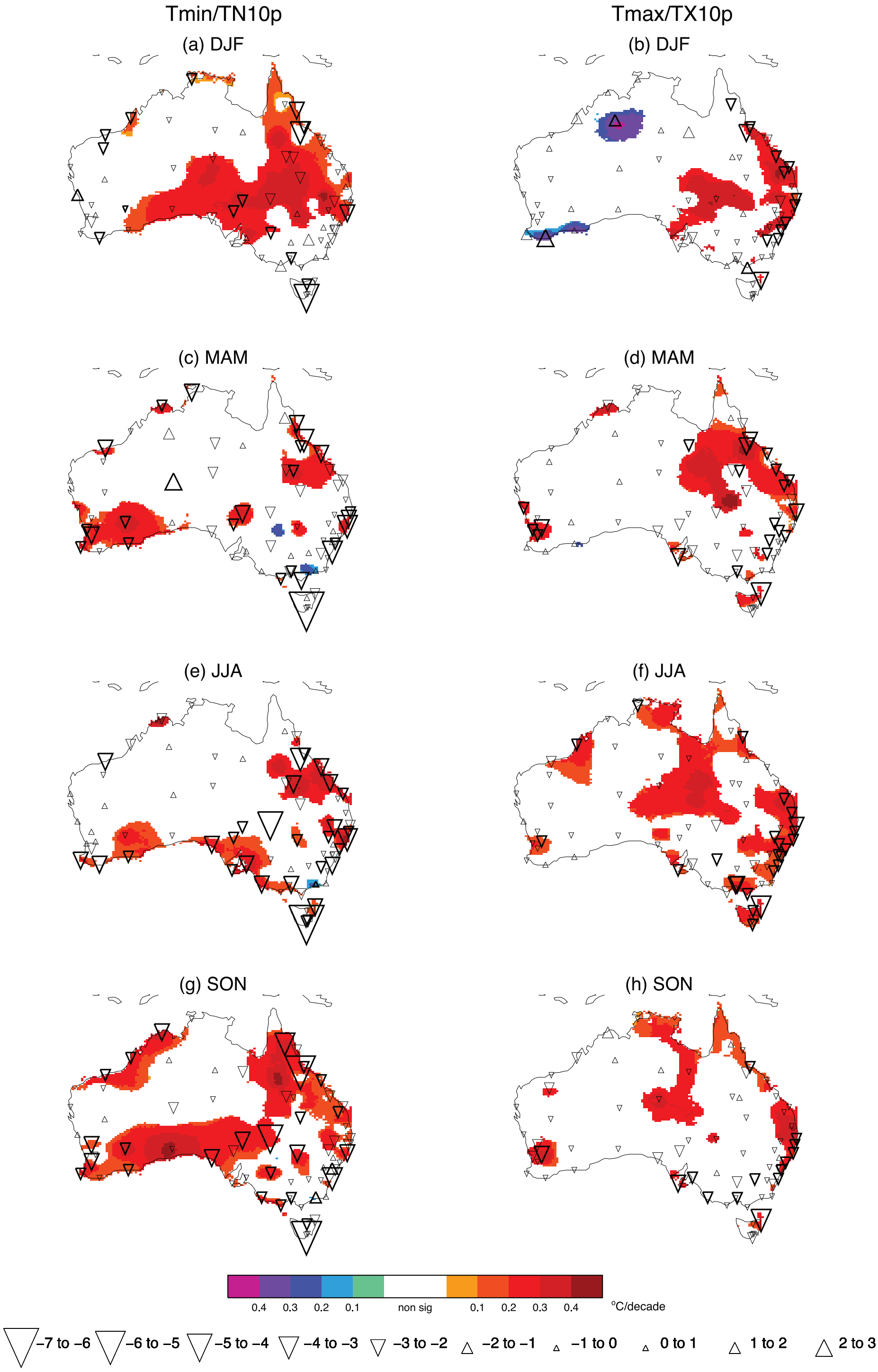


Fig. 3 Seasonal trends (°C/decade) in mean minimum temperature (left-hand side) and mean maximum temperature (right-hand side) for 1957–2005. Only statistically significant trends are shown in colour. Maps are overlaid with annual trends (per cent/decade) at each station location with sufficient high-quality data represented by upward (downward) triangles for increasing (decreasing) trends for (a), (c), (e) and (f) warm nights (TN90p) and (b), (d), (f) and (h) warm days (TX90p). The size of the triangle reflects the magnitude of the trend. Bold indicates statistically significant change. Key as per Fig. 1.

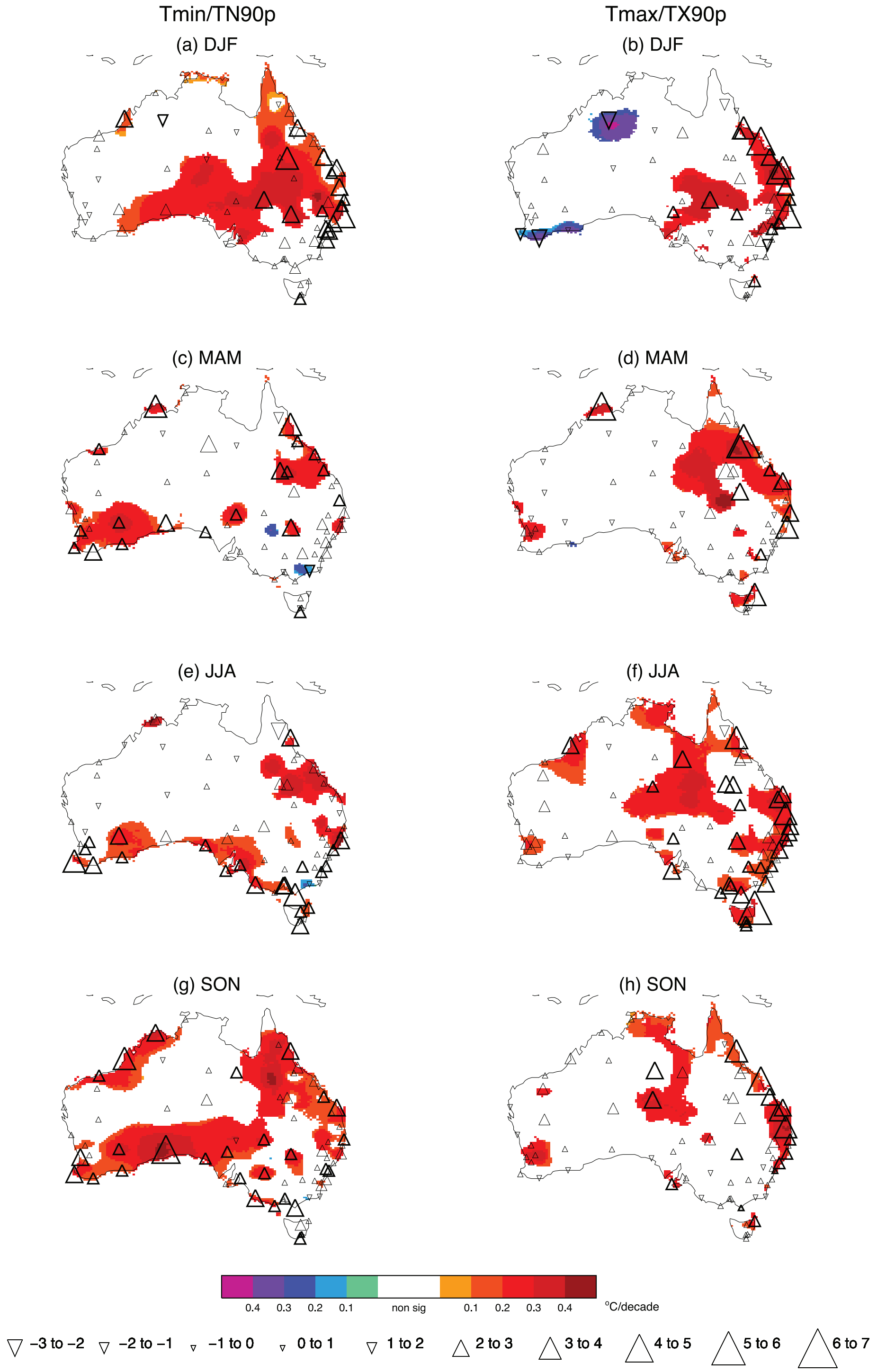


Fig. 4 **Seasonal trends (per cent/decade) in mean rainfall for 1910–2005 (left-hand side) and 1951–2005 (right-hand side). Only statistically significant trends are shown in colour. Maps are overlaid with trends (per cent/decade) at each station location with sufficient high-quality data represented by upward (downward) triangles for increasing (decreasing) trends for (a)–(h) seasonal maximum one-day precipitation totals (RX1day). The size of the triangle reflects the magnitude of the trend. Bold indicates statistically significant change.**

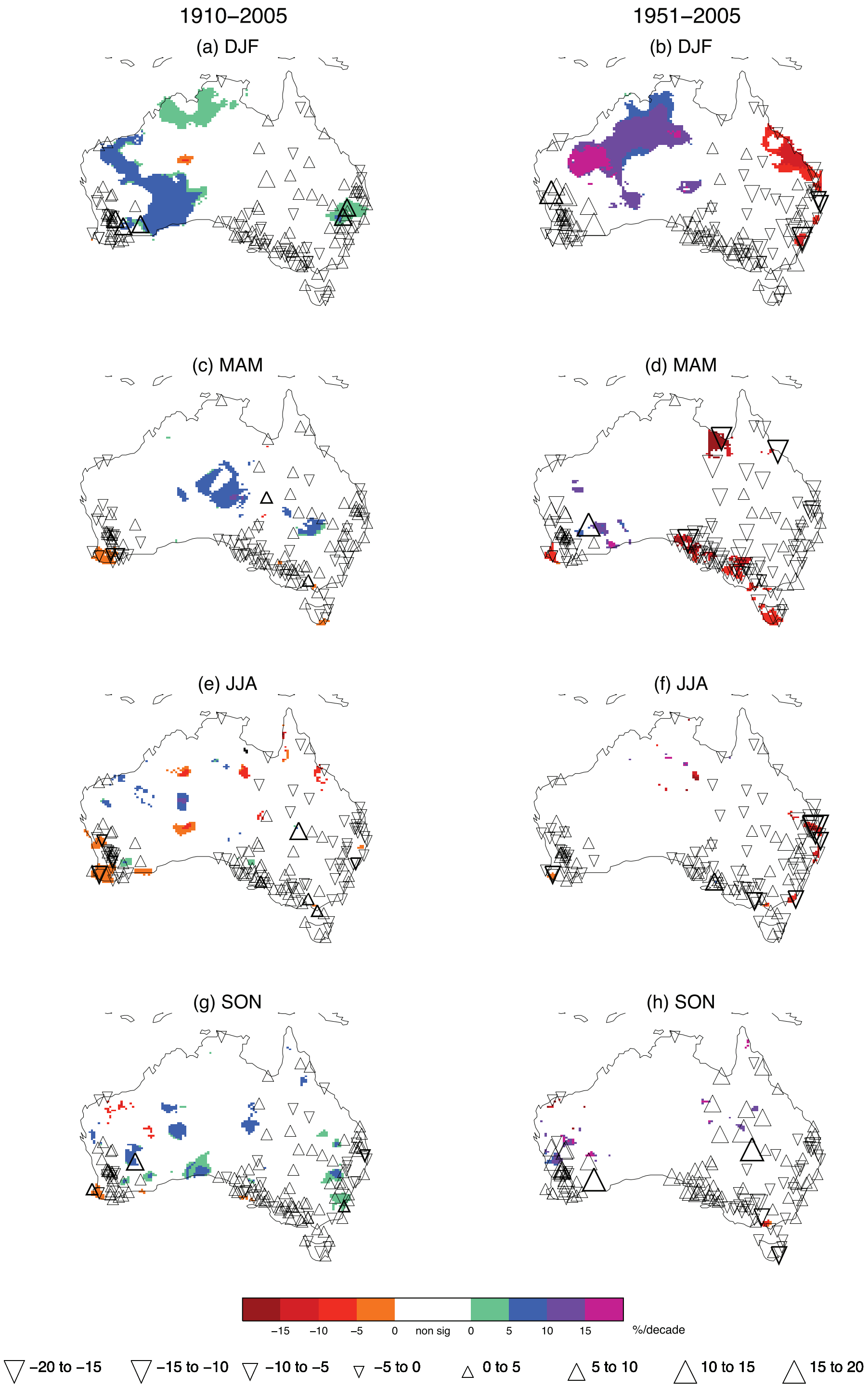


Table 3. Spatial correlations, using high-quality temperature data at stations across Australia (Trewin 2001), between annual and seasonal trends in temperature indices (Table 1) and trends in mean minimum (left) or mean maximum (right) temperature, 1957–2005 (1957–58 to 2004–05 for December–February). Correlations significant at the five per cent level are marked in bold.

		Minimum temperature						*Maximum temperature*			
Index	*Annual*	*DJF*	*MAM*	*JJA*	*SON*	*Index*	*Annual*	*DJF*	*MAM*	*JJA*	*SON*
TNx	**0.49**	**0.53**	**0.41**	**0.53**	**0.42**	TXx	**0.66**	**0.72**	**0.53**	**0.48**	**0.33**
TNn	**0.64**	**0.33**	**0.65**	**0.83**	**0.48**	TXn	**0.40**	**0.46**	**0.35**	**0.42**	0.16
TN10p	**-0.82**	**-0.61**	**-0.72**	**-0.83**	**-0.69**	TX10p	**-0.80**	**-0.84**	**-0.71**	**-0.67**	**-0.57**
TN90p	**0.79**	**0.74**	**0.67**	**0.70**	**0.60**	TX90p	**0.77**	**0.76**	**0.71**	**0.78**	**0.61**
DTR	**-0.65**	**-0.34**	**-0.73**	**-0.85**	**-0.75**	DTR	**0.61**	**0.79**	**0.55**	**0.47**	**0.60**
FD0	-0.25					SU25	**0.69**				
TR20	**0.52**					WSDI	**0.47**				
CSDI	**-0.52**										

associated significant declines (Fig. 4(f)). In spring there is generally little change in the mean across Australia from 1910–2005, except for some small areas of increases and decreases in the southwest (Fig. 4(g)). The trends in maximal one-day precipitation are increasing at most sampled locations, even in the southwest, indicating that the intensity of the rainfall is increasing. This signature also appears to be present in the most recent 50 years (Fig. 4(h)), but in general the trends are larger.

Spatial correlations

To determine how well the trends in extremes are correlated with trends in the mean across Australia, we calculated linear trends for all the stations in our study. These trends were then correlated (with the individual stations as cases) to represent the spatial rather than temporal relationship between the mean and extremes. The correlations are listed in Tables 3 and 4.

Table 4. Spatial correlations, using high-quality precipitation data at stations across Australia (Haylock and Nicholls 2000); between annual and seasonal trends in precipitation indices (Table 1) and trends in mean precipitation, 1910–2005 (1910–11 to 2004–05 for December–February). Correlations significant at the five per cent level are marked in bold.

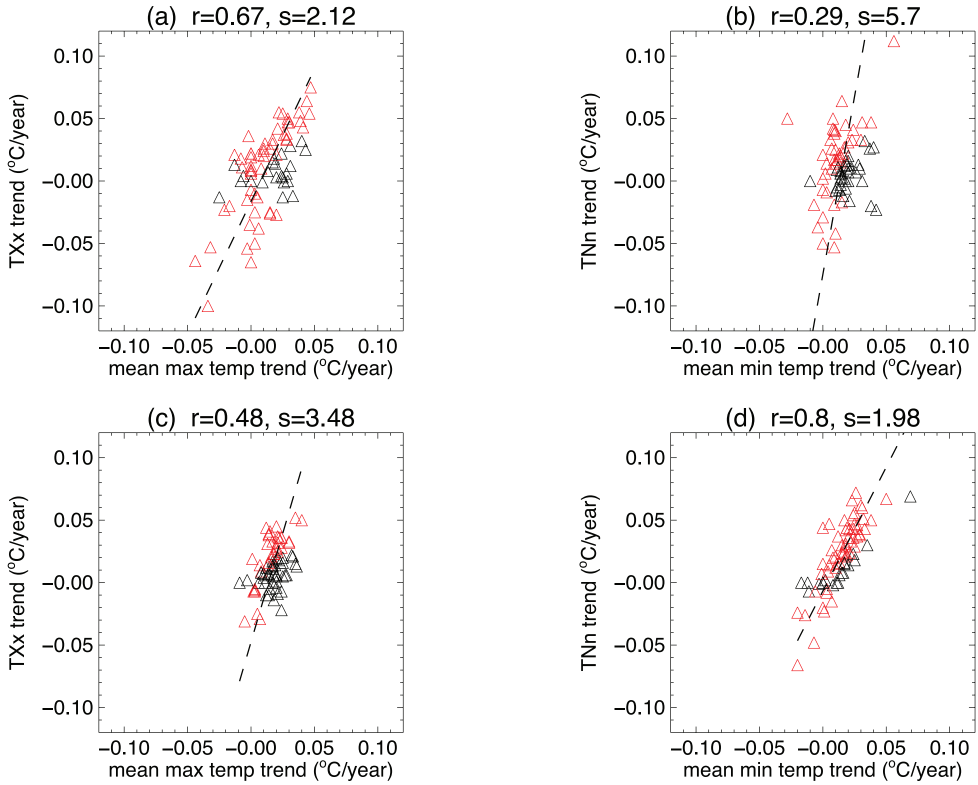
Index	*Annual*	*DJF*	*MAM*	*JJA*	*SON*
RX1day	**0.56**	**0.81**	**0.81**	**0.83**	**0.65**
RX5day	**0.60**	**0.88**	**0.87**	**0.85**	**0.79**
SDII	**0.35**				
R10mm	**0.75**				
R20mm	**0.63**				
CDD	-0.36				
CWD	0.12				
R95p	**0.55**				
R99p	**0.44**				
PRCPTOT	**0.92**				

Temperature

Table 3 indicates that there is a high spatial correlation between most temperature extremes indices and trends in mean minimum or maximum temperature in all seasons (i.e., a station with a strong trend in the mean will generally exhibit a strong trend of the same sign in the extremes). Trends in maximum temperature means and extremes are generally more highly spatially correlated than those for minimum temperature, particularly in summer (December–February). Minimum temperature extremes, however, are much more highly correlated with mean minimum temperatures in winter (June–August). Seasonally the smallest correlations occur in spring (September–November), which is also when there is the weakest correlation between the means and extremes of precipitation (see Table 4). This is in agreement with the finding of Alexander et al. (2006), who showed that global trends in temperature extremes were generally smallest in September–November irrespective of which hemisphere was analysed.

In summer, the majority of stations (71 per cent) have trends greater in magnitude in the warmest daily maximum temperature (TXx) than mean maximum temperature (Fig. 5(a)), and over half (55 per cent) of stations have greater absolute trends in the coldest daily minimum temperature (TNn) than mean minimum temperature (Fig. 5(b)). In winter, only 46 per cent of stations have greater absolute trends in extreme high maximum temperature (TXx) than mean maximum temperature (Fig. 5(c)), but 74 per cent of stations (the largest proportion in any season) have greater absolute trends in extreme low minimum temperature (TNn) than mean minimum tem-

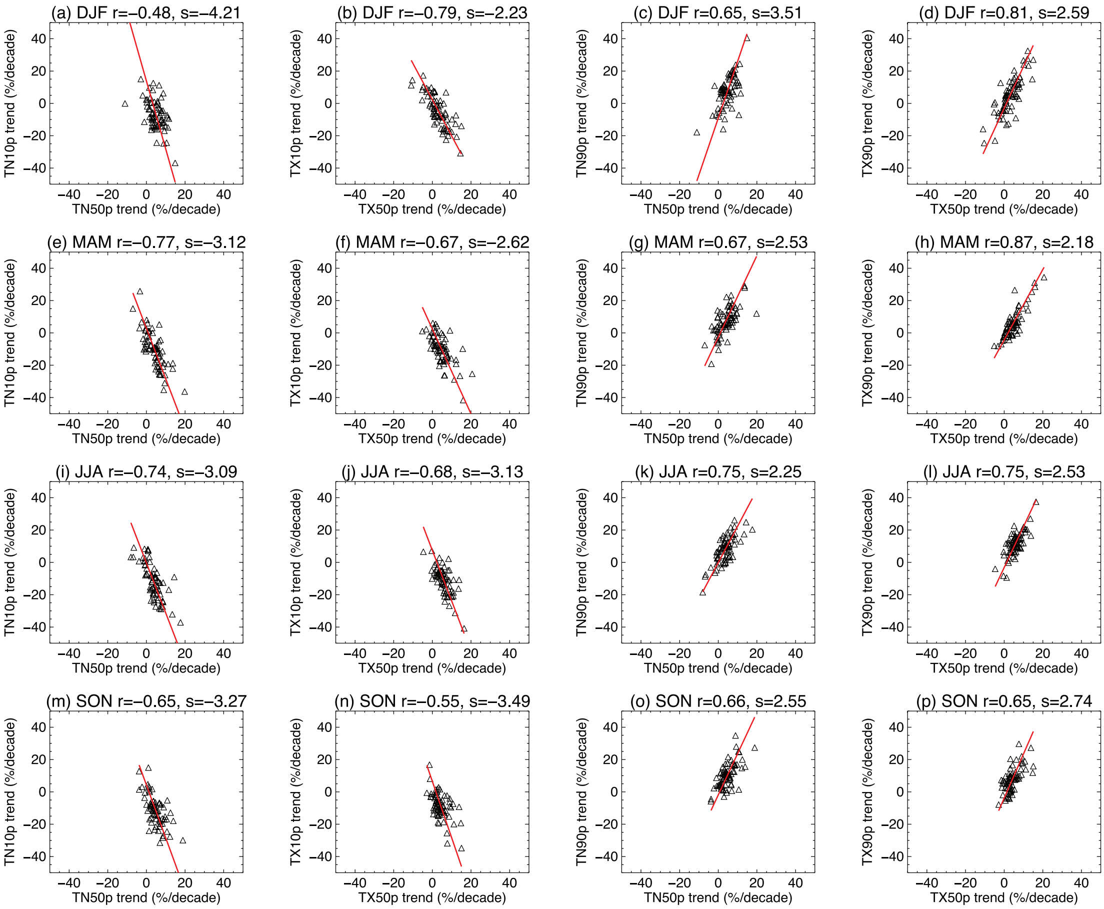
Fig. 5 Triangles represent annual trends (°C/year) in mean maximum (minimum) temperature at high-quality Australian station locations (Trewin 2001) plotted against trends in the hottest (coldest) maximum (minimum) daily temperature (°C/year) at those stations for (a) and (b) summer and (c) and (d) winter between 1957 and 2005. Red triangles indicate where the absolute seasonal trend in the warmest ((a) and (c)) or coldest ((b) and (d)) day at a station is greater than the absolute seasonal trend in mean maximum ((a) and (c)) or minimum temperature ((b) and (d)) at that station, i.e., where the magnitude of the trend in the extremes is greater than the magnitude of the mean trend. The line of best fit calculated using total least-squares regression is shown in red, s is the slope of the line and r is the spatial correlation.



perature (Fig. 5(d)). For the remaining absolute-threshold temperature indices, i.e., TXn and TNx (see Table 1), well over half of stations show increased trends (whether positive or negative) compared to the mean trend in all seasons and annually. While stations are not equally spaced, they are well distributed across the country, although since there is a greater density of stations in the east and south than the north and west, the analysis may be weighted more towards these well-sampled areas. Generally the mean and extremes trends are of the same sign but there are instances where there are increasing means with decreasing extremes and vice versa. In a few cases the extremes are increasing (decreasing) faster than the mean is decreasing (increasing). In these cases the shape of the temperature distribution could be changing, although the high signal-to-noise ratio of these types of extremes makes it difficult to draw definitive conclusions.

Figure 6, like Figs 2 and 3, shows that both the extremes and mean of maximum and minimum temperature are increasing across much of Australia in all seasons. The lower (cold) tails of the minimum temperature distribution (Figs 6(a), 6(e), 6(i) and 6(m)) are warming faster than the upper (warm) tails (Figs 6(c), 6(g), 6(k) and 6(o)) in every season. These results are consistent with the results of Trewin (2001). For maximum temperature, this differential warming of the lower (cold) (Figs 6(b), 6(f), 6(j) and 6(n)) and upper (warm) (Figs 6(d), 6(h), 6(l) and 6(p))

Fig. 6 **Seasonal trends (per cent/decade) in 10th and 90th percentile indices (Table 1) with respect to seasonal trends (per cent/decade) in the median (denoted on the horizontal axes by TN50p for minimum temperature and TX50p for maximum temperature) for (a)–(d) December–February, (e)–(h) March–May, (i)–(l) June–August and (m)–(p) September–November. Each symbol represents a station. The line of best fit calculated using total least-squares regression is shown in red, s is the slope of the line and r is the spatial correlation.**



tails of the distributions is less evident. However, there appears to be enhanced warming in the warmest maximum temperatures (TX90p) in summer (Figs 6(b) and 6(d)), with some enhanced warming in the lower (cold) tails in winter (Figs 6(j) and 6(l)). In all cases the proportional warming in the extremes is greater than the proportional warming in the median. This does not necessarily indicate a change in the shape of the frequency distribution; for example, in a normal distribution, an increase in the location parameter with no change in the scale parameter will lead to a greater proportional change in the extreme indices than in the mean index (Katz and Brown 1992). Although it is not possible to make a direct comparison because of the different units used, it does appear that in some cases the most extreme events (Fig. 5) are changing more rapidly than the distribution tails (Fig. 6). However, this can only be inferred from the results presented here and would require a full analysis of the distribution of daily temperature to answer definitively.

Precipitation

Table 4 shows that trends in precipitation extremes are highly spatially correlated with total precipitation trends. This is particularly true of maximum one-day (RX1day) and five-day precipitation (RX5day), number of days above 10 mm (R10mm) and 20 mm (R20mm), and very wet days (R95p) and extremely wet days (R99p). Consecutive dry days (CDD), consecutive wet days (CWD) and daily intensity (SDII) show smaller correlations. The correlations are also high in every season for the two indices that can be defined seasonally, although the correlations are slightly smaller in spring when the relationship between the means and extremes of maximum and minimum temperature is also weakest. The seasonal correlations are higher than the annual correlations because as the sample size reduces (e.g., from annual to seasonal), the influence of these extremes on the total precipitation is much greater.

Percentage trends in each precipitation index between 1910 and 2005 were plotted and compared. Except for daily intensity (SDII), the slope of the line of best fit is greater than 1, indicating enhanced variability in the trends of precipitation extremes compared to the mean trends. Figure 7 shows the results for very wet (R95p) and extremely wet (R99p) days. Although the correlations between the mean and R99p are smaller than R95p (Table 4), the steeper slope of the line of best fit in Fig. 7(b) compared to Fig. 7(a) indicates that the most extreme events may be changing at a faster absolute rate in relation to the mean than more moderate events. This result is expected under climate change simulations with enhanced greenhouse gas forcing (IPCC 2001), and also agrees with statistical theory that precipitation extremes are more sensitive to changes in the scale parameter of the precipitation distribution (e.g., Katz 1999).

Comparison between Australia and other parts of the world

Table 5 shows the spatial correlations between 1951 and 2003 for PRCPTOT and the precipitation indices from Table 1 for the globe and five regions defined by non-overlapping latitude bands. This indicates that the correlations between the means and extremes of rainfall in Australia are similar to the correlations for the globe and all of the regions studied.

Plotting the percentage trends shows just how similar the relationships between the means and extremes of precipitation are for Australia and the globe (Fig. 8). For the majority of indices the correlation between the means and extremes of rainfall is above 0.5 except for CDD ($r = -0.36$) and CWD ($r = 0.48$). Table 5 and Fig. 8(a) show that the annual number of days above 10 mm (R10mm) is the most strongly correlated extreme index globally. Also shown are the relationships between percentage trends in PRCPTOT and percentage trends in R95p (Fig. 8(b)), R99p (Fig. 8(c)) and RX5day (Fig. 8(d)). Unlike R10mm, these indices were all originally measured in the same units (mm) so it is easier to undertake a like-with-like comparison. The relationship between the trends in means and extremes is remarkably coherent across all latitudes for all indices studied. Although the correlations are statistically significant (Table 5) in all cases, it is clear from Fig. 8 that the slopes of the lines of best fit are significantly above 1.0 (i.e., extreme precipitation events are changing at a disproportional rate to mean

Fig. 7 **Annual trends (per cent/year) at Australian stations for (a) R95p and (b) R99p plotted against annual trends (per cent/year) in mean precipitation between 1910 and 2005. The line of best fit calculated using total least-squares regression is shown in red, s is the slope of the line and r is the spatial correlation.**

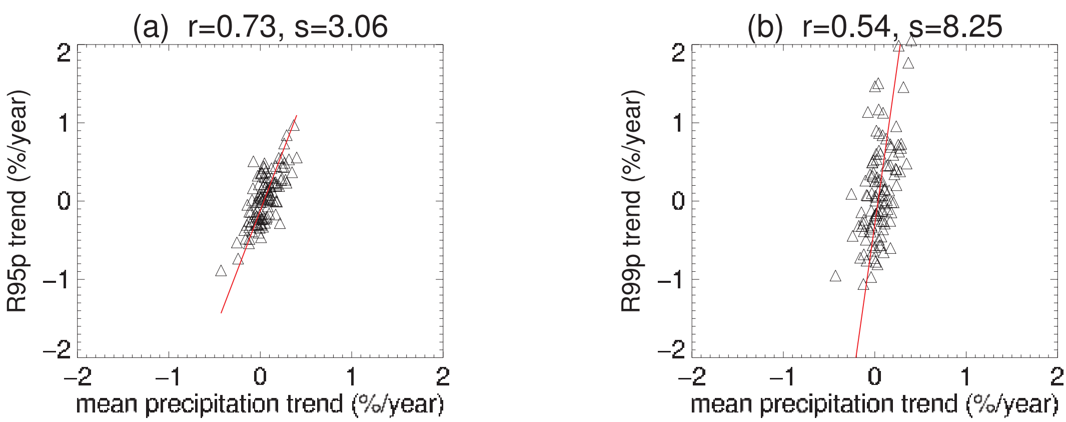
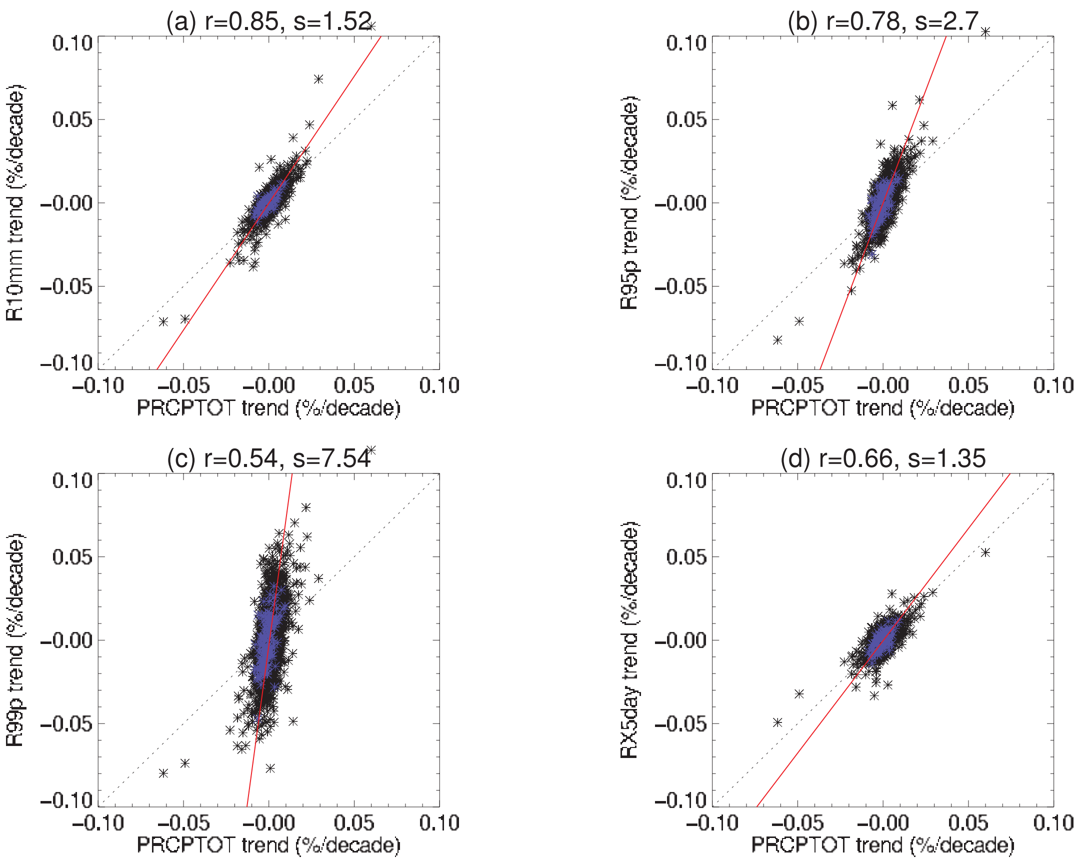


Table 5. Spatial correlations (using high-quality precipitation data, Alexander et al. (2006)) between trends in PRCPTOT (which is being used as a proxy for annual precipitation) and trends in precipitation indices (Table 1) between 1951 and 2003 for the globe and five non-overlapping latitude bands. Correlations significant at the five per cent level are marked in bold.

	R10mm	*R20mm*	*R95p*	*R99p*	*SDII*	*RX1day*	*RX5day*	*CDD*	*CWD*
Global	**0.86**	**0.76**	**0.76**	**0.52**	**0.58**	**0.50**	**0.61**	**-0.36**	**0.48**
90°S-30°S	**0.94**	**0.89**	**0.86**	**0.67**	**0.64**	**0.69**	**0.78**	**-0.36**	**0.57**
30°S-0°S	**0.88**	**0.90**	**0.88**	**0.66**	**0.47**	**0.76**	**0.78**	**-0.43**	**0.55**
0°N-30°N	**0.86**	**0.88**	**0.77**	**0.54**	**0.60**	**0.53**	**0.63**	**-0.29**	**0.42**
30°N-60°N	**0.86**	**0.75**	**0.74**	**0.51**	**0.56**	**0.48**	**0.58**	**-0.36**	**0.46**
60°N-90°N	**0.80**	**0.57**	**0.76**	**0.51**	**0.71**	**0.45**	**0.63**	**-0.51**	**0.61**

Fig. 8 Trends (per cent/year) in (a) R10mm, (b) R95p, (c) R99p and (d) RX5day on the y-axis plotted against trends (per cent/year) in annual total wet-day precipitation (PRCPTOT) for global stations from Alexander et al. (2006), with at least 40 years of non-missing data. Each symbol represents a station. The line of best fit calculated using total least-squares regression is shown in red, s is the slope of the line and r is the spatial correlation using the percentage trends. Australian stations are represented by blue asterisks.



changes when averaged across the globe). In addition, as with the results for Australia, the most extreme precipitation events (Fig. 8(c)) are much more extended in scale than more moderate events (Fig. 8(b)), indicating enhanced trends in the more extreme tails of the precipitation distribution. This is the first time, using high-quality long-term datasets, that global changes in extremes have been compared directly with changes in average precipitation.

While in this study we have been unable to do the same comparison between global mean temperature and temperature extremes, other studies (e.g., Caesar et al. 2006) have analysed trends in various percentiles for maximum and minimum temperatures for Australia and other parts of the globe. Caesar et al. (2006) analysed nine percentiles (i.e., 10th, 20th, … 90th) for maximum and minimum temperature over a large scale from a newly created daily temperature dataset. They showed that Australia had a much more uniform significant warming across the whole percentile range than for other regions studied, e.g., USA, Europe, China and Russia. This would seem to confirm that it is the whole temperature distribution which is increasing. However that study excluded the analysis of the most extreme events compared with mean trends. Therefore, it is impossible to say whether the most extreme events are behaving differently from more moderate extreme events which would seem to be the suggestion given the results from the Australian temperature stations studied here.

Discussion

We have been able to infer relationships between means and extremes in Australia using a set of standard climate extremes indices which in turn have been compared with global results. It has been shown that the relationships between the trends in means and extremes are consistent throughout Australia and the globe. Globally, the enhanced warming of minimum temperatures compared to maximum temperature extremes is the expected response (e.g., Hegerl et al. 2004) to increasing levels of atmospheric greenhouse gases (IPCC 2001). However, recent studies show that the regional responses of observed trends in means and extremes of temperature and precipitation can also largely be driven by large-scale ‘natural’ climate variability (Scaife et al. 2007), although this variability may also contain an anthropogenic component.

Southwest Western Australia is a region of Australia where a number of studies have attempted to attribute the observed climate changes. The region has seen a significant decrease in rainfall over recent decades, associated with a decrease in troughs and an increase in high pressure systems (Hope et al. 2006). Although the rainfall decrease can be captured by long climate simulations (Cai et al. 2005), the timing of the response appears to be anthropogenic in origin (Timbal et al. 2006). As trends in other regions become increasingly large (e.g., recent trends in northwest and southeast Australia), studies to separate the natural climate responses from anthropogenic influences will become increasingly important. These will require careful consideration and an appropriate experimental set-up, but might be able to begin to answer the question of whether current trends will persist into the future. One indicator that there is an anthropogenic influence on the trends observed in Australia is the fact that there is a strong link between the Australian and global patterns for changes in means versus extremes, which suggests an over-arching influence on the whole globe.

Irrespective of the cause, given the enhanced variability of trends in extremes compared to mean trends, it is likely that these extreme changes will have severe impacts on vulnerable regions. Factors such as changes in land use, population density, and water storage and usage practices will affect how certain regions are able to adapt to the extreme changes in climate, as has been highlighted by this and many other studies. In some regions, increases in rainfall would come as welcome relief, while in others unseasonable rainfall will potentially bring with it certain weed species which can kill crops and cattle (Ian Foster personal communication). Changing temperatures may have beneficial affects for some animal or plant species while pushing other ecosystems towards extinction. For this reason changes in extremes need to be assessed, not as a threat in isolation from other forms of social and environmental change, but within a framework analysing the cumulative and interacting threats and vulnerabilities of these changes. However, the relationships between means and extremes described here cannot be a substitute for a full analysis of changes in the distribution of daily temperature and precipitation, which should be the basis of any further study.

Conclusions

In this study we have updated previous analyses of long-term observed trends in temperature and precipitation extremes for Australia, analysed how these relate to trends in means and, for the first time, have compared these relationships with those for other parts of the world.

Trends in extremes are highly correlated with trends in means for both temperature and precipitation in

Australia, suggesting that the mechanisms driving mean change are also driving changes in extremes. The results also suggest that absolute trends in extremes across the country as a whole are larger than trends in means.

In Australia, the most extreme minimum and maximum daily temperature trends are greater than corresponding trends in the mean. Cold minimum temperature extremes are warming faster than warm minimum temperature extremes in every season. The upper (warm) and lower (cold) tails of the maximum temperature distribution appear to be warming at approximately the same rate except in summer, when warm maximum temperatures appear to be increasing faster than cold maximum temperatures. Whilst the tails are showing greater proportional changes than the mean, it has not been determined whether these changes are significantly different from those which could be explained by a simple increase in the mean of the frequency distribution without any other changes (e.g., variance and skewness) in the distribution.

For precipitation, if the mean is increasing then the extremes tend to increase at a faster rate and vice versa for decreasing mean precipitation. The results also tentatively suggest that the most extreme events also appear to be changing at a faster rate than more moderate extreme events.

Trends in annual mean precipitation were available for the globe permitting an analysis of the relationships between these trends and those in precipitation extremes. The relationships for Australia were found to be consistent with those for the globe.

The results are consistent with climate model simulations of the 20th century that incorporate anthropogenic forcings (e.g., Folland et al. 2001), and suggest that extremes of temperature and precipitation are changing at a faster rate than are the means.

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References

Aguilar, E., Peterson, T.C., Ramírez Obando, P., Frutos, R., Retana, J.A., Solera, M., González Santos, I., Araujo, R.M., Rosa Santos, A., Valle, V.E., Brunet India, M., Aguilar, L., Álvarez, L., Bautista, M., Castañón, C., Herrera, L., Ruano, E., Siani, J.J., Obed, F., Hernández Oviedo, G.I., Salgado, J.E., Vásquez, J.L., Baca, M., Gutiérrez, M., Centella, C., Espinosa, J., Martínez, D., Olmedo, B., Ojeda Espinoza, C.E., Haylock, M., Núnez, R., Benavides, H. and Mayorga, R. 2005. Changes in precipitation and temperature extremes in Central America and Northern South America, 1961-2003. *J. Geophys. Res., 110,* D23107, doi:10.1029/2005JD006119.

Alexander, L.V., Zhang, X., Peterson, T.C., Caesar, J., Gleason, B., Klein Tank, A.M.G., Haylock, M., Collins, D., Trewin, B., Rahim, F., Tagipour, A., Kumar Kolli, R., Revadekar, J.V., Griffiths, G., Vincent, L., Stephenson, D.B., Burn, J., Aguilar, E., Brunet, M., Taylor, M., New, M., Zhai, P., Rusticucci, M. and Luis Vazquez Aguirre, J. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *J. Geophys. Res.- Atmospheres, 111*, D05109, doi:10.1029/2005JD006290.

Caesar, J., Alexander, L. and Vose, R. 2006. Large-scale changes in observed daily maximum and minimum temperatures: Creation and analysis of a new gridded data set. *J. Geophys. Res.- Atmospheres, 111*, D05101, doi:10.1029/2005JD006280.

Cai, W.J., Shi G. and Li, Y. 2005. Multidecadal fluctuations of winter rainfall over southwest Western Australia simulated in the CSIRO Mark 3 coupled model. *Geophys. Res. Letts., 32*, L12701

Collins, D.A., Della-Marta, P.M., Plummer, N. and Trewin, B.C. 2000. Trends in annual frequencies of extreme temperature events in Australia. *Aust. Met. Mag., 49*, 277-92.

Della-Marta, P.M., Collins, D.A. and Braganza, K. 2004. Updating Australia's high quality annual temperature dataset. *Aust. Met. Mag., 53*, 75-93.

Folland, C.K., Karl, T.R., Christy, J.R., Clarke, R.A., Gruza, G.V., Jouzel, J., Mann, M.E., Oerlemans, J., Salinger, M.J. and Wang, S.W. 2001. Observed climate variability and change. In: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, and New York, USA, 881 pp.

Griffiths, G.M., Chambers, L.E., Haylock, M.R., Manton, M.J., Nicholls, N., Baek, H.-J., Choi, Y., Della-Marta, P.M., Gosai, A., Iga, N., Lata, R., Laurent, V., Maitrepierre, L., Nakamigawa, H., Ouprasitwong, N., Solofa, D., Tahani, L., Thuy, D.T., Tibig, L., Trewin, B., Vediapan, K. and Zhai, P. 2005. Change in mean temperature as a predictor of extreme temperature change in the Asia-Pacific region. *Int. J. Climatol., 25,* 1301-30

Haylock, M. and Nicholls, N. 2000. Trends in extreme rainfall indices for an updated high quality data set for Australia, 1910-1998. *Int. J. Climatol., 20,* 1533-41.

Haylock, M.R., Peterson, T., Abreu de Sousa, J.R., Alves, L.M., Ambrizzi, T., Baez, J., Barbosa, J.I., Barros, V.R., Berlato, M.A., Bidegain, M., Coronel, G., Corradi, V., Grimm, A.M., Jaildo dos Anjos, R., Karoly, D., Marengo, J.A., Marino, M.B., Meira, P.R., Miranda, G.C., Molion, L., Moncunill, D.F., Nechet, D., Ontaneda, G., Quintana, J., Ramirez, E., Rebello, E., Rusticucci, M., Santos, J.L., Varillas, I.T., Villanueva, J.G., Vincent, L. and Yumiko, M. 2006. Trends in total and extreme South America rainfall 1960-2000 and links with sea surface temperature. *Jnl Climate, 19,* 1490-512.

Hegerl, G.C, Zwiers, F.W., Stott, P.A. and Kharin, V.V. 2004. Detectibility of anthropogenic changes in annual temperature and precipitation extremes. *Jnl Climate, 17*, 3683-700.

Hennessy, K.J., Suppiah, R. and Page, C.M. 1999. Australian rainfall changes, 1910-1995. *Aust. Met. Mag., 48,* 1-13.

Intergovernmental Panel on Climate Change (IPCC) 2001. *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J.T. Houghton et al., Cambridge University Press, New York, 881 pp.

Jones, D.A. 1998. The prediction of Australian land surface temperatures using near global sea surface temperature patterns. *BMRC Research Report 70*, Bur. Met, Australia.

Katz, R.W. 1999. Extreme value theory for precipitation: sensitivity analysis for climate change. *Advances in Water Resources, 23*, 133-9.

Katz, R.W. and Brown, B.G. 1992. Extreme events in a changing climate: Variability is more important than averages. *Climatic Change, 21*, 289-302.

Kiktev, D., Sexton, D.M.H., Alexander, L. and Folland, C.K. 2003. Comparison of modeled and observed trends in indices of daily climate extremes. *Jnl Climate, 16,* 3560-71.

Klein Tank, A.M.G., Peterson, T.C., Quadir, D.A., Dorji, S., Xukai, Z., Hongyu, T., Santhosh, K., Joshi, U.R., Jaswal, A.K., Kolli, R.K., Sikder, A., Deshpande, N.R., Revadekar, J., Yeleuova, K., Vandasheva, S., Faleyeva, M., Gomboluudev, P., Budhathoki, K.P., Hussain, A., Afzaal, M., Chandrapala, L., Anvar, H., Amanmurad, D., Asanova, V.S., Jones, P.D., New, M.G. and Spektorman, T. 2006. Changes in daily temperature and precipitation extremes in Central and South Asia. *J. Geophys. Res., 111*, D16105, doi:10.1029/2005JD006316.

Lavery, B.M., Kariko, A.P. and Nicholls, N. 1992. A high-quality historical rainfall data set for Australia. *Aust. Met. Mag., 40,* 33-9.

Lavery, B., Joung, G. and Nicholls, N. 1997. An extended high-quality historical rainfall dataset for Australia. *Aust. Met. Mag., 46*, 27-38.

Manton, M.J., Della-Marta, P.M., Haylock, M.R., Hennessy, K.J., Nicholls, N., Chambers, L.E., Collins, D.A., Daw, G., Finet, A., Gunawan, D., Inape, K., Isobe, H., Kestin, T.S., Lefale, P., Leyu, C.H., Lwin, T., Maitrepierre, L., Ouprasitwong, N., Page, C.M., Pahalad, J., Plummer, N., Salinger, M.J., Suppiah, R., Tran, V.L., Trewin, B., Tibig, I. and Yee, D. 2001. Trends in extreme daily rainfall and temperature in southeast Asia and the South Pacific: 1916-1998. *Int. J. Climatol., 21*, 269-84.

New, M., Hewitson, B., Stephenson, D.B., Tsiga, A., Kruger, A., Manhique, A., Gomez, B., Coelho, B., Caio, A.S., Masisi, D.N., Kululanga, E., Mbambalala, E., Adesina, F., Saleh, H., Kanyanga, J., Adosi, J., Bulane, L., Fortunata, L., Mdoka, M.L. and Lajoie, R. 2006. Evidence of trends in daily climate extremes over Southern and West Africa. *J. Geophys. Res., 111*, D14102, doi:10.1029/2005JD006289.

Nicholls, N., Drosdowsky, W. and Lavery, B. 1997. Australian rainfall variability and change. *Weather, 52,* 66-72.

Pittock, B., Wratt, D., Basher, R., Bates, B., Finlayson, M., Gitay, H. and Woodward, A. 2001. Australia and New Zealand. In: *Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, and New York, USA, 1032 pp.

Plummer, N., Salinger, M.J., Nicholls, N., Suppiah, R., Hennessy, K.J., Leighton, R.M., Trewin, B., Page, C.M. and Lough, J.M. 1999. Changes in climate extremes over the Australian region and New Zealand during the twentieth century. *Climatic Change, 42*, 183-202.

Power, S.F., Tseitkin, F., Torok, S., Lavery, B., Dahni, R. and McAvaney, B. 1998. Australian temperature, Australian rainfall and the Southern Oscillation, 1910-1992: coherent variability and recent changes. *Aust. Met. Mag., 47*, 85-101.

Scaife, A.A., Folland, C.K., Alexander, L.V., Moberg, A. and Knight, J.R., 2006. European climate extremes and the North Atlantic Oscillation. *Jnl Climate*, in press.

Tebaldi, C., Hayhoe, K., Arblaster, J.M. and Meehl, G.A. 2006. Going to the extremes: An intercomparison of model-simulated historical and future changes in extreme events. *Climatic Change*, doi:10.1007/s10584-006-9051-4.

Timbal, B., Arblaster, J.M. and Power, S. 2006. Attribution of the late-twentieth-century rainfall decline in southwest Australia. *Jnl Climate, 19*, 2046-62.

Torok, S.J. and Nicholls, N. 1996. A historical annual temperature dataset for Australia. *Aust. Met. Mag., 45*, 251-60.

Trewin, B.C. 2001. The development of a high-quality daily temperature data set for Australia. *Eleventh Symposium on Meteorological Observations and Instrumentation*, Albuquerque, New Mexico, 14-18 January 2001, 279-84.

Tryhorn, L. and Risbey, J. 2006. On the distribution of heat waves over the Australian region. *Aust. Met. Mag., 55*, 169-82.

Vincent, L.A., Peterson, T.C., Barros, V.R., Marino, M.B., Rusticucci, M., Carrasco, G., Ramirez, E., Alves, L.M., Ambrizzi, T., Berlato, M.A., Grimm, A.M., Marengo, J.A., Molion, L., Moncunill, D.F., Rebello, E., Anunciação, Y.M.T., Quintana, J., Santos, J., Baez, J., Coronel, G., Garcia, J., Trebejo, I., Bidegain, M., Haylock, M.R. and Karoly, D. 2005. Observed trends in indices of daily temperature extremes in South America 1960-2000. *Jnl Climate, 15*, 1322-34.

Viney, N.R. and Bates, B.C. 2004. It never rains on Sunday: the prevalence and implications of untagged multi-day rainfall accumulations in the Australian high quality data set. *Int. J. Climatol., 24,* 1171-92.

Wang, X.L. and Swail, V.R. 2001. Changes in extreme wave heights in Northern Hemisphere oceans and related atmospheric circulation regimes. *Jnl Climate, 14*, 2204-20.

Wardle, R. and Smith, I. 2004. Modeled response of the Australian monsoon to changes in land surface temperatures. *Geophys. Res. Lett., 31*, L16205 doi:10.1029/2004GL020157.

Zhang, X., Aguilar, E., Sensoy, S., Melkonyan, H., Tagiyeva, U., Ahmed, N., Kutaladze, N., Rahimzadeh, F., Taghipour, A., Hantosh, T.H., Albert, P., Semawi, M., Karam Ali, M., Halal Said Al-Shabibi, M., Al-Oulan, Z., Zatari, T., Al Dean Khelet, I., Hammoud, S., Demircan, M., Eken, M., Adiguzel, M., Alexander, L., Peterson, T. and Wallis, T. 2005. Trends in Middle East Climate Extremes Indices during 1930-2003. *J. Geophys. Res., 110*, D22104, doi:10.1029/2005JD006181.