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On the distribution of heat waves over the Australian region

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This study defines a set of five indices related to different features of heat waves. The indices relate to the intensity, duration, diurnal characteristics, and frequency of heat waves. The indices are first assessed using high quality station data at ten different locations across Australia. A comparison is made between the station data results and gridded data at nearby locations from the NCEP/NCAR Reanalysis in order to examine the utility of the reanalysis data. The reanalysis data generally correlate well with the station data on a year-to-year basis, but are found to be less reliable when it comes to determining trends. The climatologies of the heat wave indices reveal different features of the synoptic climatology of the Australian region. They also reveal that heat waves are more numerous, but of shorter duration along the southern coast. Climate model simulations using the CGCM2 successfully reproduce the general features of the patterns of the reanalysis heat wave climatologies, except for those indices related to heat wave duration. Trend in heat wave indices in the model ensemble average yield increases across Australia in recent decades. By the end of the next century the features of heat waves that increase most in the model under greenhouse forcing are those relating to duration and overnight temperature.

Introduction

Anthropogenic climate change brings with it an expected increase in the frequency of heat waves (Delworth et al. 1999; McCarthy et al. 2001). Increases have already been documented in many parts of the world, including Australia (Haylock and Nicholls 2000). Heat waves can intensify droughts, increase the risk of fires and have been linked to high mortality rates (McCarthy et al. 2001). Hurricanes, tornados, floods and lightning may grab much of the media attention, but it is heat waves that are often the most deadly (Franklin 2004).

Many studies have been conducted examining the effects of extreme heat on mortality rates (Smoyer 1998; Diaz et al. 2002; Davis et al. 2003; Donaldson et al. 2003). These studies conclude that with the predicted warmer climate, more comprehensive measures, both medical and social, should be adopted to

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prevent the effects of extreme heat on the population. Large fatality events such as the 1995 Chicago heat wave (Whitman et al. 1997) and the 2003 Paris heat wave (Bouchama 2004) emphasise the need for more research on heat waves.

Heat waves are complex, multi-faceted phenomena and there is still great uncertainty as to what aspects of them make them dangerous (magnitude, duration, daytime or night-time maxima, etc.). Nine consecutive days of extreme heat in the summer of 2003 resulted in 14,800 deaths in France (Bouchama 2004). Palecki et al. (2001) compared the 1995 and 1999 heat waves in Chicago and St Louis, finding that these cities experienced many consecutive days with maximum temperature greater than 3°C above normal and minimum temperature greater than 4°C above normal. There is also speculation that elevated minimum temperatures do not allow recovery from the severe heat experienced during the day, which may be a critical factor governing impacts (Bouchama 2004). There has been considerable effort to construct and calculate simple indices for monitoring heat waves, and many different approaches have been taken. Goodess et al. (2001) identified a range of methods most suitable for assessing extremes in weather and climate in relation to the United Kingdom. A summary of studies that had used GCMs to construct scenarios of specific extremes was included in the report, incorporating work done by Huth et al. (2000) and Dai et al. (2001). This study also put together a number of proposed indicators of temperature and rainfall extremes, including measures of maximum and minimum temperatures using the 10th/90th percentiles and a heat wave duration index, defined as the maximum period greater than five consecutive days of maximum temperature more than 5°C above the long-term mean or a percentile threshold (Karl et al. 1999; Frich et al. 2002; Hulme et al. 2001).

Meehl and Tebaldi (2004) examined the future behaviour of heat waves in a greenhouse warming simulation and suggested that heat waves will become more intense, more frequent and longer lasting in the second half of the 21st century. Two definitions of heat waves were used. They first took into account work by Karl and Knight (1997). Under the presumption that no relief from warm minimum night-time temperatures may be most important for health impacts, this index used the mean of the three consecutive warmest nights per year. Their second heat wave definition used percentile thresholds for maximum temperature, and was based on heat wave definitions by Huth et al. (2000).

In the Australian context, various groups have performed studies that have included heat waves, with a variety of different definitions used. Plummer et al. (1999) used a 90th percentile threshold and examined heat wave periods covering both a single day/night and three consecutive days/nights. For these indices, they found that the frequency of extremely warm days and nights has increased since 1961. Kestin (2000) calculated indices of hot and cold winter and summer nights using the 90th and 10th percentiles as high and low thresholds. Kestin found that temperature extremes from 1957-1996 exhibited trends towards more hot extremes and fewer cold extremes. Nicholls et al. (2000) developed a large number of indices for monitoring variations in Australian climate extremes. They examined the percentage of the country warmer than the 90th percentile and cooler than the 10th percentile, as well as the areal average of very cold or warm days or nights. They found that overnight minimum temperatures in particular showed strong warming trends. Collins et al. (2000) developed a number of indices to investigate recent changes in the annual frequencies of extreme temperature events in Australia. These included the frequency of daily minimum and maximum temperatures above and below absolute thresholds as well as percentile levels. This study found that the frequency of warm temperature events has generally increased, but there was great regional variation across Australia. Manton et al. (2001) examined trends across Southeast Asia and the South Pacific from 1961–1998. Eight indices were used, including the frequency of days with maximum temperature above the 1961–1990 mean 99th percentile (hot days), and the frequency of days with minimum temperature above the 1961–1990 mean 99th percentile (warm nights). Considerable increases in both these extreme temperature indices were found.

In this paper five heat wave indices are defined and calculated at ten different stations around Australia. The locations of these stations are shown in Fig. 1. The analysis was then repeated for individual grid boxes of the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) Reanalysis data, at locations corresponding to those of the stations. This allows direct comparisons to be made between the reanalysis data and the observational station data. The reanalysis dataset runs from 1948-2004 and the station data spans approximately the same period. Periods of common overlap were used for the trend analysis. Spatial plots of the indices were then produced from the reanalysis data to show the climatology of heat waves across Australia. The analysis was repeated using the current climate simulations from the second generation Canadian Global Coupled Model (CGCM2), over the Australian region. Following this, current and projected future trends in the indices, and hence heat waves are examined in CGCM2.

This work extends past work on heat waves in Australia to include the most recent data and with a focus on the spatial distribution of a variety of different heat wave indices. Use of reanalysis data and climate model output allows us to examine spatial distributions. As shown by Frich et al. (2002) and Alexander et al. (2006), models are a valuable tool in examining climatologies and trends. However, because reanalysis data are untested for measurement of heat wave indices, a portion of the paper is devoted to comparing the reanalysis data with reliable station data. Ideally we would examine both the distribution of heat waves across the continent and their trends in reanalysis data. However, the comparison of reanalysis data with station data indicates that their utility is probably better limited to providing an indication of distributions at this point. Therefore we rely on climate model projections to give some indication of potential trends in heat wave indices. Related work by Flocas et al. (2005) evaluated the maximum and minimum temperature NCEP/NCAR reanalysis data over Greece and identified similar problems in using the data for assessing trends.

Heat wave indices

The five heat wave indices employed here are summarised in Table 1. The first index is the value of the 90th percentile of the annual maximum temperature distribution at a station, and is denoted '90p value'. The use of 90th percentiles (as opposed to other percentile values) is somewhat arbitrary, but is consistent with previous studies and provides a reasonable sample size and measure of extremes. The second index is the number of runs (heat waves) per year, where a heat wave is defined as a discrete run of consecutive days over the 90p value. The third and fourth indices relate to heat wave duration and are defined as the average run length of heat waves per year and the maximum run length per year respectively. The final index takes into account the fact that often high minimum temperatures are thought to be a factor in heat related mortalities and is based on previously mentioned studies by Meehl and Tebaldi (2004) and Karl and Knight (1997). This index is called the minimum temperature index and is defined as the mean of the warmest three consecutive nights per year.

As the area of focus in this study is to try and assess patterns and trends in heat waves over Australia, it was decided not to use the calendar year and hence divide the summer in half, but instead to split the year in the cold season. Hence, each year runs from 1 July to 30 June of the following year and is named from the year in which 1 July occurs.

Data

Station data

This study uses observational daily maximum and minimum temperature data from the high quality daily station dataset from the Bureau of Meteorology (Torok and Nicholls 1996; Nicholls et al. 2000; Trewin 2001). The dataset has been extended from 1996 to 2003 (Trewin, personal communication). The updated data have been subject to basic quality control testing. Ten stations were selected from around Australia to represent the country's diverse climate. These stations are as follows: Alice Springs, Broome, Cairns, Geraldton, Launceston, Marree, Mildura, Moree, Thargomindah and Tibooburra. The ten stations have had their daily data adjusted for inhomogeneities. Their locations are shown in Fig. 1 and exact latitude and longitude are given in Table 2. Heat wave indices were calculated for each station.

Table 1. Heat wave indices summary. The T1 value is defined as the 90th percentile value of maximum temperature based on the entire data record.

Index no.	*Index name*	*Definition*
1.	90p value	The value of the 90th percentile maximum temperature for each year
2.	Number of runs	The number of runs of consecutive days (1 or more) over the T1 value per year
3.	Average run length	The average length of a run of consecutive days over the T1 value per year
4.	Maximum run length	The longest run of consecutive days over the T1 value per year
5.	Minimum temperature index	The mean of the warmest three consecutive minimum temperatures per year

Fig. 1 **Station locations.**

Table 2. **Station locations.**

	Longitude E	*Latitude S*
Alice Springs	133.88	23.80
Broome	122.23	17.93
Cairns	145.27	16.88
Geraldton	114.68	28.78
Launceston	147.20	41.57
Marree	138.05	29.65
Mildura	142.08	34.23
Moree	149.83	29.48
Thargomindah	143.82	24.98
Tibooburra	142.02	29.43

NCEP data

The second dataset used in this study was obtained from the online archived global reanalysis of NCEP/NCAR (Kalnay et al. 1996). This dataset was chosen for this study because it provides a more consistent approach to assessing the spatial coherence of heat waves across the continent and for comparing these with similar fields from CGCM2. An analysis of observations from the full high quality network identified by Trewin (2001) would also be worthwhile. Although observational data directly affect the values, the model also has a strong influence on the analysis value. The maximum and minimum temperature are derived using every time step (30 minutes) in the model. This contrasts with the observational data, which are based on the maximum and minimum temperature from all possible times. The model estimate based on 30-minute time steps will, all else being equal, produce a slight underestimate of the maximum and overestimate of the minimum because of its limited temporal resolution. The data were provided on a regular grid of dimensions 2.5° latitude and 2.5° longitude. The area chosen for this study is the Australian region, spanning from 8.57°–46.66°S and 108.75°–161.25°E. The heat wave indices are calculated for the reanalysis data at individual grid boxes. The use of the reanalysis data as well as the station data allows comparisons between the two to be made in order to validate the reanalysis data.

CGCM2 data

The reanalysis data were also compared with data from the second version of the CGCM2 (Flato et al. 2000). Some assessment of the model has been completed by Flato and Boer (2001), with comparison made to its predecessor CGCM1. They found that the model successfully reproduces the broad features of mean climate and that variability is generally well simulated over land areas. The data used for this comparison are from an ensemble of three 111-year simulations using the IPCC Special Report on Emission Scenarios (SRES) 'A2' greenhouse gas (GHG) and aerosol forcing scenario (Nakicenovic et al. 2000). The A2 scenarios have relatively high GHG emissions. The data are provided on a Gaussian grid, approximately 3.75° latitude by 3.75° longitude and are available online (Canadian Climate Center 2004).

Station data trends

The five heat wave indices were calculated for the ten different stations. We calculate trends at each station using a linear fit to the time series. Results show wide variability amongst the stations (Table 3). Broome and Cairns show mostly decreasing trends in the indices, whilst all the other stations showed mostly increasing trends. The trends in the indices for Launceston are shown in Fig. 2. For Launceston, all the indices except for the number of runs index show increasing trends. This particular index shows no real trend.

The results highlight first the fact that not all heat wave indices display the same trend at the same location, though they are generally similar. Thus it is important not to use only a single index in assessing heat wave trends. The diverse nature of the station trends across the country makes it difficult to conclude whether heat waves are worsening or not. In particular, one would like to know whether the seemingly diverse trends exhibited here display spatial coherence across the continent. The gridded reanalysis data potentially provide a means to see if this is so.

Table 3. Trends in each of the five heat wave indices at each station location. The trends over 50 years are shown for station values (Stn), for the nearest reanalysis grid box (NCEP) and the nearest CGCM2 grid box. Trends in bold type are those where the NCEP and CGCM2 trends show opposing signs to the station trends. Units are as follows: 90p value (°C/50 years), number of runs (no. runs/50 years), average run length (days/50 years), maximum run length (days/50 years), and minimum temperature index (°C/50 years).

	90p value			*No. runs*			*Avg. run*			*Max. run*			*Min. index*		
Station	*Stn*	*NCEP*	*CGCM2*	*Stn*	*NCEP*	*CGCM2*	*Stn*	*NCEP*	*CGCM2*	*Stn*	*NCEP*	*CGCM2*	*Stn*	*NCEP*	*CGCM2*
Alice	0.6	**-0.2**	0.4	0.8	0.7	**-1.6**	0.9	**-0.4**	1.2	0.6	**-3.0**	-0.1	-1.2	**1.3**	**1.4**
Broome	-0.5	-0.4	-0.4	-0.5	-0.1	-1.4	-0.5	-0.8	**0.9**	-1.6	-0.1	**3.3**	-0.4	-0.2	**0.7**
Cairns	-0.1	-0.1	**0.5**	-1.3	**1.2**	**2.3**	-0.8	-0.6	-1.4	-1.9	-1.7	**6.2**	0.7	**-0.1**	0.5
Geraldton	0.7	0.4	1.1	1.3	4.7	1.5	0.1	**-1.3**	0.4	0.7	**-1.5**	2.8	0.1	0.3	1.0
Launceston	0.9	1.0	0.3	0.7	1.4	1.8	0.9	1.5	0.9	4.4	3.9	8.2	1.7	1.0	2.4
Marree	0.3	**-0.5**	0.8	-2.1	-0.4	-0.9	1.7	0.1	1.0	3.6	**-0.5**	1.8	-0.9	-0.4	**1.9**
dMoree	0.5	**-0.1**	**-2.5**	3.7	2.0	**-0.8**	-0.8	-0.8	-3.7	-1.6	**1.1**	-6.4	1.3	**-0.6**	0.8
Thargomindah	1.0	**-0.2**	**-0.1**	0.5	0.4	**-0.3**	1.2	**-0.5**	0.1	4.2	**-3.1**	0.6	0.2	0.1	1.1
Tibooburra	1.6	0.0	0.4	4.5	0.5	**-0.8**	0.2	0.1	1.2	6.5	2.6	5.0	2.0	**-0.1**	0.9

Fig. 2 The different heat wave indices for Launceston, the solid line is the station data and the dashed line represents data from the nearest NCEP/NCAR grid box: (a) 90p value, (b) number of runs, (c) average run length, (d) maximum run length, and (e) minimum temperature index.

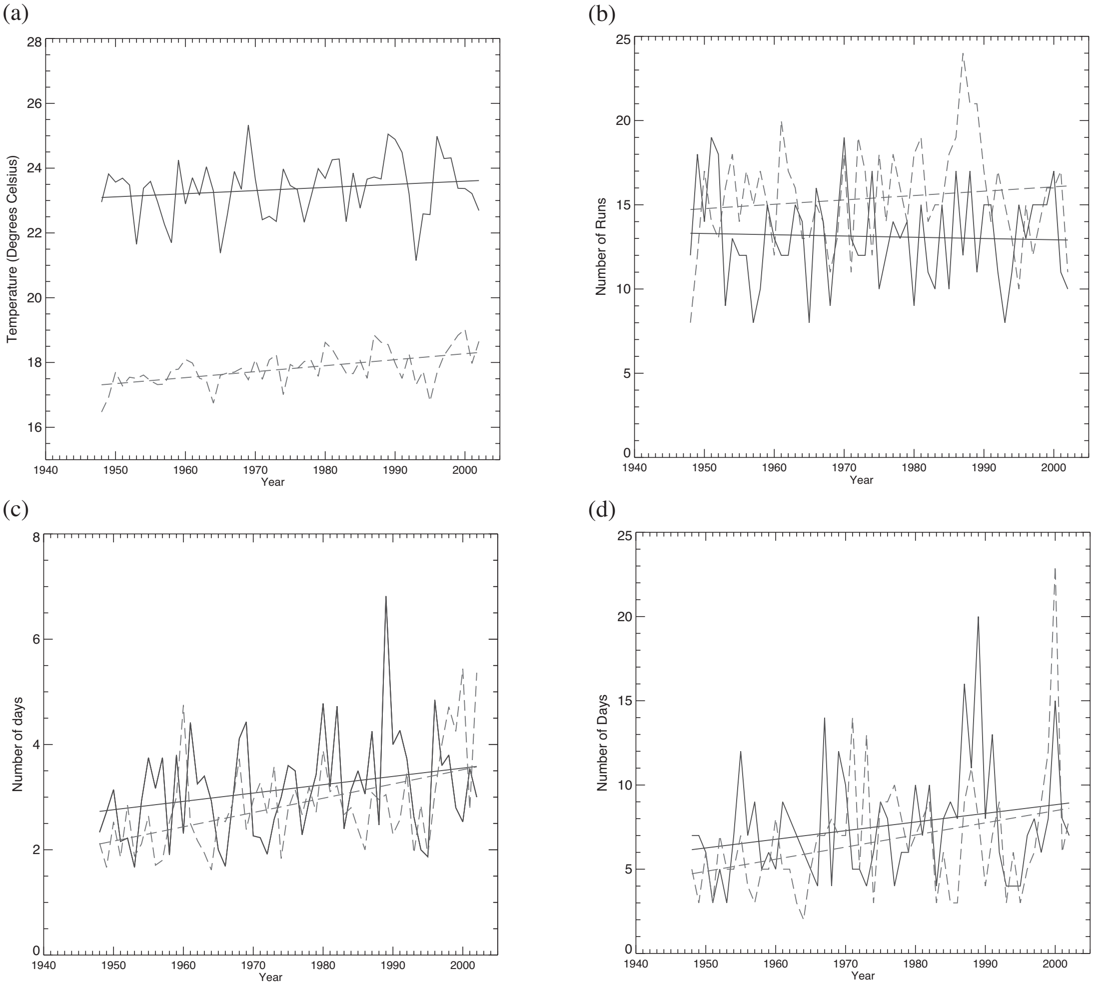
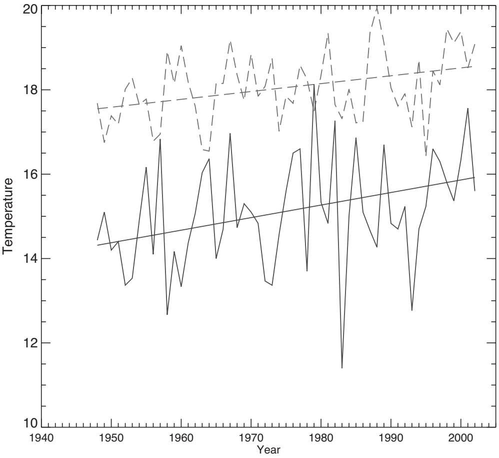


Fig. 2 **Continued.**



Comparison of station data with grid box data

Before using the reanalysis data for spatial and trend analyses, it is important to test it against the station data. This was done by calculating the heat wave indices at individual grid boxes corresponding to the station locations and comparing the results to those obtained from the stations. This method is only approximate since we are comparing data at different spatial scales (point values versus grid averages). The maximum temperature distributions of the reanalysis grid boxes over Alice Springs and Launceston are shown in Figs 3 and 4. Alice Springs represents a typical case, with the reanalysis distribution capturing well the shape characteristics of the station data distribution. Launceston represents a worst case among the stations, with the reanalysis distribution being much narrower than the observed distribution, but otherwise well placed. Some differences can be explained from the fact that one is a point measurement and the other is a grid average. It is also worth noting that the grid box encompassing Launceston also samples ocean temperatures and this may account for some of the differences seen. The grid average tends to narrow the distribution, and values from the NCEP/NCAR data distribution would not be expected to attain the same high values as the station data.

By contrast with the distributions, the reanalysis grid box heat wave index trends are in mixed agreement with the station trends. The trend results for the grid box corresponding to Launceston are shown in Fig. 2. The sign of the trends in the heat wave indices for this particular grid box corresponds well to those in the Launceston station data. All the indices for the reanalysis data show increasing trends for Launceston. The trends for station data, the reanalysis data and the CGCM2 data for all stations are sum-

Fig. 3 **Maximum temperature distribution for Alice Springs, the solid line represents the station data, and the dashed line represents the nearest NCEP/NCAR reanalysis grid box.**

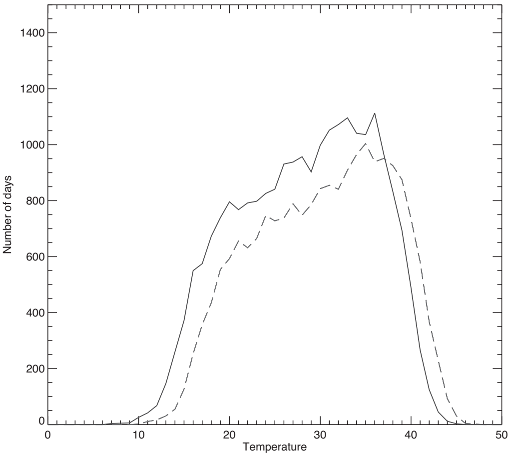


Fig. 4 **Maximum temperature distribution for Launceston, the solid line represents the station data, and the dashed line represents the nearest NCEP/NCAR reanalysis grid box.**

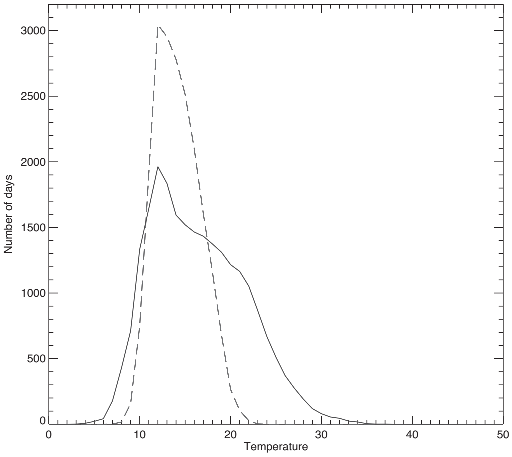


Table 4. **Correlation coefficient between the heat wave index time series of annual values at each station calculated from station data and reanalysis data. Correlations are shaded according to the following scale: 0–0.3 no shade; 0.3–0.5 light shade; 0.5–0.7 medium shade; 0.7–1 dark shade.**

	90p value	*No. of runs*	*Avg run*	*Max run*	*Min index*
Alice Springs	0.86	0.71	0.60	0.63	0.14
Broome	0.56	0.24	0.10	0.16	0.34
Cairns	0.53	0.21	0.05	0.01	0.01
Geraldton	0.86	0.47	0.52	0.49	0.56
Launceston	0.75	0.36	0.72	0.42	0.59
Marree	0.87	0.68	0.73	0.72	0.69
Mildura	0.80	0.51	0.53	0.56	0.55
Moree	0.82	0.68	0.56	0.63	0.58
Thargomindah	0.51	0.04	0.21	0.38	0.25
Tibooburra	0.63	0.55	0.46	0.70	0.35

marised in Table 3. There is mixed agreement in the trends. The table illustrates the differences in trend characterisation between the three datasets, with differences in both magnitude and sign in some cases.

The reanalysis trends at Broome agree well with the station data. The CGCM2 trends at Broome show less agreement. For that location the CGCM2 trends in the minimum temperature and average and maximum run length indices all show opposite signs to those of the station data. At Tibooburra, the signs of both the reanalysis and CGCM2 trends agree well with the station data, but not the magnitudes of the trends overall. For the grid boxes representing Alice Springs and Thargomindah, the trends in the indices for both the reanalysis and CGCM2 are mixed and do not match well with the station trends. For Alice Springs, the reanalysis trends in 90p value, average and maximum run lengths show a decrease, while the number of runs and the minimum temperature indices show increasing trends. The CGCM2 trends mostly show increases, apart from the maximum run length and number of runs, which show a decrease. This contrasts with the trends found in the station data. The station data trends at Alice Springs and Thargomindah both show increasing trends in everything except the minimum temperature index, which shows a decreasing trend in Alice Springs and no real trend in Thargomindah. Amongst the indices, the maximum run length index seems to be the most unreliable with many of the stations showing different trends to the reanalysis grid boxes as well as the CGCM2 grid boxes. In contrast the number of runs and average run indices show the most agreement in trends between the reanalysis and the station data. The average run index also shows good agreement between the station data and CGCM2. However, the trends in the number of runs index did not match well with the CGCM2 trends.

Table 4 shows the correlation coefficient calculated between the observational data and the reanalysis data for each index. The correlation coefficient is fairly high in most cases – for most stations and most indices. This implies that the reanalysis data do a reasonable job of capturing the interannual variability in the station data.

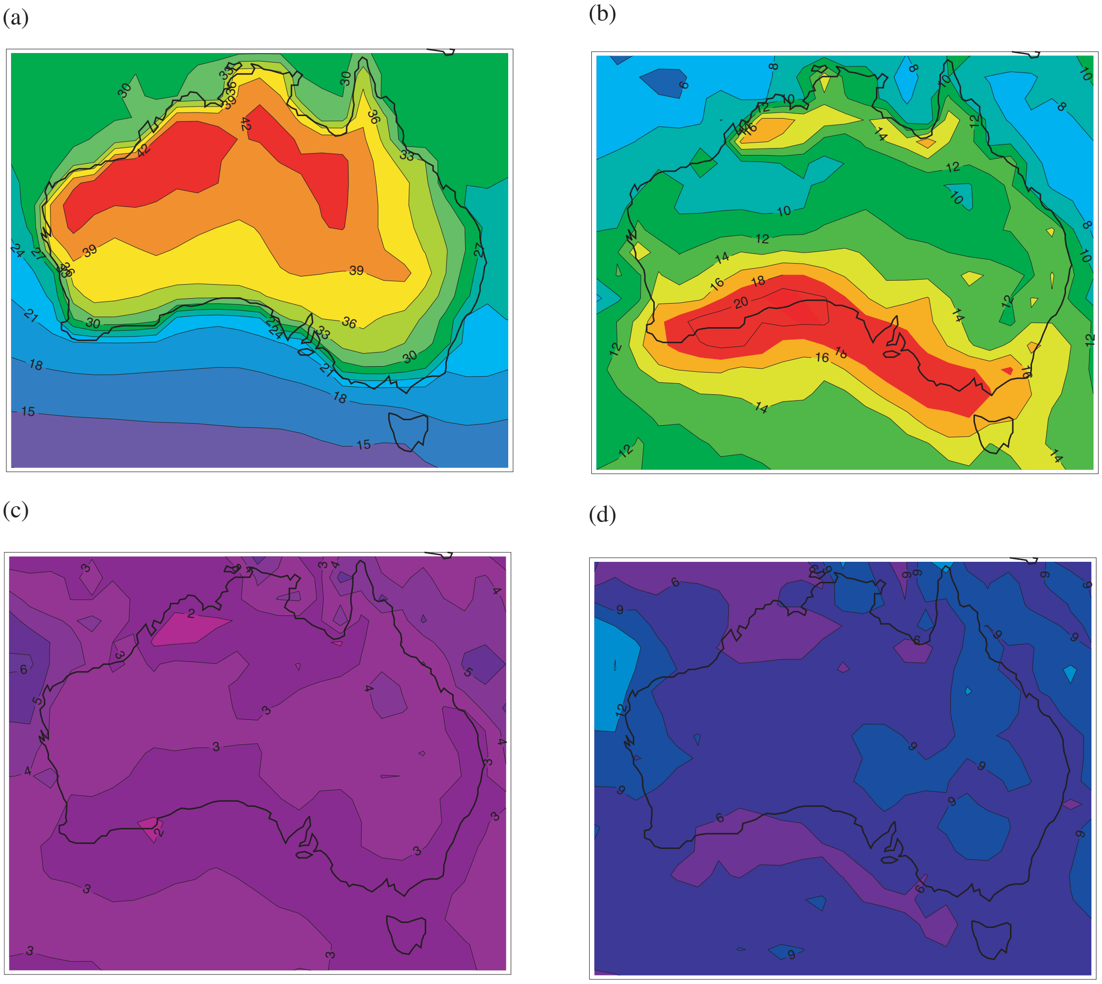
In summary, the reanalysis data capture the distribution of maximum temperature reasonably well for most of the stations and perhaps much of the interannual variability. However, they are not particularly accurate in matching the magnitude and direction of trends in heat wave indices at the stations tested. Thus it seems that more systematic testing is needed before the reanalysis data may be relied upon for trend analysis of heat wave events. In the sections that follow we use the reanalysis data to provide an indication of the broad distribution of heat wave indices across the continent, but not to examine trends in the indices.

Climatology of heat waves

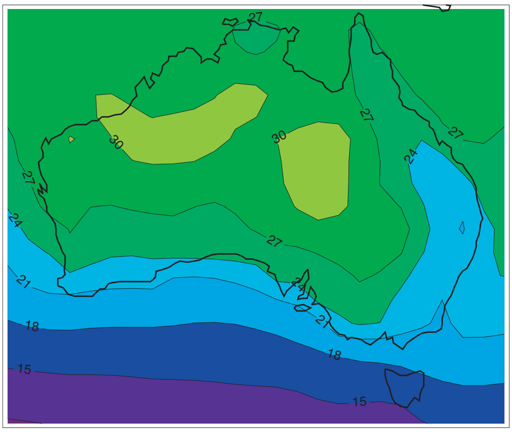
Reanalysis climatologies

The heat wave indices were calculated over the whole of Australia in the reanalysis data, and climatologies over thirty years from 1960–1989 produced. The climatologies are shown in Fig. 5. This time frame was chosen so as to avoid the accelerated warming over the last fifteen years, and also, as the reanalysis data are anchored to observational data, to choose a time frame where observational data were plentiful (Jones

Fig. 5 **Climatologies of the indices using the NCEP/NCAR reanalysis data from 1960–1989: (a) 90p value (°C), (b) number of runs, (c) average run length (days), (d) maximum run length (days), and (e) minimum temperature index (°C).**



(e)



and Trewin 2002). Note that the reanalysis data over the oceans must be interpreted with caution, due to the lack of observations there. Some of the ocean features may not be trustworthy and the focus in this paper is the results over the continent.

The climatologies of the heat wave indices reveal different features about the physical nature of heat waves. The 90p value index provides an indication of the magnitude of maximum temperatures and heat waves. The climatology for the 90p value reflects the hotter temperatures in the interior of the continent (Fig. 5(a)). The number of runs index provides a measure of the number of discrete heat wave events each season. The climatology of the number of runs index shows a maximum along the south coast of

Australia, which reflects the high frequency frontal nature of climate in this region (Fig. 5(b)). In a synoptic regime with frequent pre-frontal airmass episodes there are more heat wave events. The relatively static character of central Australian weather can also be seen here, with fewer runs in that region.

The climatologies of the average run length and the maximum run length indicate the physical duration of heat waves across Australia (Figs 5(c) and 5(d)). The maximum run length climatology shows the duration of the longest heat wave per year. Like the average run length, the longest heat waves are in central Australia. The longest heat waves span approximately eight to ten days, which is more than twice the average heat wave length of three to four days. Heat waves are harder to sustain in southern Australia due to the frequency of synoptic-scale systems passing through the region. These indices both support the idea of shorter heat waves in the frontal belt, and longer heat waves in central Australia.

The 30-year climatological values for the five indices of the observational data generally compare better to the reanalysis values than to those of CGCM2 (Table 5). The number of runs, average and maximum run length indices show good agreement with the reanalysis data and much less agreement with the values from CGCM2. The 90p value and minimum temperature indices show similar agreement for both the reanalysis and CGCM2 values.

CGCM2 climatologies

The data from CGCM2 starts in 1961 and the climatologies are calculated over 30 years from 1961–1990 (Fig. 6). Historically, models were tested by comparison of means and standard deviations of different variables with observational data. This study employs indices that are based on the tail of the temperature distribution, which is a more severe test of the model. The CGCM2 90p value climatology is in good agreement with the reanalysis climatology, reflecting the hotter temperatures in the interior of the continent (Fig. 6(a)). The CGCM2 number of runs climatology shows a maximum to the south, as in the reanalysis climatology, though the magnitude is underestimated and the pattern is less coherent (Fig. 6(b)).

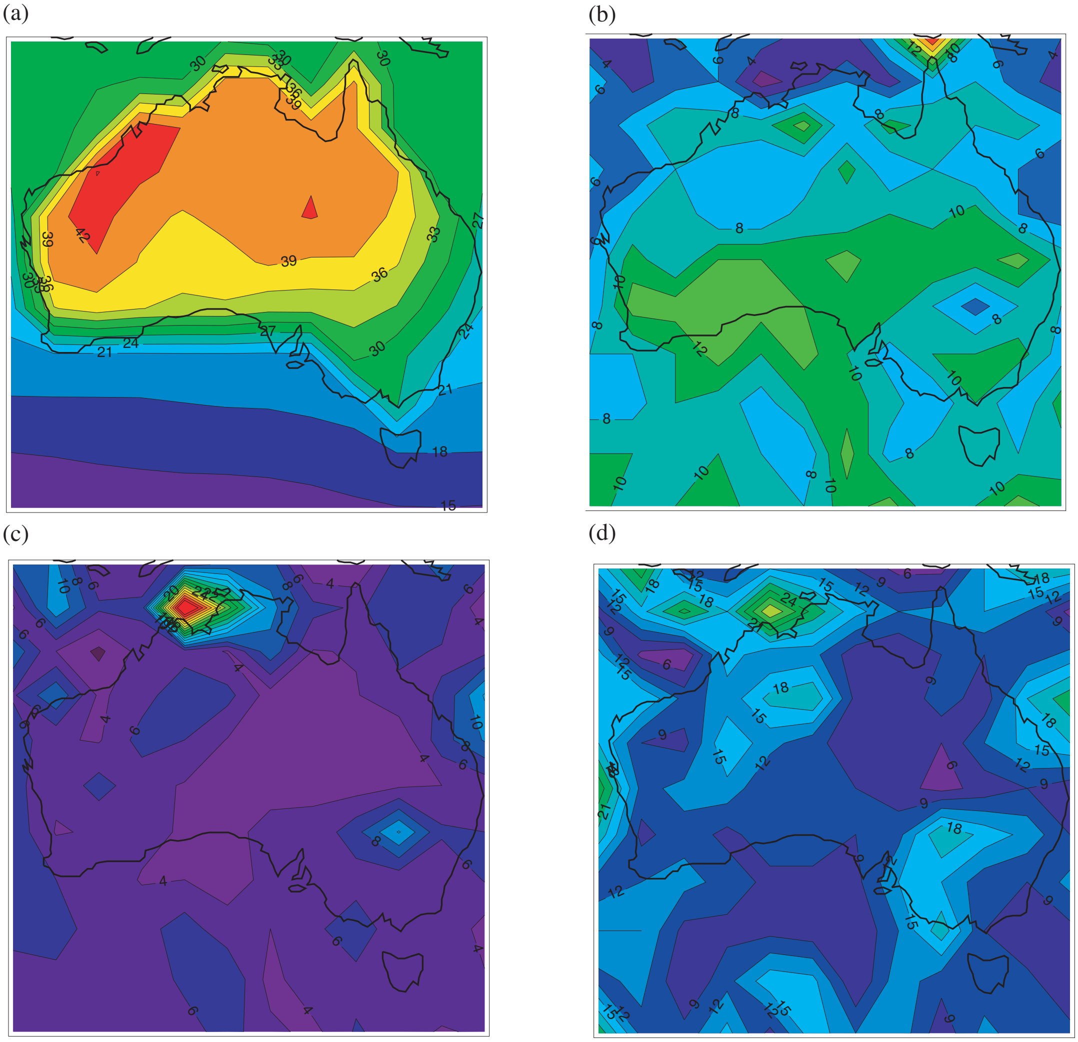
The CGCM2 average and maximum run length climatologies show a slightly confused spatial pattern, with some distinct maxima not reflected in the reanalysis data (Figs 6(c) and 6(d)). However, the general sense of the pattern is not too dissimilar if smoothed, reflecting broad maxima in central eastern and central western Australia. The minimum temperature index climatology shows that the model accurately simulates the cool tongue of temperatures running up the east coast (Fig. 6(e)). This climatology again reflects the hotter temperatures in the north of the continent and corresponds well to the reanalysis climatology of this index.

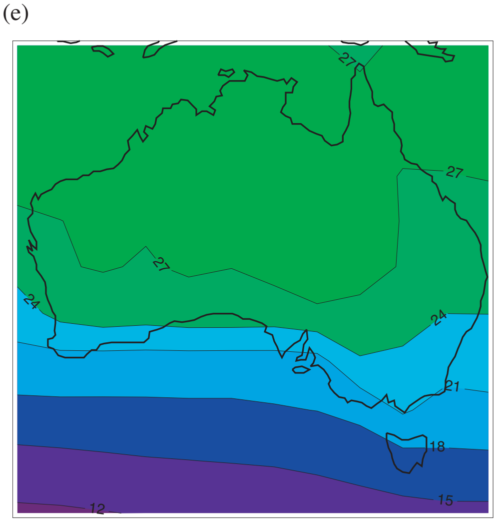
The CGCM2 climatologies of the indices generally correspond well with the reanalysis climatologies, except for those indices relating to the duration of heat waves. This is not unexpected, as both CGCM2 and the reanalyses are known to be an imperfect simulation of the surface temperature field. CGCM2 does seem to pick out patterns of the indices related to the different synoptic regimes across the continent: mixed conditions in the north, more long-lived air masses in the interior (longer heat waves), and frontal conditioning of heat indices in the south (more heat waves per year, but of a shorter duration per heat wave). The magnitudes of the CGCM2 indices are generally similar to those of the reanalysis data. The

Table 5. Thirty-year climatological values for each of the five heat wave indices at each station location. The values are shown for station values (Stn), for the nearest reanalysis grid box (NCEP) and the nearest CGCM2 grid box. Units are as follows: 90p value (°C), number of runs (no. runs), average run length (days), maximum run length (days), and minimum temperature index (°C).

	90p value			*No. runs*			*Avg. run*			*Max. run.*			*Min. index*		
Station	*Stn*	*NCEP*	*CGCM2*	*Stn*	*NCEP*	*CGCM2*	*Stn*	*NCEP*	*CGCM2*	*Stn*	*NCEP*	*CGCM2*	*Stn*	*NCEP*	*CGCM2*
Alice	37.9	39.9	38.2	11.1	11.7	8.4	3.2	2.9	4.6	8.9	8.1	10.3	27.7	28.5	27.5
Broome	35.9	32.3	41.7	15.1	8.9	8.5	2.4	3.1	4.1	5.9	5.9	9.7	28.8	29.7	28.6
Cairns	32.3	33.8	26.9	9.9	13.0	3.3	3.2	3.3	7.2	7.9	9.2	10.4	25.8	24.7	27.1
Geraldton	33.7	26.5	39.0	16.7	11.6	10.5	3.0	4.5	3.4	7.8	11.5	8.9	24.5	25.2	25.9
Launceston	23.5	17.9	15.9	13.1	16.2	8.0	3.3	2.8	4.3	7.6	6.9	10.0	15.2	18.1	16.3
Marree	38.8	39.1	37.2	12.6	13.6	10.4	3.4	3.3	3.7	9.3	9.9	9.0	27.9	29.4	27.6
Mildura	33.4	36.4	32.0	17.0	15.7	11.0	2.8	3.0	4.3	8.3	9.4	10.3	23.0	27.4	22.9
Moree	34.0	33.0	30.9	11.2	11.6	7.7	3.3	3.7	6.2	8.3	9.3	14.7	24.3	21.8	24.1
Thargomindah	38.3	40.8	37.4	11.3	11.7	8.3	3.2	3.2	4.7	8.7	8.8	11.3	28.9	29.1	27.4
Tibooburra	37.1	42.0	36.8	12.4	16.6	9.6	3.4	1.8	3.9	9.1	4.1	9.6	27.8	28.4	27.2

Fig. 6 Climatologies of the indices using CGCM2 from 1961–1990: (a) 90p value (°C), (b) number of runs, (c) average run length (days), (d) maximum run length (days), and (e) minimum temperature index (°C).





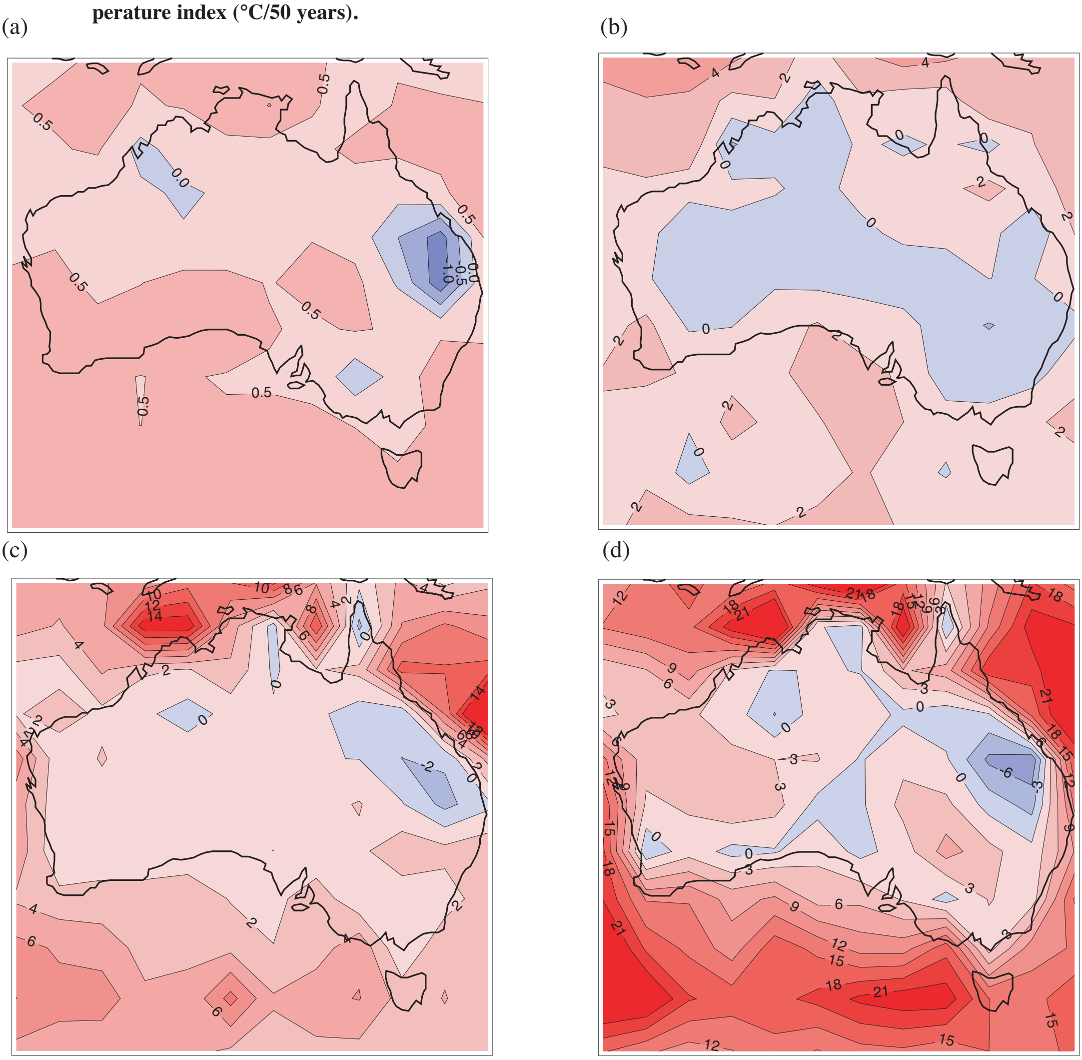
most notable exceptions to this are for the duration indices in several areas. Overall the model does a reasonable job given the need to simulate spatial patterns in the extremes of the temperature distribution.

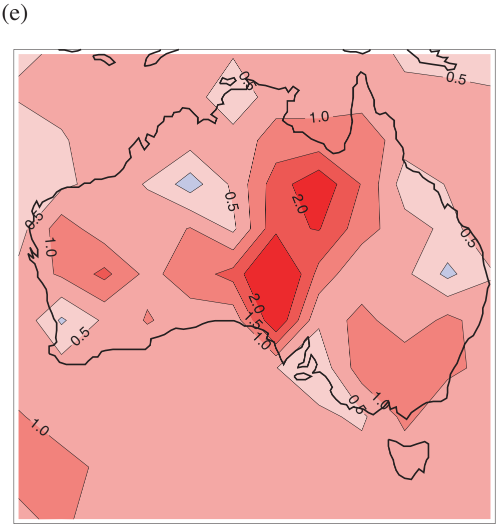
Model trends

Current climate

Before analysing projections in the climate model we first examined the model simulations of heat wave changes over recent decades. Linear trends were fitted to the CGCM2 data for the period covering 1961–2003 (Fig. 7). We expect that the model patterns will differ somewhat from what we would

Fig. 7 **Trends of the indices using CGCM2 from 1961–2003: (a) 90p value (°C/50 years), (b) number of runs (runs/50 years), (c) average run length (days/50 years), (d) maximum run length (days/50 years), and (e) minimum temperature index (°C/50 years).**

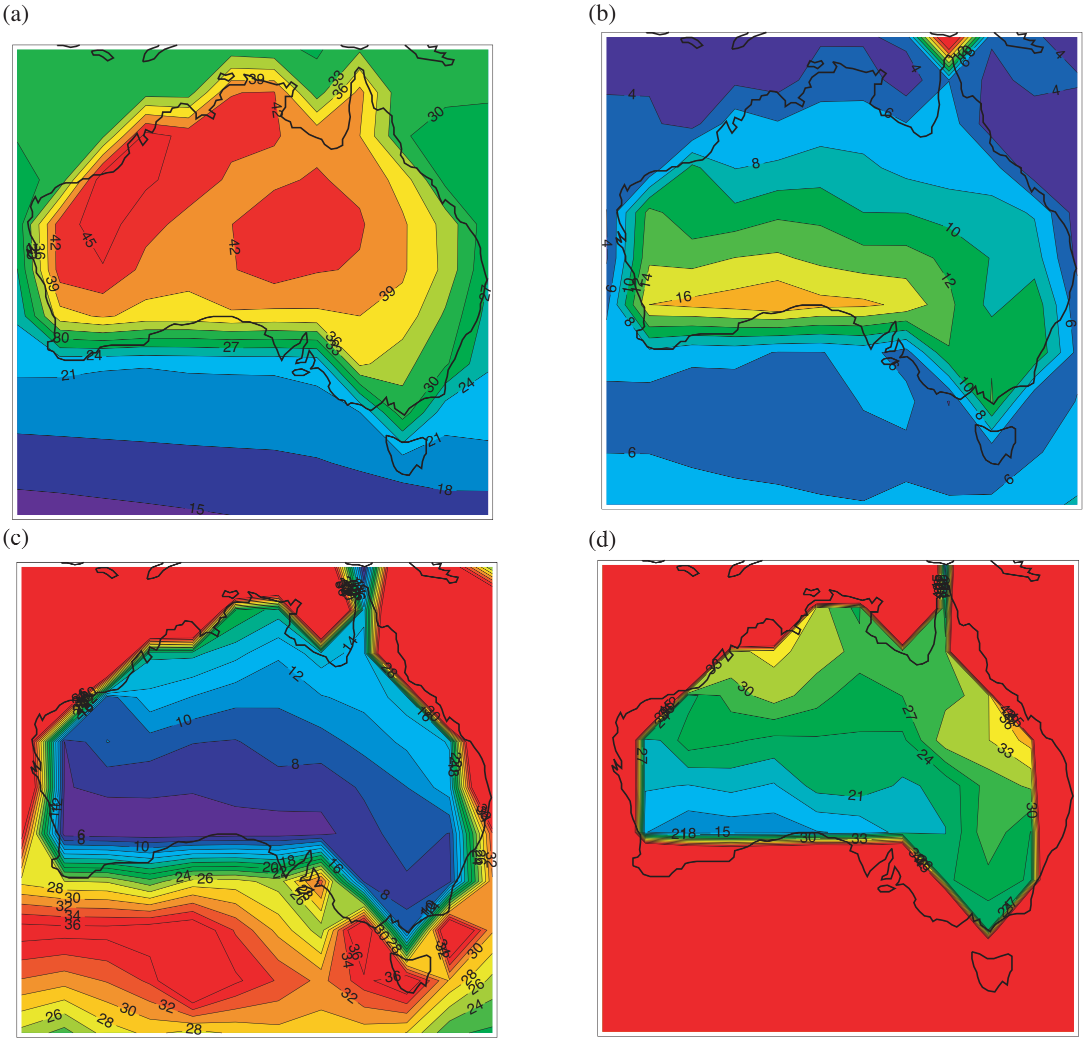


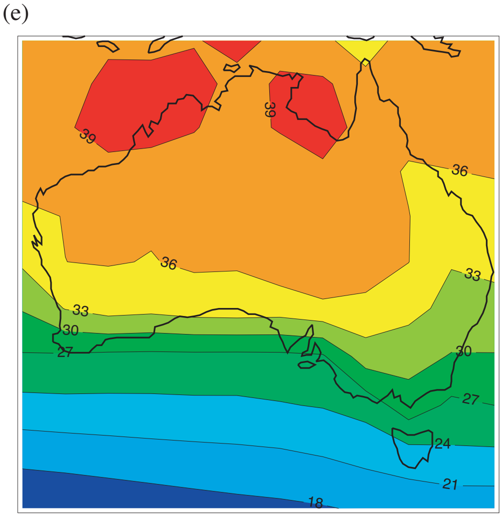


expect from observational data. The reason is that the model results are for an average of a three-member ensemble. The ensemble average pattern will smooth out some of the natural variability in the model, revealing more of any large-scale forcing response. Observed patterns correspond to a single realisation of the real world and will have contributions from both natural variability and forcing.

Most of the model indices (with the exception of the number of runs index) show a fairly uniform increase across the country. The broadscale pattern of increase in the model ensemble suggests that the forced response is toward an increase in heat waves. This contrasts with the observed trends in the station data/reanalysis data, which show stations/areas of increasing and decreasing

Fig. 8 Climatologies of the indices using CGCM2 from 2061–2100: (a) 90p value (°C), (b) number of runs, (c) average run length (days), (d) maximum run length (days), and (e) minimum temperature index (°C).





trend, although the more reliable station data do show a tendency for increases. If the forced response is toward an increase in heat waves, then natural variability in the observed trends may be masking a more general continental increase in heat waves. Alternatively, the model could simply be underestimating the spatial variability of the response in the indices. However, this seems unlikely given that the patterns in the model index climatologies (Fig. 6) exhibit similar spatial variability to the reanalysis data (Fig. 5).

Future climate

As discussed, changes in the frequency, intensity or duration of high temperature events may have a great effect on human health. It is therefore of interest to examine future climate scenarios from a GCM and associated changes in heat wave indices.

Spatial climatological maps of the indices were produced using the CGCM2 data for the period 2061–2100 for the SRES A2 scenario (Fig. 8). These maps show the climatological average values of the heat wave indices over this period. Note that there is a discontinuity at the coastline on some of the heat index plots. That is because temperature distributions over the ocean are much narrower than over land. Increases in mean temperature on the narrower ocean distributions produce much larger changes in values of heat indices. The patterns of the maps are more organised than for the 1961–1990 climatologies (Fig. 6), with less spatial variability. All the indices show increases from their values for the 1961–1990 climatology, with particularly marked increases for the minimum temperature index. The mean of the three consecutive warmest nights increases by amounts approaching 10°C over much of the continent. If warm nights tend to be one of the factors relevant to the impacts of heat waves, this could have substantial implications. The increase in minimum temperature index is a bit less extreme in the southwest and southeast corners of the continent where the maritime influence is stronger. The 90p index shows the smallest relative increase over the century, increasing by a few degrees over most of the continent. Together, these two indices reflect a more rapid increase in minimum than maximum temperature extremes.

The indices that reflect the number and duration of heat waves also show somewhat asymmetric increases. The number of heat waves each year increases only marginally over much of the continent, while the average duration of heat waves (and the maximum heat wave length each year) increases substantially over most of the continent in the model. Thus the model describes a world where the most salient features of heat wave increases are longer lasting and more extreme heat waves and large increases in overnight minimum temperature extremes.

Conclusions

Heat waves can be represented by a variety of different indices that measure different properties such as intensity, duration, frequency, and diurnal behaviour. We have employed a variety of such indices in this study, drawn from the literature. While previous studies have examined trends in heat wave indices at individual sites or at a continental average for Australia, this study uses reanalysis data to provide a spatial representation of heat wave climatologies. The reanalysis data does a reasonable job in replicating the distribution of maximum temperatures and interannual variability of heat wave indices at individual stations across the continent. Comparison of reanalysis trends with station data trends suggests that the reanalysis dataset is not a robust indicator of trends in heat wave indices.

The climatology of heat wave patterns from the reanalysis data indicates that different indices reveal different patterns. These patterns in turn reflect different features of the synoptic climatology of Australia. The 90th percentile index climatology pattern reflects interior and northern warmth. The number of runs index has a maximum along the southern coast, indicating that there are more discrete heat wave events there. This maximum reflects the higher frequency characteristics of the more predominantly frontal regime along the south coast. The duration of heat wave events is fairly uniform across the continent, though slightly longer in the interior. Heat wave events are thus shorter lived, but greater in number along the southern coast. The longest heat wave events are more than twice the duration of the average event. This result holds consistently across the continent. The CGCM2 climatologies are in general agreement with the reanalysis climatologies in terms of magnitude and broadscale patterns of each of the indices. The model seems to capture many features of the pattern related to the synoptic conditioning of the indices, thus building confidence in use of the model for assessing trends.

The trends in the CGCM2 model ensemble average for recent decades show a uniform increase in heat wave intensity, number, and duration across the continent. The model ensemble smooths out contributions from natural variability and reflects more directly the response to the model's prescribed greenhouse forcing. The spatial coherence of the model trend patterns would be in part due to the use of an ensemble average. Interestingly, the reanalysis trend patterns over the same period (not shown here) also display large scale spatial coherence, albeit with regions of increase and decrease, perhaps reflecting a greater influence from natural variability.

Carrying through the SRES simulation in CGCM2 to 2100, each of the heat wave indices display increases, particularly those relating to duration and minimum temperatures. Thus, the model projects more intense, longer heat waves under continued greenhouse forcing. This is consistent with previous studies. The marked projected increase in heat waves in Australia underscores the need for more research linking them with human health and ecosystem impacts.

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