SEASONAL AND ANNUAL TRENDS OF AUSTRALIAN MINIMUM/MAXIMUM DAILY TEMPERATURES DURING 1856-2014

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1. INTRODUCTION

Australia has the among the longest archival temperature records in the Southern Hemisphere extending as far back as 1856 (BOM, 2015). 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 (Isaac and van Wijngaarden, 2012).

This study examined whether there is any difference between trends of daily minimum and maximum temperatures (van Wijngaarden and Mouraviev, 2016). 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 (McNider et al, 2012). This study also examined whether the trends exhibited any seasonal dependence or were influenced by urban/rural surroundings.

The Australian Bureau of Meteorology (BOM) provides monthly averaged daily minimum and maximum temperatures at a number of stations (BOM, 2015). Torok and Nicholls (Torok and Nicholls, 1996) 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 compared each time series to nearby stations to 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.

Recently, the Australian Climate Observations Reference Network generated a new homogenized temperature dataset (Trewin, 2013; ACORN, 2015). This network consists of 112 stations and covers the period from 1910 onwards.

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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 (BOM, 2015). Australian data has also been analyzed by NOAA's National Climate Data Center (NCEI, 2015) as part of the Global Historical Climate Network (GHCN) analysis and both raw and adjusted monthly averaged daily minimum and maximum temperatures are available from the Royal Dutch Meteorological Institute until the early 1990s (KNMI, 2015). 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.

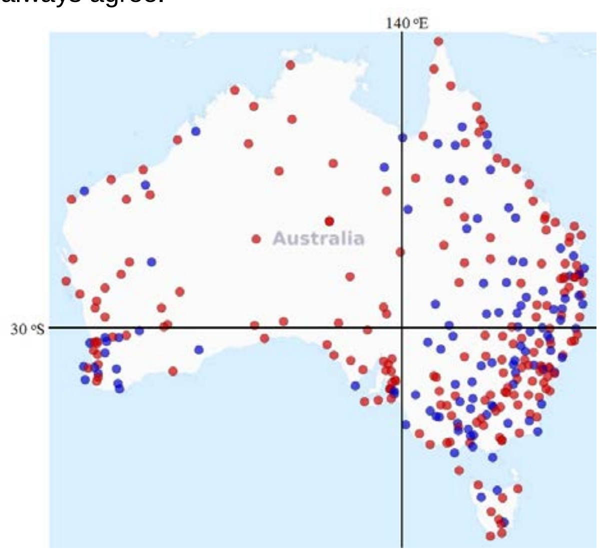


Fig. 1: Locations of stations examined. A red (blue) circle denotes a station where data was taken for less (more) than 100 years.

This study examined temperatures observed at 299 stations shown in Fig. 1. 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.

2. DATA DESCRIPTION

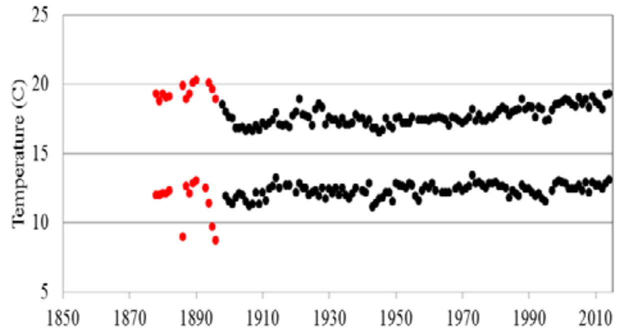
Monthly averaged daily minimum and maximum values were downloaded from the Australian Bureau of Meteorology. The annual and seasonal averages were only computed if all monthly values in a year or season were present. The seasons are defined as winter (December – February), spring (March – May), summer (June – August) and fall (September – November). An average of 89 years of observations was available at each station. 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 have also been closed in recent decades. Annual averaged minimum and maximum temperatures could be found for 88% of the years that stations were operational.

The temperature relative to the 20th century was computed. A number of stations had spurious data as is illustrated in Fig. 2. 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 steps occurred in the late 1800s but data for a few stations show a sudden upward jump during the 20th century.

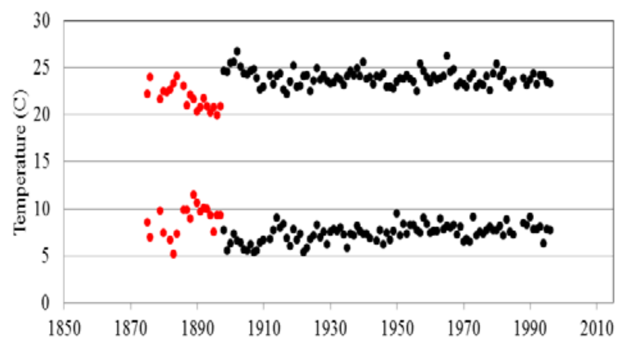
3. DATA ANALYSIS AND RESULTS

This study adopted two criteria for determining whether a data point was spurious. 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 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.

a) Gabo Island



b) Inverell



c) Moruya Heads

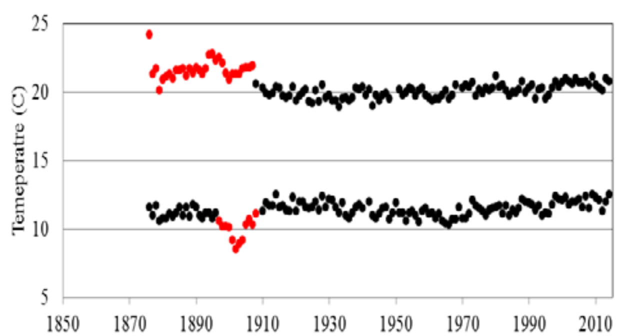


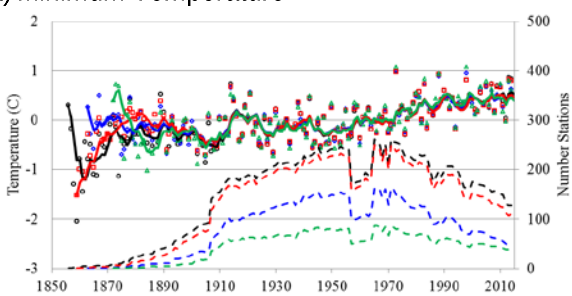
Fig. 2. The average minimum and maximum annual temperature data are plotted for various stations. The red points are suspect as is discussed in the text.

Application of these criteria is shown in Fig. 3. It shows plots of the annual minimum and maximum 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 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.

Table 1 shows the trends for the annual minimum and maximum temperatures for the intervals 1880-2014 and 1907-2014. The uncertainty of each trend in this study was defined by the 95% confidence interval using the statistical t-test. The 1970-2014 trends for minimum and maximum temperature change vary little depending on the value of Ns used to determine the presence of a discontinuity. There is a sub-

a) Minimum Temperature



b) Maximum Temperature

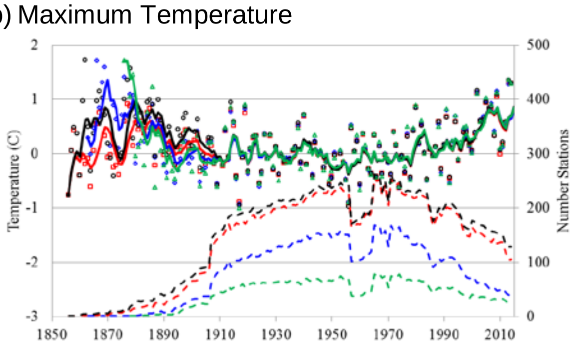


Fig. 3 Plot of a) Minimum and b) Maximum Temperature relative to the 20th century. Raw data are displayed as black circles. Red squares (blue diamonds) are data filtered using N_s = 10 (5) points to determine whether a discontinuity occurred as discussed in the text. Green triangles show data for stations 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 number of stations.

stantial increase in the maximum temperature trend for 1880-2014 evaluated using raw data as compared to when inhomogeneous data is discarded using Ns = 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 are 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. 3 also shows the minimum temperature increased steadily throughout the 20th century while the maximum temperature remained approximately constant until suddenly increasing by approximately 0.5 ^{o}C around 2000. During 1907-2000, the minimum (maximum) temperature trend was 0.64 ± 0.24 (0.18 ± 0.29) ^{o}C per century.

The seasonal trends were found for the interval 1907-2014 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 the summer while the maximum temperature increased the least during the winter. The minimum temperature trend exceeded the maximum temperature trend for all but the summer season.

Table 1: Minimum/Maximum Annual Trends.

Temperature	**Description**	**Trend (^{o}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
	No Discontinuities	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
	No Discontinuities	0.35 ± 0.19	0.58 ± 0.27

a) Minimum Temperature

b) Maximum Temperature

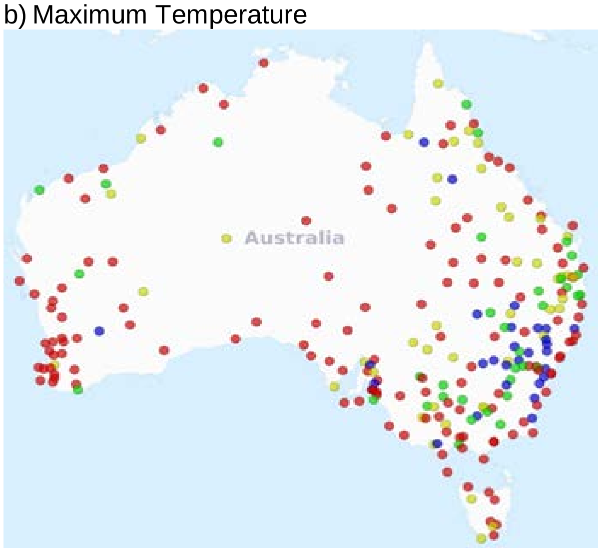
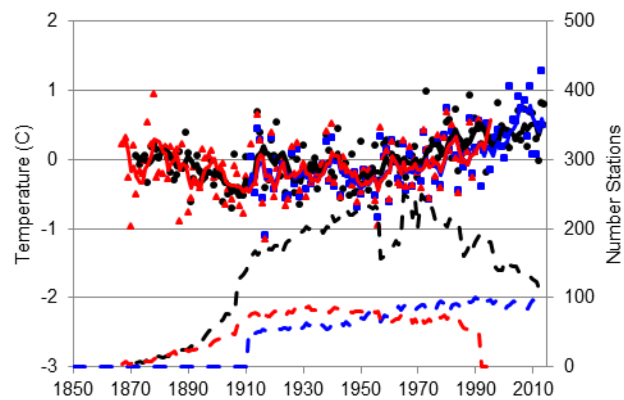


Fig. 4 Trends at stations having data present for at least 50% of all years during 1907-2014 for a) Minimum and b) Maximum Annual Temperature. Red (yellow) denotes a statistically significant (insignificant) increasing trend while blue (green) denotes a statistically significant (insignificant) decreasing trend.

Fig. 4 shows the trends for stations having at least 50% of data for all years during 1907-2015. The latitudinal and longitudinal trend dependence was also examined. The minimum temperature trend increased much more than the maximum temperature trend for the region north of 30 ^{o}S latitude and east of 140 ^{o}E longitude. The difference between minimum and maximum temperature trends was not significant for other parts of Australia. Similarly, 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.

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. Fig. 5 compares the time series found by averaging the adjusted ACORN and GHCN data over available stations. The 5 year averaged curves of the three analyses follow each other very closely and even nearly overlap for the minimum temperature. The maximum temperature data are also in excellent

a) Minimum Temperature



b) Maximum Temperature

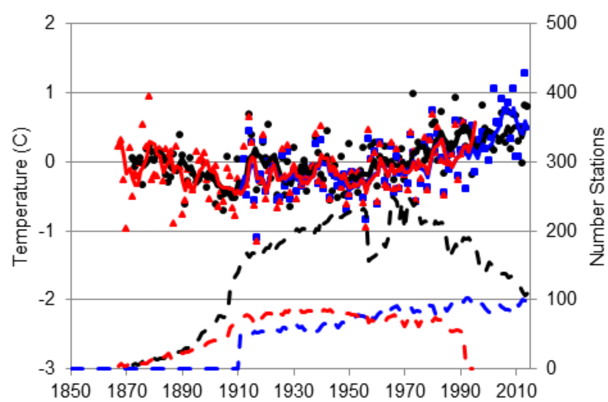


Fig. 5. Comparison of adjusted GHCN and ACORN data as well as this work for a) Minimum and b) Maximum Annual Temperature. The red triangles are the GHCN results, blue squares are the ACORN results and the black dots are from this work. The solid red, green and black curves are the 5 year running averages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

agreement from 1910 onwards. The difference between the earlier GHCN adjusted maximum temperature data and this work is not surprising given that there were comparatively few stations in the 19th century when the largest inhomogeneities occurred. The close agreement in Fig. 5 between the independent analyses of ACORN, GHCN and this work is especially surprising given that different stations were used. It is noteworthy that the ACORN and GHCN adjusted data, which have a multitude of adjustments for each station, yield temperature trends comparable to this work that adopts a very different strategy of discarding inhomogeneous data.

4. CONCLUSIONS

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 very closely with two independent studies. 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. Many adjustments did not correspond with evident inhomogeneities in the original time series. 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 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) ^{o}C per century. Averaging the maximum and minimum trends yields a mean temperature trend during 1907-2014 of 0.63 ± 0.32 ^{o}C per century. This estimate is comparable to the global average temperature change observed during the 20th century (IPPC, 2014).

5. Acknowledgements

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