Effects of changes in algorithms used for the calculation of Australian mean temperature

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There was a change in November 1994 in the algorithm used for the calculation of mean monthly temperatures reported internationally by Australian stations, from one based on daily maximum and minimum temperatures to one based on three-hourly observations. A comparison of the pre and post-1994 methods, along with other methods based on fixed-hour observations which are in use in other countries, was carried out. Averaged over Australia as a whole, mean temperatures calculated using the post-1994 method were found to be 0.14ºC cooler than those calculated using the pre-1994 method, whilst other methods tested based on fixed-hour observations were found to produce means between 0.17ºC and 0.43ºC cooler than those derived from maximum and minimum temperatures. There were regional variations in the observed differences, with the largest differences occurring in coastal areas. The observed differences occurred in all seasons, being smallest in the (southern) spring and similar in all other seasons.

The observed differences are substantial in the context of the trend in Australian temperatures over the last century, and reinforce the importance of documenting and taking into account such inhomogeneities in the record in making assessments of observed climate change.

Introduction

Mean monthly and annual temperatures have, historically, been the most common indicator used for the assessment of climate change, both in the context of historically observed change and projected future change (IPCC 2001). Whilst substantial recent attention has been given to indicators such as mean daily maximum and minimum temperatures (e.g. Easterling et al. 1997), as well as to temperatures at the daily timescale, mean temperatures are still the most commonly-used parameter in the ongoing monitoring of temperature, particularly at the global and hemispheric scale. Mean temperature anomalies are the principal element in the datasets maintained by the Climatic Research Unit (CRU) at the University of East Anglia (Jones 1999) and the data from the Global Historical Climatology Network (Peterson and Vose 1997) maintained by the (US) National Climatic Data Center (NCDC). They are likely to remain critical in assessment of historic changes, as in many countries

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observations of daily maximum and minimum temperatures did not commence until well after the commencement of observations at fixed hours, reducing the potential length of historic record for daily maxima and minima compared with means. As an example, in Finland (Heino 1994), maxima and minima were not archived until 1901, whereas many observations at fixed hours were made during the nineteenth century.

In Australia, mean temperatures had historically been calculated using the arithmetic mean of daily maximum and minimum temperatures. This followed a decision of the 1881 Intercolonial Meteorological Conference (Government of Victoria 1881), at which representatives of a number of the (then) colonies in what would become Australia, as well as New Zealand, agreed on standard procedures in a wide variety of matters relating to the operation of the meteorological network. Whilst it is not cited as a specific reason for the decision, discussion minuted at the meeting on other issues suggests that the ability to adopt uniform practices throughout the network was a high priority. In the Australian network as it existed then (and exists now), maximum and minimum temperatures were observed at almost all stations in the network, but only a small minority of stations took observations more than twice per day. The majority of stations took observations only at 0900 and 1500, or at 0900 only, and were therefore not usable for the calculation of means based on fixed hours.

In November 1994, a change was made to the method of calculating mean temperatures reported in CLIMAT messages. CLIMAT messages are the means by which monthly climate data are transmitted internationally, and form the basis for international data sets such as those maintained by CRU and NCDC. From that date onwards the mean daily temperatures have been calculated using the mean of all available fixed-hour observations. Most of the Australian stations that transmit CLIMAT messages make reports at three-hourly intervals (a total of eight per day). These reports are, in general, made at 0000, 0300, ..., 2100 local clock time. However, prior to the installation of automated measuring equipment (which took place at most of the stations concerned between 1990 and 1996), many stations took seven observations per day, missing the 0000 observation (or the 2100 observation in Western Australia), and the number of observations per day could be further reduced for short periods as a result of temporary staff shortages. A project is in progress to include observations at hourly and higher frequencies in the Australian climate database, but, at present, such observations are only available for, at most, a few years, and national databases of such observations only commence in mid-2002. Data prior to that date are stored in local station- and state-based databases, rendering them difficult to use on a national basis.

Mean temperatures reported within Australia, such as those used in the Bureau of Meteorology's annual climate statement (e.g. Bureau of Meteorology 2003), continue to be based on the (max+min)/2 method, using daily maximum and minimum temperatures from a large number of long-term stations (Torok and Nicholls 1996), and have not been affected by the change in the method used for CLIMAT messages.

The principal purpose of this paper is to investigate the impact of the 1994 change in method of mean temperature calculation on the homogeneity of Australian temperature data used in global data sets.

Methods of defining a mean temperature

The 'true mean' temperature of a day may be defined as the integral of the temperature over 24 hours, divided by the time unit used. It is not possible to define the temperature curve precisely using observations at finite time intervals. The use of automated measurement systems allows for measurements to be made at very small intervals (e.g. one second), very closely approximating the exact temperature curve, but such systems are relatively recent (and not in universal use), necessitating the approximation of daily mean temperature through the historic record by means of observations at specific times, or parameters such as daily maxima and minima.

A large number of different algorithms are used in various parts of the world for the calculation of daily (and consequently monthly and annual) mean temperature. These algorithms may be divided into three broad categories:

1. $(T_x + T_n)/2$, with the maximum (T_x) and minimum (T_n) temperatures recorded over some set 24-hour period ending at a specified time. (It is well-known (e.g. Karl et al. 1986) that the choice of observation time can affect the calculated value of mean temperature, but for the purpose of this paper only a single fixed time will be considered).
2. The mean of observations at fixed times which are taken at regular intervals. (The most common manifestation of this is the mean of eight three-hourly observations at 0000, 0300, 0600, ..., 2100 UTC, but some countries use the mean of four six-hourly observations, 24 hourly observations, or other combinations).
3. Algorithms based on means (often weighted) of temperatures measured at irregularly-spaced fixed hours. An example of this, used in a number of

European countries, is $T_{mean} = (T_{0700} + T_{1400} + 2T_{2100})/4$ (where T_{nnnn} is the temperature at time nnnn). A more complex type of algorithm is used in some countries; for example, Sweden uses the algorithm $aT_{0600} + bT_{1200} + cT_{1800} + dT_x + eT_n$, where a, b, c, d and e are parameters which are functions of month and station longitude.

Brooks (1921) notes that at that time, the first method was used (following work by Buchan) through most English-speaking countries. He discussed a number of algorithms of the third type, with a view to assessing which of them best approximated the 'true mean'.

The *WMO Guide to Climatological Practices* (WMO 1983) recommends that 'it is advisable to use a true mean or a corrected value to correspond to a mean of 24 direct observations a day. The mean of 4 equally spaced observations may suffice as a close approximation to the true mean'. Despite this, such methods are only used over part of the world's land area. World Weather Records (NOAA 1997 and earlier years) gives information on the algorithms used over approximately 85 per cent of the world's non-Antarctic land area. Of this area, methods falling into category 1 are used over 43 per cent of the area (the largest countries involved being the United States, Canada and Australia); methods falling into category 2 are used over 41 per cent of the area (including China and the countries of the former Soviet Union); and methods falling into category 3 are used over 16 per cent of the area (mostly in Europe and South America).

Impact of changes in mean temperature calculation algorithms on the climate record – international experience

Changes in algorithms used for the calculation of mean daily temperatures are a well-known source of inhomogeneities in the climate record (Mitchell 1953; IPCC 1990; Heino 1994, 1997; Jones et al. 1999) and can be difficult to detect because, if a change occurs, it is likely that the change will have occurred at the same time across a national network. This, in turn, will render largely ineffective methods for the detection of, and adjustment for, inhomogeneities which are based on comparisons with neighbouring stations, such as the methods used for homogenising the CRU and GHCN data sets (Peterson and Vose 1997; Jones et al. 1999). IPCC (1990) note, however, that 'As long as each country continues the same practice, the shape of the temperature record is unaffected'. This emphasises that, as long as calculation methods remain unchanged in time at a specific site, it does not matter, in the monitoring of climate change, if there are differences between sites.

Collison and Tabony (1984), in a comparison of daily mean temperatures calculated from maximum and minimum temperatures with those calculated using the mean of 24-hourly observations, found, in a study of fifteen British sites, that differences were generally less than 0.3ºC, with means derived from 24-hourly observations generally warmer than those from maxima and minima in winter, and cooler in summer.

Weber (1993) compared daily mean temperatures calculated from maximum and minimum temperatures in Switzerland with those calculated using the formula:

$$T_{mean} = (T_{0700} + T_{1300} + 2T_{2100})/4$$

Whilst his results were complicated by a change in the observation time used for daily maximum and minimum temperatures, he found that means calculated using maxima and minima were 0.06ºC to 0.83ºC warmer than those calculated using fixed-hour observations, depending on the station. He also found that there were smaller spatial differences between stations in the observed trends of mean temperature if the mean temperature was calculated using daily maxima and minima than if it was calculated using fixed-hour temperatures. He concluded that this suggested that daily maxima and minima were less sensitive to small local variations in observation time than fixed-hour observations were.

Station selection and data

Thirty-five stations were selected for use in this study (Table 1). These were selected to satisfy the following criteria:

(a) A minimum of 20 years of record in the 1973-1999 period.
(b) A mean of at least 7.0 observations per day over the period of record.
(c) At least eight observations per day on a regular basis since at least January 1994.

Four stations which did not satisfy condition (b) (but did satisfy conditions (a) and (c)) were also included on the basis that they had at least 7 observations per day on a regular basis since at least 1973 (in most of these cases the low mean number of observations per day arose from missing data prior to 1970).

Data availability was the only consideration used in the selection of stations for this study, with no consideration given to spatial coverage. There are substantial areas of Australia, particularly over the interior, where no stations met the data availability criteria.

Table 1. Station coordinates.

Station name	*Latitude (deg S)*	*Longitude (deg E)*
Broome	17.94	122.23
Port Hedland	20.37	118.63
Learmonth	22.23	114.03
Carnarvon	24.88	113.67
Meekatharra	26.61	118.54
Geraldton	28.79	114.69
Perth Airport	31.94	115.96
Albany	34.94	117.80
Esperance	33.83	121.89
Kalgoorlie	30.78	121.45
Darwin	12.42	130.88
Tennant Creek	19.63	134.18
Alice Springs	23.80	133.88
Woomera	31.14	136.81
Ceduna	32.13	133.70
Adelaide Airport	34.96	138.53
Adelaide (Kent Town)	34.92	138.62
Mount Gambier	37.74	140.78
Mount Isa	20.68	139.48
Cairns	16.88	145.75
Townsville	19.25	146.76
Rockhampton	23.37	150.47
Gladstone	23.86	151.26
Amberley	27.64	152.71
Brisbane Airport	27.42	153.11
Charleville	26.41	146.26
Sydney Airport	33.94	151.17
Sydney (Observatory Hill)	33.86	151.20
Nowra	34.95	150.53
Canberra	35.30	149.19
Mildura	34.24	142.08
Melbourne RO	37.81	144.97
Launceston Airport	41.54	147.20
Hobart Airport	42.84	147.50
Hobart (Ellerslie Road)	42.89	147.32

The set of 35 stations includes 20 of the 32 mainland Australian stations that have routinely reported CLIMAT messages in the period since November 1994. The other twelve stations failed to meet the minimum data requirements for this study.

Data from 1973 to 1999 (inclusive) were used in this study. 1973 was chosen as the starting point because it was the first year in which current practices for observation times during periods of daylight savings time were used. (Daylight savings time was observed during the summer of 1971-72, but observations during that summer remained at the same UTC time, moving forward one hour by local clock time).

During periods of daylight savings time, observations in those states which observe it are taken at the same local clock time (i.e. one hour UTC earlier) as is used during the remainder of the year. Daylight savings time is currently observed in the states of New South Wales, Victoria, Tasmania, South Australia, and in the Australian Capital Territory. It generally commences in late October (except in Tasmania where it commences in early October) and finishes in late March, although there have been some variations to this pattern in individual years, and both Queensland and Western Australia observed daylight savings time for short periods during the record, but do not do so at present.

Methods

For each station, a daily mean temperature was calculated for each day using seven different methods:

- (max + min)/2. Maxima and minima, in all cases, were taken for the 24 hours ending at 0900 local clock time.
- six methods using fixed-hour observations as described in Table 2.

Temperature differences were then calculated for each day between the means calculated by each of the six fixed-hour methods and the mean calculated by the (max+min)/2 method. For each of the six methods, the difference was set to missing if the hourly observations available on that day failed to fulfil the minimum data requirements for that method listed in Table 2. The differences for a day were set to missing for all six methods if either the minimum or maximum temperature was missing for that day.

Once the temperature differences were calculated for each day of the 1973-1999 period for each of the six methods, mean values of the differences were then calculated for each station over that period.

The methods listed in Table 2 are intended to reflect the following situations:

- means of four six-hourly observations using the two possible combinations of observing hours (methods A and B).
- daily means of all observations using the seven observations/day practice followed at many stations prior to the 1990's (method C).
- means of eight three-hourly observations subject to a condition that all observations were available (method D).
- means of all available observations subject to conditions on minimum number of daily observations (methods E and F).

Methods A, B and D are equivalent to methods used in some other parts of the world. Method C is intended to act as a method based on fixed-hour observations that could be extended backwards into the historical record (something that would be

Table 2. Description of mean temperature calculation methods used.

Designation	*Description*
A	Mean of 4 observations at 0300, 0900, 1500 and 2100 local time. All 4 observations required for mean to be calculated.
B	Mean of 4 observations at 0000, 0600, 1200 and 1800 local time. All 4 observations required for mean to be calculated.
C	Mean of 7 observations at 0300, 0600, 0900, 1200, 1500, 1800 and 2100 local time (replace 2100 with 0000 for stations in Western Australia). All 7 observations required for mean to be calculated.
D	Mean of all observations with minimum of 8 observations required for the day. This is effectively equivalent to a mean of 8 observations at 0000, 0300, ..., 2100 local time.
E	Mean of all observations with minimum of 7 observations required for the day.
F	Mean of all observations with minimum of 1 observation required for the day.

impossible on an eight observations/day criterion because of the lack of stations observing eight times per day prior to 1990). Method F reflects the actual practice followed in the collation of Australian CLIMAT messages since 1994, whilst method E is a refinement of this to eliminate days with numerous missed observations.

Results and discussion

Mean differences observed for each method in each season at each station are shown in Tables 3(a)-(e). These differences averaged over Australia, using the Thiessen polygon method (Thiessen 1911), are shown in Table 4. The 95 per cent confidence intervals for estimated mean difference, calculated using a standard Student's t-test, are shown in Table 3(a) (annual mean differences). They are omitted for brevity from Tables 3(b)-(e), in which the confidence intervals range from ± 0.02°C to ± 0.07°C for the seasonal mean differences. The areally averaged differences will also have uncertainties arising from the incomplete spatial sampling of the Australian continent.

The results show that, in most cases, mean temperatures calculated using the (max+min)/2 method in Australia are higher than those calculated using methods based on fixed-hour observations. Means calculated using eight three-hourly observations are 0.31ºC lower, whilst those based on four six-hourly observations are 0.17 to 0.43ºC lower, depending on the observation hours chosen.

In general, the differences are greatest near the coasts, particularly at those coastal sites which are most exposed to sea breezes, such as Port Hedland, Esperance, Cairns and Gladstone. These sites are characterised, particularly in summer, by a rapid rise to the daily maximum temperature during the morning, followed by a cooling after midday (Fig. 1), reducing the number of three-hourly observations at which the temperature is near the daily maximum. (In contrast, away from the coasts the temperature typically reaches its maximum between 1400 and 1700 local time).

The smallest differences occur at inland sites. At Alice Springs, fixed-hour means are consistently lower than those calculated using the (max+min)/2 method. This is the only one of the sites examined where this is the case, although some other inland sites (e.g. Mount Isa, Charleville and Mildura) show positive differences for some methods.

It is unclear from the available data why the observed differences vary from station to station, apart from the coastal/inland contrasts noted above, nor is it clear why means calculated using observations at 0000, 0600, 1200 and 1800 are consistently cooler than those using observations at 0300, 0900, 1500 and 2100. A possible explanation lies in the timing of local sunrise and sunset (and, hence, the proportion of the year for which the 0600 and 1800 observations are during daylight hours) – which

Fig. 1 Mean hourly temperatures at Port Hedland for the period December 2002 – February 2003.

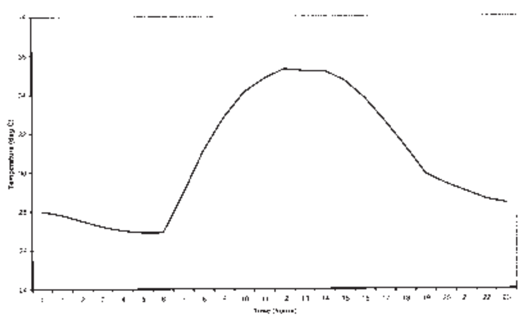

Table 3(a). Differences (ºC) between mean temperatures calculated by stated methods and by (max+min)/2, annual, with 95% confidence interval.

Station name	*Mean calculation method*					
	A	*B*	*C*	*D*	*E*	*F*
Broome	-0.20 ± 0.03	-0.77 ± 0.02	-0.33 ± 0.02	-0.50 ± 0.02	-0.42 ± 0.02	-0.37 ± 0.02
Port Hedland	-0.36 ± 0.02	-1.03 ± 0.02	-0.43 ± 0.01	-0.70 ± 0.01	-0.69 ± 0.01	-0.68 ± 0.01
Learmonth	-0.49 ± 0.02	-0.84 ± 0.02	-0.47 ± 0.01	-0.67 ± 0.02	-0.66 ± 0.02	-0.66 ± 0.02
Carnarvon	-0.42 ± 0.03	-0.66 ± 0.02	-0.43 ± 0.02	-0.60 ± 0.03	-0.48 ± 0.02	-0.48 ± 0.02
Meekatharra	0.02 ± 0.02	-0.24 ± 0.02	-0.13 ± 0.02	-0.11 ± 0.02	-0.12 ± 0.02	-0.25 ± 0.02
Geraldton	-0.47 ± 0.02	-0.78 ± 0.02	-0.40 ± 0.02	-0.62 ± 0.02	-0.59 ± 0.02	-0.53 ± 0.02
Perth Airport	-0.41 ± 0.02	-0.55 ± 0.02	-0.34 ± 0.02	-0.48 ± 0.02	-0.48 ± 0.02	-0.47 ± 0.02
Albany	-0.57 ± 0.03	-0.80 ± 0.02	-0.51 ± 0.02	-0.69 ± 0.02	-0.59 ± 0.02	-0.56 ± 0.02
Esperance	-0.72 ± 0.03	-0.99 ± 0.02	-0.72 ± 0.02	-0.85 ± 0.03	-0.77 ± 0.02	-0.78 ± 0.02
Kalgoorlie	-0.10 ± 0.03	-0.30 ± 0.02	-0.17 ± 0.01	-0.24 ± 0.02	-0.18 ± 0.02	-0.15 ± 0.02
Darwin	-0.51 ± 0.02	-0.54 ± 0.02	-0.30 ± 0.01	-0.53 ± 0.02	-0.53 ± 0.02	-0.53 ± 0.02
Tennant Creek	-0.20 ± 0.02	-0.25 ± 0.02	0.15 ± 0.02	-0.25 ± 0.02	0.02 ± 0.02	0.07 ± 0.02
Alice Springs	0.29 ± 0.02	0.04 ± 0.02	0.63 ± 0.02	0.16 ± 0.02	0.18 ± 0.02	0.19 ± 0.02
Woomera	-0.05 ± 0.02	-0.13 ± 0.02	0.23 ± 0.02	-0.08 ± 0.03	0.13 ± 0.02	0.10 ± 0.02
Ceduna	-0.27 ± 0.03	-0.37 ± 0.03	0.08 ± 0.03	-0.33 ± 0.03	-0.07 ± 0.02	-0.06 ± 0.02
Adelaide Airport	-0.08 ± 0.02	-0.24 ± 0.02	0.11 ± 0.02	-0.16 ± 0.02	-0.16 ± 0.02	-0.16 ± 0.02
Adelaide (Kent Town)	-0.31 ± 0.02	-0.37 ± 0.02	-0.06 ± 0.02	-0.34 ± 0.02	-0.33 ± 0.02	-0.33 ± 0.02
Mount Gambier	-0.48 ± 0.02	-0.70 ± 0.03	-0.23 ± 0.02	-0.60 ± 0.03	-0.31 ± 0.02	-0.31 ± 0.02
Mount Isa	0.05 ± 0.03	-0.17 ± 0.03	0.46 ± 0.02	-0.10 ± 0.03	0.30 ± 0.02	0.30 ± 0.02
Cairns	-0.47 ± 0.01	-0.76 ± 0.02	-0.36 ± 0.01	-0.62 ± 0.02	-0.45 ± 0.01	-0.43 ± 0.02
Townsville	-0.16 ± 0.02	-0.57 ± 0.01	-0.12 ± 0.02	-0.37 ± 0.02	-0.37 ± 0.02	-0.36 ± 0.02
Rockhampton	-0.37 ± 0.02	-0.71 ± 0.02	-0.18 ± 0.02	-0.55 ± 0.02	-0.51 ± 0.02	-0.38 ± 0.02
Gladstone	-0.68 ± 0.01	-0.98 ± 0.03	-0.56 ± 0.01	-0.84 ± 0.02	-0.64 ± 0.01	-0.62 ± 0.01
Amberley	-0.18 ± 0.03	-0.83 ± 0.03	0.03 ± 0.02	-0.52 ± 0.03	-0.26 ± 0.02	0.68 ± 0.04
Brisbane Airport	-0.25 ± 0.01	-0.60 ± 0.01	-0.12 ± 0.01	-0.43 ± 0.02	-0.43 ± 0.02	-0.43 ± 0.02
Charleville	-0.02 ± 0.02	-0.39 ± 0.03	0.30 ± 0.02	-0.23 ± 0.03	0.15 ± 0.02	0.13 ± 0.02
Sydney Airport	-0.19 ± 0.02	-0.37 ± 0.02	-0.08 ± 0.02	-0.28 ± 0.02	-0.28 ± 0.01	-0.28 ± 0.01
Sydney (Observatory Hill)	-0.32 ± 0.02	-0.44 ± 0.02	-0.22 ± 0.02	-0.38 ± 0.02	-0.38 ± 0.02	-0.38 ± 0.02
Nowra	-0.38 ± 0.02	-0.57 ± 0.02	-0.17 ± 0.02	-0.47 ± 0.02	-0.47 ± 0.02	-0.44 ± 0.02
Canberra	-0.33 ± 0.02	-0.46 ± 0.02	-0.01 ± 0.02	-0.40 ± 0.02	-0.35 ± 0.02	-0.33 ± 0.02
Mildura	-0.12 ± 0.02	-0.09 ± 0.03	0.21 ± 0.02	-0.10 ± 0.03	0.13 ± 0.02	0.13 ± 0.02
Melbourne RO	-0.40 ± 0.02	-0.38 ± 0.02	-0.19 ± 0.02	-0.39 ± 0.02	-0.39 ± 0.02	-0.39 ± 0.02
Launceston Airport	-0.22 ± 0.02	-0.38 ± 0.02	0.01 ± 0.02	-0.30 ± 0.02	-0.30 ± 0.02	-0.29 ± 0.02
Hobart Airport	-0.33 ± 0.02	-0.41 ± 0.02	-0.13 ± 0.02	-0.37 ± 0.02	-0.36 ± 0.02	-0.36 ± 0.02
Hobart (Ellerslie Road)	-0.51 ± 0.02	-0.59 ± 0.02	-0.35 ± 0.02	-0.55 ± 0.02	-0.55 ± 0.02	-0.55 ± 0.02

depends to some extent on the position of a station within its local time zone. This possibility cannot, however, be tested objectively without an examination of mean diurnal temperature curves with a high temporal resolution (less than 1 hour), which is not possible with the available data. The differences between methods C and D in eastern Australia are the result of the omission of the 0000 observation (which is generally cooler than the daily mean) from means calculated using the former method. In Western Australia, where the 2100 observation is omitted, the difference between the two methods is less marked.

The differences between means calculated using (max+min)/2 and those generated in post-1994 Australian CLIMAT messages are smaller (-0.14ºC) than those observed for methods based on a fixed number of fixed-hour observations (A, B and D). A specific issue in the case of method F is the possibility of large discrepancies between methods in individual months arising from temporary reductions in the number of observations. An example of this has occurred at Halls Creek (18.23ºS, 127.67ºE), a station that was not included in this study because it failed to meet the criteria for the minimum number of obser-

Table 3(b). Differences (ºC) between mean temperatures calculated by stated methods and by (max+min)/2, autumn (March-May).

Station name	*Mean calculation method*					
	A	*B*	*C*	*D*	*E*	*F*
Broome	-0.23	-0.81	-0.34	-0.54	-0.44	-0.39
Port Hedland	-0.43	-1.01	-0.47	-0.72	-0.71	-0.71
Learmonth	-0.29	-0.61	-0.31	-0.45	-0.44	-0.45
Carnarvon	-0.43	-0.61	-0.42	-0.57	-0.45	-0.43
Meekatharra	-0.10	-0.33	-0.20	-0.21	-0.22	-0.32
Geraldton	-0.63	-0.82	-0.51	-0.73	-0.69	-0.65
Perth Airport	-0.56	-0.64	-0.43	-0.60	-0.60	-0.56
Albany	-0.64	-0.93	-0.62	-0.77	-0.70	-0.65
Esperance	-0.62	-0.96	-0.69	-0.76	-0.73	-0.73
Kalgoorlie	-0.12	-0.35	-0.19	-0.27	-0.21	-0.23
Darwin	-0.55	-0.52	-0.30	-0.54	-0.53	-0.53
Tennant Creek	-0.23	-0.20	0.13	-0.22	0.01	0.05
Alice Springs	0.27	0.08	0.63	0.18	0.19	0.20
Woomera	-0.07	-0.06	0.22	-0.04	0.13	0.12
Ceduna	-0.21	-0.31	0.14	-0.26	0.00	0.01
Adelaide Airport	-0.03	-0.23	0.15	-0.13	-0.13	-0.13
Adelaide (Kent Town)	-0.27	-0.39	-0.05	-0.33	-0.31	-0.31
Mount Gambier	-0.55	-0.69	-0.33	-0.60	-0.40	-0.40
Mount Isa	-0.01	-0.03	0.39	-0.02	0.24	0.26
Cairns	-0.58	-0.80	-0.47	-0.68	-0.54	-0.53
Townsville	-0.19	-0.56	-0.15	-0.38	-0.38	-0.38
Rockhampton	-0.42	-0.72	-0.25	-0.57	-0.54	-0.44
Gladstone	-0.69	-0.97	-0.58	-0.83	-0.66	-0.63
Amberley	-0.23	-0.95	-0.06	-0.60	-0.33	0.45
Brisbane Airport	-0.40	-0.72	-0.27	-0.56	-0.56	-0.56
Charleville	0.00	-0.48	0.27	-0.27	0.13	0.11
Sydney Airport	-0.10	-0.33	-0.03	-0.21	-0.22	-0.22
Sydney (Observatory Hill)	-0.28	-0.38	-0.17	-0.33	-0.33	-0.33
Nowra	-0.46	-0.60	-0.23	-0.53	-0.53	-0.51
Canberra	-0.40	-0.54	-0.10	-0.47	-0.43	-0.43
Mildura	-0.27	-0.07	0.14	-0.14	0.06	0.07
Melbourne RO	-0.38	-0.31	-0.15	-0.35	-0.35	-0.35
Launceston Airport	-0.26	-0.42	-0.04	-0.34	-0.33	-0.31
Hobart Airport	-0.31	-0.39	-0.12	-0.35	-0.35	-0.35
Hobart (Ellerslie Road)	-0.48	-0.53	-0.33	-0.51	-0.50	-0.50

vations per day, but which reports CLIMAT messages. In September 1995 the observation schedule was temporarily reduced to four observations per day, at 0600, 0900, 1200, and 1500 local time. The absence of night-time observations created a sharp upward bias in the mean of the available fixed-hour observations, which was 30.6ºC, compared with a mean of 29.2ºC using (max+min)/2.

Whilst seasonal changes vary from station to station, averaged across Australia as a whole, the differences for most methods are smallest in spring. There are minimal differences between the other three seasons for each individual method.

Conclusions

The results of this study indicate that a change from the use of (max+min)/2 to a mean based on regular fixed-hour observations (as recommended in the WMO Guide to Climatological Practices) would introduce an inhomogeneity of between -0.18ºC and -0.43ºC into the Australian mean temperature record. This would be a substantial inhomogeneity in the context of the overall Australian temperature trend, which has been estimated (Torok and Nicholls 1996) at 0.54ºC/century for maxima and 0.98ºC/century for minima over the 1910-1993 period. The use of 24 hourly observations could

Table 3(c). Differences (ºC) between mean temperatures calculated by stated methods and by (max+min)/2, winter (June - August).

Station name	*Mean calculation method*					
	A	*B*	*C*	*D*	*E*	*F*
Broome	-0.13	-0.87	-0.31	-0.50	-0.43	-0.33
Port Hedland	-0.40	-0.96	-0.39	-0.68	-0.67	-0.65
Learmonth	-0.11	-0.41	-0.10	-0.26	-0.25	-0.26
Carnarvon	-0.29	-0.34	-0.23	-0.36	-0.27	-0.27
Meekatharra	-0.10	-0.32	-0.15	-0.21	-0.21	-0.33
Geraldton	-0.59	-0.65	-0.43	-0.62	-0.59	-0.58
Perth Airport	-0.50	-0.53	-0.38	-0.51	-0.51	-0.51
Albany	-0.50	-0.60	-0.41	-0.58	-0.46	-0.44
Esperance	-0.62	-0.77	-0.58	-0.68	-0.63	-0.63
Kalgoorlie	-0.14	-0.44	-0.18	-0.33	-0.22	-0.22
Darwin	-0.76	-0.66	-0.41	-0.71	-0.71	-0.71
Tennant Creek	-0.33	-0.17	0.12	-0.27	-0.01	0.05
Alice Springs	0.02	0.01	0.52	0.02	0.03	0.03
Woomera	-0.21	-0.18	0.11	-0.16	0.01	0.00
Ceduna	-0.43	-0.36	0.01	-0.40	-0.14	-0.13
Adelaide Airport	-0.06	-0.17	0.09	-0.11	-0.11	-0.11
Adelaide (Kent Town)	-0.25	-0.30	-0.07	-0.28	-0.27	-0.27
Mount Gambier	-0.35	-0.51	-0.21	-0.42	-0.26	-0.26
Mount Isa	-0.02	0.03	0.56	-0.04	0.39	0.41
Cairns	-0.59	-0.78	-0.41	-0.66	-0.50	-0.48
Townsville	0.00	-0.50	0.08	-0.25	-0.25	-0.25
Rockhampton	-0.31	-0.60	-0.03	-0.46	-0.41	-0.30
Gladstone	-0.68	-0.93	-0.55	-0.81	-0.62	-0.60
Amberley	-0.13	-0.81	0.17	-0.54	-0.14	0.77
Brisbane Airport	-0.36	-0.74	-0.20	-0.55	-0.55	-0.55
Charleville	-0.18	-0.41	0.23	-0.28	0.05	0.05
Sydney Airport	-0.10	-0.23	0.06	-0.17	-0.17	-0.17
Sydney (Observatory Hill)	-0.32	-0.38	-0.18	-0.35	-0.35	-0.36
Nowra	-0.40	-0.57	-0.22	-0.49	-0.49	-0.47
Canberra	-0.28	-0.39	-0.01	-0.34	-0.30	-0.29
Mildura	-0.39	-0.22	-0.01	-0.29	-0.08	-0.07
Melbourne RO	-0.28	-0.16	-0.07	-0.22	-0.22	-0.22
Launceston Airport	-0.08	-0.21	0.06	-0.14	-0.14	-0.14
Hobart Airport	-0.19	-0.23	-0.03	-0.21	-0.21	-0.20
Hobart (Ellerslie Road)	-0.31	-0.31	-0.17	-0.31	-0.31	-0.31

become feasible with impending improvements in the archiving of hourly data, but the results of Barg (1976), who found that means calculated using 24 hourly observations were similar to those calculated using eight three-hourly observations in Germany, suggest that it would result in an inhomogeneity of similar magnitude to those found using three- or six-hourly observations.

This study indicates that inhomogeneities would occur in all seasons, although they would be somewhat smaller in spring than in other seasons.

The magnitude of these systematic differences reinforces the importance of documenting the method of calculation of mean temperature throughout the period of observations prior to assessing trends in observed temperature.

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Table 3(d). Differences (ºC) between mean temperatures calculated by stated methods and by (max+min)/2, spring (September - November).

Station name	*Mean calculation method*					
	A	*B*	*C*	*D*	*E*	*F*
Broome	-0.12	-0.85	-0.35	-0.48	-0.44	-0.38
Port Hedland	-0.11	-1.15	-0.32	-0.63	-0.62	-0.60
Learmonth	-0.45	-1.05	-0.54	-0.75	-0.75	-0.75
Carnarvon	-0.16	-0.64	-0.30	-0.45	-0.34	-0.35
Meekatharra	0.21	-0.14	0.00	0.04	0.03	-0.14
Geraldton	-0.12	-0.68	-0.17	-0.40	-0.37	-0.31
Perth Airport	-0.20	-0.53	-0.23	-0.37	-0.37	-0.37
Albany	-0.45	-0.79	-0.42	-0.62	-0.51	-0.50
Esperance	-0.75	-1.11	-0.76	-0.93	-0.84	-0.82
Kalgoorlie	-0.01	-0.29	-0.10	-0.19	-0.12	-0.07
Darwin	-0.42	-0.55	-0.28	-0.48	-0.48	-0.48
Tennant Creek	-0.03	-0.21	0.29	-0.16	0.15	0.22
Alice Springs	0.46	0.05	0.76	0.26	0.27	0.28
Woomera	0.07	-0.25	0.30	-0.12	0.18	0.16
Ceduna	-0.17	-0.47	0.13	-0.33	-0.04	-0.02
Adelaide Airport	-0.01	-0.26	0.15	-0.14	-0.14	-0.14
Adelaide (Kent Town)	-0.24	-0.43	-0.03	-0.34	-0.33	-0.33
Mount Gambier	-0.32	-0.66	-0.10	-0.48	-0.19	-0.18
Mount Isa	0.30	-0.16	0.69	0.02	0.51	0.53
Cairns	-0.28	-0.73	-0.24	-0.52	-0.34	-0.32
Townsville	-0.12	-0.67	-0.14	-0.40	-0.40	-0.40
Rockhampton	-0.33	-0.85	-0.16	-0.60	-0.54	-0.37
Gladstone	-0.75	-1.12	-0.64	-0.95	-0.73	-0.71
Amberley	-0.05	-0.80	0.14	-0.42	-0.20	0.97
Brisbane Airport	-0.04	-0.51	0.06	-0.28	-0.28	-0.28
Charleville	0.15	-0.30	0.48	-0.13	0.31	0.31
Sydney Airport	-0.14	-0.46	-0.08	-0.30	-0.30	-0.30
Sydney (Observatory Hill)	-0.30	-0.55	-0.23	-0.42	-0.42	-0.42
Nowra	-0.27	-0.54	-0.06	-0.41	-0.41	-0.40
Canberra	-0.08	-0.38	0.19	-0.23	-0.17	-0.14
Mildura	0.04	-0.10	0.33	-0.02	0.23	0.23
Melbourne RO	-0.34	-0.48	-0.18	-0.41	-0.41	-0.41
Launceston Airport	-0.17	-0.42	0.04	-0.30	-0.30	-0.29
Hobart Airport	-0.29	-0.47	-0.11	-0.38	-0.37	-0.36
Hobart (Ellerslie Road)	-0.54	-0.73	-0.40	-0.64	-0.64	-0.64

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Table 3(e). Differences (ºC) between mean temperatures calculated by stated methods and by (max+min)/2, summer (December - February).

Station name	*Mean calculation method*					
	A	*B*	*C*	*D*	*E*	*F*
Broome	-0.33	-0.57	-0.32	-0.46	-0.38	-0.38
Port Hedland	-0.51	-1.02	-0.55	-0.76	-0.75	-0.75
Learmonth	-1.10	-1.32	-0.94	-1.21	-1.21	-1.21
Carnarvon	-0.83	-1.11	-0.83	-1.02	-0.89	-0.89
Meekatharra	0.05	-0.18	-0.15	-0.07	-0.09	-0.21
Geraldton	-0.56	-0.98	-0.50	-0.76	-0.71	-0.60
Perth Airport	-0.36	-0.49	-0.30	-0.42	-0.42	-0.42
Albany	-0.72	-0.91	-0.60	-0.81	-0.70	-0.67
Esperance	-0.89	-1.18	-0.88	-1.05	-0.94	-0.93
Kalgoorlie	-0.13	-0.10	-0.21	-0.15	-0.15	-0.07
Darwin	-0.32	-0.43	-0.21	-0.37	-0.37	-0.37
Tennant Creek	-0.21	-0.44	0.04	-0.37	-0.08	-0.03
Alice Springs	0.41	0.02	0.63	0.21	0.22	0.23
Woomera	0.03	-0.01	0.28	-0.02	0.20	0.10
Ceduna	-0.29	-0.33	0.03	-0.33	-0.09	-0.10
Adelaide Airport	-0.24	-0.31	0.04	-0.27	-0.27	-0.27
Adelaide (Kent Town)	-0.47	-0.37	-0.08	-0.42	-0.41	-0.41
Mount Gambier	-0.72	-0.93	-0.28	-0.90	-0.40	-0.39
Mount Isa	-0.10	-0.52	0.16	-0.38	0.03	0.00
Cairns	-0.42	-0.72	-0.33	-0.61	-0.41	-0.40
Townsville	-0.32	-0.56	-0.25	-0.44	-0.44	-0.44
Rockhampton	-0.44	-0.68	-0.26	-0.57	-0.53	-0.41
Gladstone	-0.61	-0.91	-0.48	-0.76	-0.55	-0.55
Amberley	-0.34	-0.75	-0.14	-0.55	-0.38	0.51
Brisbane Airport	-0.20	-0.43	-0.06	-0.31	-0.31	-0.31
Charleville	-0.04	-0.36	0.23	-0.25	0.10	0.06
Sydney Airport	-0.41	-0.48	-0.29	-0.45	-0.45	-0.45
Sydney (Observatory Hill)	-0.40	-0.46	-0.29	-0.43	-0.43	-0.43
Nowra	-0.39	-0.54	-0.16	-0.47	-0.46	-0.40
Canberra	-0.58	-0.51	-0.12	-0.55	-0.48	-0.47
Mildura	0.13	0.02	0.37	0.03	0.30	0.28
Melbourne RO	-0.61	-0.59	-0.37	-0.60	-0.60	-0.60
Launceston Airport	-0.35	-0.47	-0.04	-0.41	-0.42	-0.41
Hobart Airport	-0.52	-0.55	-0.25	-0.54	-0.53	-0.52
Hobart (Ellerslie Road)	-0.73	-0.78	-0.50	-0.75	-0.75	-0.75

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Table 4. National means of differences (ºC) between mean temperatures calculated by stated methods and by (max+min)/2

Period	*Mean calculation method*					
	A	*B*	*C*	*D*	*E*	*F*
Autumn (Mar - May)	-0.21	-0.43	-0.04	-0.32	-0.20	-0.17
Winter (Jun - Aug)	-0.25	-0.42	-0.02	-0.34	-0.20	-0.16
Spring (Sep - Nov)	-0.03	-0.45	0.08	-0.25	-0.10	-0.06
Summer (Dec - Feb)	-0.21	-0.43	-0.07	-0.34	-0.20	-0.19
Annual	-0.17	-0.43	-0.01	-0.31	-0.17	-0.14