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Australian summer maximum temperature lags

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The difference in timing between when the annual temperature cycle reaches its peak and the time of maximum solar radiation is referred to as the lag in summer maximum temperatures. Values of the lag at a number of Australian extratropical locations are calculated using a harmonic method applied to the daily temperature record. The results are more precise than from previous studies based on the use of monthly data, and, in addition, reveal the existence of significant trends since about 1900 over southeastern Australia. These trends indicate that now, the warmest time of the year occurs about one week later than at the start of the twentieth century. Since about 1950, there also appears to have been significant increases in the lag over southwestern Western Australia.

Introduction

Outside of the tropics in the southern hemisphere, solar radiation at the top of the atmosphere peaks in late December. In the following weeks, although direct solar radiation decreases, surface temperatures continue to rise due to the excess of incoming radiation over other energy losses. A balance between the energy fluxes usually occurs a few weeks later when temperatures typically reach their maximum. Thereafter, temperatures decline as the flux balance reverses and the surface loses energy. Therefore the warmest and coldest times of the year usually occur some time after the corresponding maxima or minima in solar radiation, i.e. after the summer and winter solstices.

For example, Melbourne's warmest surface air temperatures are generally observed in late January. However, maximum daily solar radiation at the top of the atmosphere at this latitude occurs around December 23. This implies a lag in air temperatures behind solar radiation of around a month. This difference in timing is referred to as the lag of the seasons and, although varying in magnitude across the globe, is, on average, about thirty days (El-Hussainy and Essa 1997).

Previous studies have applied Fourier analysis to monthly mean temperatures to calculate lag values at various locations (Prescott 1942; Prescott and Collins 1951; Trenberth 1983; and El-Hussainy and Essa 1997).

In his pioneering study, Prescott (1942) considered the first three harmonics in a Fourier series decomposition of the annual cycle:

$$T(x) = a_0 + a_1\cos x + a_2\cos 2x + a_3\cos 3x + b_1\sin x + b_2\sin 2x + b_3\sin 3x$$

where $T(x)$ is the temperature for any month, a_0 is the

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mean annual temperature, a_i and b_i are amplitudes, and x is time expressed in degrees, varying from 0-360° to correspond to the twelve months of the year. However, he found it sufficient to use just the first term (i=1) of the Fourier series to describe the variation of monthly temperatures. Prescott used mean monthly temperatures at 389 Australian stations, but without reference to the year or years of data analysed. Prescott's results showed a clear increase in lag with latitude and an increase in lag toward coastal regions. The longest lags, of over 40 days, were found at sites along the Western Australian coast, Kangaroo Island, islands in Bass Strait and the northern Tasmanian coast. Relatively short lags were calculated around the Great Dividing Range inland of the southeastern Australian coast.

El-Hussainy and Essa (1997), in a similar treatment of temperatures in Egypt, attributed smaller than expected lags to the effect of surrounding mountains. Prescott and Collins (1951) and Trenberth (1983) investigated temperature lags over the United States using similar Fourier methods based on monthly data. Both studies showed that values increased towards the coast and, in the proximity of the Great Lakes, lags increased by approximately five days compared to other continental regions. These results indicated the important influence that large water bodies have on local temperatures. Prescott and Collins (1951) also explored temperature lags from other regions of the globe and found that along western continental margins, lags were between 45 to 65 days; along eastern continental margins, between 35 and 50 days; and within continental basins and over highlands, around 10 to 25 days. However, there has been little discussion about the reasons for these variations.

Given that the lag is often of the order of a month, lag values based on monthly mean data are somewhat imprecise. Following the identification of high quality station records, Torok and Coutts (1992) analysed daily temperature records using a ten-day running average and identified peaks and troughs in maximum and minimum temperatures at a number of sites in southeastern Australia. They noted differences in lag times for peaks in maximum and minimum temperatures and also departures of the temperature curves from a simple sinusoidal curve.

The main aim of this paper is to analyse high quality daily observations at a large sample of Australian locations and calculate summer temperature lags using harmonic fits to the data. Another aim is to investigate changes in lag values over time. Further details on methodology and additional results, including the peaks and troughs of maximum and minimum temperatures, can be found in Alexander (2003).

Data

Daily maximum and daily minimum temperature data were obtained from the Bureau of Meteorology. Nineteen high quality Australian station records were selected with data dating from as early as 1857. These stations, shown in Fig. 1, were chosen to provide a comprehensive coverage of the continent and to include continental, coastal, urban and rural regions. Each record includes flags which indicate whether the data were quality controlled and acceptable, not quality controlled, considered wrong, considered suspect, or inconsistent with other known information. Almost all of the quality flags for the stations used in this study indicated that the data were quality controlled and acceptable.

The time of the summer solstice, when the sun is vertically overhead at the Tropic of Capricorn, is 21 December. However, at present, the time of closest approach of Earth to the sun occurs on 4 January and, outside of the tropics, this is sufficient to shift the overall maximum daily insolation from 21 December to 23 December. Within the tropics, the sun passes directly overhead twice annually. The sun is directly over the equator every six months at the vernal and autumnal equinoxes and, all else being equal, leads to a double peak in maximum temperatures over the course of a year. The amplitudes of both the solar radiation and temperature variations are relatively small in the tropics causing difficulty in identifying meaningful lags. For this reason we focus on locations south of the Tropic of Capricorn.

Methodology: fitting a single harmonic to daily temperature data

For the purposes of this study, the warmest time of the year is not considered the day when the maximum daily temperature occurs, but is that time when an average over a number of days reaches a peak. A problem with the use of running averages is that, depending on the length of the window, the average can exhibit more than one peak, leaving the timing somewhat indeterminate. Rather than use running averages, we make use of the fact that temperatures, averaged over the long-term, tend to follow the seasonal march of the sun and therefore can be expected to vary similarly. One method of defining the warmest time of the year is to fit the data using a single harmonic function. If the period (365 days) is prescribed then the phase lag of any fitted harmonic pinpoints the timing of maxima precisely.

We represent time t in terms of Julian day J

$$t = \omega J = \frac{2\pi}{365} J$$

Fig. 1 **Australian station locations used in this study.**

so that December 31 corresponds to $t = 2\pi$ (and also $t = 0$) (and omit 29 February in leap years.☐

If we assume that daily temperatures throughout the whole year or part of the year $T(J)$ can be best explained by a single harmonic we can write

$$T(J) = T_0 + d \sin(\omega J + \phi)$$

where T_0 is the mean value, d is the amplitude and ϕ is the phase angle.

Expanding,

$$T(J) = T_0 + d\,[\sin(\omega J)\cos(\phi) + \cos(\omega J)\sin(\phi)]$$

which can be regarded as a linear function

$$y = a + b_1 x_1 + b_2 x_2$$

where $y = T(J)$, $a = T_0$ and x_1 and x_2 are the variables, sin (ωJ) and cos (ωJ) respectively, and b_1 and b_2 are the coefficients d cos (ϕ) and d sin (ϕ), respectively (x_1 and x_2 are uncorrelated over the full period 2π). Simple multiple linear regression between $T(J)$ (the dependent variable) and the independent variables sin (ωJ) and cos (ωJ) yields a, b_1 and b_2. It follows that

$$\frac{b_2}{b_1} = \tan(\varphi) \text{ or } \varphi = \tan^{-1}\left(\frac{b_2}{b_1}\right)$$

The amplitude of the harmonic is given by

$$d = \frac{b_1}{\cos(\varphi)}$$

A zero phase angle corresponds to a harmonic with a maximum near April 1 (Julian day 91). Here we define the lag in calendar days L_D relative to December 31 as follows

$$L_D = \left(91.25 - \frac{365}{2\pi}\varphi\right)$$

The lag relative to the time of maximum incident solar radiation (December 23) is therefore $L = L_D + 8$. Thus $\phi = \pi/3$ (=60°) corresponds to $L_D = 30$ days (or January 30) and $L = 38$ days.

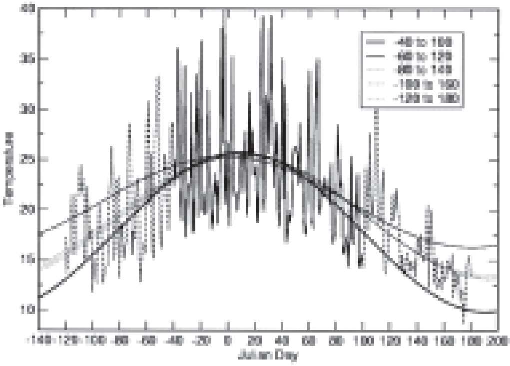
For any year, the fitted harmonic depends on which data are used in the multiple linear regression. If a year's worth of data is used, the resultant harmonic will be that which most closely matches the entire 365 days. This is not ideal since it will partly reflect the distribution of maximum temperatures during the coldest part of the year. In the case of fitting daily maximum temperatures for summer, it is therefore preferable to restrict the data to the warmest months. On the other hand, restricting the fit to too few days can lead to unrealistic harmonics. Assuming that the warmest time of the year is sometime near January 30, we can define a window made of an equal number of days before and after this date. An example of a sampling window is Julian days -40 to 100, corresponding to dates from 22 November through to 10 April.

This method differs slightly from Fourier analysis since it does not require the data to be uniformly distributed throughout a full cycle.

Calculating the mean lag for Melbourne summer maximum temperatures

Figure 2 shows temperature data for Melbourne for dates surrounding January 1902. The maximum temperatures can be seen to have begun exceeding 30°C near Julian day -60, or November 1, of the previous year. The last date when the daily maximum exceeded 30°C can be seen to have been near Julian day 110, or April 20. Also shown in the figure are harmonic fits to the data based on five sampling windows of different lengths varying between 140 and 300 days. The derived lag values (L_D) vary from +9 for the smallest window to -2 (i.e. 29 Dec.), +11, +13 and +10 days for the successively longer windows. While each value is technically correct according to the window used, the results illustrate that care must be taken in defining a representative value. If too small a window is chosen, the data can behave very differently to the long-term seasonal cycle and the resultant fitted har-

Fig. 2 **Melbourne summer maximum temperatures 1901-1902. Julian Days 0 and 1 represent 31 December 1901 and 1 January 1902 respectively. The five curves represent the harmonics fitted to data within five different sampling windows.**



monic can look very strange. There is very little difference between the derived lag values based on sampling windows of 220 days (window = -80 to +140) and longer. Consequently, we can state that for summer 1902, maximum temperatures peaked near Julian day 11 corresponding to a lag *L* (relative to December 23) of about 19 days. Unless stated otherwise, we also use a fixed window length of 220 days for all analyses discussed below.

As a check on the consistency of the method, the summer maximum lags at Melbourne were compared with those calculated for nearby Laverton, less than 20 km away. The results for all years between 1945 and 2001, the period for which the data overlap, are shown in Fig. 3. This indicates that, as would be expected, the lags are very similar in any year. The correlation coefficient of 0.961 indicates that 92.3 per cent of the variation in the lags is accounted for by a simple linear relationship between both sets of data.

Figure 4 shows the individual lag values for Melbourne calculated for each year between 1857 to 2001. There is considerable variation in the lag values from year to year. The long-term average value based on just post-1900 values is 30 days (i.e. 22 January) with a standard deviation of six days. Table 1 shows the equivalent results based on the use of window lengths between 140 and 300 days and indicates that 220 days is sufficient to define a robust mean value.

Fig. 3 **Correlation between summer maximum lags at Melbourne and Laverton for the period 1945 to 2001.**

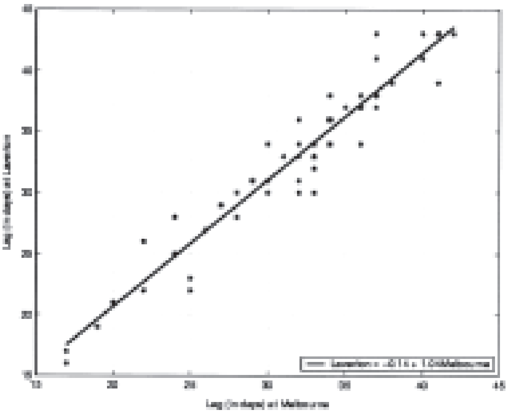
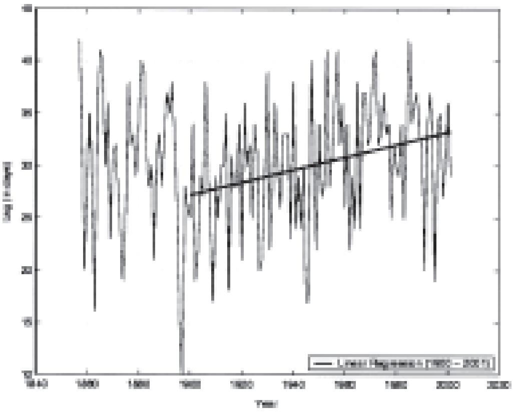


Fig. 4 **Melbourne summer maximum lags from 1857 to 2001. Also shown is the linear regression trend line fitted for the period 1900 to 2001.**



The long-term (1900 to 2001) average date for summer maximum temperatures of January 22 for Melbourne compares with 26 January derived by Torok and Coutts (1992) for the period 1857 to 1991 using a 10-day running average, and also 28 January found by Alexander (2003) for the period 1958 to 2001 using a 41-day running average. Aside from the different time periods involved, the differences in timing between the harmonic and running average

Table 1. Summary statistics for the linear least squares trend fit to the lag values for Australian locations based on all available data post 1900. These include the regression coefficient (change in lag per day), mean lag (in days), correlation (*r*) and standard deviation of the mean for five different sampling windows (expressed as dates in Julian days). Statistics (based on a sampling window of -80:140) for the period (1959 – 2001) common to all stations are also shown.

Melbourne			***1900-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	0.094	0.09	0.06	0.052	0.057	-0.008
mean	33.14	32.24	30.23	28.1	26.81	32.07
r-value	0.17	0.356	0.294	0.253	0.285	-0.018
st dev (mean)			5.79			5.41

Laverton			***1945-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	0.017	0.08	0.047	0.049	0.06	-0.004
mean	35.61	34.91	32.74	30.53	29.37	33.12
r-value	0.021	0.178	0.119	0.125	0.158	-0.01
st dev (mean)			6.55			5.73

Sydney			***1900-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	0.045	0.112	0.101	0.066	0.066	0.03
mean	29.36	32.74	29.61	27.23	25.78	32.67
r-value	0.042	0.253	0.336	0.27	0.3	0.053
st dev (mean)			8.36			7.08

Deniliquin			***1900-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	0.019	0.072	0.048	0.042	0.048	-0.035
mean	28.09	27.38	26.2	24.9	23.97	27.51
r-value	0.049	0.273	0.223	0.201	0.24	-0.079
st dev (mean)			6.21			5.54

Cape Otway			***1900-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	0.07	0.147	0.08	0.073	0.071	-0.04
mean	40.77	39.69	37.15	35.13	33.87	39.16
r-value	0.107	0.338	0.276	0.276	0.276	-0.065
st dev (mean)			8.25			7.72

Cape Leeuwin			***1908-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	0.044	0.019	0.021	0.021	0.024	0.155
mean	48.9	48.76	47.3	46.4	46.01	46.86
r-value	0.082	0.049	0.074	0.083	0.095	0.226
st dev (mean)			7.57			8.38

Adelaide			***1957-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	0.149	-0.06	-0.057	-0.093	-0.094	-0.031
mean	37.58	33.71	32.09	30.47	29.84	31.86
r-value	0.074	-0.116	-0.12	-0.195	-0.19	-0.063
st dev (mean)			6.16			6.19

Alice Springs			***1943-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	-0.058	-0.061	-0.009	-0.041	-0.038	0.009
mean	14.95	16.02	15.24	12.98	12.17	15.07
r-value	-0.046	-0.104	-0.021	-0.107	-0.108	0.012
st dev (mean)			7.16			7.01

Brisbane			***1951-1999***			***1957-1999***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	0.297	0.151	0.002	-0.026	-0.051	-0.041
mean	23.06	27.9	27.65	25.61	24.69	27.93
r-value	0.104	0.112	0.003	-0.05	-0.121	-0.058
st dev (mean)			8.64			8.87

Table 1. Continued.

Canberra			***1941-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	0.059	0.074	0.062	0.059	0.065	0.024
mean	27.87	29.33	28.03	26.38	25.46	28.65
r-value	0.073	0.182	0.175	0.182	0.215	0.052
st dev (mean)			6.14			5.7
Carnarvon			***1949-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	-0.201	0.082	0.005	0.002	-0.006	0.081
mean	59.38	51.87	48.19	45.42	43.79	47.86
r-value	-0.15	0.115	0.008	0.003	-0.013	0.111
st dev (mean)			8.78			9.07
Ceduna			***1943-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	-0.165	0.269	0.021	0.013	0.025	0.023
mean	12.86	26.78	27.68	25.2	24.51	27.74
r-value	-0.051	0.199	0.033	0.023	0.045	0.027
st dev (mean)			10.91			10.72
Hobart			***1945-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	-0.069	0.045	0.011	0.013	0.032	0
mean	34.46	34.91	31.82	28.89	27.14	31.86
r-value	-0.037	0.097	0.027	0.031	0.08	0
st dev (mean)			6.78			6.17
Meekathara			***1952-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	-0.297	-0.059	-0.068	-0.08	-0.081	-0.023
mean	22.58	24.78	23.62	22.08	21.02	23.12
r-value	-0.238	-0.102	-0.135	-0.162	-0.173	-0.038
st dev (mean)			7.32			7.41
Perth			***1946-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	-0.076	-0.029	-0.015	-0.002	0	0.138
mean	38.98	38.61	37.45	36.63	36	36.56
r-value	-0.111	-0.075	-0.041	-0.006	0	0.279
st dev (mean)			6.63			5.96
Snowtown			***1910-2000***			***1958-2000***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	0.013	0.042	0.036	0.019	0.024	0.098
mean	30.33	28.52	27.62	26.29	25.58	28.12
r-value	0.015	0.137	0.142	0.077	0.098	0.206
st dev (mean)			6.53			5.86
Thargomindah			***1959-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	0.294	0.017	-0.015	-0.027	-0.048	-0.015
mean	13.4	20.14	19.63	18.51	18.19	19.63
r-value	0.104	0.016	-0.021	-0.037	-0.064	-0.021
st dev (mean)			8.9			8.9
Tibooburra			***1912-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	-0.052	0.014	0.008	-0.007	-0.005	0.026
mean	20.51	22.3	21.14	19.46	18.59	21.4
r-value	-0.059	0.043	0.033	-0.031	-0.021	0.063
st dev (mean)			6.3			5.16
Wilson's Prom			***1959-2001***			***1959-2001***
	-40:100	*-60:120*	*-80:140*	*-100:160*	*-120:180*	*-80:140*
reg. Coeff	-0.079	0.079	0.085	0.055	0.043	0.085
mean	38.98	41.74	39.72	37.55	36.51	39.72
r-value	-0.039	0.135	0.163	0.12	0.1	0.163
st dev (mean)			6.5			6.5

methods may be due to the asymmetry in temperatures over the summer season, i.e. the descent into winter occurs over a shorter period than does the gradual onset of summer.

Table 1 summarises the results of analyses for all the locations used in this study. Inspection of the results also indicates that the lag sometimes increases in going from a window length of 140 days to 180 days but, in all cases, the lag decreases with window length beyond 180 days. This confirms that an optimum window length is about 220 days since this appears to yield values representative of window lengths between 180 and 260 days and is evidence of 'convergence'.

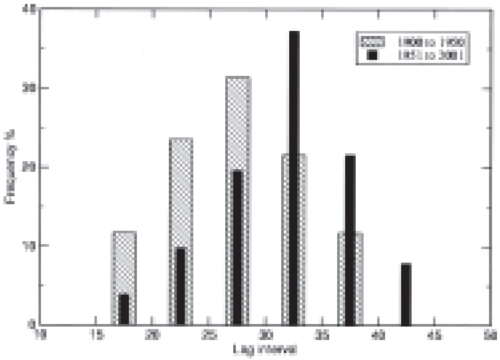
Trends in Melbourne lag values

Figure 4 indicates that, for the period 1857 to about 1900, the mean lag for Melbourne appears to have decreased slightly but, after about 1900, has increased gradually. While the decrease may be real, it is possible that data quality over the period 1857-1900 could be an issue, particularly as Fig. 4 indicates that the calculated lag values are more variable compared with those calculated for later periods. It is known that a change in measurement practice took place over this period associated with the change to Stevenson screens (see Discussion section). Given this uncertainty, the analysis of trends has focussed on the period after 1900 since Stevenson screens are known to have been employed from around that time.

Table 1 shows that the trend in lag values after 1900 amounts to about +6 days per 100 years with an associated correlation coefficient of +0.294. This indicates that the trend is highly significant at a level greater than 99 per cent. Furthermore, Table 1 shows that while the magnitude of the calculated trend varies slightly with window length, the existence of a significant positive trend post-1900 is unambiguous. Consequently, it appears that Melbourne's highest maximum temperatures occurred, on average, about six days later at the end of the 20th century compared with the beginning.

The secular change in lag is summarised in the histograms for the periods 1901 to 1950 and 1951 to 2001 (see Fig. 5) which also show the skewness of the distributions. There tends to be a sharp cut-off at the longer lags and a broader distribution of the shorter lags. The longest lag of 42 days occurred on 3 February 1985, and the shortest lag of 17 days occurred three times on 9 January 1909, 1945 and, surprisingly in the following year 1946 (see Fig. 4). The derived lag value ($L = 19$ days) for 1902 (see Fig. 4) is therefore amongst the shortest values.

Fig. 5 **Histograms of Melbourne summer lags for the two periods 1900 to 1950 and 1951 to 2001.**



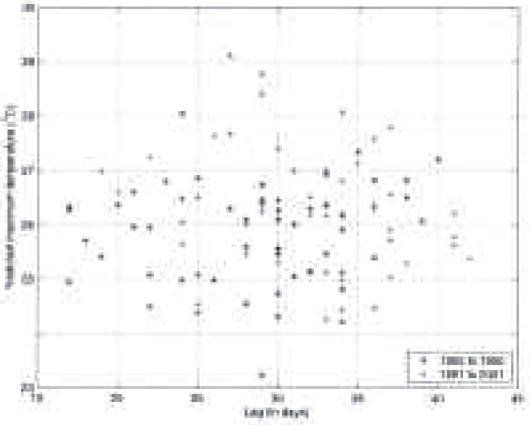
Does the lag depend on the temperature? To investigate this question, the correlation between lag and summer maximum temperature for Melbourne was explored. In addition to the lag, the harmonic fit yields an estimate of the actual peak in temperatures (T_0+d) for each year. Figure 6 shows the result of comparing the yearly values for both along with a distinction between 1900 to 1950 values, and 1951 to 2001 values. There is no correlation between lag and temperature.

Spatial distribution of lags for Australia

Table 1 summarises the results for all stations used in this study. Not all stations have records going back to the start of the 20th century and mean values have been calculated from data for all years post 1900 and also for the fixed period (1959-2001) when all stations have data.

The spatial distribution of the lags calculated in this study is shown in Fig. 7(a). The results reveal a pattern of lag increasing with both latitude and proximity to the oceans, reinforcing the results found in previous studies. The lag values also are longer for western coastal regions compared with eastern regions as first noticed by Prescott and Collins (1951). For example, the mean lag at Cape Leeuwin is about 47 days, yet at Sydney is about 30 days. The lag decreases inland, evidenced by the lags at Alice Springs and Tibooburra of only 15 and 21 days respectively. This is consistent with the decrease of maritime compared with continental influences.

Fig. 6 **Comparison between Melbourne summer lags and summer maximum temperatures (1900-2001).**



High standard deviations in lag are a feature of the temperate Australian climate (Table 1), e.g. the fact that the warmest time of the year can occur around, say, 20 January one year and 30 January the next year is not unusual. The geographical variation is shown in Fig. 7(b) but, surprisingly, does not indicate any systematic pattern.

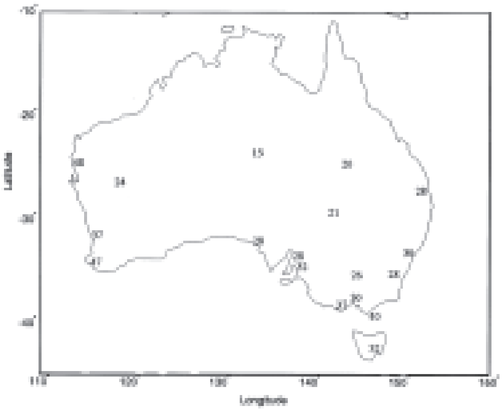
Spatial distribution of lag trends

Four other stations, Sydney, Cape Otway, Deniliquin and Cape Leeuwin, have long temperature records. The summer maximum lags for Sydney (Fig. 8) exhibit a strong positive trend from 1900 to 2001 and appear to have increased by about ten days over this period (see Table 1). For a sample size of 100 independent points, a correlation is significant at the five per cent level if it exceeds 0.2. Given the trend correlation coefficient in this case is +0.336, this trend is highly significant. Cape Otway (Fig. 9) and Deniliquin (Fig. 10) also exhibit significant increases post-1900 of about +5 and +8 days respectively. The (approximately) two days increase at Cape Leeuwin post 1908 (Fig. 11) is not statistically significant.

The spatial distribution of the lag trends is presented in Fig. 12(a) but represents different periods according to available data and indicates that there has been an increase in lag values over southeastern Australia based on the results for Sydney, Deniliquin, Melbourne and Cape Otway.

Fig. 7 **Long-term average summer maximum lags for selected stations (a) and standard deviations (b).**

(a)



(b)

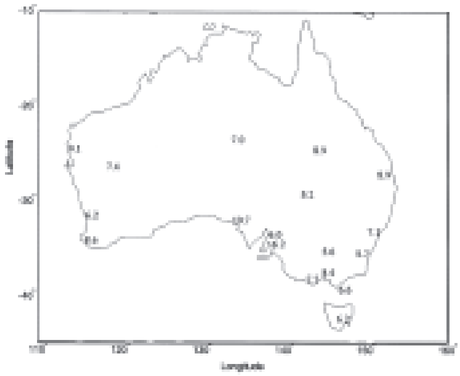


Figure 12(b) offers commonality by presenting the results based on the same period (1959 – 2001) for all locations. Trends with statistical significance at the 95 per cent level are highlighted. In this case the only significant trends are those estimated for Perth (+14 days per century) and Cape Leeuwin (+16 days per century). Thus while the trends over southeastern Australia are significant over the long term, they are not as apparent over the more recent 43-year period. This suggests that, while a shift in lag values has taken place, it has not continued. This is not unexpected since it is impossible for lag values to continue increasing (or decreasing) indefinitely.

Fig. 8 **Summer maximum lags (in days) for Sydney (1860-2001).**

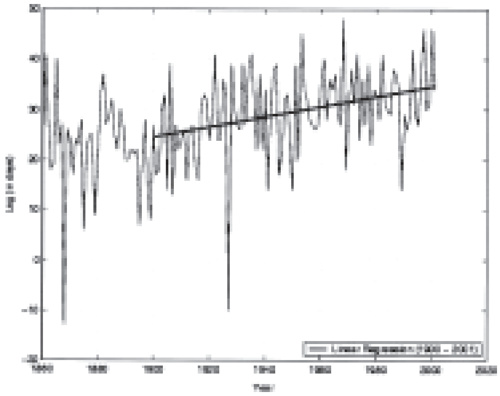


Fig. 9 **Summer maximum lags (in days) Cape Otway (1867-2001).**

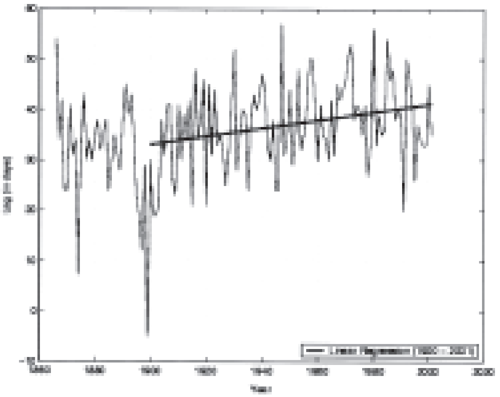


Fig. 10 **Summer maximum lags (in days) Deniliquin (1900-2001).**

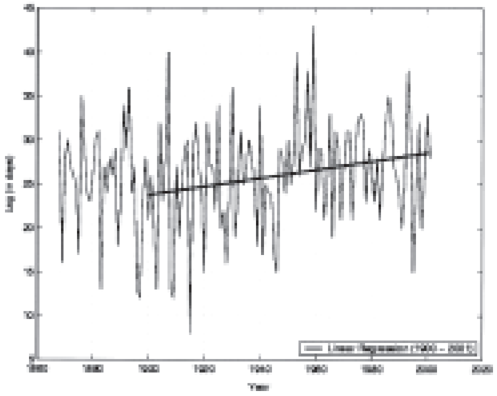
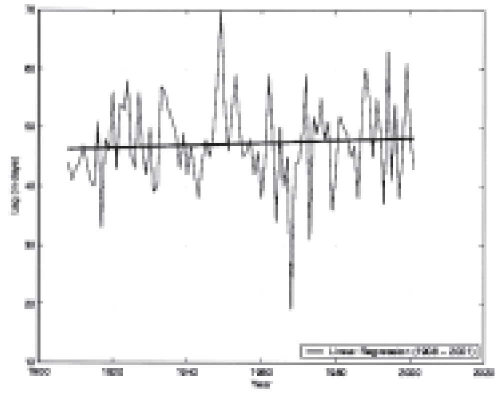


Fig. 11 **Summer maximum lags (in days) Cape Leeuwin (1908-2001).**

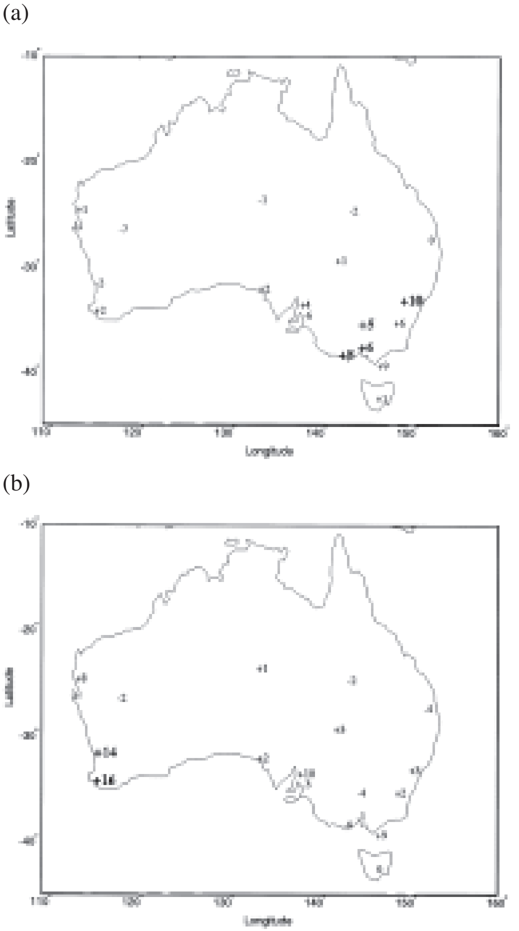


Discussion

While the difference between the continental and the maritime lags can be understood in terms of the different heat capacities of land surfaces versus those of the surfaces of water bodies, a more difficult question is the cause of the variation of the lag around the coastline. Given that, in mid-latitudes, the prevailing winds tend to be from the west, it could be expected that temperatures (and lags) along western margins will be more maritime than those along eastern margins. However Carnarvon station, located near 25°S, is better described as subtropical rather than mid-latitude, yet exhibits the longest lag (49 days) of all the stations considered. From a meteorological perspective, the differences may reflect greater sea-breeze circulations compared to offshore advection by the general circulation and this effect appears to be evident in the lags of sea-surface temperatures. Coastal circulation features may play a role, since along the Western Australian coast, the Leeuwin Current (Tomczak and Godfrey 1994) advects warm water poleward, and off southeastern Australia, summer sea-surface temperatures are depressed by upwelling (Bye 1986). Both of these oceanographic processes cause the highest sea-surface temperatures to occur relatively late in the season, which may retard the temperature signal. The reason for the west-east differential seen here and observed over other continents remains to be identified.

El-Hussainy and Essa (1997) looked at trends in lag values over a 22-year period (1972 – 1993) at four Egyptian stations representing urban, semi-rural, mountainous and coastal localities. All four stations

Fig. 12 **Lag trends for Australian stations. (a) Determined using all available data. (b) Determined using only data from 1958 to 2001. Bold values are statistically significant (at the 5% level).**



exhibited small increases with the largest trend occurring at a station (Bahtim) which had rapidly changed from a rural to an urban regime.

In the case of Melbourne, there may have been a decrease over the latter half of the 19th century but whether this was real is not certain due to questions about data quality. On the other hand, there is more reliable evidence that summer maximum temperature lags for Sydney, Melbourne, Deniliquin and Cape Otway increased by between five and ten days over the past 100 years. Over the more recent period of 1959 to 2001, common to all locations studied here, there is no evidence of significant trends other than at Perth and Cape Leeuwin, where values have increased over recent decades.

A commonly held impression is that, unlike the past, hot summer temperatures have become less frequent during school holidays compared with the first days after schools return. In the case of Melbourne, this impression has some basis in fact for people with memories of summers early in the century, since there appears to have been a shift over this time frame. This impression does not appear to hold for those whose experience is confined to the latter part of the century (except for Perth and Cape Leeuwin), since there is no evidence of a significant shift over recent decades.

Several hypotheses for the reasons why summer maximum temperatures could occur later in the year are considered here. Given that the lag values presented here depend on the method used to calculate them, it is possible that the trends may simply be an artefact of the harmonic method. While it is the case that the results are dependent on window length, for window lengths of 220 days or more this dependence is not an issue and, where significant trends have been identified, their existence appears robust. Any trends are therefore likely to be real features of the data.

A second explanation involves changes in instrumentation or observing practices which may have introduced artificial trends. Stevenson screens are placed around meteorological thermometers in order to minimise the effects of radiation on thermometers so that the readings closely reflect ambient air temperatures. Stevenson screens were introduced in Australia at the turn of the century (Hughes 1995; Torok and Nicholls 1996). Nicholls et al. (1996) found that, in Australian conditions, mean temperatures in a Stevenson screen are lower than in open screens used earlier. However, it is unclear whether the changeover would have had any effect on the timing of maximum temperatures. Other factors, such as site moves or changes from mercury-in-glass thermometers to automatic weather stations, may also have an influence. While such changes often result in shifts in absolute temperatures, the effects on capturing the warmest period in a season would be expected to be minimal.

Another candidate explanation is that the trends represent the effects of urbanisation. Expansion of the city and the range in surface properties can affect temperatures mainly by the heat island effect, which suggests that built up areas generally record higher temperatures, particularly overnight minima (Torok et al. 2001). However, the urban heat island effect is more pronounced in winter (Sturman and Tapper 2000) and significant trends are apparent for Cape Otway and

Cape Leeuwin, both of which are non-urban sites. Therefore, urbanisation alone is unlikely to account for the observed trends.

The final and most likely explanation is that the trends represent a real climatic signal. Because the lag increases with proximity to the oceans, positive trends could imply that the summertime climates of southeastern Australia and possibly southwestern Australia have become more 'maritime', or less 'continental'. An important question is whether the positive lag trends are due primarily to changes in the ocean or changes over the continent, or from some other cause. This study does not address this question but further investigations could delve further by, for example, analysing long-term high-quality wind records for changes in the nature of sea-breeze circulations around the coast. Another potentially useful approach would be to analyse the results of climate model simulations to see if they include trends in summer temperature lags.

Conclusions

The main aim of this study is to provide an updated analysis of Australian summer maximum temperature lags using harmonic fits to daily data from long, high-quality records. The results confirm those from previous studies based on monthly data, but provide more precise values. Lags are longer for western coastal regions compared to eastern regions, and decrease towards the interior. The results also identify and quantify some statistically significant long-term trends in lag values at locations in southeastern Australia and shorter term trends in southwestern Western Australia.

The trends are unlikely to have emerged simply as a result of the methodology employed, changes in observing practice, instrument shielding, urbanisation or other non-climatic factors. It is concluded that the trends represent a feature of the climate system independent of changes in temperature. One explanation is that the summer climate may be exhibiting more maritime (i.e. relatively long lag) in contrast to continental (i.e. relatively short lag) influences. This in turn may reflect changes over inland regions, or in the ocean, or both. Given that the continent as a whole has warmed over the past 100 years (Torok and Nicholls 1996), it is possible that higher temperatures inland may have resulted in more frequent or stronger sea-breeze circulations at the coast. This would also be consistent with the finding that the lag appears independent of local temperature. However, the trends are not uniformly apparent at all coastal stations analysed, possibly indicating changes in the continental general circulation. These hypotheses could be investigated further by careful analyses of high-quality wind and sea-surface temperature records or by suitable climate model experiments.

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