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Trends in annual frequencies of extreme temperature events in Australia

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A number of indices have been developed to investigate recent changes in the annual frequencies of extreme temperature events in Australia. A high-quality daily temperature dataset including 88 station records is used to determine trends in these indices, generally over the period 1957 to 1996. Indices investigated include measures of the frequencies of daily maximum and minimum temperatures above and below fixed temperature thresholds, as well as frequencies above and below specified percentile levels. Trends in consecutive days and nights of extreme temperature are also considered. These trends indicate that occurrences of warm temperature extreme events have generally increased over the investigation period, whilst numbers of extremely cool temperature events have decreased. The trends are particularly strong for indices based on minimum temperature, with many statistically significant at the 95 per cent confidence level. Some of the trends display considerable regional variation. Examples of this are a downward trend in the frequency of warm extremes in parts of the far southeast, counter to the national trend, and an especially strong decrease in the frequency of relatively cool days along the east coast. A number of measures of daily temperature variability are also examined with many records showing significant declines for these indices. These trends may provide the first evidence of decreases in intraseasonal temperature variability consistent with those observed over large parts of the northern hemisphere landmass.

Introduction

Several studies have examined trends in Australian mean temperatures. Torok and Nicholls (1996) used a set of high-quality, non-urban temperature records to show that both annual mean maximum and minimum temperatures have increased over most of Australia during the period 1910 to 1993. Most of this increase in temperature was found to have occurred since about 1950. Whilst providing important information about what is happening to the mean temperature, investigations of mean variables provide little information about what might be happening at the extreme ends of the distribution. It is the extreme temperature events such as heat waves, cold snaps and frost events

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that have the greatest economic and social impacts by affecting mortality rates, energy consumption, crop production and fire risk. Intuitively it could be expected that if mean temperatures increase, the frequency of extremely warm events should also increase and the frequency of extremely cold events should decrease. However, it is possible that a temperature distribution could skew such that mean values are changed with little or no impact on the extreme ends of the distribution. Alternatively, Katz and Brown (1992) have shown that small changes in mean temperature can be associated with large changes in the frequency of extremes due to changes in variability.

Determining real trends in extreme climatic events is more difficult than for mean variables (Nicholls 1995). Analyses of temperature extremes requires data at greater temporal resolution (e.g. at the daily, rather than monthly, timescale) but digitised high-resolution data are generally less readily available than data at monthly or longer timescales. Also, when investigating trends at the extreme ends of a climatic distribution, the likelihood of complications due to erroneous data is increased because outliers can be falsely considered as true data extremes, rather than incorrect data. Missing data are also of great concern when considering extreme temperature events. Even a relatively small number of missing daily data values, whilst not necessarily affecting the monthly mean value significantly, create doubt about whether or not the hottest or coldest day of the month has been missed. Consecutive days of missing data are particularly difficult to deal with as extreme temperatures often occur over several consecutive days during the passage of weather systems.

Inhomogeneities or discontinuities caused by changes such as site location, exposure, instrumentation and observation practice will not only affect mean climatic values but also the extremes of the climatic distribution. Nicholls (1995) describes situations in which changes in exposure at an observation site could have greater impacts on values of extreme temperature than mean temperature. Also, Trewin and Trevitt (1996) showed that many techniques traditionally used to correct a discontinuity in the mean may not necessarily remove the discontinuity in the extremes. This is particularly so in situations where neighbouring stations with different local topography have been used to calculate the adjustment. Temperature differences between such sites are more likely to be temperature dependent.

Due to the problems described above, a suitable Australian daily temperature dataset has been unavailable for investigations of extreme temperature until recently. An early version of such a dataset was used by Plummer et al. (1999) to determine that, consistent with warming trends in mean maximum and minimum temperatures over Australia, there has been an increase in the frequency of warm days and nights and a decrease in cool days and nights over the period 1961 to 1995. A decrease in the frequency of cool nights was found to be the most significant and consistent trend. Plummer et al. (1999) also found an increase in the frequency of warm events (three consecutive warm days or nights) and a decrease in numbers of cool events (three consecutive cool days or nights). This study represents an update of the Plummer et al. study, using a dataset with higher station density and a wider variety of extreme temperature measures. This provides better resolution of regional differences in trends and a more complete picture of how frequencies of extreme events such as frost and unusually warm or cold periods at any time of the year have changed.

An Australian high-quality daily temperature dataset

This study uses an Australian high-quality daily temperature dataset described by Trewin (1999). All station records in this dataset have undergone strict quality control measures. These include comparisons between data at neighbouring stations and checks for internal consistency, such as ensuring that each daily maximum temperature was consistent with the minimum temperature on the same day, and that fixed-hour observations were within the bounds set by the maximum and minimum temperature on any given day. Suspect data were investigated by examining the synoptic weather situation at the time of observation and any data subsequently deemed to be erroneous removed or adjusted. All maximum and minimum temperatures on the day following one or more missing observations were assumed to be accumulated since the last observation, and were also removed from the dataset.

Potential discontinuities in each temperature series of the dataset were identified using graphical examinations and a statistical technique based on that of Easterling and Peterson (1995). An intensive study of available station history information was also undertaken to find supporting evidence for any identified discontinuities. A discontinuity deemed to be artificial, rather than a natural climate variation, was then corrected at the daily time-scale using statistical relationships between neighbouring stations. However, rather than making adjustments according to mean temperatures, station records were adjusted at different percentile levels throughout the distribution. Hence, temperatures at the higher end of a station record distribution can be adjusted by different magnitudes to those at the middle or lower end of the distribution. Trewin and Trevitt (1996) showed this technique to be particularly useful for correcting station records intended for examining trends in extreme daily temperatures.

Limited Australian daily data are available in digitised format prior to 1957, and homogeneity assessments have not yet been made for post-1996 data. Consequently, the daily temperature records used in this study generally span the period from 1957 to 1996, with some records starting earlier. There are 103 corrected station records in the dataset of Trewin (1999). However, four records (Adelaide, Brisbane, Melbourne and Sydney) were not used here to avoid potential warming biases associated with urbanisation. This study was intended to concentrate on changes in extreme events due to broadscale and regional climate change, not local climate change. The authors plan to examine temperature changes in urban centres in a later study. A further eleven station records failed an initial data quantity test leaving a total of 88 records for examination. A year was considered missing in a station record if it contained greater than ten per cent missing daily values or more than three months during the year contained greater than 20 per cent missing daily values. If a record then had less than 30 years remaining the station was not used. Information about the station records used in this analysis can be found in Table 1.

Selecting the indices

A number of indices were defined to investigate historical frequencies of extreme temperature events in Australia. The selection of a concise list of indices to examine was complicated by a number of competing interests. For example, for policy makers and the general public it is often appropriate to present results in terms of numbers of days or nights above or below simple, fixed thresholds such as 10°C or 40°C. However, trying to choose thresholds that are meaningful throughout the entire region of investigation can be difficult, especially for Australia. A threshold considered extreme in one part of the country might be considered quite normal in another.

A number of indices based on fixed temperature thresholds are presented in this study. The selection of these temperature thresholds was based on what was felt most Australians would consider an extreme day or night, whilst not making the threshold so extreme that the indices would only be applicable to limited parts of the country. Maximum temperatures above 35°C and below 15°C were chosen to define hot and cold days respectively, while minimum temperatures above 20°C and below 5°C were chosen to define hot and cold nights.

To overcome problems associated with applying a fixed threshold over a wide region, it is possible to use thresholds based on fixed percentile values, calculated for each individual station record. A percentile-based index will be relevant for all station records as extreme events are defined relative to the station's own climatological temperature ranges. However, as with fixed thresholds, some decisions still need to be made as to which percentile levels actually define 'extreme ' events.

The more extreme the percentile threshold the higher the proportion of erroneous data that is counted as extreme. However, this should not be a problem with the dataset used in this analysis which has been checked thoroughly for outliers. Consequently the 95th percentile value was chosen to define extremes at the high end of the distribution and the 5th percentile used at the low end. This means that, on average, about 18 days and nights per year would be considered hot, and 18 days and nights considered cold. This seemed a reasonable balance between selecting too many days, and not all of them being 'extreme', and not enough days so that only trends in the absolute hottest and coldest events of the year were determined.

Once the extreme percentile levels have been chosen there are a variety of ways of determining which temperature values these correspond to. Percentile values can be based on all days during the period defined as normal or they can be calculated after removing the annual temperature cycle. In the first case, calculated trends provide information about changes in the hottest and coldest days and nights of the annual cycle. Some studies of extreme events have taken this approach (e.g. Manton et al. 2000) and for many purposes this is the most appropriate. The hottest and coldest days of the annual temperature cycle have the greatest social and economic impacts and consequently trends in the frequency of these events are of greater interest to policymakers. However, this method provides no information about the intermediate parts of the annual cycle, unless analyses are undertaken at seasonal or monthly time-scales.

The large number of indices used in this study make it difficult to concisely present results at the annual, seasonal and monthly timescales. Consequently, this study concentrates on trends in annual frequencies in anticipation that shorter timescales will be examined in subsequent studies. To obtain a more complete picture of changes over the whole year, percentile values in this study were determined after removing the average annual temperature cycle. Therefore, the trends in percentile-based indices presented here indicate changes in the numbers of relatively warm or cold events throughout the

Table 1. High-quality daily temperature stations used in this analysis. Start and end years denote periods over which appropriate data were available. Most stations also have earlier daily data available in hardcopy format and post-1996 data which have not yet been checked for homogeneity.

Station name	*Station number*	*Latitude (°S)*	*Longitude (°E)*	*Start year*	*End year*
Albany	9741	34.93	117.80	1950	1996
Alice Springs	15590	23.80	133.88	1942	1996
Amberley	40004	27.63	152.72	1942	1996
Barcaldine	36007	23.55	145.28	1957	1996
Bathurst	63005	33.43	149.57	1921	1996
Birdsville	38002	25.90	139.33	1957	1996
Boulia	38003	22.92	139.90	1949	1996
Bourke	48013	30.03	145.95	1957	1995
Broome	3003	17.93	122.23	1940	1996
Bundaberg	39128	24.90	152.31	1957	1996
Butlers Gorge	96003	42.27	146.27	1957	1992
Cabramurra	72091	35.93	148.38	1962	1996
Cairns	31011	16.88	145.74	1943	1996
Camooweal	37010	19.92	138.12	1957	1993
Canberra	70014	35.30	149.18	1940	1996
Cape Borda	22801	35.75	136.58	1963	1996
Cape Bruny	94010	43.48	147.13	1957	1996
Cape Leeuwin	9518	34.37	115.13	1957	1996
Cape Otway	90015	38.85	143.52	1958	1993
Carnarvon	6011	24.88	113.67	1949	1996
Ceduna	18012	32.13	133.70	1943	1996
Charleville	44021	26.42	146.27	1943	1996
Charters Towers	34084	20.03	146.27	1962	1996
Cobar	48027	31.48	145.82	1957	1996
Coffs Harbour	59040	30.32	153.12	1952	1996
Cunderdin	10035	31.65	117.23	1957	1996
Dalwallinu	8039	30.28	116.66	1957	1996
Darwin	14015	12.42	130.88	1941	1996
Deniliquin	74128	35.55	144.93	1957	1996
Dubbo	65012	32.22	148.57	1957	1996
Eddystone Point	92045	40.98	148.33	1959	1993
Esperance	9789	33.83	121.88	1957	1996
Forrest	11052	30.83	128.12	1947	1994
Gabo Island	84016	37.57	149.92	1957	1995
Gayndah	39039	25.63	151.62	1957	1996
Geraldton	8051	28.78	114.68	1942	1996
Giles	13017	25.03	128.28	1957	1996
Grove	94069	42.98	147.07	1957	1996
Gunnedah	55024	31.02	150.27	1959	1996
Halls Creek	2012	18.23	127.67	1945	1996
Hobart	94029	42.88	147.32	1944	1996
Inverell	56017	29.78	151.12	1957	1996
Kalgoorlie	12038	30.78	121.45	1943	1996
Kalumburu	1021	14.28	126.63	1957	1995
Kerang	80023	35.73	143.92	1962	1996
Launceston	91104	41.57	147.20	1940	1995
Laverton	87031	37.87	144.74	1945	1996
Longreach	36031	23.43	144.27	1957	1996
Low Head	91057	41.05	146.78	1957	1996
Mackay	33119	21.12	149.22	1960	1996
Marree	17031	29.65	138.05	1957	1996
Meekatharra	7045	26.62	118.53	1951	1996
Mildura	76031	34.23	142.08	1947	1996
Moree	53048	29.48	149.83	1880	1996

Table 1. Continued

Station name	*Station number*	*Latitude (°S)*	*Longitude (°E)*	*Start year*	*End year*
Moruya	69018	35.92	150.15	1921	1996
Mount Gambier	26021	37.73	140.78	1942	1996
Nhill	78031	36.33	141.63	1957	1996
Nowra	68076	34.95	150.53	1956	1996
Nuriootpa	23321	34.47	139.00	1957	1996
Oodnadatta	17114	27.57	135.43	1942	1984
Orbost	84030	37.68	148.45	1957	1996
Palmerville	28004	16.00	144.07	1957	1996
Perth	9021	31.93	115.93	1945	1996
Port Hedland	4032	20.37	118.63	1950	1996
Port Lincoln	18070	34.72	135.85	1957	1996
Port Macquarie	60026	31.43	152.92	1921	1994
Richmond (NSW)	67105	33.60	150.77	1943	1996
Richmond (Qld)	30045	20.73	143.13	1957	1996
Rockhampton	39083	23.37	150.47	1940	1996
Rutherglen	82039	36.10	146.50	1965	1996
Sale	85072	38.10	147.13	1946	1996
Scone	61089	32.07	150.92	1959	1996
St George	43034	28.05	148.60	1962	1996
Tarcoola	16044	30.70	134.58	1962	1996
Tennant Creek	15135	19.63	134.18	1957	1996
Tewantin	40264	26.38	153.03	1962	1995
Thargomindah	45017	28.00	143.82	1957	1996
Thursday Island	27022	10.58	142.22	1953	1992
Tibooburra	46037	29.43	142.02	1921	1996
Townsville	32040	19.25	146.77	1941	1996
Wagga	72150	35.17	147.45	1942	1996
Walgett	52088	30.03	148.12	1957	1996
Wandering	10648	32.67	116.67	1957	1995
Williamtown	61078	32.78	151.83	1951	1995
Wilsons Promontory	85096	39.13	146.42	1957	1996
Wittenoom	5026	22.23	118.33	1959	1996
Woomera	16001	31.13	136.82	1950	1996
Yamba	58012	29.43	153.37	1921	1996

whole year, rather than at the hottest and coldest times of the year. They do not provide information about which seasons have changed the most.

To calculate the maximum and minimum temperature values corresponding to the 95th and 5th percentiles of each station record, initially long-term (1961 to 1990) temperature averages were determined for every day of the calendar year. This was done by calculating an average for each month, assigning that value to the 16th day of each month and then linearly interpolating between these mid-points to determine the theoretical average for every other day of the year. There are other, more complex ways to determine daily normals but Trewin (personal communication) has found these make little difference to the technique used here, largely due to day-to-day variability being far greater than the day-to-day differences in climatology. Using these daily normals, each record was converted into a series of daily temperature anomalies. Daily anomaly values during the 1961 to 1990 period were then ranked for each calendar month and 95th and 5th percentile values determined for each month. Daily maxima or minima above the 95th percentile for the relevant month were then defined as extremely warm and those below the 5th percentile for the month were considered extremely cool. Annual totals of extremes were obtained by simply adding the numbers of extreme days or nights each month. Missing daily data were assumed to be non-extreme values.

Indices of extended periods of unusually warm and cool temperature were also defined based on occurrences of three, four or five consecutive days or nights of extreme temperature. Periods of extreme temperature lasting six, seven or eight days were counted as two extreme events, nine, ten or eleven days counted as three events, and so on. Again, missing data were considered to be non-extreme. Extended periods of extreme temperature have been shown to have greater impacts on mortality rates than single day occurrences due to coping mechanisms gradually being eroded the longer the temperature remains extreme (Jones et al. 1982). To allow for extreme temperature events spanning the transition of a year, a count of consecutive extreme days or nights was extended into the following year by a maximum of two days, with the first extreme day or night being considered as the date of the event.

Some international studies of extreme climatic indicators have included a measure of growing season length based on temperature. However, generally these indices are not appropriate for the relatively warm Australian climate. In Australia, growing seasons tend to be crop specific and more dependent on rainfall patterns. Consequently there is no easily defined growing season index for Australia and none were calculated in this study. However, the occurrence of frost events has some relevance to agriculture in Australia so two frost indices were examined - the total number of frost events (daily minimum temperatures below 0°C) per year and the length of frost season (number of days between first and last frost).

Katz and Brown (1992) showed that changes in the frequencies of extreme events are more dependent on changes in variability than changes in the mean climate. Consequently, several measures of temperature variability were also defined in this study based on the standard deviation and inter-daily differences of maximum, minimum and mean temperatures. Annual standard deviation values were calculated from the daily temperature anomaly series. However, annual mean inter-daily differences were based on day-to-day temperature differences, not differences of temperature anomalies. For comparison with other studies, the annually averaged diurnal temperature range and Extreme Temperature Range (ETR), or difference between the highest maxima and lowest minima during the year, were also calculated. ETR has been suggested as a useful indicator of greenhouse warming because the hottest days and coldest nights of a year both tend to occur during cloud free skies.

Indices were also chosen to be as consistent as possible with those used in overseas studies. Significant work has been undertaken to identify a standard set of global extreme temperature indices (e.g. Folland et al. 1999). This is an extremely difficult task. Not only do people from different regions have different ideas about what constitutes an extreme climate event but there is also a great variety of ways of treating missing data, calculating percentiles and trend values, defining seasons, etc. There is also a great variety in data quality and availability throughout the globe. The indices defined in this study have been based on those recommended in an index dictionary by Frich (personal communication), adapted to suit the Australian climate and data availability. This should allow some comparison between Australian results and those from elsewhere. In all, 26 temperature indices were chosen for examination in this study (Table 2).

Time series of annual index values were determined for each temperature record. For simplicity the calendar year was used to define a year, despite this splitting the warmest season in Australia. As the majority of results presented here are trend values, this definition should make little difference to the final analyses. Station records with more than 20 per cent of years either missing or recording zero for any particular index were considered invalid for that index i.e. four out of five years in a station record had to include at least one extreme event, as defined by the index. Consequently some indices were only relevant to particular regions of the country.

Trends in the series of annual index values were calculated for each station using linear regression. Only trends at stations where an index was deemed valid are plotted in Figs 1 to 7. These trends were calculated over all available years of record (generally at least 1957 to 1996) rather than over a fixed period. Table 1 shows the periods over which each station trend was calculated. The significance of each trend was examined at the 95 per cent confidence level using a Kendall-tau test (Press et al. 1996).

Annual Australian averages were also calculated for each index using an area-weighted Thiessen polygon technique (Lavery et al. 1997). This method involves assigning a polygon around each station location and weighting station values according to the proportion of landmass each polygon represents. If an index is considered invalid for a station, or an annual value is missing due to lack of data, the corresponding station polygon will be considered as a hole and not included in the total Australian landmass. Consequently area-weighted averages presented here will only include regions of the country where the index was deemed valid. For example, the Australian average of numbers of days hotter than 35°C (Fig. 1(a)) would not include the Tasmanian landmass as this index was found to be inappropriate for all stations in that State.

Table 2. Temperature extreme indices used in analysis. All indices calculated on an annual basis.

Index Name	*Description*
Hot days	Frequency of daily maximum temperatures ≥ 35°C
Hot nights	Frequency of daily minimum temperatures ≥ 20°C
Relatively warm days	Frequency of daily maximum temperature anomalies ≥ 95th percentile
Relatively warm nights	Frequency of daily minimum temperature anomalies ≥ 95th percentile
Hot day events	Frequency of three to five consecutive days ≥ 35°C
Hot night events	Frequency of three to five consecutive nights ≥ 20°C
Relatively warm day events	Frequency of three to five consecutive relatively warm days ≥ 90th percentile
Relatively warm night events	Frequency of three to five consecutive relatively warm nights ≥ 90th percentile
Cold days	Frequency of daily maximum temperatures ≤ 15°C
Cold nights	Frequency of daily minimum temperatures ≤ 5°C
Relatively cool days	Frequency of daily maximum temperature anomalies ≤ 5th percentile
Relatively cool nights	Frequency of daily minimum temperature anomalies ≤ 5th percentile
Cold day events	Frequency of three to five consecutive days ≤ 15°C
Cold night events	Frequency of three to five consecutive nights ≤ 5°C
Relatively cool day events	Frequency of three to five consecutive relatively cool days ≤ 10th percentile
Relatively cool night events	Frequency of three to five consecutive relatively cool nights ≤ 10th percentile
Frost days	Frequency of daily minimum temperatures ≤ 0°C
Frost season length	Number of days between first and last frost day
Inter-daily difference (Max T)	Mean inter-daily difference of maximum temperatures
Inter-daily difference (Mean T)	Mean inter-daily difference of mean temperatures
Inter-daily difference (Min T)	Mean inter-daily difference of minimum temperatures
Standard deviation (Max T)	Standard deviation of daily maximum temperature anomalies
Standard deviation (Mean T)	Standard deviation of daily mean temperature anomalies
Standard deviation (Min T)	Standard deviation of daily minimum temperature anomalies
Diurnal temperature range (DTR)	Mean difference between daily maximum and minimum temperatures
Extreme temperature range (ETR)	Difference between highest maximum and lowest minimum temperature during year

The spatial averages presented here should be considered as another index, indicative of what is occurring at the regional scale and not interpreted as a measure of what is happening at all point locations in the region. The trend maps presented only provide information about the sign of trend and whether the trend is statistically significant or not. Consequently, trend values were also calculated using the annual Australian averages of each index to provide an indication of the magnitude of trends (Table 3). To give an indication of the spread of station trend values, the highest and lowest station trend values have also been included in Table 3. All trends of spatially averaged values were calculated over the 40-year period 1957 to 1996 as this was the most common period between all station records. All stations were included in the analysis apart from Oodnadatta, which was excluded to avoid any discontinuity associated with its closure in 1984. Statistical significance was also calculated for the trends of spatially averaged values.

Trends in warm extreme indices

Generally the frequency of warm maximum and minimum temperature extremes has increased throughout Australia over the investigation period. Trends in the annual frequency of hot days (Fig. 1(a)) have increased through most of the country with several significant positive trends found, mainly in the eastern half of the country. However, some station records in parts of southeast Australia and the far southwest show declining trends for this index. Some of these negative trends were significant. The Australian average of numbers of hot days per year was found to be increasing at a rate of 0.16 days/year (Table 3) i.e. over the 40 years examined, on average, the numbers of hot days per year at Australian stations has increased by about 6 (Fig. 8(a)). However, the Australian trend was not found to be significant at the 95 per cent level.

Increases in the numbers of hot nights (Fig. 1(b))

Table 3. Trends in area-weighted averages of index values calculated over the period 1957 to 1996. Highest and lowest station trends are also shown, calculated over all available years of record for each station. Significant trends at the 95 per cent confidence level are shown in bold for the area-weighted averages only.

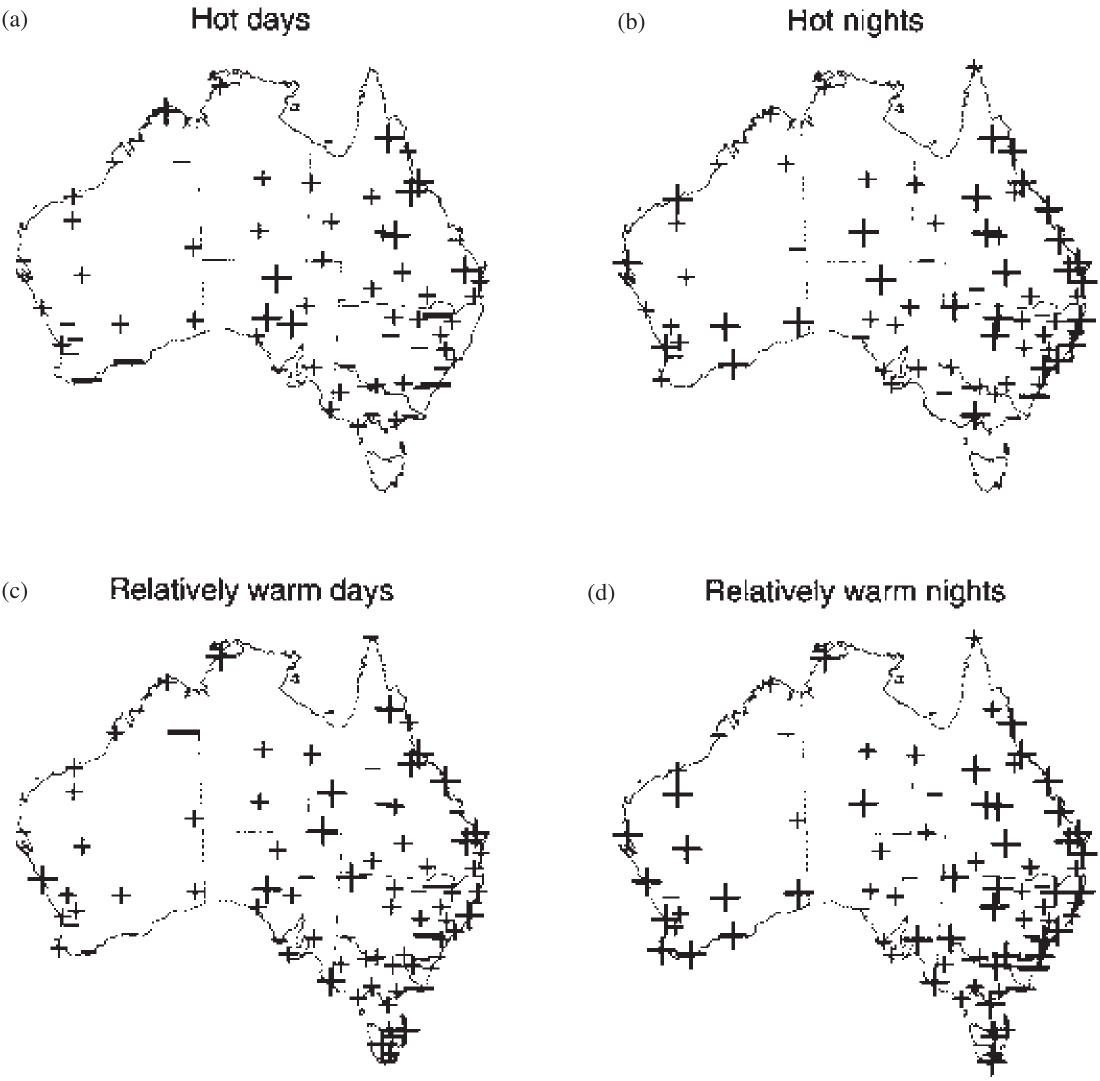
Index Name	*Trend of area-weighted average*	*Highest station trend*	*Lowest station trend*	*Trend unit*
Hot days	0.16	1.19	-0.27	Days/year
Hot nights	**0.26**	1.31	-0.13	Nights/year
Relatively warm days	0.14	0.71	-0.29	Days/year
Relatively warm nights	**0.21**	0.58	-0.18	Nights/year
Hot day events	0.05	0.25	-0.05	Events/year
Hot night events	**0.08**	0.50	-0.09	Events/year
Relatively warm day events	0.04	0.19	-0.07	Events/year
Relatively warm night events	0.04	0.14	-0.06	Events/year
Cold days	-0.12	0.18	-1.62	Days/year
Cold nights	**-0.24**	0.52	-0.88	Nights/year
Relatively cool days	-0.07	0.14	-0.79	Days/year
Relatively cool nights	**-0.23**	0.22	-1.01	Nights/year
Cold day events	-0.05	0.06	-0.51	Events/year
Cold night events	**-0.08**	0.14	-0.26	Events/year
Relatively cool day events	-0.02	0.02	-0.18	Events/year
Relatively cool night events	**-0.06**	0.05	-0.19	Events/year
Frost days	**-0.14**	0.36	-0.54	Frosts/year
Frost season length	**-0.61**	0.76	-2.29	Days/year
Inter-daily diff (Max T)	-0.02	0.88	-1.03	°C/century
Inter-daily diff (Mean T)	-0.06	0.22	-0.92	°C/century
Inter-daily diff (Min T)	0.03	1.10	-1.40	°C/century
Standard deviation (Max T)	0.01	1.29	-1.55	°C/century
Standard deviation (Mean T)	-0.08	0.66	-0.97	°C/century
Standard deviation (Min T)	**-0.26**	1.18	-1.94	°C/century
Diurnal temperature range (DTR)	-0.69	5.42	-3.95	°C/century
Extreme temperature range (ETR)	-2.25	7.83	-16.72	°C/century

have been larger than those for hot days with many positive trends found to be significant at the 95 per cent confidence level, particularly along the east coast of the country. The increase in the Australian average of hot nights per year was found to be a statistically significant trend of 0.26 nights/year (Fig. 8(b)). This is equivalent to an average increase of about ten in the annual frequency of hot nights over the 1957 to 1996 period.

Trends in the number of daily maximum temperature values above the 95th percentile have also generally increased (Fig. 1(c)), although the Australian average trend was not found to be significant at the 95 per cent confidence level. Some of the records in Victoria and New South Wales that showed a decline in the number of hot days, show a positive trend for the percentile based index. This indicates that, while numbers of the very hottest days of the year have decreased, the numbers of relatively warm days throughout the whole annual cycle have increased. The analysis would need to be undertaken at a seasonal or monthly timescale to determine at what times of the year the strongest increases have occurred.

Trends in numbers of overnight minima above the 95th percentile (Fig. 1(d)) were mostly positive and significant apart from a small region in far eastern Victoria and southeast New South Wales. In New Zealand, regional changes in temperature extremes have been attributed to changes in atmospheric circulation (Plummer et al. 1999). It is likely that regional variations in Australia are also due to such changes.

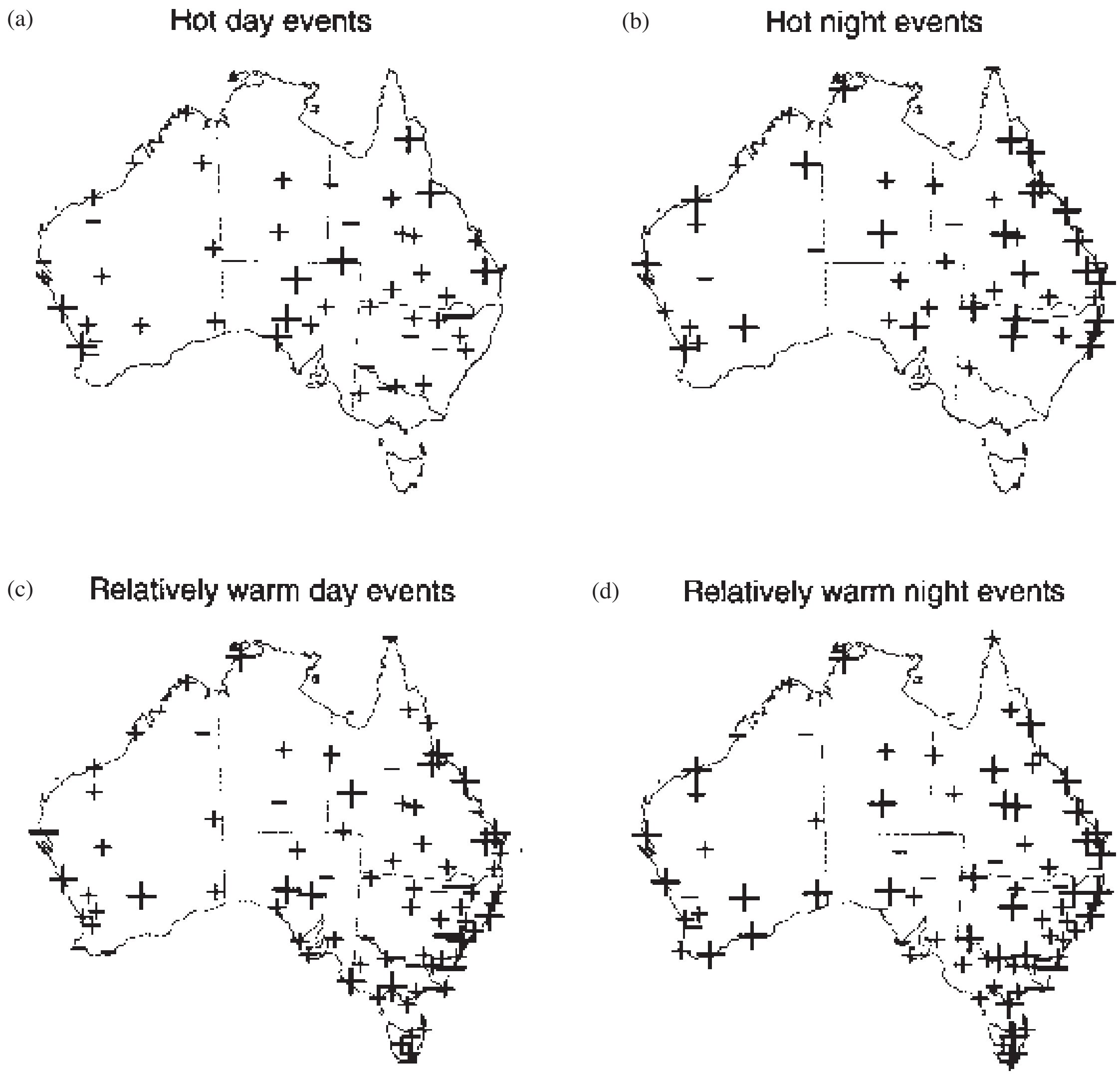
Fig. 1 Sign of trends in annual frequency of (a) hot days, (b) hot nights, (c) relatively warm days and (d) relatively warm nights. Positive/negative symbols denote positive/negative trends and symbols for significant trends at 95% confidence level are larger than those for non-significant trends. Note that periods of trend differ between stations but are generally at least from 1957 to 1996.



Investigation of this index at the seasonal timescale may provide a better understanding of the reasons for the difference between the far southeast corner and the remainder of the country. The seasons with greatest discrepancy would then indicate what changes might have occurred in the mean circulation. The all-Australian average of this index was found to have increased significantly.

Changes in the frequency of spells of hot days and nights based on fixed temperature thresholds of 35°C and 20°C (Figs 2(a) and (b)) tend to be similar to the changes in total numbers of hot days and nights. However, fewer station trends are calculated for these indices, particularly in far southern and northern parts, due to the criterion of no more than 20 per cent of years recording zero for the index. Consecutive days above a threshold are less common than single day occurrences and consequently a greater proportion of years do not record an extreme temperature event lasting at least three days or nights. Australian averages of these indices were found to be increasing at rates of 0.05 hot daytime events/year and 0.08 hot night-time events/year. Only the trend for night-time hot spells was significant.

Fig. 2 As in Fig. 1 but for events of three to five consecutive (a) hot days, (b) hot nights, (c) relatively warm days and (d) relatively warm nights.

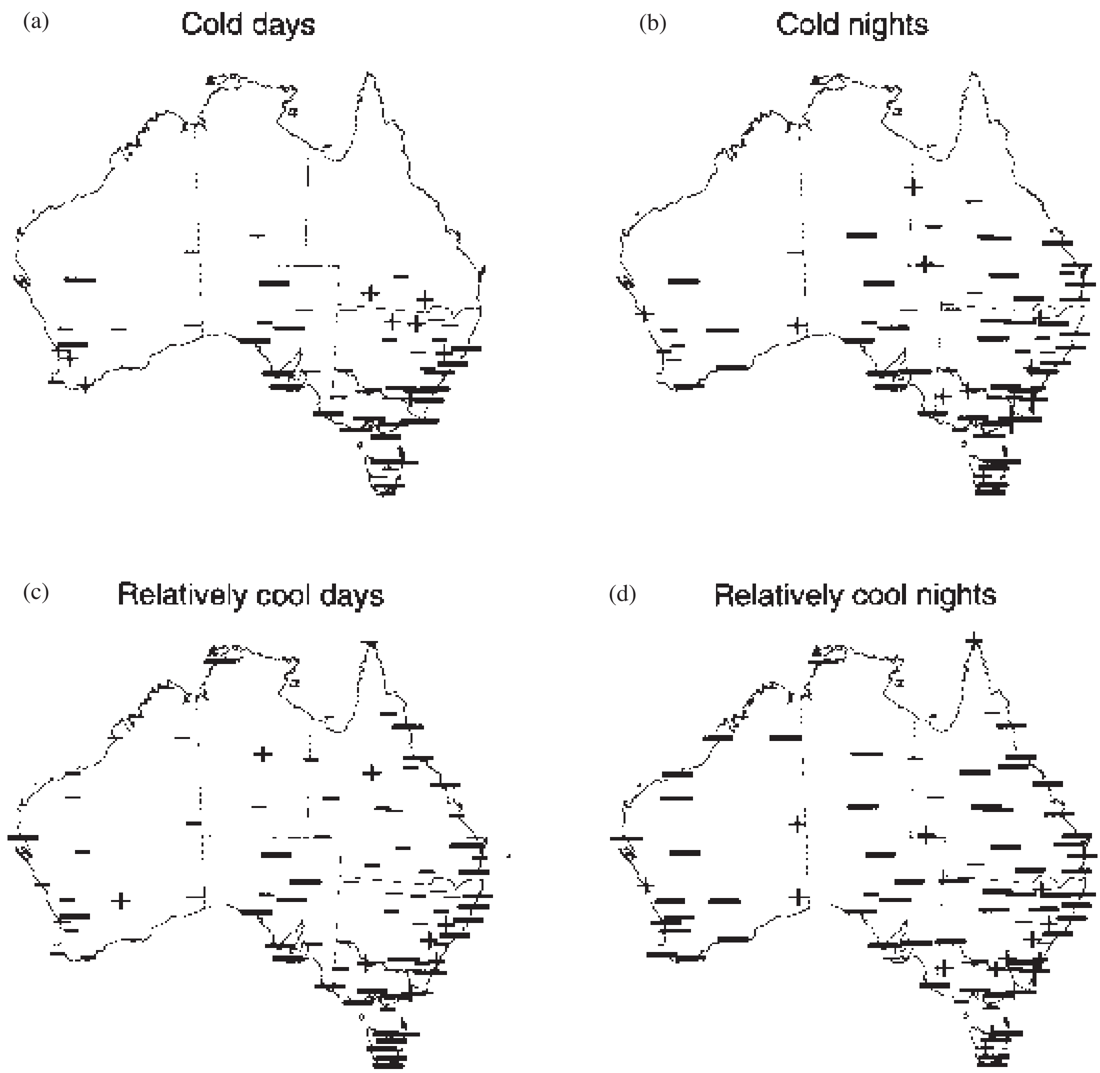


Trends in indices measuring annual numbers of relatively warm day or night spells were calculated using the 90th, rather than the 95th, percentile definition. Since the percentile values were based on daily temperature anomalies, these indices provide a measure of unusually warm periods at any time of the year. The 95th percentile threshold corresponds to only about 18 extreme days or night per year and, as these can occur at any time of the year, the chances of three consecutive extreme days or nights are small. Few stations were found to record enough relatively warm events based on a 95th percentile definition to be able to calculate a meaningful trend. Consequently, the threshold was lowered to the 90th percentile for these warm spell indices. Trends in the frequency of relatively warm spells of days and nights above the 90th percentile (Figs 2(c) and (d)) agree closely with the trends in total numbers of relatively warm days or nights at corresponding stations. The Australian average trends for relatively warm spells were not significant at the 95 per cent level for either daytime or night-time occurrences.

Trends in cool extreme indices

The frequency of both cold days (Fig. 3(a)) and nights (Fig. 3(b)) have predominantly decreased over the

Fig. 3 **As in Fig. 1 but for (a) cold days, (b) cold nights, (c) relatively cool days and (d) relatively cool nights.**



investigation period, consistent with increases in the numbers of warm extremes. The trends in area-weighted averages over the parts of Australia where these indices were considered meaningful were -0.12 cold days/year and -0.24 cold nights/year. Only the decline in average numbers of cold nights was significant. Thresholds to define extremely cold days and nights were especially hard to select. These levels could have been relaxed to include more of the country but higher thresholds would not have been considered particularly extreme in southern parts.

The indices of relatively cool days (Fig. 3(c)) and nights (Fig. 3(d)) based on a 5th percentile definition mainly show decreasing trends over the examination period. For trends in maxima below the 5th percentile, most significant trends were at coastal stations, particularly along the east coast, although the all-Australian trend was not significant. Changes in the numbers of minima below the 5th percentile level show the most consistent results of all indices. Most records in Australia show a significant decline for this index, resulting in a strong and significant decline in the all-Australian average. This result is consistent with many previous studies which indicate that mean minimum temperatures have increased at a faster rate than mean maximum temperatures in Australia (e.g. Torok and Nicholls 1996).

Fig. 4 **As in Fig. 1 but for events of three to five consecutive (a) cold days, (b) cold nights, (c) relatively cool days and (d) relatively cool nights.**

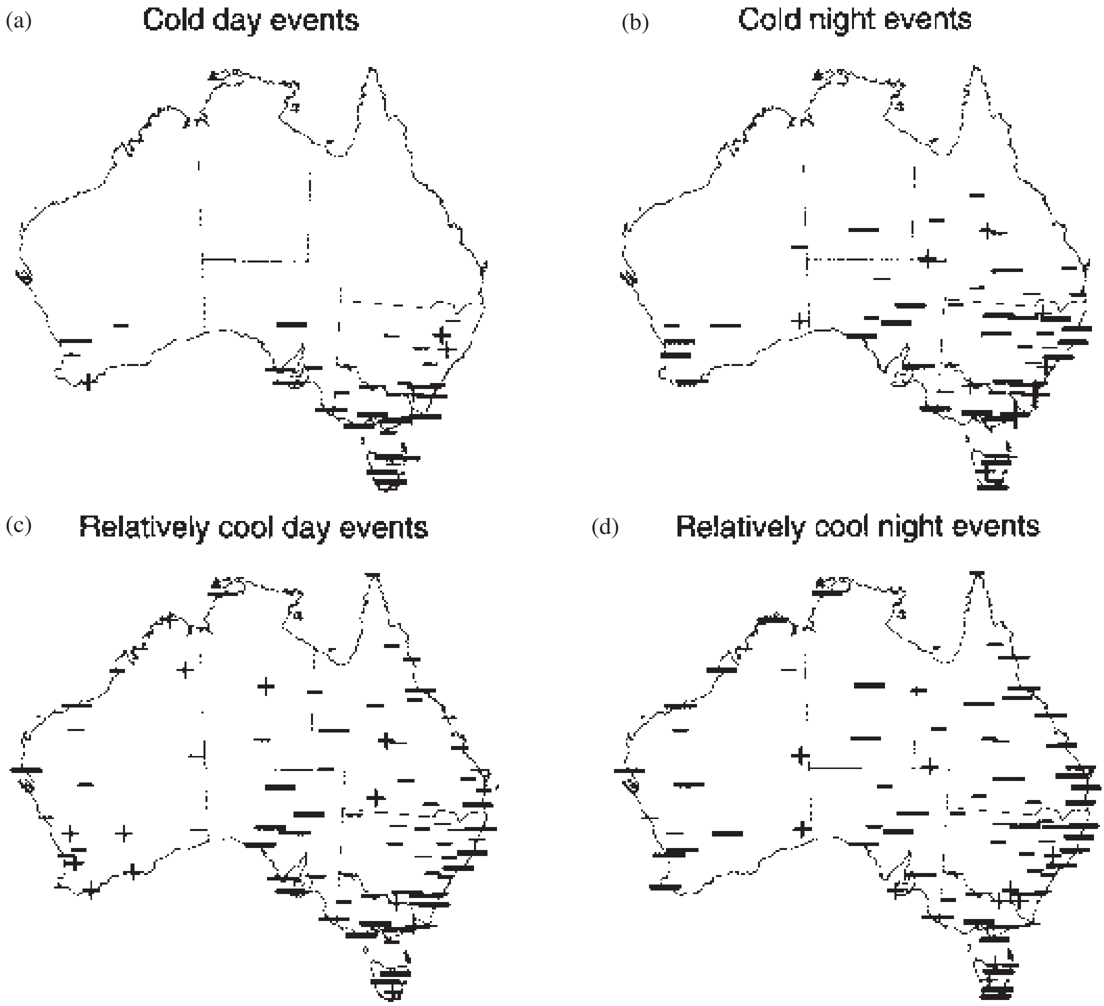


Fig. 5 **As in Fig. 1 but for (a) annual frequency of frost days and (b) length of frost season.**

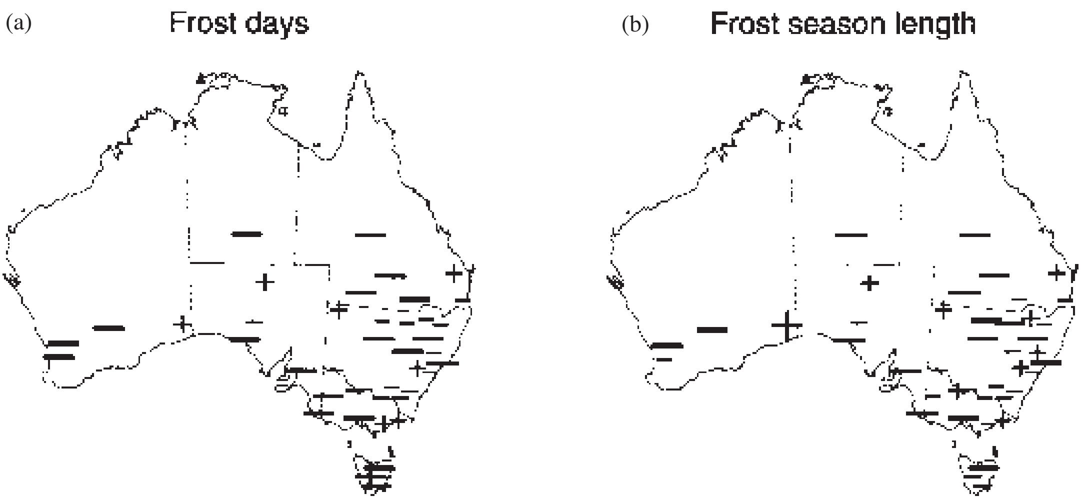


Fig. 6 **As in Fig. 1 but for annual mean inter-daily differences of (a) maximum, (b) mean and (c) minimum temperatures and annual standard deviation of daily (d) maximum, (e) mean and (f) minimum temperature anomalies.**

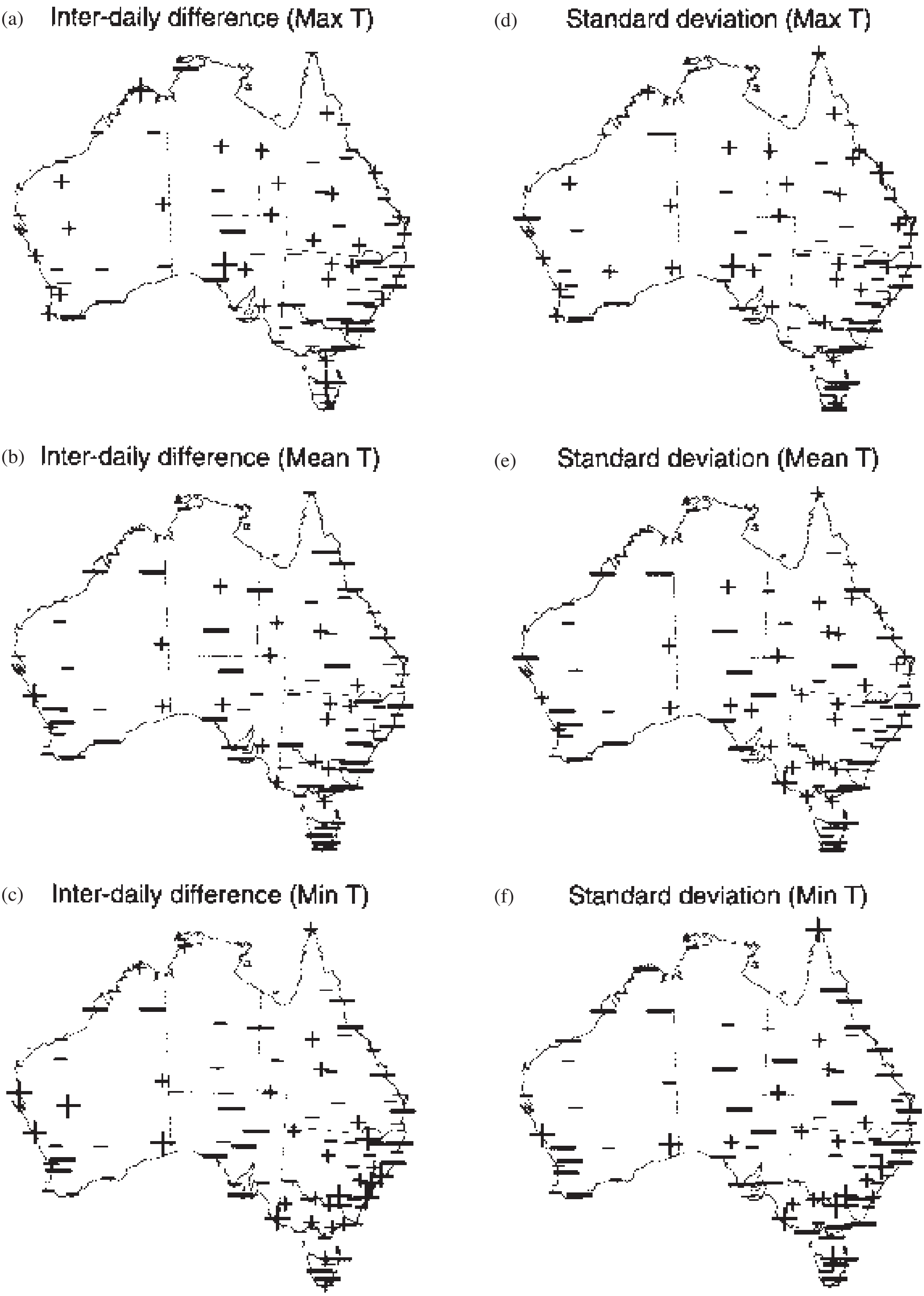
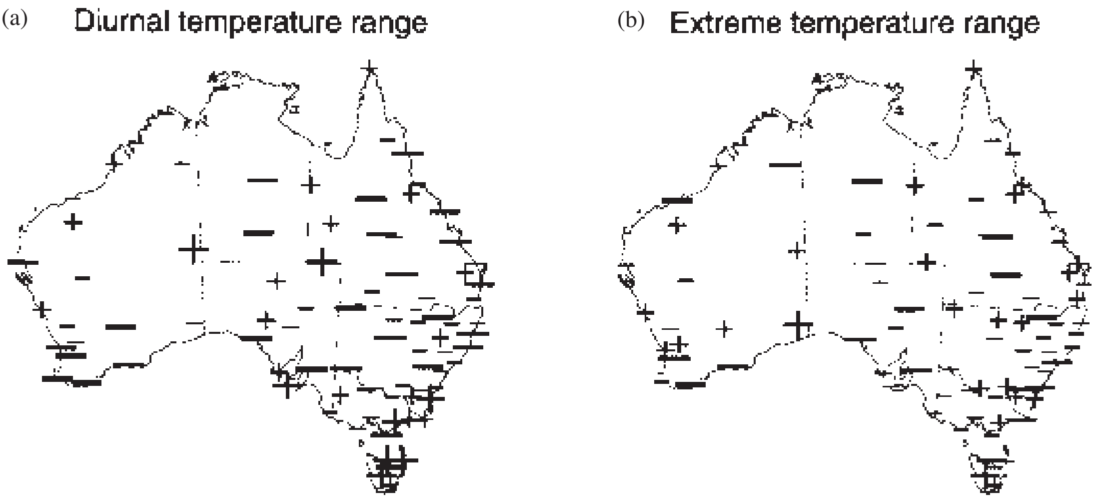


Fig. 7 As in Fig. 1 but for (a) annual mean diurnal temperature range and (b) extreme temperature range.



The number of occurrences of three to five consecutive days below 15°C and nights below 5°C have mainly declined where these indices are valid (Figs 4(a) and (b)). Trends in the areal averages of these indices were found to be a non-significant decline of -0.05 events/year for daytime events and a significant decline of -0.08 events/year for night-time events. The relatively cool event indices (Figs 4(c) and (d)) suggest that the numbers of unusually cool periods throughout the whole year have also decreased throughout Australia. As with the indices of relatively warm spells, the indices measuring numbers of cool spells on a percentile basis required the threshold to be relaxed to increase the numbers of events observed. Consequently, the indices of relatively cool spells were based on 10th, rather than 5th, percentile thresholds. Most stations along the southeast Australian coast show significant declines in the numbers of relatively cool daytime events whereas significant declines in night-time events are more widely distributed throughout the country. Only cool spells based on overnight minima showed a significant decline for the area-weighted average.

Other important indicators of climate change associated with extremely cold minima are those relating to numbers of frost events. In order to increase the number of stations at which the frost indices were relevant, the criteria of no more than 20 per cent years recording no frosts was relaxed to no more than 50 per cent of years i.e. a station only had to report, on average, at least one frost event every two years to be included in the analysis. Despite this, these indices remained valid for only about half of all stations, most of these being located in southeast Australia.

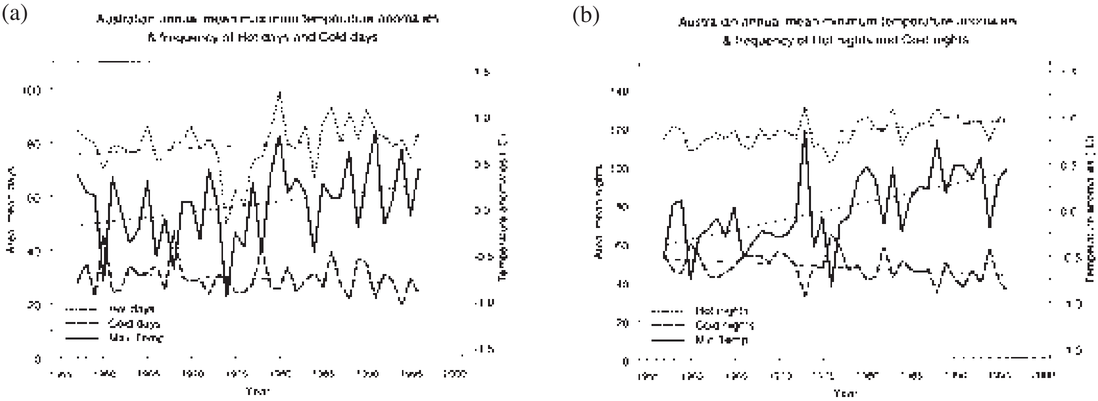
Generally significant declining trends were determined for both the numbers of frost events per year (Fig. 5(a)) and length of frost season (Fig. 5(b)). The area-weighted averages for both these indices also display significant declines, with annual numbers of frost days decreasing by an average of 5.6 over the 40 year period and the average length of frost season shortening by around 24 days. A study of frost occurrence in northeast Australia from 1894 to 1992 by Stone et al. (1996) also found trends toward fewer frosts per year and earlier date of last frost.

Trends in variability indices

Generally the sign of trends in measures of Australian daily temperature variability tend to vary more regionally than those for extreme temperatures. However, the majority of trends based on the standard deviation and inter-daily differences of daily temperature show decreases for maximum, minimum and mean temperature (Fig. 6). Many of these declines were found to be significant, although significant changes in daily maximum temperature variability were mainly confined to southern parts. The trends in all-Australian averages of these indices were not significant, apart from the declining trend in standard deviation of daily minimum temperatures. This decrease in minimum temperature variability, combined with increasing mean minimum temperatures, accounts for the especially strong declines in numbers of cold nights and frost events.

Using slightly different analysis methods and shorter periods of record, previous studies of inter-

Fig. 8 **Time series of Australian mean annual (a) maximum temperature and frequencies of hot and cold days and (b) minimum temperature and frequencies of hot and cold nights. Linear trends are also shown. Annual mean temperature data provided by Collins and Della-Marta (1999).**



period temperature variability in Australia have found little or no trend (Plummer 1996 and Karl et al. 1995). However, these studies were based on area-averaged measures. By undertaking analyses at individual stations the results are mixed but do provide some evidence of decreases in day-to-day temperature variability consistent with those observed over large parts of the Northern Hemisphere land mass (Karl et al. 1995). Climate simulations with enhanced atmospheric greenhouse gas concentrations suggest that a warmer climate could result in a decrease in high-frequency temperature variability (Karl et al. 1995).

Results from the index based on diurnal temperature range (Fig. 7(a)) are consistent with several previous studies (e.g. Plummer et al. 1995, Torok and Nicholls 1996) in showing decreasing trends in diurnal temperature range over recent decades. The all-Australian average showed a decline of -0.69°C/century over the 1957 to 1996 period. Decreases in diurnal temperature range have been found in enhanced greenhouse climate simulations (Watterson 1997). Some decreases in ETR (Fig. 7(b)) were found to be significant at the 95 per cent level with a decrease of -2.25°C/century determined for the all-Australian average of ETR. The all-Australian trends for both these temperature range indices were not significant at the 95 per cent level, but were significant at the 90 per cent level.

Correlations between frequency of extreme events and mean temperatures

The current lack of digitised daily data prior to 1957 prevents direct comparisons between trends in mean and extreme temperature values during early parts of the 20th century. To gain a better understanding of the relationship between mean annual temperatures and the extreme indices defined here, correlations were calculated between time series of area-averaged index values and annual mean temperatures. Indices based on maximum and minimum temperature were correlated with annual mean maximum and minimum temperature respectively.

The magnitude of correlations between weighted-averages of numbers of extreme days or nights and the relevant annual mean temperatures over 1957 to 1996 ranged between 0.61 and 0.93. Correlations between numbers of three to five day extreme events and the relevant mean temperature series were similar, with magnitudes ranging from 0.63 to 0.88. Some of these relationships were out of phase e.g. years with high annual mean maximum temperature tend to have low numbers of cold days. Assuming these strong correlations extend prior to 1957, these comparisons suggest that the cooler years during the early decades of the 20th century would have reported fewer extreme warm events and more extreme cold events than years during later decades. Correlations between temperature variability measures and their respective mean temperature series were weak, with magnitudes of correlation ranging from 0.07 to 0.16. This is consistent with the relatively high regional variations in trends in the variability measures used here.

Conclusions

Examination of the trends in extreme temperature indices shows that the frequency of warm events has generally increased over at least the 1957 to 1996 period, whilst the number of cool extremes has decreased. These results are consistent with previous studies of Australian temperature extremes (Plummer et al. 1999) and with increasing trends in Australian mean minimum and maximum temperatures during the period (Figs 8(a) and (b)). Generally, changes in indices associated with minimum temperatures have been stronger than those associated with maximum temperatures, with the most consistent trends in Australia being declines in the numbers of extremely cold minima and frost events. No trends in the Australian-averaged indices based on maximum temperature were found to be significant but many associated with minimum temperature were.

Whilst trend values have been quoted for all indices it should be noted that most of the indices show large interannual variations which can mask background trends. Also, these trends are generally only calculated over about 40 years, during a time of relatively rapid temperature rise in Australia. It is possible that natural decadal variability has influenced the trends over this time. Most studies involving instrumental climate records examine trends over the century timescale. Unfortunately this was not possible in this case. If it were possible to calculate extreme temperature trends over a longer period these trend values may not be as strong, particularly as Torok and Nicholls (1996) have shown little trend in mean maximum and minimum temperatures from 1910 to 1950.

Work is currently underway within the Bureau of Meteorology to digitise a greater number of Australian daily temperature series prior to 1957. These records will need to have data quality issues addressed before being used for investigations of extreme events but should provide valuable data to determine whether the changes identified here are typical over a longer period of time. It is also hoped that indices similar to those presented here will eventually form part of a set of extreme indices routinely monitored along with analyses of mean variables.

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