Send Orders for Reprints to reprints@benthamscience.ae

The Open Atmospheric Science Journal, 2016, *10*, 39-55

The Open Atmospheric Science Journal

Content list available at: www.benthamopen.com/TOASCJ/

DOI: 10.2174/1874282301610010039

RESEARCH ARTICLE

Seasonal and Annual Trends in Australian Minimum/Maximum Daily Temperatures

W. A. van Wijngaarden* and A. Mouraviev

Physics Department, Petrie Building, York University, 4700 Keele St., Toronto, ON Canada

Received: July 14, 2016 Revised: August 29, 2016 Accepted: September 02, 2016

Abstract: Seasonal and annual trends in Australian minimum and maximum temperatures were studied. Records of daily minimum and maximum temperatures averaged over each month, extending as far back as 1856 were examined. Over 1/2 million monthly temperature values were retrieved from the Australian Bureau of Meteorology for 299 stations. Each station had an average of 89 years of observations. Significant step discontinuities affected the maximum temperature data in the 19th century when Stevenson screens were installed. The temperature trends were found after such spurious data were removed and averaged over all stations. The resulting trend in the minimum (maximum) daily temperature was 0.67 ± 0.19 (0.58 ± 0.26) ^{o}C per century for the period 1907-2014. Decadal fluctuations were evident in the maximum daily temperature with most of the increase occurring in the late 20th century. The minimum and maximum daily temperature trends were also found for the various seasons. The minimum daily temperature trend exceeded the maximum daily temperature trend for all seasons except during June to August. The largest increases in minimum temperature as well as the smallest maximum temperature increases were found for the region north of 30 ^{o}S latitude and east of 140 ^{o}E longitude. There was also evidence that urban stations had greater increases in maximum daily temperature than those located in a rural environment.

Keywords: Minimum/Maximum daily temperatures, Seasonal effects, Step inhomogeneity detection, Trends.

INTRODUCTION

Archival records of temperature provide invaluable information for studying climate change [1]. Stations with the longest data records are predominantly located in the Northern Hemisphere, especially in Western Europe and the United States [2]. For the Southern Hemisphere, Australia has records extending as far back as 1856 [3]. Its meteorological instruments and procedures are likely to be more uniform than in the case of Europe or South America which have many national jurisdictions. This is important as changes in apparatus or observation methodology can cause inhomogeneities that if not taken properly into account can significantly perturb temperature trends [4 - 9].

A second reason to study Australia is to examine whether there is any difference between trends in minimum and maximum daily temperatures. Some studies have found the minimum daily temperature appears to be increasing more than the maximum daily temperature due to turbulent mixing of warmer air to the surface caused by changes in the intensity of the stable boundary layer, for example, due to urbanization and other local and regional land uses [10 - 13]. It has also been suggested that changing cloud cover may be partially responsible for decreasing the daily temperature range [14]. One study did find evidence of urban heat island features in southeast Australian towns [15]. It is also interesting to see if the trends exhibit a seasonal dependence. Previous work has found that Arctic and North American temperatures have increased more during December to May than during June to November [6, 16].

A number of studies have analyzed Australian temperatures [17 - 19]. In particular, the Australian Bureau of Meteorology (BOM) provides the monthly averaged minimum and maximum daily temperatures, hereafter just referred

* Address correspondence to this author at the Centre for Physics Department, Petrie Building, York University, 4700 Keele St., Toronto, ON Canada; Tel/Fax: 416-736-2100 x77750; E-mail: wlaser@yorku.ca

to as the minimum and maximum temperatures, at a number of stations [3]. This includes data that is a composite of observations made at different sites near a given location. The resulting time series at many stations have obvious inhomogeneities. Torok and Nicholls [17] examined data from 224 stations covering the period 1910-1994. Some of these time series were created by making a composite of data observed at nearby stations. Various statistical analyses were used to compare each time series to nearby stations to detect and correct discontinuities. The mean number of adjustments to minimum (maximum) temperature was 6.6 (6.1) per station. Minimum and maximum temperatures were found to have both increased since 1950, with minimum temperatures increasing more than the maximum temperatures.

Daily minimum and maximum temperatures have been studied for 38 stations in southeastern Australia for the period 1860-2009 [20]. The data were examined for inhomogeneities and reference series were created using neighbouring station data. Over half of the nearly 200 adjustments made to each of the minimum and maximum temperature data during 1860-1950 were supported by changes recorded in the station histories. The minimum temperature appears to have steadily increased by about 1 ^{o}C during the last century and a half. The maximum temperature appears to have been about stable until 2000 when it increased abruptly by about 0.5 ^{o}C.

A homogenized daily minimum and maximum temperature dataset has been generated by the Australian Climate Observations Reference Network (ACORN) [19, 21 - 23]. This network consists of 112 stations and covers the period from 1910 onwards. Sixty of the stations have data for every month in all years during 1910-2014. Inhomogeneities arising from changes in instruments and the station site location were detected using a combination of metadata and statistical methods. A so called percentile matching algorithm was developed to make adjustments to correct the data. The adjusted ACORN data of daily minimum and maximum temperatures is available from the Australian Bureau of Meteorology [3]. Australian data has also been analyzed by NOAA's National Climate Data Center as part of the Global Historical Climate Network (GHCN) analysis and both raw and adjusted monthly averaged minimum and maximum daily temperatures are available from the Royal Dutch Meteorological Institute and NOAA's National Center for Environmental Information [2, 24]. The adjustments made to station data by ACORN and GHCN ranged from a few hundredths of a degree to nearly 2 ^{o}C and do not always agree with each other. A very small annual temperature adjustment may result from positive and negative adjustments made in different seasons. The inhomogeneities are not always apparent nor supported by station history metadata and concerns have been raised about their accuracy [25]. The ACORN analysis unlike that of GHCN did have access to metadata. ACORN has made a valiant effort to record the history of each station [22, 23]. Unfortunately, the available documentation does not adequately describe all pertinent changes to the measurement site and/or relocation of meteorological instruments. The station data have also been used to develop gridded datasets with a resolution of 0.05^{o} x 0.05^{o} [18].

This study examined the minimum and maximum temperatures observed at 299 stations. Each time series was first checked for inhomogeneities. Spurious data were removed rather than attempting to make corrective adjustments. The change in temperature relative to the 20th century was computed and averaged over all stations. The minimum and maximum temperature trends were then found. The results agreed closely with the ACORN and GHCN analyses that independently adjusted data for inhomogeneities, but the present work considered a longer time interval of 1880-2015 and considerably more stations. The trends did exhibit decadal variations. Seasonal trends were also found. The trend dependences on latitude and longitude as well as whether the station was located in either a rural or urban environment were also examined.

DATA ANALYSIS

Monthly averaged daily minimum and maximum values were downloaded from the Australian Bureau of Meteorology [3]. Stations were considered that had at least 50 years of data or were in close proximity to an ACORN station or a part of the ACORN network. The annual and seasonal averages were only computed if all monthly values in a year or season were present. The 299 stations listed in the **Appendix A** had an average of 89 years of observations. Fig. (**1**) shows the station locations. The longest records of observations were found for Melbourne and Sydney where data extend back to the 1850s. A significant increase in the number of operating stations occurred in 1907. A number of stations closed in recent decades. Annual averaged minimum and maximum temperatures could be found for 88% of the years that stations were operational. Stations having daily data for the ACORN network as well as monthly adjusted data from the GHCN archive are listed in the **Appendix B**.

The temperature relative to the 20th century was computed. This extended reference period, as opposed to the period 1961-1990, was chosen since a number of stations closed before 1961. The different reference periods changed the trends by considerably less than the trend uncertainty. It was evident that a number of stations had spurious data as is

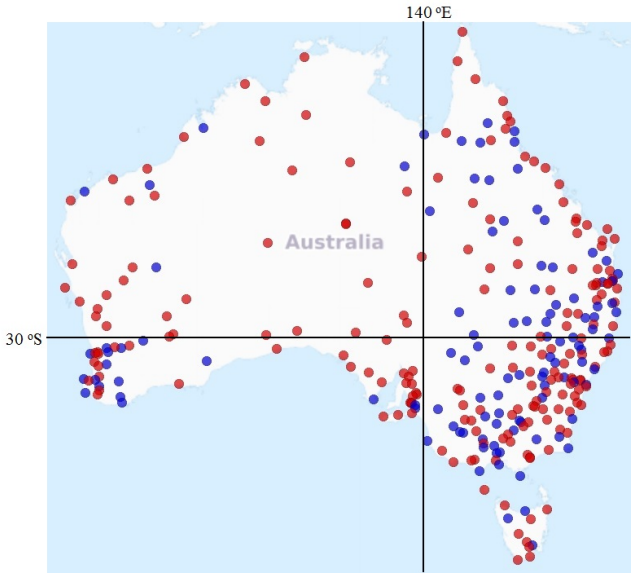

Fig. (1). Stations examined in this study. A red (blue) circle denotes a station where data was taken for less (more) than 100 years.

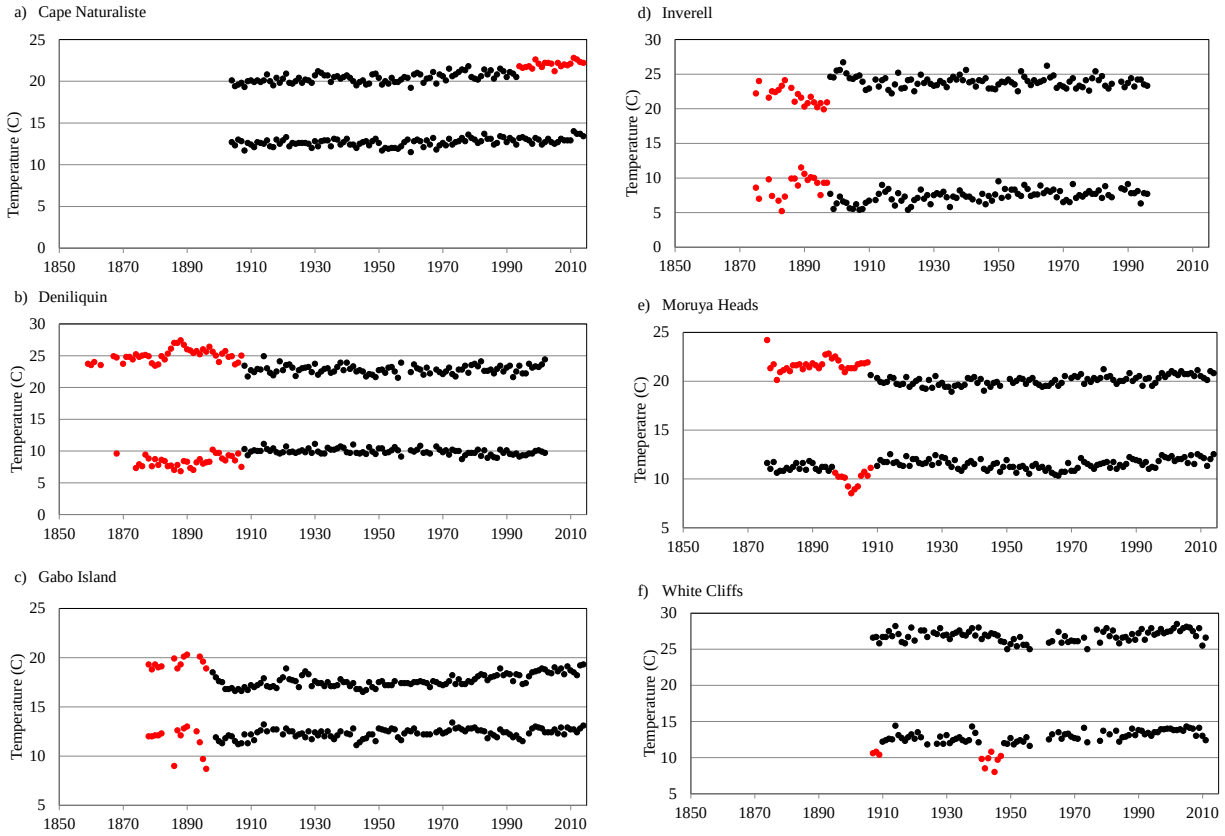

Fig. (2). The average minimum and maximum annual temperature data are plotted for various stations. The red points are suspect as is discussed in the text.

illustrated in Fig. (**2**). Some data values were very distant from the average minimum or maximum temperatures. This occurred most often when a station began operation in the late 1800s as is shown for Deniliquin, Gabo Island and Inverell. The same stations also had missing observations for a number of years during their first two decades of operation. Step discontinuities were also evident in some time series. These frequently preceded a gap in the data which

may indicate that either two different time series were appended or a change in instruments had occurred. Most of these steps occurred in the late 1800s as shown by the data for Deniliquin, Moruya Heads and White Cliffs. However, the data for a few stations show a sudden upward jump during the 20th century such as occurred in the maximum temperature for Cape Naturaliste in 1994. These temperature discontinuities were not exhibited at nearby stations indicating that they are not the result of a climate fluctuation.

This study adopted two criteria for determining whether a data point was spurious and required removal. The first criterion was to keep the first two decades of data only if data were present for at least two thirds of those years. Many time series of stations starting operation in the late 19th century exhibited missing data that cast doubt on the reliability of the observations. The second criterion was to detect step discontinuities [5, 7 - 9]. The data in each time series was examined as follows. For a minimum or maximum temperature occurring at year t_d, the average and standard deviation were found immediately before and after, over intervals $[t_d - N_s + 1, t_d]$ and $[t_d + 1, t_d + N_s]$. The means (standard deviations) evaluated in the intervals extending over N_s years before and after year t_d were denoted by μ_L and μ_R (σ_L and σ_R), respectively. The shorter of the time series occurring either before or after year t_d was removed if $|\mu_L - \mu_R| > \sigma_L + \sigma_R$. A station time series was discarded entirely if a second discontinuity was detected.

Application of these criteria is shown in Fig. (**3**). It shows plots of the minimum and maximum daily temperature relative to the 20th century averaged over all stations for the raw data as well as when data having discontinuities were removed. The procedure to detect discontinuities was considered for the cases of N_s = 5, 6, 7, 8, 9, 10 years. Fig. (**3**) shows the amount of data discarded increased as N_s decreased from 10 to 5, as well as the result of discarding station time series in their entirety if a single discontinuity was found. However, the differences between the 5 year running

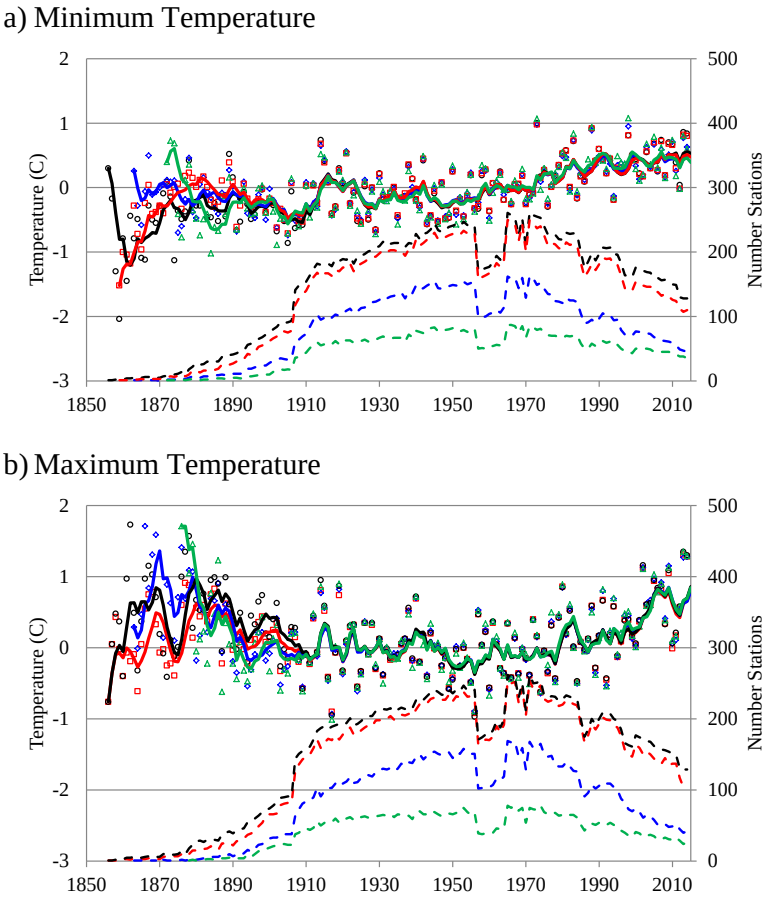

Fig. (3). Plot of (**a**) Minimum and (**b**) Maximum Temperature relative to the 20th century. Raw data are displayed as black circles. Red squares (blue diamonds) are data filtered using N_s = 10 (5) points to determine whether a discontinuity occurred as discussed in the text. Green triangles show data for stations where no discontinuities were found. The solid curves are the corresponding running 5 year averages which closely overlap in many years. The dashed curves show the corresponding number of stations.

average change in temperature for raw data and the cases of N_s = 10 - 5 were negligible for the minimum temperature data after 1880 and maximum temperatures following 1907. The differences between the curves shown in Fig. (**3**) are largest for the data in the 19th century when there are relatively few stations.

RESULTS

Table **1** shows the trends for the minimum and maximum daily temperatures for the intervals 1880-2014 and 1907-2014. The uncertainty of each trend in this study was defined by the 95% confidence interval found using the statistical t-test. The possibility of correlation effects was examined by binning the data over multi-year intervals. This had negligible effect on the trends. The 1907-2014 trends for both minimum and maximum temperature change vary little depending on the value of N_s used to determine the presence of a discontinuity. The maximum temperature trend for 1880-2014 evaluated using raw data is much smaller than the trends obtained after inhomogeneous data were discarded using N_s = 5 - 10. Table **1** also lists the trends found when time series were entirely removed if a single discontinuity was found. The time series shown in Fig. (**3**) were relatively insensitive to inhomogeneities that affect different stations at random times. Only systemic changes such as for example, the installation of Stevenson screens at all stations around 1900 will affect the averaged time series. This can be expected to have affected measurements of maximum temperatures more than minimum temperatures as the Stevenson screen prevents the exposure of the thermometer to direct sunlight.

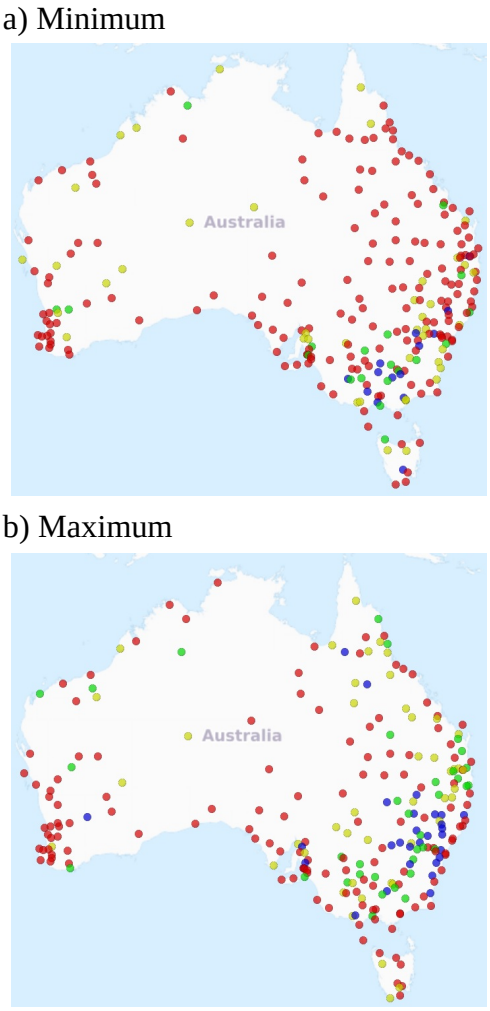

Fig. (4). Trends at stations having data present for at least 50% of all years during 1907-2014 for (**a**) Minimum and (**b**) Maximum Annual Temperature. Red (blue) dots represent increasing (decreasing) trends significant at the 5% level. Yellow (green) dots represent increasing (decreasing) trends that are not statistically significant.

Fig. (**3**) shows the minimum temperature increased steadily throughout the 20th century while the maximum temperature remained approximately constant until suddenly increasing by approximately 0.5 °C around 2000. Considering the period 1907-2000, the minimum (maximum) temperature trend was 0.64 ± 0.24 (0.18 ± 0.29) °C per century. It should be noted that a number of Australian stations either ceased to operate or data was otherwise unavailable after 2000 as is the case worldwide [11]. Considering only stations operating after 2000, the minimum (maximum) temperature trend for 1907-2014 was 0.82 ± 0.19 (0.62 ± 0.26) °C per century. These values are compatible with those listed in Table **1**.

Table 1. Minimum and maximum annual temperature trends. See the text for a discussion of how inhomogeneous data were removed.

Temperature	Description	Trend (°C per Century)	
		1880-2014	1907-2014
Minimum Temperature	Raw Data	0.64 ± 0.14	0.73 ± 0.20
	$N_S = 10$	0.52 ± 0.14	0.70 ± 0.19
	$N_S = 5$	0.55 ± 0.13	0.67 ± 0.19
	Inhomogeneous Data Removed	0.70 ± 0.14	0.73 ± 0.20
Maximum Temperature	Raw Data	0.06 ± 0.20	0.56 ± 0.26
	$N_S = 10$	0.17 ± 0.19	0.57 ± 0.25
	Ns = 5	0.28 ± 0.19	0.58 ± 0.26
	Inhomogeneous Data Removed	0.35 ± 0.19	0.58 ± 0.27

Table **2** shows the seasonal trends for the minimum and maximum temperatures for the interval 1907-2014. These trends were found after inhomogeneous data was removed using the procedure discussed previously with $N_s = 5$. The minimum and maximum temperatures increased in all seasons. The minimum temperature trend is smallest during June to August while the maximum temperature increased the least during December to February. The minimum temperature trend exceeded the maximum temperature trend for all seasons except during June to August.

Table 2. Seasonal dependence of minimum/maximum temperature trends.

Temperature	Season	Period	Trend (°C per Century)
Minimum Temperature	Dec. – Feb.	1908-2015	0.79 ± 0.28
	March – May	1907-2015	0.80 ± 0.35
	June – Aug.	1907-2015	0.50 ± 0.34
	Sept. – Nov.	1907-2015	0.65 ± 0.28
Maximum Temperature	Dec. – Feb.	1908-2015	0.46 ± 0.37
	March – May	1907-2015	0.60 ± 0.33
	June – Aug.	1907-2015	0.78 ± 0.29
	Sept. – Nov.	1907-2015	0.58 ± 0.50

Figs. (**4**-**6**) show the trends for stations having at least 50% of data for all years during 1907-2015. The trend significance was found using a t-test at the 5% level. It appears that especially in southeastern Australia that the maximum temperatures are increasing more for stations near the coast but some cooling is evident at inland stations. The reason for this is not clear although a number of these coastal stations are in an urban environment. Table **3** shows 70% (55%) of all stations exhibited statistically significant increasing annual minimum (maximum) temperature trends. Only 6% (12%) of stations exhibited statistically significant decreasing annual minimum (maximum) temperature trends. Less than 14% of stations exhibited statistically significant decreasing minimum or maximum temperature trends in any season. The percentage of stations experiencing increasing/decreasing temperature trends did not drastically change if stations having at least 75% of data for all years during 1907-2015 were considered; only the total number of stations decreases by about half. For example, the percentage of stations exhibiting statistically significant increasing annual minimum (maximum) temperature trends was 80% (54%) whereas 7% (14%) of stations exhibited statistically significant decreasing annual minimum (maximum) temperature trends.

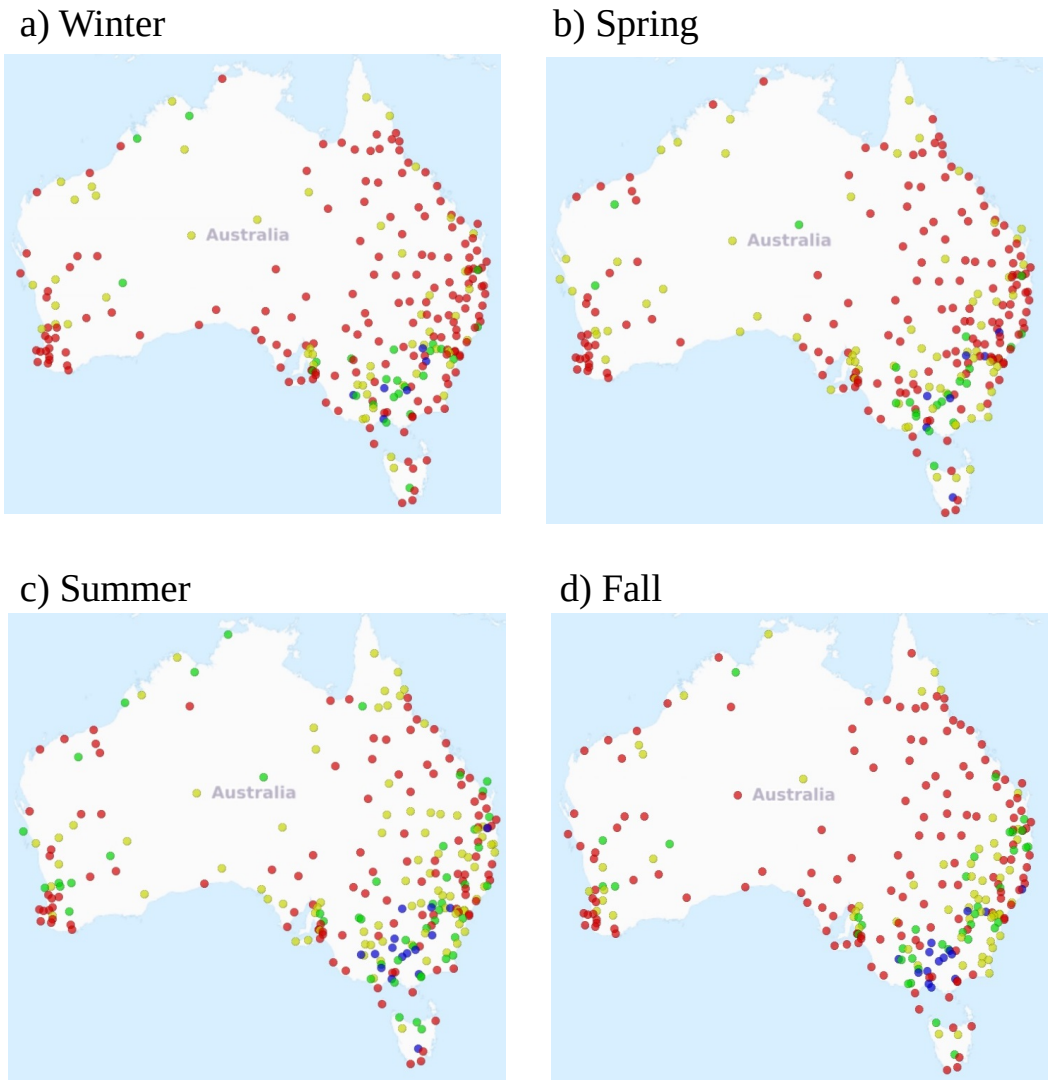

Fig. (5). Minimum Temperature trends at stations having data present for at least 50% of all years during 1907-2015 for (**a**) December – February, (**b**) March - May, (**c**) June - August and (**d**) September - November. Red (blue) dots represent increasing (decreasing) trends significant at the 5% level. Yellow (green) dots represent increasing (decreasing) trends that are not statistically significant.

Table 3. Number of stations experiencing statistically significant increasing/decreasing temperature trends in Figs. (4 - 6). The number of trends that is not statistically significant is in brackets.

Temperature	Time Period	Number Stations with Increasing Trend	Number Stations with Decreasing Trend	Total Station Number
Minimum	Annual	175 (41)	14 (19)	249
	Dec. – Feb.	169 (53)	7 (24)	253
	March – May	159 (70)	7 (21)	257
	June – Aug.	113 (81)	16 (48)	258
	Sept. – Nov.	144 (62)	15 (37)	258
Maximum	Annual	135 (45)	29 (35)	244
	Dec. – Feb.	84 (80)	34 (54)	252
	March – May	123 (78)	13 (40)	258
	June – Aug.	163 (61)	6 (28)	258
	Sept. – Nov.	95 (67)	33 (62)	257

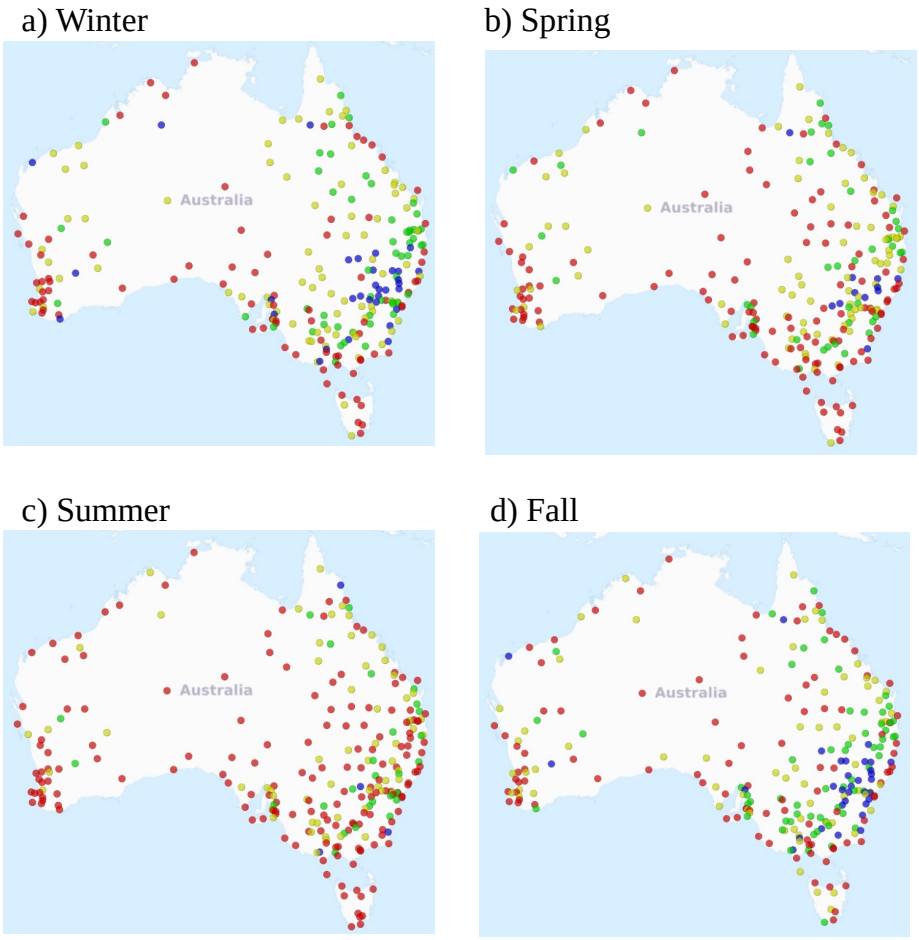

Fig. (6). Maximum Temperature trends at stations having data present for at least 50% of all years during 1907-2015 for (**a**) December - February, (**b**) March – May, (**c**) June - August and (**d**) September - November. Red (blue) dots represent increasing (decreasing) trends significant at the 5% level. Yellow (green) dots represent increasing (decreasing) trends that are not statistically significant.

Table 4. Latitude/longitudinal dependence of annual temperature trends for 1907-2014.

Temperature	Latitude	Longitude	Trend (°C per Century)	Number Stations
Minimum Temperature	North of 30 °S	East of 140 °E	0.98 ± 0.26	77
		West of 140 °E	0.61 ± 0.23	37
	South of 30 °S	East of 140 °E	0.30 ± 0.22	128
		West of 140 °E	0.77 ± 0.21	57
Maximum Temperature	North of 30 °S	East of 140 °E	0.30 ± 0.22	77
		West of 140 °E	0.68 ± 0.29	37
	South of 30 °S	East of 140 °E	0.57 ± 0.34	128
		West of 140 °E	0.69 ± 0.28	57

The latitudinal and longitudinal trend dependence is shown in Table **4**. The minimum temperature trend increased much more than the maximum temperature trend for the region north of 30 °S latitude and east of 140 °E longitude. The difference between minimum and maximum temperature trends was not significant for other parts of Australia. Table **5** also shows evidence that urban stations experienced a somewhat greater increase in maximum temperature than those

located in a rural environment defined as a region having a population under 10,000. The change in minimum temperature was comparable for both urban and rural stations. This larger increase in maximum temperature in urban areas is believed to be caused by the replacement of the natural ground cover by black asphalt, concrete *etc*. [26]. Removal of trees and vegetation eliminates cooling shade and reduces evapotranspiration [27].

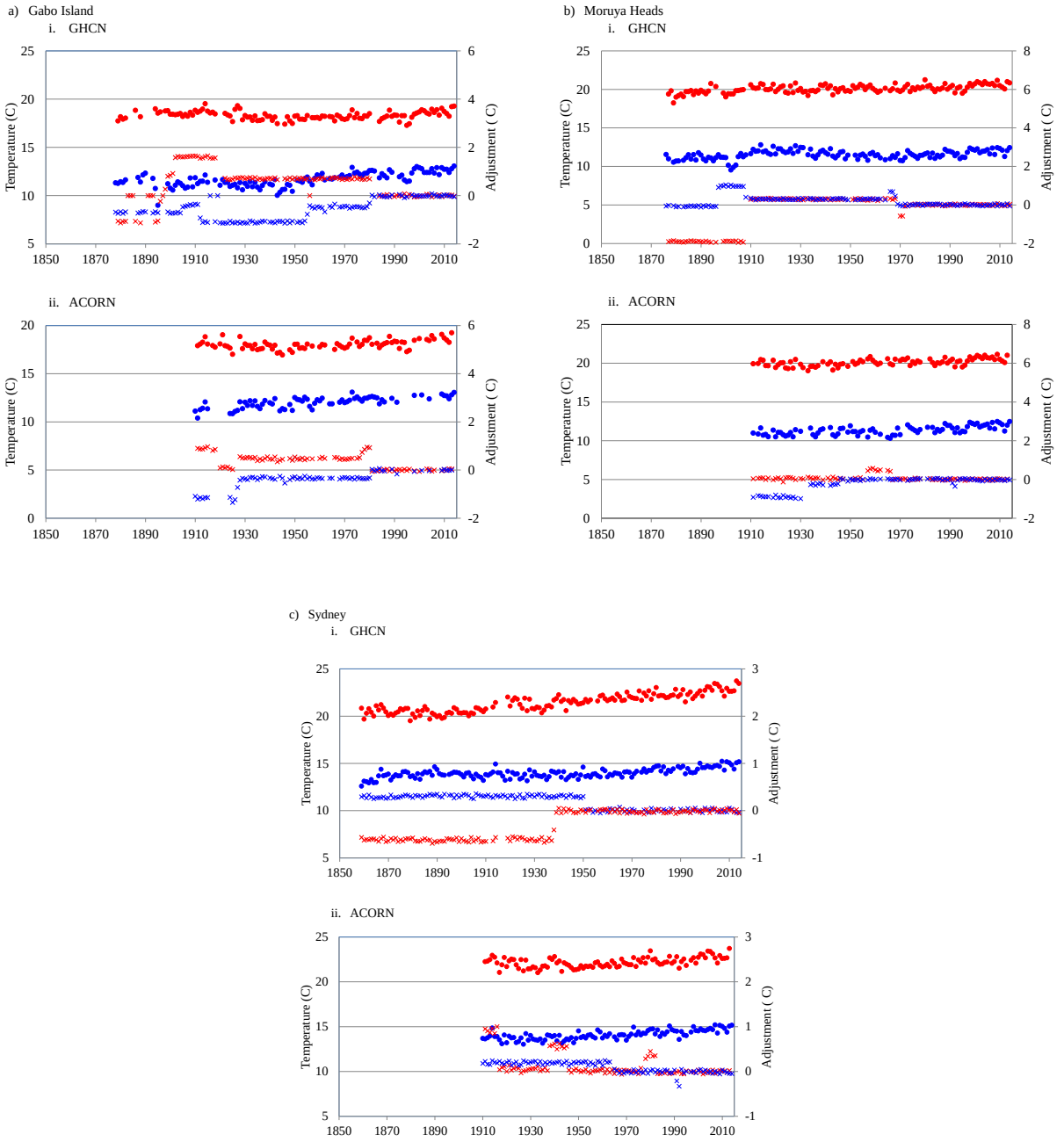

Fig. (7). GHCN and ACORN Data for (**a**) Gabo Island (**b**) Moruya Heads and (**c**) Sydney showing minimum (blue dots) and maximum (red dots) annual temperatures obtained by adding the adjustments (crosses) to the raw data.

The results were compared to the homogenized ACORN and GHCN data. The average temperature value was computed for each month using the homogenized ACORN data if not more than 3 daily values were missing. These monthly minimum and maximum temperature values were then treated as described in the previous section. An average of 67 (70) years of minimum (maximum) temperature data were available for the 112 ACORN stations. Fig. (**7**) shows the ACORN and GHCN homogenized data and adjustments for three stations. The temperature adjustments were found

using the unadjusted monthly average temperatures [2, 3, 24]. The adjustment corrections are as small as a few hundredths of a degree Centigrade which is considerably less than the measurement accuracy. Corrections as large as nearly 2 ^{o}C, affect the monthly mean data at some stations in the late 19th and early 20th centuries. This can greatly alter the resulting trend. For the case of Sydney, which has the second longest record of data available, the maximum temperature trend found using the raw data is 1.1 ± 0.2 ^{o}C per century while the GHCN adjusted data yields a trend of 1.8 ± 0.2 ^{o}C per century. The ACORN and GHCN adjustments sometimes disagree. For Sydney, the ACORN adjustment is +1 ^{o}C for the years 1910-1914 while the GHCN adjustment is -0.6 ^{o}C. Moreover, some homogenized time series still exhibit suspicious points such as the dip in the minimum temperature at Moruya Heads in the 1890s.

Table 5. Rural/urban dependence of annual temperature trends for 1907-2014. A rural station is defined as having a population under 10,000. There were 247 rural and 52 urban stations.

Temperature	Type	Trend (^{o}C per Century)
Minimum Temperature	Rural	0.68 ± 0.19
	Urban	0.67 ± 0.18
Maximum Temperature	Rural	0.54 ± 0.27
	Urban	0.77 ± 0.24

Fig. (**8**) plots the minimum and maximum temperatures relative to the 20th century for the time series found by averaging the adjusted ACORN and GHCN data over available stations given in Appendices A and B with that obtained using the procedure for discarding inhomogeneous data discussed in this paper. The data is only plotted in Fig. (**8**) if at least 5 stations report data in a given year. The 5 year averaged curves of the ACORN analysis and this work nearly overlap in all years. There are some differences with the GHCN analysis. The GHCN minimum and maximum temperatures are somewhat lower than this work during the 1870s and 1880s when there were comparatively few stations. The GHCN maximum temperatures are higher than both the ACORN analysis and this work after 2000. These differences are not surprising given that the three analyses used different station datasets. Indeed, the same results are obtained for the period after 2000 if one only considers the subset of stations common to all three datasets. Closely overlapping minimum and maximum temperatures were obtained during the 20th century when the three datasets were comprised of the largest number of stations. The three independent analyses show similar decadal fluctuations in the minimum/maximum temperatures. Most notably, all indicate an increase in maximum temperature of about 0.5 ^{o}C occurred around 2000. This agrees with a previous study that examined data obtained for stations located in southeastern Australia [20].

CONCLUSION

There are significant downward step discontinuities affecting Australian temperature data in the 19th century. This is not altogether surprising given that Stevenson screens were not universally installed until around 1900. These would have the effect of reducing the observed maximum temperature. The maximum temperature trend for Australia therefore is significantly different if raw or adjusted data is used. In contrast, the minimum temperature trends found using the raw and adjusted data are comparable.

This study found trends after inhomogeneous data were removed. The resulting time series found by averaging the temperatures relative to the 20th century for 299 stations agreed closely with the ACORN and GHCN analysis. In contrast to the present work, the ACORN and GHCN datasets each made multiple adjustments to the minimum and maximum temperatures observed at each station, and their adjustments frequently disagreed. For the ACORN dataset comprised of 112 stations, over 1,000 adjustments were made to the minimum and maximum temperatures. Many adjustments did not correspond with evident inhomogeneities in the original time series nor did they coincide with changes recorded in the station metadata history. Climate studies frequently wish to determine the temperature change occurring over a large geographical region. This work shows that averaging the temperature anomalies over many stations after large inhomogeneities have been discarded, gives a reliable estimate of the temperature trends. The reason is that small random temperature adjustments, which may be difficult if not impossible to accurately estimate at a given station, do not dramatically affect the average temperature trend.

Minimum daily temperatures over Australia have increased steadily throughout the 20th century. Maximum temperatures remained nearly constant until abruptly increasing around 2000. Similar temporal temperature changes have also been noted elsewhere such as in Europe and the Arctic (van Wijngaarden, 2014). For the period 1907-2014, the Australian minimum (maximum) temperature trend is 0.67 ± 0.19 (0.58 ± 0.26) °C per century. The mean temperature trend was found by plotting the average of the maximum and minimum temperatures for each year during 1907-2014. This yielded a mean temperature trend of 0.63 ± 0.19 °C per century. The minimum temperature increased least during June to August while the maximum temperature increase was smallest during December to February. Northeastern Australia experienced the largest minimum and the smallest increasing maximum temperature trend. Urban stations exhibited maximum temperature trends that were about 30% larger than those experienced in rural areas. Hence, the actual Australian mean temperature change during 1907-2014 may be a bit lower if this urban heat island effect is considered. Nevertheless, this estimate is comparable to the global average temperature change observed during the 20th century [1].

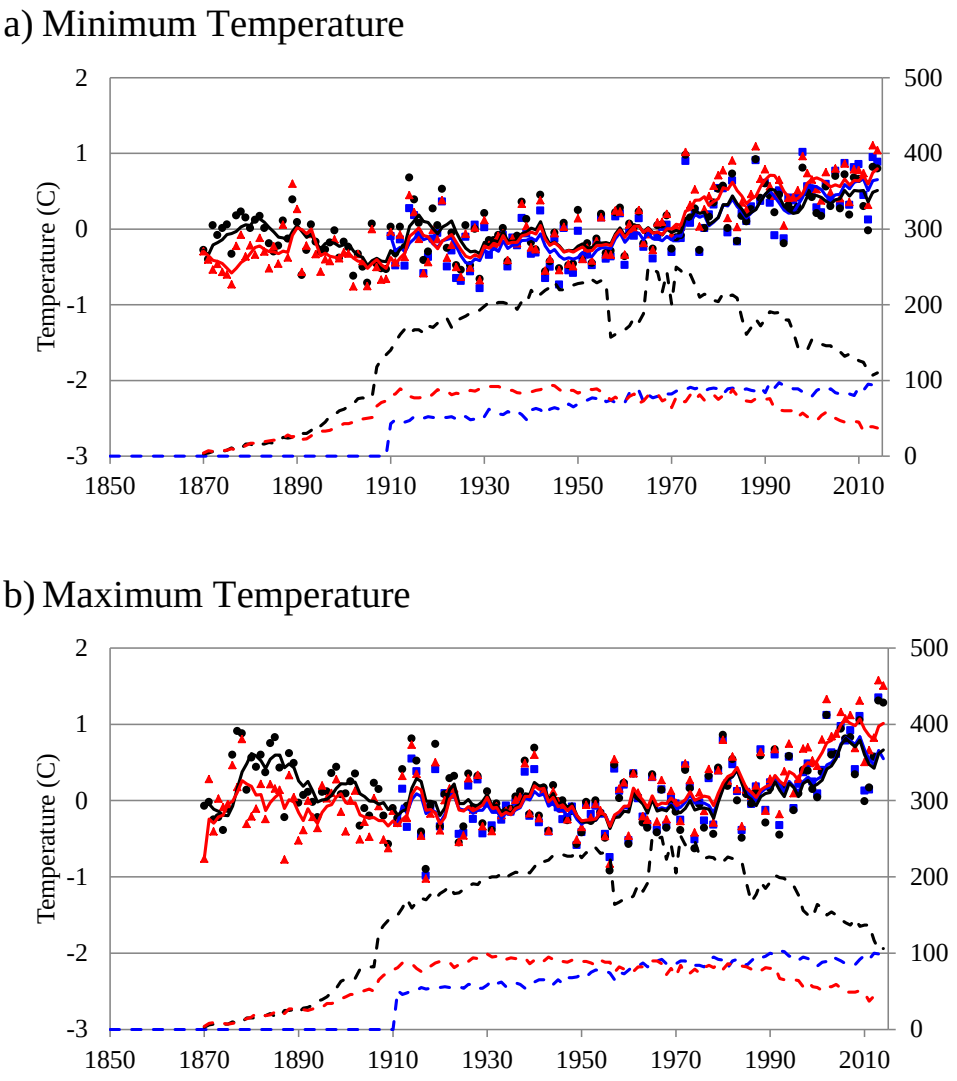

Fig. (8). Comparison of adjusted GHCN and ACORN data as well as this work relative to the 20th century for (**a**) Minimum and (**b**) Maximum Annual Temperature. The red triangles are the GHCN results, blue squares are the ACORN results and the black dots are from this work. The solid red, green and black curves are the 5 year running averages which closely overlap in many years. The dashed lines give the corresponding number of stations.

APPENDIX

Appendix A. Australian bureau of meteorology station list. [+] denotes stations where monthly data was retrieved from the corresponding GHCN dataset as discussed in the text and [1] represents a station in an urban environment having a population exceeding 10,000.

Station	BOM Number	Latitude °S	Longitude °E	Station	BOM Number	Latitude °S	Longitude °E
Adelaide West[1]	23000	34.93	138.59	Cairns[1]	31011	16.88	145.75
Adelaide Airport[1]	23034	34.93	138.52	Cambooya	41011	27.72	151.87
Adelong	72000	35.32	148.07	Camooweal[+]	37010	19.92	138.12
Albany[+]	9500	34.94	117.8	Camperdown	90011	38.22	143.15
Alexandra	88001	37.2	145.72	Canberra[1]	70351	35.3	149.18
Alice Springs[1]	15540	23.71	133.87	Canowindra	65006	33.57	148.67
Alice Springs Airport[1]	15590	23.8	133.88	Cape Borda	22801	33.75	136.6
Amberley	40004	27.63	152.72	Cape Bruny[+]	94010	43.5	147.15
Armidale[1+]	56002	30.52	151.65	Cape Leeuwin[+]	9518	34.37	115.12
Balladonia	11017	32.45	123.87	Cape Moreton[+]	40043	27.03	153.47
Ballarat[1+]	89002	37.52	143.77	Cape Naturaliste[+]	9519	33.53	115
Balranald	49002	34.63	143.55	Cape Otway[+]	90015	38.85	143.5
Barcaldine	36007	23.55	145.28	Cape Schanck	86017	38.5	144.88
Bathurst[1+]	63005	33.43	149.57	Cardwell[+]	32004	18.25	146.02
Beechworth	82001	36.32	146.67	Carnamah	8025	29.68	115.88
Bega	69002	36.67	149.82	Carnarvon	6011	27.87	113.67
Belair[1]	23703	35	138.62	Casino	58063	28.88	153.03
Benalla[+]	82002	36.55	145.98	Cassilis	62009	32	149.98
Berrigan	74009	35.67	145.82	Ceduna	18012	32.12	133.7
Beulah	77004	35.95	142.42	Charleville	44021	26.4	146.27
Biloela	39006	24.37	150.52	Charters Towers	34002	20.08	146.27
Birchip	77007	35.98	142.9	Childers	39025	25.23	152.28
Birdsville	38002	25.9	139.35	Clare	21014	33.83	138.62
Bollon[+]	44010	28.02	147.47	Clermont	35019	22.82	147.63
Bombala	77005	36.92	149.23	Cleve	18014	33.7	136.48
Boulia[+]	38003	22.92	139.9	Cloncurry	29008	20.7	140.5
Bourke[+]	48013	30.08	145.93	Clunes[+]	88015	37.3	143.78
Bowen	33007	20.02	148.25	Cobar	48027	31.48	145.82
Braidwood	69010	35.45	150	Coen	27005	13.93	143.2
Brewarrina	48015	29.97	146.87	Coffs Harbour[1]	59040	30.32	153.12
Bridgetown[+]	9510	33.95	116.13	Collarenebri	48031	29.53	148.57
Brisbane[1+]	40214	27.48	153.03	Collie	9628	33.37	116.15
Brisbane Eagle[1]	40842	27.4	153.1	Condobolin	50014	33.08	147.15
Broken Hill[1+]	47007	31.97	141.47	Cook	18110	30.62	130.4
Broome	3003	17.95	122.22	Cooktown	31016	15.43	145.18
Bundaberg[1+]	39015	24.87	152.35	Coolgardei	12018	30.95	121.17
Burdekin	33001	19.57	147.4	Coonabarabran[+]	64008	31.27	149.27
Burketown[+]	29004	17.73	139.53	Coonamble	51010	30.95	148.38
Bushy Park	95003	42.72	146.9	Cootamundra	73009	34.63	148.02
Busselton	9515	33.65	115.35	Corowa	74034	36	146.35
Butlers Gorge	96003	42.28	146.28	Crohamhurst	40062	26.82	152.85
Cabramurra	72091	35.94	148.38	Crookwell	70025	34.47	149.47
Croydon	29012	18.2	142.23	Innisfail[+]	32025	17.52	146.02
Cue[+]	7017	27.43	117.9	Inverell[+]	56017	29.77	151.1
Cunderdin	10286	31.62	117.22	Ipswich[1]	40101	27.62	152.75
Cunnamulla[+]	44026	28.07	145.73	Isisford	36026	24.27	144.43

Appendix A contd.....

Station	BOM Number	Latitude °S	Longitude °E	Station	BOM Number	Latitude °S	Longitude °E
Currie	98001	39.93	143.85	Ivanhoe	49019	32.9	144.28
Dalwallinu	8039	30.28	116.66	Jenolan Caves	63036	33.82	150.03
Darwin[1]	14015	12.4	130.87	Jerrys Plains[+]	61086	32.48	150.9
Deniliquin[+]	74128	35.55	144.93	Jervis Bay[+]	68034	35.08	150.8
Derby[+]	3007	17.3	123.62	Junee	73019	34.85	147.57
Donnybrook[+]	9534	33.57	115.82	Kalamunda[1]	9058	31.98	116.07
Dubbo[1+]	65012	32.2	148.57	Kalgoorlie-Boulder[1]	12038	30.78	121.45
Dwellingup	9538	32.72	116.05	Kalumburu	1021	14.28	126.63
East Sale[1]	85072	38.1	147.13	Kapunda	23307	34.35	138.92
Echuca[+]	80015	36.15	144.75	Katanning[+]	10579	33.68	117.55
Eddystone	92045	40.99	148.35	Katoomba[+]	63039	33.72	150.28
Emerald[+]	35027	23.53	148.17	Kellerberrin[+]	10073	31.63	117.72
Esperance	9789	33.83	121.89	Kempsey	59017	31.05	252.82
Eucla[+]	11003	31.68	128.9	Kerang[+]	80023	35.73	143.92
Euroa	82016	36.77	145.55	Killarney	41056	28.33	152.3
Farina	17024	30.07	138.27	Kingscote	22807	35.65	137.63
Forbes[+]	65016	33.38	148	Kyancutta	18044	33.12	135.55
Forrest	11052	30.38	128.12	Lady Elliot	39059	24.1	152.7
Gabo Island[+]	84016	37.57	149.9	Lake Cargelligo	75039	33.28	146.37
Gatton-Lawes	40082	27.55	152.33	Lameroo	25509	35.33	140.52
Gayndah[+]	39039	25.63	151.62	Launceston[1]	91104	41.53	147.2
Georgetown, NSW	21020	33.37	138.4	Laverton, VIC[1]	87031	37.85	144.73
Georgetown, QLD[+]	30018	18.3	143.55	Laverton, WA	12045	28.62	122.42
Geraldton[1]	8051	28.78	114.7	Learmonth	5007	22.24	114.1
Giles	13017	25.03	128.28	Lismore[1+]	58037	28.8	153.25
Gilgandra	51018	31.72	148.67	Lithgow[1]	63224	33.48	150.13
Gladstone[1]	39123	23.85	151.25	Longerenong	79028	36.67	142.3
Glen Innes	56011	29.73	151.73	Longreach	36031	23.44	144.28
Goondiwindi[+]	41038	28.55	150.3	Low Head[+]	91057	41.05	146.8
Grenfell	73014	33.9	148.17	Maatsuyker	94041	43.65	146.27
Grove	94069	42.99	147.07	Macedon	87036	37.42	144.55
Gunnedah	55023	30.98	150.25	Mackay[1]	33119	21.12	149.22
Guyra	56016	30.22	151.67	Maffra	85055	37.97	146.98
Gympie	40093	26.15	152.63	Mandurah[1]	9572	32.5	115.77
Halls Creek	2012	18.22	127.65	Manjimup	9573	34.23	116.15
Hamelin Pool[+]	6025	26.4	114.17	Marble Bar[+]	4020	21.17	119.75
Harrington	60023	31.87	152.7	Marree	17031	29.65	138.05
Hay Miller[+]	75031	34.52	144.82	Maryborough[+]	40126	37.05	143.73
Herberton[+]	31029	17.38	145.38	Meekathara	7045	26.6	118.53
Hillston	75032	33.48	145.53	Melbourne[1+]	86071	37.82	144.97
Hobart[1+]	94029	42.88	147.33	Menindee	47019	32.4	142.42
Horn Island	27058	10.58	142.29	Menzies[+]	12052	29.68	121.02
Horsham[+]	79023	36.65	142.1	Merredin	10092	31.48	118.28
Hughenden[+]	30024	20.83	144.2	Mildura[1]	76031	34.22	142.08
Hume Reservoir	72023	36.1	147.02	Miles[+]	42033	26.67	150.18
Milthorpe	63053	33.45	149.18	Rabbit Flat	15548	20.18	130.01
Mitchell	43020	26.48	147.97	Richmond, NSW	67021	33.62	150.75
Molong	65023	33.1	148.87	Richmond RAAF	67033	33.6	150.78
Morawa	8093	29.22	116	Richmond, QLD[+]	30045	20.72	143.13
Moree	53048	29.49	149.85	Robe	26026	37.16	139.76
Moruya Heads[+]	69018	35.9	150.15	Rockhampton[1]	39083	23.38	150.47

Appendix A contd.....

Station	BOM Number	Latitude °S	Longitude °E	Station	BOM Number	Latitude °S	Longitude °E
Moss Vale	68045	34.55	150.37	Roebourne	4035	20.78	117.12
Mount Barker, SA[+]	23733	35.07	138.85	Roma[+]	43030	26.57	148.78
Mount Barker, WA	9581	34.62	117.65	Roseworthy[+]	23020	34.53	138.68
Mount Gambier[1]	26021	37.73	140.78	Rottnest Island[+]	9038	32	115.5
Mount Hope	49032	32.85	145.88	Rutherglen	82039	36.1	146.51
Mount Surprise	30036	18.15	144.32	Sale	85072	38.12	147.13
Mount Victoria	63056	33.6	150.25	Sandgate[1]	40242	27.32	153.07
Mudgee[+]	62021	32.58	149.58	Scone	61069	32.05	150.87
Mungindi	52020	28.97	148.98	Seymour	88053	37.02	145.17
Murrurrundi	61051	31.77	150.83	Snowtown	21046	33.78	138.22
Nanango	40158	26.67	152	Southern Cross[+]	12074	31.22	119.32
Narrabri	54120	30.32	149.77	Southport[1]	40190	27.95	153.4
Newcastle[1+]	61055	32.92	151.78	St. Arnaud[+]	79040	36.62	143.27
Nhill[+]	78015	36.33	141.63	St. George	43109	28.03	148.58
Nimmitabel	70067	36.52	149.28	St. Lawrence	33065	22.33	149.53
Normanton[+]	29041	17.67	141.08	Stanley[+]	91094	40.77	145.3
Northam	10111	31.65	116.67	Stanthorpe	41095	28.65	151.93
Nowra[1]	68076	34.95	150.53	Strathalbyn[+]	23747	35.25	138.88
Nullagine[+]	4027	21.88	120.12	Streaky Bay	18079	32.8	134.22
Nuriootpa	23321	34.47	139	Swan Hill	77042	35.35	143.57
Nungan	51039	31.55	147.18	Sydney[1+]	66062	33.85	151.2
Omeo[+]	83025	37.08	147.6	Sydney Airport[1]	66037	33.95	151.18
Onslow[+]	5016	21.63	115.1	Tambo	35069	24.88	146.25
Oodnadatta	17043	27.56	135.45	Tamworth[1+]	55054	31.07	150.83
Orbost	84030	37.68	148.45	Tarcoola[+]	16044	30.72	134.57
Ouyen	76047	35.07	142.32	Taree[1+]	60030	31.9	152.48
Palmerville[+]	28004	16.98	144.07	Tennant Creek	15135	19.64	134.18
Parkes Macarthur+[+]	65026	33.13	148.15	Tenterfield	56032	29.05	152.02
Pemberton	9592	34.45	116.03	Terang	90077	38.25	142.92
Perth[1+]	9097	31.95	115.85	Thargomindah	45017	27.98	143.82
Perth Airport[1]	9021	31.9	116	Tibooburra[+]	46037	29.42	142.02
Picton	68052	34.18	150.62	Toowoomba[1]	41103	27.58	151.92
Pittsworth	41082	27.72	151.63	Townsville[1]	32040	19.25	146.75
Port Douglas	31052	16.48	145.47	Trangie	51048	32.03	147.98
Port Hedland[1]	4032	20.1	119.57	Urana	74110	35.33	146.27
Port Lincoln[1]	18070	34.72	135.87	Urandangie	37043	21.6	138.3
Port Macquarie[1+]	60026	31.43	152.92	Victor Harbour	23751	35.55	138.62
Port Pirie[1]	21043	33.18	138.02	Victoria River	14825	16.4	131.01
Portland	90070	38.35	141.6	Wagga[1]	72151	35.13	147.37
Quambone	51042	30.93	147.87	Wagga[1]	72150	35.16	147.46
Queenscliff	87054	38.27	144.67	Walgett[+]	52026	30.02	148.31
Quilpie	45015	26.62	144.27	Walterhall	39069	23.63	150.39
Quirindi	55049	31.5	150.67	Wandering[+]	10648	32.67	116.67
Waratah	97014	41.45	145.53	Winton	37051	22.38	143.03
Warialda	54029	29.55	150.58	Wittenoom	5026	22.23	118.33
Weipa	27045	12.68	141.92	Woomera	16001	31.13	136.82
Wellington	65034	32.55	148.93	Wyalong	73054	33.93	147.24
Wentworth	47053	34.12	141.92	Wyndham	1005	15.47	128.1
White Cliffs[+]	46042	30.85	143.08	Yalgoo	7091	28.35	116.68
Wilcannia[+]	46043	31.55	143.37	Yamba[+]	58012	29.43	153.35
Williamtown[+]	61078	32.78	151.82	Yongala	19062	33.02	138.7

Appendix A contd.....

Station	BOM Number	Latitude °S	Longitude °E	Station	BOM Number	Latitude °S	Longitude °E
WilsonsPromontory[+]	85096	29.12	146.42	York[+]	10144	31.88	116.75
Wiluna[+]	13012	26.58	120.22	Young	73056	34.32	148.3
Windorah	38024	25.42	142.65				

Appendix B. Australian climate observations reference network (ACORN) station list.

Site Name	Site Number	Latitude °S	Longitude °E	Station	BOM Number	Latitude °S	Longitude °E
Adelaide	23090	34.92	138.62	Gunnedah	55024	31.03	150.27
Albany	9741	34.94	117.80	Halls Creek	2012	18.23	127.66
Alice Springs Airport	15590	23.80	133.89	Hobart	94029	42.89	147.33
Amberley	4004	27.63	152.71	Horn Island	27058	10.58	142.29
Barcaldine	36007	23.55	145.29	Inverell	56242	29.78	151.11
Bathurst	63005	33.43	149.56	Kalgoorlie-Boulder	12038	30.78	121.45
Birdsville	38026	25.90	139.35	Kalumburu	1019	14.30	126.65
Boulia	38003	22.91	139.90	Katanning	10579	33.69	117.56
Bourke	48245	30.04	145.95	Kerang	80023	35.72	143.92
Bridgetown	9510	33.96	116.14	Kyancutta	18044	33.13	135.56
Brisbane Airport	40842	27.39	153.12	Launceston Airport	91311	41.55	147.21
Broome Airport	3003	17.95	122.24	Laverton RAAF	87031	37.86	144.76
Bundaberg	39128	24.91	152.32	Learmonth	5007	22.24	114.10
Burketown	29077	17.75	139.54	Longreach	36031	23.44	144.28
Butlers Gorge	96003	42.28	146.28	Low Head	91293	41.05	146.79
Cabramurra	72161	35.94	148.38	Mackay	33119	21.12	149.22
Cairns	31011	16.87	145.75	Marble Bar	4106	21.18	119.75
Camooweal	37010	19.92	138.12	Marree	17031	29.65	138.06
Canberra	70351	35.30	149.20	Meekatharra	7045	26.61	118.54
Cape Borda	22823	35.75	136.60	Melbourne	86071	37.81	144.97
Cape Bruny	94010	43.49	147.15	Merredin	10092	31.48	118.28
Cape Leeuwin	9518	34.37	115.14	Mildura	76031	34.24	142.09
Cape Moreton	40043	27.03	153.47	Miles	42112	26.66	150.18
Cape Otway	90015	38.86	143.51	Morawa	8296	29.20	116.02
Carnarvon	6011	24.89	113.67	Moree	53115	29.49	149.85
Ceduna	18012	32.13	133.70	Moruya Heads	69018	35.91	150.15
Charleville	44021	26.41	146.26	Mount Gambier	26021	37.75	140.77
Charters Towers	34084	20.05	146.27	Nhill	78015	36.31	141.65
Cobar	48027	31.48	145.83	Normanton	29063	17.69	141.07
Coffs Harbour	59040	30.31	153.12	Nowra	68072	34.95	150.54
Cunderdin	10286	31.62	117.22	Nuriootpa	23373	34.48	139.01
Calwallinu	8039	30.28	116.66	Oodnadatta	17043	27.56	135.45
Darwin	14015	12.42	130.89	Orbost	84145	37.69	148.47
Deniliquin	74258	35.56	144.95	Palmerville	28004	16	144.08
Dubbo	65070	32.22	148.58	Perth	9021	31.93	115.98
Eddystone Point	92045	40.99	148.35	Point Perpendicular	68151	35.09	150.80
Esperance	9789	33.83	121.89	Port Hedland Airport	4032	20.37	118.63
Eucla	11003	31.68	128.88	Port Lincoln	18192	34.60	135.88
Forrest	11052	30.85	128.11	Port Macquarie	60139	31.43	152.87
Gabo Island	84016	37.57	149.92	Rabbit Flat	15666	20.18	130.01
Gayndah	39066	25.62	151.62	Richmond (NSW)	67105	33.60	150.78
Georgetown	30124	18.30	143.53	Richmond (QLD)	30045	20.73	143.14
Geraldton	8051	28.80	114.70	Robe	26026	37.16	139.76
Giles	13017	25.03	128.30	Rockhampton	39083	23.38	150.48
Grove	94220	42.99	147.07	Rutherglen	82039	36.10	146.51

Appendix B contd.....

Site Name	Site Number	Latitude °S	Longitude °E	Station	BOM Number	Latitude °S	Longitude °E
Sale	85072	38.12	147.13	Wagga Wagga	72150	35.16	147.46
Scone	61363	32.03	150.83	Walgett	52088	30.04	148.12
Snowtown	21133	33.77	138.22	Wandering	10917	32.67	116.67
St. George	43109	28.05	148.59	Weipa	27045	12.68	141.92
Sydney	66062	33.86	151.21	Wilcannia	46043	31.56	143.37
Tarcoola	16098	30.71	134.58	Williamtown	61078	32.789	151.84
Tennant Creek	15135	19.64	134.18	Wilsons Promontory	85096	39.13	146.42
Thargomindah	45025	27.99	143.81	Wittenoom	5026	22.24	118.34
Tibooburra	46037	29.43	142.01	Woomera	16001	31.16	136.81
Townsville	32040	19.25	146.77	Wyalong	73054	33.93	147.24
Victoria River Downs	14825	16.40	131.01	Yamba	58012	29.43	153.36

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

The financial assistance of the Canadian Natural Science and Engineering Research Council is gratefully acknowledged.

REFERENCES

[1] Stocker TF, Qin D, Plattner GK, *et al.* Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the 5th Assessment Report of the Intergovernmental Panel on Climate Change. In: Cambridge, UK and New York, NY, USA: Cambridge University Press 2013.

[2] National Centers for Environmental Information. Available at: www.ncdc.noaa.gov [Accessed on: 15 June 2016]

[3] Australian Government, Climate Data Online. Available at: www.bom.gov.au/climate/data [Accessed on: 15 June 2016]

[4] van Wijngaarden WA, Vincent LA. Examination of trends in hourly surface relative humidity in canada during 1953-2003. J Geophys Res 2005; 110: D22102.
[http://dx.doi.org/10.1029/2005JD005925]

[5] Vincent LA, van Wijngaarden WA, Hopkinson R. Surface temperature and humidity trends in Canada for 1953-2005. J Clim 2007; 20: 5100-13.
[http://dx.doi.org/10.1175/JCLI4293.1]

[6] Isaac V, van Wijngaarden WA. Surface water vapor pressure and temperature trends in north america during 1948-2010. J Clim 2012; 25: 3599-609.
[http://dx.doi.org/10.1175/JCLI-D-11-00003.1]

[7] Verbesselt J, Hyndman R, Newnham G, Culvenor D. Detecting trend and seasonal changes in satellite image time series. Remote Sens Environ 2010; 114: 106-15.
[http://dx.doi.org/10.1016/j.rse.2009.08.014]

[8] Verbesselt J, Hyndman R, Zeileis A, Culvenor D. Phenological change detection while accounting for abrupt and gradual trends in satellite image time series. Remote Sens Environ 2010; 114: 2970-80.
[http://dx.doi.org/10.1016/j.rse.2010.08.003]

[9] Verbesselt J, Zeileis A, Herold M. Near real-time disturbance detection using satellite image time series. Remote Sens Environ 2013; 123: 98-108.
[http://dx.doi.org/10.1016/j.rse.2012.02.022]

[10] Klotzbach PJ, Pielke RA Sr, Pielke RA Jr, Christy JR, McNider RT. An alternative explanation for differential temperature trends at the surface and in the lower troposphere. J Geophys Res 2009; 114: D21102.
[http://dx.doi.org/10.1029/2009JD011841]

[11] McNider RT, Christy JR, Biazar A. A Stable Boundary Layer Perspective on Global Temperature Trends. Earth Environ Sci 2010; 13: 012003.

[12] McNider RT, Steeneveld GJ. Response and sensitivity of the nocturnal boundary layer over land to added longwave radiative forcing. J Geophys Res 2012; 117(D14)
[http://dx.doi.org/10.1029/2012SJDOI7578]

[13] Salamanca F, Georgescu M, Mahalov A, Moustaoui M. Summertime response of temperature and cooling energy demand to urban expansion in a semiarid environment. J Appl Meteorol Climatol 2015; 54: 1756-72.
[http://dx.doi.org/10.1175/JAMC-D-14-0313.1]

[14] Karl TR, Jones PD, Knight RW, *et al.* A new perspective on recent global warming: Asymmetric trends of daily maximum and minimum temperature. Bull Am Meteor 1993; 74: 1007: 1023.

[15] Torok SJ, Morris CJ, Skinner C, Plummer N. Urban heat island features of southeast Australian towns. Aust Met Mag 2001; 50: 1-13.

[16] van Wijngaarden WA. Arctic temperature trends from the early nineteenth century to the present. Theor Appl Climatol 2015; 122: 567-80. [http://dx.doi.org/10.1007/s00704-014-1311-z]

[17] Torok SJ, Nicholls N. A historical annual temperature dataset for Australia. Aust Met Mag 1996; 45: 251-60.

[18] Jones DA, Wang W, Fawcett R. High-quality spatial climate datasets or Australia. Aust Met Ocean J 2009; 58: 233-48.

[19] Trewin B. A daily homogenized temperature dataset for Australia, Int. J Clim 2013; 33: 1510-29. [http://dx.doi.org/10.1002/joc.3530]

[20] Ashcroft L, Karoly DJ, Gergis J. Southeastern Australian climate variability 1860-2009: a multivariate analysis. Int J Clim 2014; 34: 1928-44. [http://dx.doi.org/10.1002/joc.3812]

[21] Trewin B. Techniques involved in developing the Australian Climate Observations Reference Network – Surface Air Temperature dataset, Center for Australian Weather and Climate Technical Report No 049. 2012. ISBN: 978 0 643 10815 8

[22] Fawcett RJ, Trewin BC, Braganza K, *et al.* On the sensitivity of Australian temperature trends and variability to analysis methods and observation networks, Center for Australian Weather and Climate Research Technical Report No 050. 2012. ISBN: 978 0 643 10819 6

[23] Australian Climate Observations Reference Network - Surface Air Temperature Dataset. Available at: https://data.gov.au/dataset/acorn-sat. [Accessed on: 15 June 2016]

[24] KNMI Climate Explorer. Available at: https://climexp.knmi.nl [Accessed on: 15 June 2016]

[25] Quirk T. The australian temperature anomaly, 1910-2000. Energy Environ 2009; 20: 97-100. [http://dx.doi.org/10.1260/095830509787689231]

[26] Oke TR. The energetic basis of the urban heat island. Q J R Meteorol Soc 1982; 108: 1-24.

[27] Santos F. Trees – Natural Air Conditioners. Scientific Scribbles University of Melbourne [Accessed on: 24 August 2016]; Available at: https://blogs.unimelb.edu.au/sciencecommunication/2013/08/23/