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Title:

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Date:

2022-04-01

Citation:

Ashcroft, L., Trewin, B., Benoy, M., Ray, D. & Courtney, C. (2022). The world's longest known parallel temperature dataset: A comparison between daily Glaisher and Stevenson screen temperature data at Adelaide, Australia, 1887–1947. *International Journal of Climatology*, 42 (5), pp.2670-2687. <https://doi.org/10.1002/joc.7385>.

Persistent Link:

<https://hdl.handle.net/11343/299062>

The world's longest known parallel temperature dataset: a  
comparison between daily Glaisher and Stevenson Screen  
temperature data at Adelaide, Australia, 1887–1947

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Resubmitted to *International Journal of Climatology*

23 July 2021

Keywords: meteorological instruments, observations, centennial, climate, Australia, homogenisation

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as doi: [10.1002/joc.7385](https://doi.org/10.1002/joc.7385)

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## Abstract

Weather observing stations are subject to changes in instrumentation, location and surrounding environment over time. Parallel observations between old and new conditions are therefore vital to ensure that a reliable dataset can be built and used for long-term climate analysis. Here we examine the world's longest known sets of parallel temperature observations: daily data for Adelaide, South Australia, recorded using two different thermometer screens for 60 years from 1887 to 1947. These data are globally significant for their length and completeness, but the daily Glaisher stand observations have only recently been digitised for analysis.

We find maximum temperatures recorded in Glaisher stands are warmer than Stevenson screen observations, with the difference increasing with absolute temperature, while minimum temperatures recorded in the Glaisher stand are consistently slightly cooler. These differences are similar to those identified using monthly means, as well as other studies of shorter datasets. However, the daily resolution enabled us to identify periods of inconsistent relationships due to changes in observations times (particularly from 1938 onwards), and quantify the differences during extreme events. In particular, percentile analysis revealed that the differences for extremely high temperatures are only slightly greater than the average difference during the warmer months.

The data provide an opportunity to attempt the development of 160-year continuous temperature record for one of the oldest colonial cities in the southern hemisphere. As expected, we find temperatures in recent decades to be the highest since 1859, although the Glaisher stand maximum temperature data in the 1860s are notably warm, likely due to dry conditions and persistent inhomogeneities. While the relationships we have identified cannot be applied to other 19th century Glaisher stand observations without careful metadata examination, they provide a possible tool for analysis and re-examination of historical mid-latitude temperature observations elsewhere around the world.

## 1. Introduction

Land-based temperature observations form a key component of global datasets of climate variability and (e.g. Hansen *et al.*, 2010; Jones and Wigley, 2010; Morice *et al.*, 2012; Lenssen *et al.*, 2019; Osborn *et al.*, 2021). Observations recorded at the same location using the same method over a long period of time are the ideal dataset, as these will capture variations only in the weather and climate (Trewin, 2010). However, in practice these kinds of datasets are very rare: infrastructure is built or demolished; there are frequent changes to environmental features like plants or grass coverage; weather stations are moved; instruments are replaced; and observation methods change. Such non-climatic aspects can cause changes in an instrumental record that are as large as natural or human-

induced climate variations, making it hard to separate real variability in the weather and climate from other influences.

One way to overcome the impact of methodological changes or site moves is to ensure that parallel observations are taken whenever possible between different instrument exposures (Venema *et al.*, 2016). Current guidelines from the World Meteorological Organization (WMO, 2011, 2017) recommend at least one year of overlapping data between old and new conditions when a station is moved or instrumentation is upgraded, although preferably two or more (and five years for precipitation observations). The parallel observations then allow a relationship to be calculated between the old and new observing technique or location, enabling climatologists to quantify the size of non-climatic changes and combine the two series.

For temperature observations, one major non-climatic influence is the shelter in which thermometers or temperature probes are housed. The WMO standard suggests that thermometers be placed in a large thermometer screen such as a Stevenson screen (Figure 1). The design of the Stevenson screen, with louvred walls, slanted roof, and white colour was developed by Thomas Stevenson in the 1860s to reduce the influence of solar radiation and protect instruments from rain and snow, while ensuring free flow of ambient air around the thermometers inside (World Meteorological Organization, 2018; Naylor, 2019). However, many early instrumental temperature records were taken in other types of thermometer shelters, including the Glaisher stand, also known as a Greenwich stand as it was used at the Greenwich Observatory until the 1930s (Parker, 1994; Trewin, 2010). The Glaisher stand (Figure 1) is an open thermometer shelter that is manually rotated to keep the open side out of the sun year round (Parker, 1994) It was the dominant thermometer shelter type in Australia and most British colonies until the mid to late 19th century, when many stations shifted to the Stevenson screen after much debate (Nicholls *et al.*, 1996; Naylor, 2019). This change in methodology has made it difficult to combine historical and modern temperature observations for Australia, and in turn gain an accurate picture of pre-1910 climate variability and change (Ashcroft *et al.*, 2012; Trewin *et al.*, 2020).

A number of studies were undertaken in the late 19<sup>th</sup> and early 20<sup>th</sup> centuries comparing observations taken in the two thermometer shelters (Laing, 1977; Parker, 1994), as the meteorological societies of the time attempted to realise “the dream of all thoughtful meteorologists” and find a “uniform method of taking all meteorological observations [to] be adopted throughout the world (Mawley, 1897). The majority of these studies were in the United Kingdom (Plummer, 1873; Gaster, 1882; Ellis, 1891; Mawley, 1897; Margary, 1924), and conducted using relatively short datasets, typically in the order of 2–3 years. The exceptions are Gill (1882) who carried out a parallel observation study in Cape Town, South Africa in 1881, and Margary (1924), who analysed 40 years of parallel observations taken at Camden Square in London from 1881 to 1920.

More recently, Brunet *et al.* (2011) compared six years of parallel observations taken in a Montsouri shelter and a Stevenson screen at two locations in Spain. A Montsouri shelter, or French screen, is similar to a Glaisher stand, but larger and taller, and generally fixed in one position. It was a common thermometer shelter across Europe in the late 19th and early 20th century (Mawley, 1897; Sparks, 1972; Brunet *et al.*, 2011).

In general, all of these comparisons showed that maximum, or early afternoon, temperatures measured in a Glaisher stand were around 1°C warmer than those in a Stevenson screen during summer, with much smaller (sometimes negative) differences in winter. The differences in Cape Town (1.3 °C in summer) and Spain (up to 1.5°C) were slightly larger than those in most British studies, possibly due to the sunnier climate in these locations. Most studies found that minimum temperatures in a Glaisher stand were slightly lower than those in a Stevenson screen, with little seasonal variation in the differences. For extremes, Laing (1977) found little evidence of larger differences on hot days (above 29.4 °C) than in summer mean maximum temperatures, although the sample size of such days during her comparison periods were small.

However, a longer parallel dataset exists, which may enable a more nuanced assessment of the difference between the exposures of both shelters. South Australian Government Astronomer and meteorologist Charles Todd and his successors took observations in a Glaisher stand at the West Terrace Observatory in Adelaide from 1858 to 1947, and observations in a Stevenson screen from 1887 to 1947. The 60 years of overlap is the longest known parallel record in the world for these two thermometer screens.

Until recently, only the monthly averages of this long-term experiment have been available for contemporary analysis. Todd himself conducted some analysis of the overlapping records during 1887 and 1888 (Appendix A), coming to similar conclusions to his English peers. Using a sling thermometer as a measure of the ‘true temperature’, he determined that observations taken in the Stevenson screen were closer to the ‘truth’ than either a Glaisher stand or an Australian-designed thermometer shed (Figure 1, Appendix A), although the instruments inside a Stevenson screen were slower to respond to dramatic temperature changes. More than 100 years later, Richards *et al.* (1993) compared monthly means between the two series from 1887 to 1947, as summarised by Nicholls *et al.* (1996). But assessing only monthly differences fails to capture the relationship between observations at the two shelters during daily temperature extremes, which can often differ substantially from relationships between monthly or annual averages (Trewin *et al.*, 2020).

In 2014, logbooks of the daily observations from the Glaisher stand were uncovered by volunteers with the Australian Meteorological Association. The logbooks were imaged, and the data transcribed, giving us a new opportunity to reassess the parallel observations at the daily scale. Given that the Glaisher stand—and similar open shelters—were the dominant shelter used in the mid 19th Century,

examining these overlapping observations are an important source of information for developing long-term homogenous climate records in Australia, and around the world.

In this study, we examine the parallel measurements for Adelaide at the daily scale for the first time. We describe the parallel dataset, metadata about the West Terrace site and the initial quality control applied to the newly transcribed data. Next, we run a range of statistical analyses on the overlapping data to quantify the relationship between the two series. Given the long length of the parallel record, sub-period comparisons are included in our analysis based on identified changes in the relationship between the two series.

As Adelaide is prone to extreme temperatures (Gergis *et al.*, 2020), several historically significant heat events are explored using the new parallel records as well as a re-examination of heatwave and cold event frequency since 1859. We also attempt to develop a continuous climate record for Adelaide, combining the historical Glaisher stand data with Stevenson screen data to the present day. Finally, we discuss how these results compare to the monthly analysis of Richards *et al.* (1993), and other global parallel studies, highlighting the value of these new observations as well as their limitations.

## 2. Data

### 2.1. Glaisher stand data development

To conduct a comparison between the Glaisher and Stevenson screen data, we first needed to recover, image and digitise the daily temperature observations recorded at the Adelaide West Terrace observatory from November 1856 to December 1952. Much of this dataset was incorporated in a long-term temperature observing experiment set up by Charles Todd in 1887 (see Appendix A). The data were taken using a thermometer in a Glaisher stand (Figure 1) and written in two volumes titled "Adelaide Temperature Analysis" (Figure 2). The volumes are day-book style (with columns for each year and rows for each date, and separate pages for each of the twelve months), Note that these are not the original recordings but transcriptions done at some point between 1963 and 1977 from original field books. Transcription errors are a possibility between the field books and the day-book volumes, but given they are official Bureau of Meteorology documents, we make the assumption that the transcription was done by a trained professional so the potential for errors is likely to be low. Additionally, any gross errors are likely to be detected as part of the quality control process (section 2.2).

We imaged the books using a photographic imaging workstation that enabled the capture of the entire page of data without damaging the documents. Images of the original data are located at <https://www.met-acre.net/MERIT/AMETA.html> and were catalogued in accordance with archival best practises (World Meteorological Organization, 2016).

Daily minimum and maximum temperature from the data books recorded in degrees Fahrenheit to one decimal point are available for all days of the week for each year. Monthly summaries of the daily data were also provided in the data books, and these were consulted but regrettably not digitised. The dataset is almost temporally complete, with 854 missing days, of which 738 occurred in the first 2 years of the series. This leaves 1859–1952 with 0.16% missing data, and this is the dataset we examine in this paper. The data were digitised by a volunteer professional key-data operator. We did not use double key data entry but instead employed data entry templates that reflected the format of the written data. One template was used for each year, resulting in 72 spreadsheets. This methodology was chosen by the operator, a deliberate strategy to allow a relaxed and intuitive capture of the data which reduced the likelihood for digitisation errors (e.g. Ashcroft *et al.*, 2018; Wilkinson *et al.*, 2019). We then consolidated the separate spreadsheets into single files of maximum and minimum temperature.

## 2.2. Glaisher data quality control

Quality control procedures was then applied to minimise errors in the digitisation process or identify errors in the original transcription of the data using ClimPACT2 quality control tests (Alexander and Herold, 2016) and manual examination of values where the difference between the Glaisher and Stevenson screen observations were larger than 4°C. This threshold was decided after testing lower values to minimise the number of false errors identified.

The values identified were then checked against the journals and corrected, retained as correct observations, or, in rare cases when the handwriting was unclear, deleted. In addition to these systematic checks, we also conducted random cross checks of month-long slices of the dataset. A total of 0.35% of the data checked this way required correction, in line with other data digitisation efforts (Brönnimann *et al.*, 2006; Ashcroft *et al.*, 2018). The largest number of errors occurred due to column-slip by the key operator, affecting 42 data points, as well as 7s, 9s and 1s being easily misread in the cursive text.

The quality control procedure left 68,534 readings covering January 1859 – December 1952. These data were converted from degrees Fahrenheit to degrees Celsius (one decimal place) for all following analyses.

## 2.3. Additional and Stevenson screen data

The Glaisher stand data were then compared with the pre-digitised daily maximum and minimum temperature data taken in a Stevenson screen, ascribed to the Bureau of Meteorology station Adelaide (West Terrace) (Bureau of Meteorology station number 023000) for 1887–1952. Whilst routine quality control for pre-1950s Bureau of Meteorology data is generally limited, the 1910–1952 data received additional quality control as part of the development of the Australian homogenised

temperature dataset, ACORN-SAT (Trewin, 2013; Trewin *et al.*, 2020). We checked the 1887–1910 Stevenson screen data using the ClimPACT2 quality control procedure for this study (Alexander and Herold, 2016), but no gross errors were identified. A recent version of the ACORN-SAT series for Adelaide (ACORN-SAT 2.1, Trewin *et al.*, 2020) was then used to take the dataset to 2019. This series uses the West Terrace data from 1910 to 1977, with observations thereafter being made at Kent Town (Bureau of Meteorology station number 023090), about 3 km to the east.<sup>1</sup>

While there are no cloud observations available for the Glaisher data period, average cloud cover data from 1955 to 2020 from Adelaide Airport (Bureau of Meteorology station number 023034), as well as rainfall data from Kent Town and West Terrace were used to explore data quality in Section 4. The cloud cover averages were calculated from 3 hourly observations, while rainfall data were taken from West Terrace from 1839 until Kent Town data become available in February 1977. Finally, we used monthly temperature data from Mount Barker (station number 023733) and Melbourne (086071) in section 4 as an additional comparison with the 19th century Glaisher data, but note that we use raw data, rather than homogenised records.

### 3. Stevenson and Glaisher data comparison

Plotting the differences between the daily Glaisher stand and Stevenson screen data shows the Glaisher stand maximum temperatures are consistently warmer than those from the Stevenson screen, with mean annual differences typically in the range of 0.4 to 1.0 °C (Figure 3). The maximum data from January 1948 onwards appear to be identical from both data sources and so have been excluded from comparison.

Figures 3(a and b) show clear seasonal and absolute temperature variation in maximum temperature differences: the mean difference in summer is 0.8 to 0.9 °C whilst that in winter is negligible, and the differences tend to increase as the absolute temperature increases. This is consistent with the monthly analysis of Richards *et al.* (1993) and Nicholls *et al.* (1996).

Minimum temperature differences (Figures 4a and b) on the other hand are smaller, with no indication of any significant seasonal variation in the relationship between the two, and a much smaller spread of differences that is more closely centred around zero (comparing Figures 3f and 4f). Minimum temperatures from 1938 onwards have been excluded from comparison in Figure 4, as an assessment of the Stevenson screen metadata indicated that from May 1938 onwards, observations were made for a day extending from midnight to midnight rather than the standard 0900 to 0900. While this has minimal impact on maximum temperature, this practice tends to lead to a negative bias in mean minimum temperatures (Trewin, 2012). Comparison of maximum and minimum temperatures with

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<sup>1</sup> A site was re-established in 2017 near the original West Terrace location, but the post-2017 data from this location are not used in this dataset.

fixed-hour observations (Trewin, 2012) confirmed that the midnight observation time was not used for the Glaisher stand post-1938, and so the observations are not directly comparable.

Figures 3 and 4c additionally reveal clear breakpoints in the differences between the two series over time. Using the identification method of Trewin et al (2020), these breakpoints are located at 1892, 1901 and 1925 for maximum temperature, and for minimum temperature in the mid-1890s and 1938. The 1938 minimum temperature breakpoint can be explained by the change in observation time, but the causes of other breakpoints are unclear from metadata. They may indicate a change in one or both of the screens, such as a change in instrument configuration which affected one instrument more than the other (or did not affect one instrument at all). As no maximum temperature inhomogeneity was identified in 1925 for the ACORN-SAT dataset (Australian Bureau of Meteorology, 2021), which uses the Stevenson screen data, it is likely that whatever issue caused the 1925 breakpoint primarily affected the Glaisher stand.

Given these breakpoints, the remainder of this section focuses on the two periods from 1910 to 1924, and from 1926 to 1937 as the difference series indicate data within these periods are homogeneous for both maximum and minimum temperature. This also corresponds with the period during which the Stevenson screen data were quality-controlled as part of the ACORN-SAT dataset.

### 3.1. Quantifying the relationship between temperature series during extremes

The digitised daily data allow a comparison of the behaviour of extreme temperatures in the two screens for the first time. To assess changes across the frequency distribution, we established a transfer function quantifying the relationship between the two datasets, defined for each month by finding the 5<sup>th</sup>, 10<sup>th</sup>, ..., 95<sup>th</sup> percentile points of daily temperature anomalies (differences from the monthly average) for each data set during the period of overlap. This is also the methodology used for homogeneity adjustments, where parallel data exist, in the ACORN-SAT dataset (Trewin *et al.*, 2020). A separate transfer function is defined for each of the 12 months, in each case based on that month and the month before and after (e.g. January to March for the February transfer function). Large changes in the transfer function for each month across the percentiles indicate a changing relationship between the parallel observations dependent on the absolute temperature.

The outcomes of this assessment are shown for sample months (February and July) in Figure 5 for 1910–1924 and 1926–1937 respectively. Overall, there are few clear signals of high or low extremes behaving differently to each other, or to monthly means. In particular, there is no evidence of a substantially larger difference for very hot days in the warmer months than there is for the mean, or even for low extremes. In the warm November–March period (not shown), the differences for 1910–1924 maximum temperatures are 0.88 °C for the 95<sup>th</sup> percentile, 0.86 °C for the 5<sup>th</sup> percentile and 0.79 °C for the mean, whilst in the 1926–1937 period the values are 1.30 °C, 1.32 °C and 1.18 °C

respectively. This is a somewhat surprising result, as the differences might be expected to be largest on sunny days, which would be expected to also be the warmest days. The lack of such a finding may reflect the fact that sunny conditions predominate in Adelaide in the warmer months with November–March recording sunshine for more than 70% of the possible hours (Australian Bureau of Meteorology, 2020), and hence it is not only hot days that are sunny. Ideally, it would be preferable to stratify our results into clear, partly cloudy and cloudy days, but daily cloud amount and sunshine data are not readily available for either period.

In winter, there are indications towards the Glaisher stand being slightly cooler on the colder nights and warmer days, although the signal is not consistent across both periods. The maximum temperatures during 1910–1924 in particular show increasing differences as the observed temperature increases, but this is not seen in the 1926–1937 relationship (Figure 5c).

#### 4. Building a 1859–2019 temperature series for Adelaide

Next, we attempt to create a single, homogenous daily series for Adelaide covering the period from 1859 to the present. To minimise switching between datasets, we decided to merge the Glaisher stand data directly with the homogenised post-1910 data drawn from the ACORN-SAT dataset, rather than merge the Glaisher data with the unhomogenised 1887–1910 Stevenson screen data and then combine this merged series with the ACORN-SAT record.

We undertook an assessment the homogeneity of the Glaisher stand data prior to 1910, using the RHTestsV4 absolute inhomogeneity identification method (Wang *et al.*, 2010). While best homogenisation practise recommends assessing a dataset using reference series from neighbouring stations (Venema *et al.*, 2012), this is difficult for pre-1910 temperature data in Australia (Ashcroft *et al.*, 2012) due to the limited number of potential reference stations (especially before 1890) and uncertainty about instrument exposures at those stations.

Using RHTestsV4 without a reference series found no inhomogeneities in the minimum temperature Glaisher stand series prior to 1910, and one inhomogeneity in maximum temperature, in January 1872. The lack of other breakpoints implies that the issues responsible for the maximum temperature breakpoints in the 1892–1901 period in the difference series between the Glaisher stand and Stevenson screen (Figure 3c) primarily affected the Stevenson screen data. This hypothesis is supported by the results of Ashcroft *et al.* (2012), who found a breakpoint in 1892 in the monthly Stevenson screen maximum temperature data.

There are no metadata to explain the breakpoint identified in the Glaisher series in January 1872. In fact, the inhomogeneity is not detected when the available maximum temperature data for Mount Barker (about 30 km to the southeast) is used as a reference series. Comparison with data from Melbourne (650 km to the south east, but within the same synoptic regime), also reveals a relatively stable relationship, particularly after the mid-1860s when the Melbourne station became established at the Melbourne Observatory in the Domain, where it remained until 1908. The difference between annual maximum temperatures in Adelaide and Melbourne remains around 2.5–3.5°C from 1866.

One explanation for the apparent jump in maximum temperatures pre-1872 could be a decrease in rainfall and cloud cover, corresponding to an increase in daytime temperatures. Comparing rainfall observations with the diurnal temperature range (DTR, Figure 6a) shows a modest correlation, and rainfall observations during the period reveal below average totals associated with the Goyder drought of the 1860s ((Gergis and Ashcroft, 2013; Freund *et al.*, 2017). However, years of similar conditions do not show as great an increase in DTR. Monthly assessment of this relationship (not shown) revealed prolonged dry conditions during November and December, but the largest DTR anomalies

during January, March and November. Overall, there is no strong seasonality in the pre-1872 dry period to indicate maximum temperatures should be higher than during any other drought.

A comparison between available cloud cover data and modern rainfall and DTR values additionally indicate that cloud coverage would need to be far outside previously observed values to elicit such an increase in maximum temperatures (Figure 6b and c). Given these findings, it is likely that an undocumented inhomogeneity remains in the Glaisher stand dataset, although comparison with Melbourne data suggest it is unlikely to be substantially greater than 0.5°C. The pre-1872 maximum temperature data should therefore be treated with caution.

We merged the Glaisher stand data with the ACORN-SAT series using the daily percentile-matching method described in Trewin *et al.* (2020), with the homogeneous period of overlapping data from 1910 to 1924 used to define the transfer function for the merge. It should be noted that the ACORN-SAT series is notionally for the Kent Town site that was used as Adelaide's primary weather station after 1977. The 1910–1977 West Terrace data was adjusted to be equivalent to Kent Town, which has generally warmer maximum temperatures and cooler minima. Hence the adjustment in merging the Glaisher stand data with the ACORN-SAT series will not exactly match the difference between the Glaisher stand and Stevenson screen at West Terrace.

Annual mean maximum and minimum temperature data for the homogeneous record (Figure 7) indicate that both maximum and minimum temperatures have risen over the post-1950 period, after having been relatively stable prior to 1950. High maximum temperatures prior to 1872 are also evident (the 1860–1869 mean maximum temperature is only 0.1 °C lower than that for 2010–2019), and dry conditions suggest that the temperatures during this time may well have been warm. However, we have also established that an unresolved inhomogeneity is likely responsible for at least some of the high maximum temperature values.

Comparing the recent decade (2010–2019) with the more reliable data for the pre-industrial period (1872–1900) shows a warming of 1.1 °C for both maximum and minimum temperature. The 1872–1900 and 1900–1950 means are within 0.1 °C of each other for both maxima and minima, indicating that temperatures in Adelaide in the first half of the 20<sup>th</sup> century were similar to those in the late 19<sup>th</sup> century. This is consistent with the broader results for southeastern Australia found by Ashcroft *et al.* (2012).

## 5. A re-examination of Adelaide temperature extremes

The combined series also allows us to examine long-term variability in daily temperatures, particularly extremes. Gergis *et al.* (2020) recently explored changes in heatwaves and cold events in Adelaide from 1838, but only applied a basic homogenisation procedure to a section of the Glaisher stand data. It is therefore useful to compare our results to theirs.

Our combined series generally shows more heatwaves over the whole period (Figure 8a), with one to five more heatwaves per decade identified using the homogenised series compared to Gergis *et al.* (2020). Five additional heatwaves are identified in the 1860s using our homogenised dataset, although as noted in section 4, there are some potential inhomogeneity issues with the Glaisher record before 1872. However, Gergis *et al.* (2020) found the vast majority of the extremes they identified were supported by documentary evidence, suggesting that despite the data quality issues, there may well have been a higher number of heatwaves in the 1860s compared to the surrounding decades.

A similar increase is seen in cold extremes (Figure 8b), with up to ten more cold events identified using the homogenous combined series during the 1920s and 1940. These differences could be largely attributed to the more rudimentary procedure used by Gergis *et al.* (2020) to combine the datasets, which did not account for the changing in observation times in the Glaisher data in 1938. It must also be noted that small changes to the temperature values as a result of homogenisation can lead to a genuine hot or cold event being included or excluded in one dataset and not the other, due to the nature of the definitions used.

The goal of Gergis *et al.* (2020) was not to develop a homogeneous record for Adelaide, but to determine whether the historical records could be used in conjunction with documentary records to explore long-term variability in temperature extremes. Our comparison with their results suggests that despite some differences in the absolute count of heatwaves and cold events, both series show a clear increase in heatwaves and a decrease in cold events for Adelaide since 1859.

### 5.1. January 1939 heatwave

Now we understand the relationship between the Glaisher and Stevenson screen data in Adelaide at the daily scale, there is an opportunity to reassess significant extreme temperature events in Adelaide's history. We focus on heatwaves here as the accuracy of observations during historical heat extremes in southeastern Australia has long been a source of discussion (Nicholls, 1997, 2014). The January 1939 heatwave was the most exceptional of the 20<sup>th</sup> century for Adelaide (as it was for much of southeastern Australia) in terms of societal impact (Coates *et al.*, 2014). The 46.1 °C measured in the Stevenson screen at West Terrace on 12 January was the highest temperature recorded at that site until 46.6 °C was observed on 24 January 2019. Maximum temperatures reached 44 °C or above on four of the five days from 9 to 13 January 1939, a sequence which remains unmatched.

Figure 9 shows a comparison of the raw Stevenson screen and Glaisher stand data at West Terrace in January 1939. As expected from our earlier comparisons, the Glaisher stand data are consistently warmer during the heatwave. A maximum of 47.6 °C was observed in the Glaisher stand on 12

January (a value sometimes publicly quoted as Adelaide's record high), 1.5 °C higher than the Stevenson screen value on the same day.

The mean difference between the Glaisher stand and Stevenson screen maximum temperatures over the peak period of the heatwave, from 6 to 13 January, is also 1.5 °C. This is broadly consistent with the differences found in section 3 of 1.2 °C for mean maximum temperatures during the warmer months in the 1926–1937 period. This period can be considered largely representative of the January 1939 data, as the 1938 observation time change has no significant impact on maximum temperatures, only minima.

Minimum temperatures during the 1939 heatwave also illustrate the importance of the 1938 observation time change for extreme high minimum temperatures. For example, the midnight-midnight minimum temperatures reported from the Stevenson screen were 33.2 °C on 10 January and 32.6 °C on 13 January, whereas neither minimum exceeded 26 °C in the 0900–0900 Glaisher stand data, indicating that on both occasions the temperature at 0900 the previous day had been below 26 °C. Interestingly, the January 1939 heatwave was not classified as extreme in our combined series or the series used by Gergis *et al.* (2020), illustrating the difficulty in using heatwave definitions to capture every event that has large societal impact (Perkins and Alexander, 2013).

## 5.2. February-March heatwave 1872

A prolonged heatwave also affected Adelaide in late February and early March 1872. In the Glaisher stand data, the temperature reached 38 °C (and hence 100 °F (37.8 °C)) on nine consecutive days from 27 February to 7 March, with a peak of 40.4 °C on 5 March. Although there are remaining concerns about the quality of the Glaisher data around 1872, Gergis *et al.* (2020) found extensive documentary evidence to support the occurrence of an extreme and lengthy heat event.

The most prolonged heatwave of this type in Adelaide occurred in 2008 (Australian Bureau of Meteorology, 2008), when the temperature reached 37.8 °C on 13 consecutive days from 5 to 17 March, with the last 12 being 38 °C or above. Prior to the 2008 event, there had been no instance of more than seven consecutive days of 37.8 °C or above in the Stevenson screen data at Adelaide, which makes the 1872 event notionally more extreme than any event in the Stevenson screen data between 1887 and 2007.

A full assessment of the significance of the 1872 event requires it to be assessed in the merged data set which, in effect, makes the Glaisher stand data at West Terrace comparable with the Stevenson screen data at Kent Town. In the merged dataset, there are still nine consecutive days with maximum temperatures of 37.8 °C or above, although one day of 37.9 °C breaks the sequence of 38 °C days. Conversely, the merged dataset has a sequence of ten consecutive nights of 20 °C or above from 27 February to 8 March 1872, which is not present in the original Glaisher stand data; placing this in

perspective, the post-1887 Stevenson screen data have four sequences of ten or more such nights, with the longest being 14 nights in January-February 1890. The merged dataset therefore confirms that the 1872 heat event was historically significant, although the specific indicators vary slightly between the raw and merged data.

It is also of interest that late February and March are climatologically the most likely time for prolonged heatwaves of this type in Adelaide. Four of the seven instances of seven or more consecutive days of 37.8 °C or above in the post-1887 Stevenson screen record were wholly or partly in March, as were two of the four instances of ten or more consecutive nights of 20 °C or above. One reason for this seasonality could be that the sub-tropical ridge — a region of semi-permanent high pressure — is strengthening and at its southernmost location during February and March (Timbal and Drosowsky, 2013), inhibiting incursions of cold, higher latitude air masses.

## 6. Discussion and conclusions

Uncovering the daily data from the Glaisher stand in Adelaide has allowed us to examine a 60-year daily relationship between Glaisher stand and Stevenson screen temperatures for the first time. A number of changes are apparent in the relationship during the 60-year overlapping period, from causes such as changes in observation times and other unidentified variations in observation practises. This makes it important to conduct an assessment of related metadata when using these data.

Notwithstanding these changes over the 60-year period, there are clear and consistent signals in the relationship between the two series. Maximum temperatures in the Glaisher stand in the warmer months are typically 0.8 to 0.9 °C warmer than in the Stevenson screen (with some variation between sub-periods), with little difference in winter, while minimum temperatures are slightly cooler all year. These results are consistent with those obtained by Richards *et al.* (1993) in their earlier assessment of the Adelaide data using monthly averages, and those reported by Charles Todd himself in the late 19th Century (Todd, 1900). They are also broadly consistent with the results of earlier studies in the United Kingdom and South Africa, and of the results found by Brunet *et al.* (2011).

A strong warming signal, with an increase in heat waves and a decrease in cold events, is clear when we use the recovered Glaisher stand data to develop a homogeneous temperature series for Adelaide for 1859–2019. The daily data additionally enable us to re-examine infamous heat events in Adelaide's past (Gergis *et al.* 2020). In many cases, a change in observing environment will affect extremes differently to means (Trewin, 2013), so it cannot be assumed that a given change in mean temperatures will show a similar signal in extremes. In this case, however, the Adelaide data show no clear evidence that extreme temperatures have inter-screen differences greatly different to those for means. For example, it had previously been surmised that the 1.5 °C difference between the screens on the extreme hot day of 13 January 1939 was an indicator that very hot days would show larger

differences than mean summer temperatures. But in fact, that difference was only slightly more than typical mean differences during summer in the preceding decade, a period when the mean difference between the temperature series was larger than it had been at other times in the 60-year dataset. These differences still need to be considered however when using the Glaisher stand data to assess the severity of historical Adelaide heatwaves.

Comparison of the results from Adelaide with the British, South African and Spanish studies using shorter parallel series also show no clear evidence of a strong geographical signal in the magnitude of inter-screen differences, with the Adelaide results falling within the range of those studies. This suggests that our results, at least in a broad sense, are likely to be applicable across a range of mid-latitude locations. Tropical locations may show different behaviour, but there was little known historical use of the Glaisher stand (which was mostly used in British colonies) in the tropics; for example, in India the standard late 19<sup>th</sup> century exposure was a cage below a thatched roof (Parker, 1994).

While our results add to the efforts of Brunet *et al.* (2011) and provide another relationship between Glaisher and Stevenson screen observations that may be useful for adjusting historical temperature records, they are only applicable to properly managed and operated Glaisher stands. Some 19<sup>th</sup> century sites met this standard, but many 19<sup>th</sup> century Australian sites had other exposures, including south-facing walls and open exposures under verandahs or similar. This is reflected in many sites, particularly in New South Wales, showing inhomogeneities in the transition to Stevenson screens which are substantially larger than those found here for Adelaide (Ashcroft *et al.*, 2012). As such, applying corrections based on the Adelaide data to regional or national averages in Australia is likely to result in 19<sup>th</sup> century temperatures that are still unrepresentatively warm relative to Stevenson screens.

There are many avenues to explore with this new dataset, and we have only attempted some angles of examination in this study. Future work could conduct a more detailed comparison of this parallel series compared to other international series or reanalyses, as well as additional assessments of the relationship between rainfall and the temperature differences. The Glaisher stand and Stevenson screen data are freely available from Zenodo and the Bureau of Meteorology respectively. Future data recovery efforts (Climate History Australia, 2020) will also enable the development of a continuous temperature record for Adelaide from 1838, making it one of the longest records in the Southern Hemisphere.

## Acknowledgements

This work would not have been possible without the dedicated digitisation efforts of the Australian Meteorological Association. LA acknowledges the support of the Australian Research Council Centre of Excellence for Climate Extremes (CE170100023). Many thanks to David Martin, Dörte Jakob,

Acacia Pepler for their comments on an earlier version of the manuscript, and Phil Jones and an anonymous reviewer for their valuable suggestions. The original data books are held in the archive files of the South Australian Regional Office of the Bureau of Meteorology. They are also listed in the national Archives of Australia Series AP810/57. Images of the data books are available at <https://www.met-acre.net/MERIT/AMETA.html>. The digitised data are available for future analysis at Zenodo (\*\*doi to be added\*\*)

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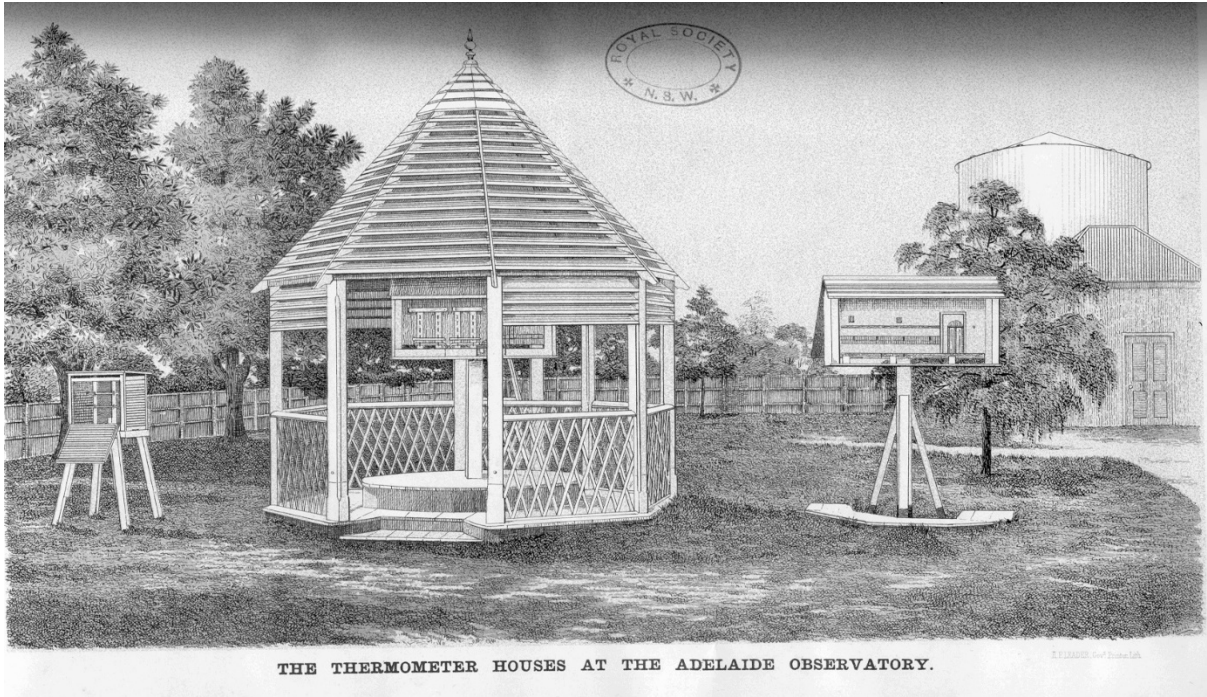
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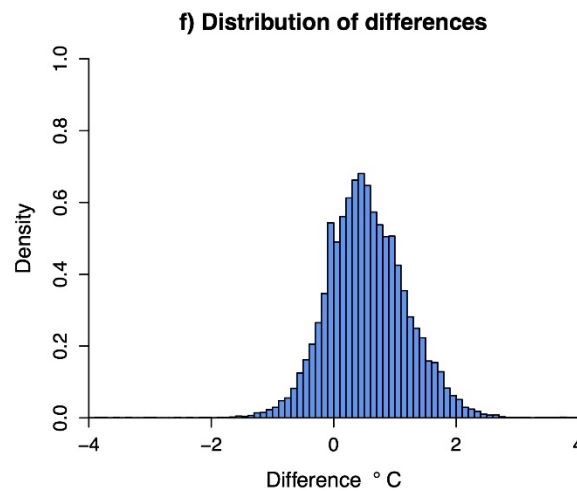
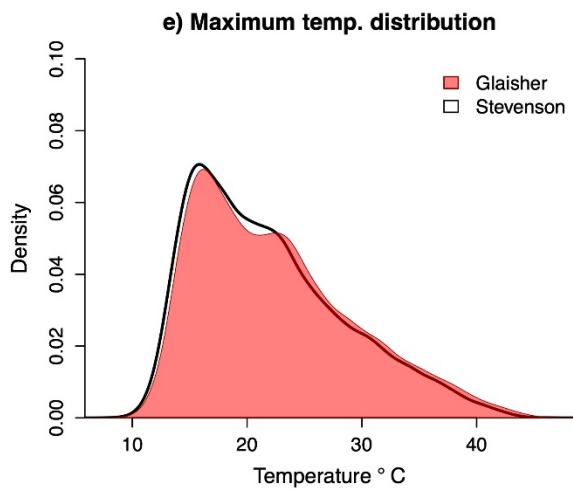
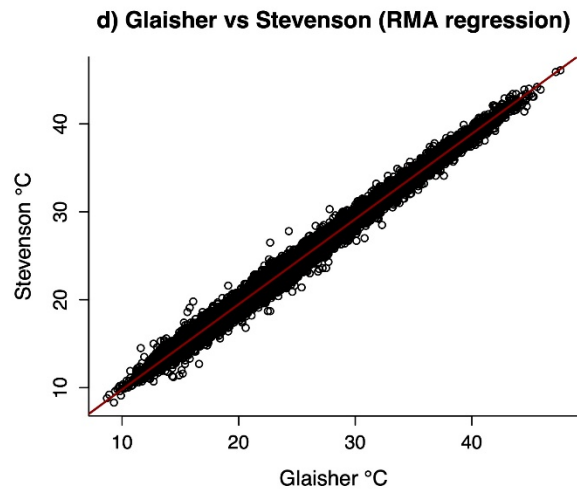
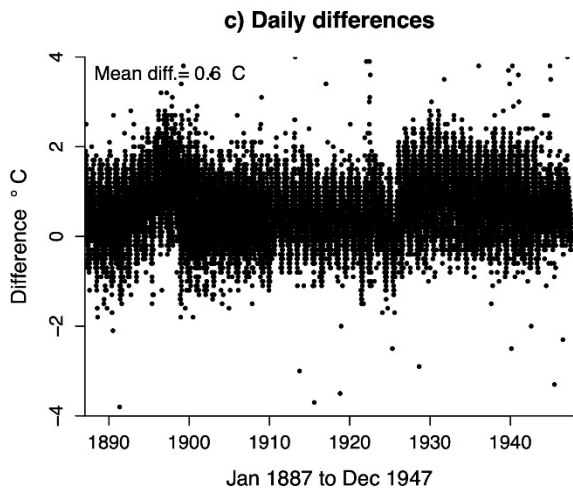
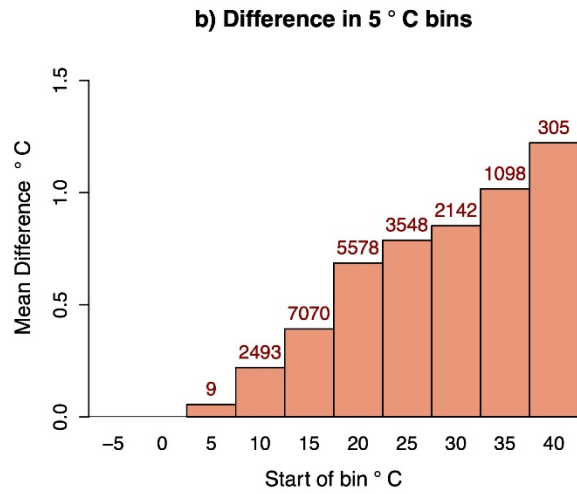
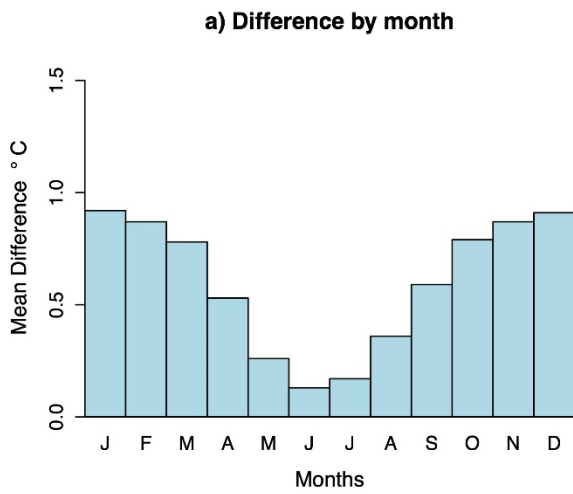
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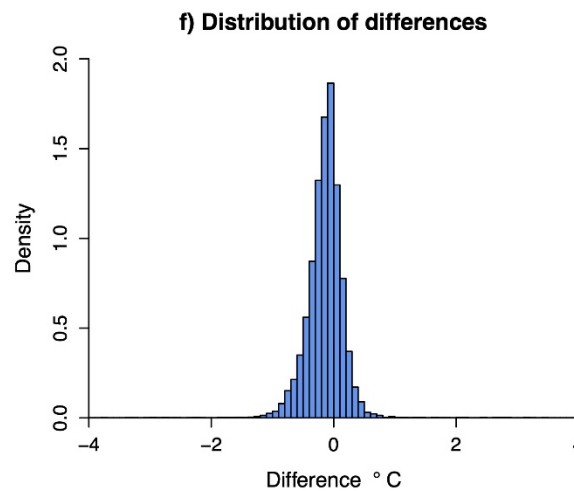
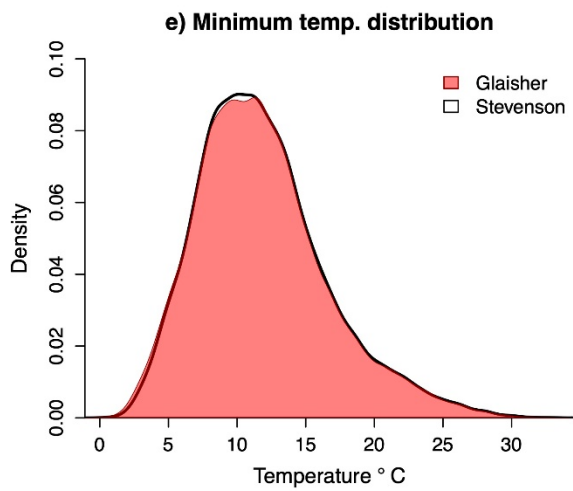
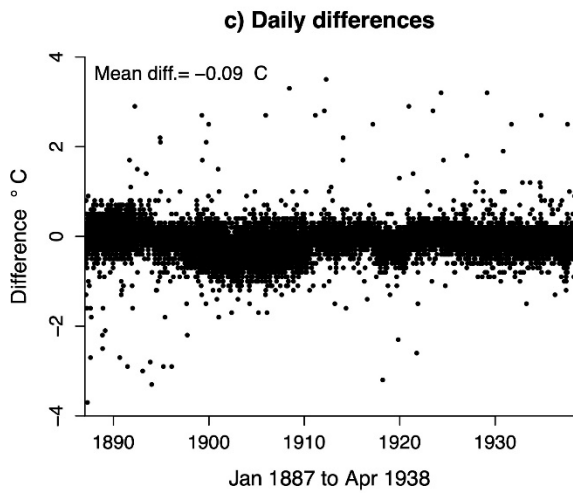
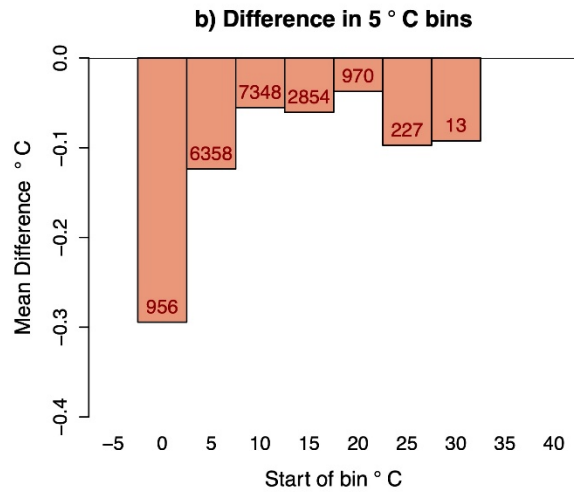
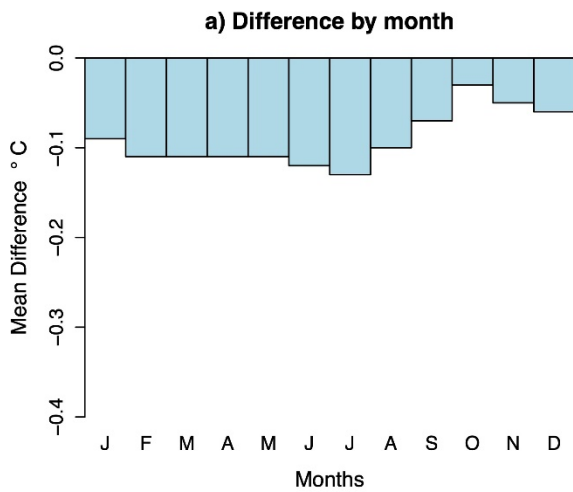


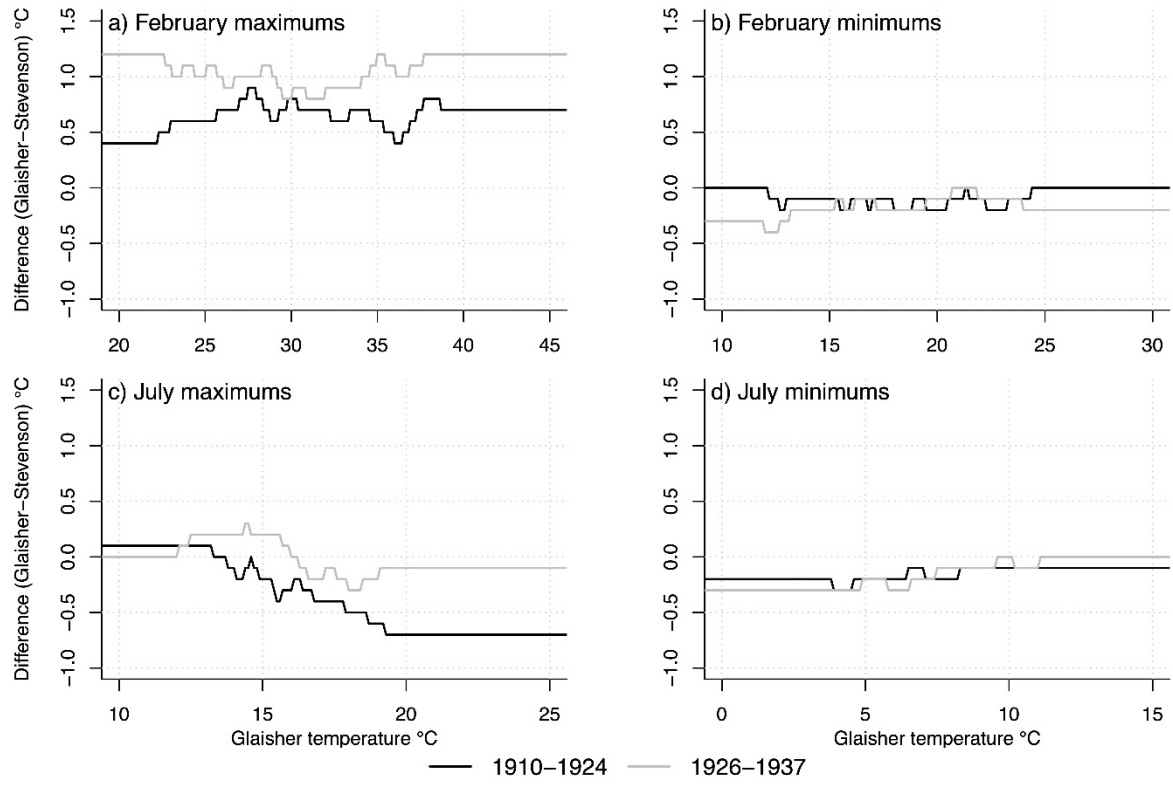
DAILY MAX AND MIN  
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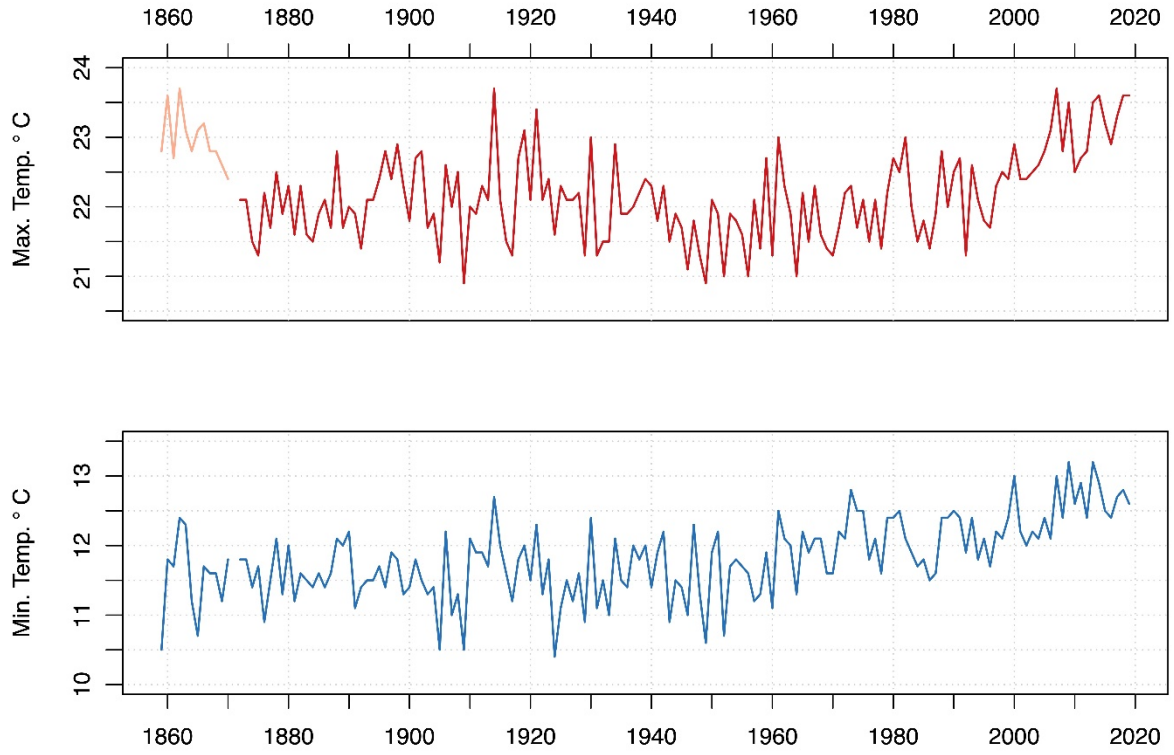
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	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	85.6	63.8	77.1	59.9	81.2	64.6	75.6	49.9	62.8	53.8	57.0	48.1	65.4	51.2	66.8	53.7	68.3	45.7
2	80.9	62.1	66.5	63.4	77.8	58.3	78.2	52.8	60.8	45.4	66.8	50.3	68.0	49.2	66.0	55.8	75.8	50.1
3	88.8	69.8	69.6	58.5	81.2	55.5	72.5	58.7	64.7	42.4	65.7	56.0	65.2	48.3	66.2	48.9	79.5	54.9
4	89.5	66.2	70.8	50.1	83.8	62.3	80.8	60.6	69.8	46.8	62.8	53.3	63.1	48.2	67.8	46.7	71.8	61.4
5	86.6	66.6	62.7	55.8	72.2	60.8	65.6	55.8	71.0	46.6	65.8	50.0	66.0	43.6	65.4	48.9	65.2	52.9
6	71.8	60.9	61.5	48.6	72.9	52.6	65.2	46.9	74.2	47.5	69.6	49.8	71.7	47.9	64.2	42.8	60.5	49.0
7	62.0	47.6	62.8	52.1	68.5	56.1	63.3	51.8	74.4	48.9	63.0	52.8	75.8	55.9	71.1	49.1	60.0	45.7
8	64.3	44.8	63.6	47.8	65.8	52.4	65.0	47.8	67.3	59.6	62.8	44.4	82.6	49.4	74.8	47.0	60.9	47.4
9	65.8	52.6	63.6	52.8	66.5	57.4	67.0	41.4	60.7	54.1	59.3	43.1	76.3	65.3	79.0	53.1	60.9	48.9
10	70.3	44.9	64.1	52.9	67.7	53.9	72.6	42.9	65.8	53.7	59.2	44.5	70.3	50.1	60.8	54.9	61.6	42.4
11	73.1	50.8	65.9	56.3	70.7	60.3	76.2	44.8	67.2	50.8	63.4	47.2	67.8	56.7	62.3	44.6	63.8	45.0
12	72.4	55.1	62.2	49.5	74.3	56.8	77.8	52.6	55.6	52.2	58.1	46.1	63.9	41.0	60.8	53.2	69.0	54.6
13	77.3	56.9	62.8	45.8	72.0	55.9	60.9	56.7	61.9	53.9	60.0	46.4	68.9	48.8	59.6	52.3	73.1	52.5
14	76.7	56.8	61.8	46.9	75.0	59.2	60.8	45.2	61.2	52.9	61.6	46.6	74.2	47.8	64.3	54.4	76.4	50.6

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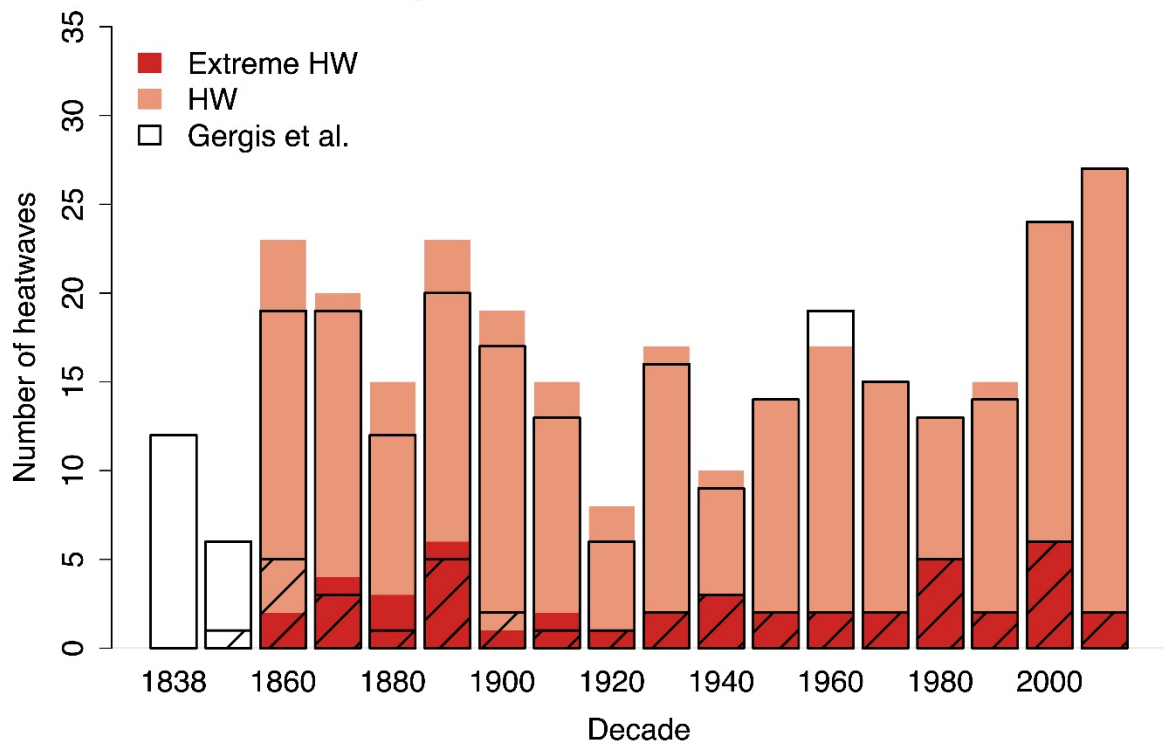




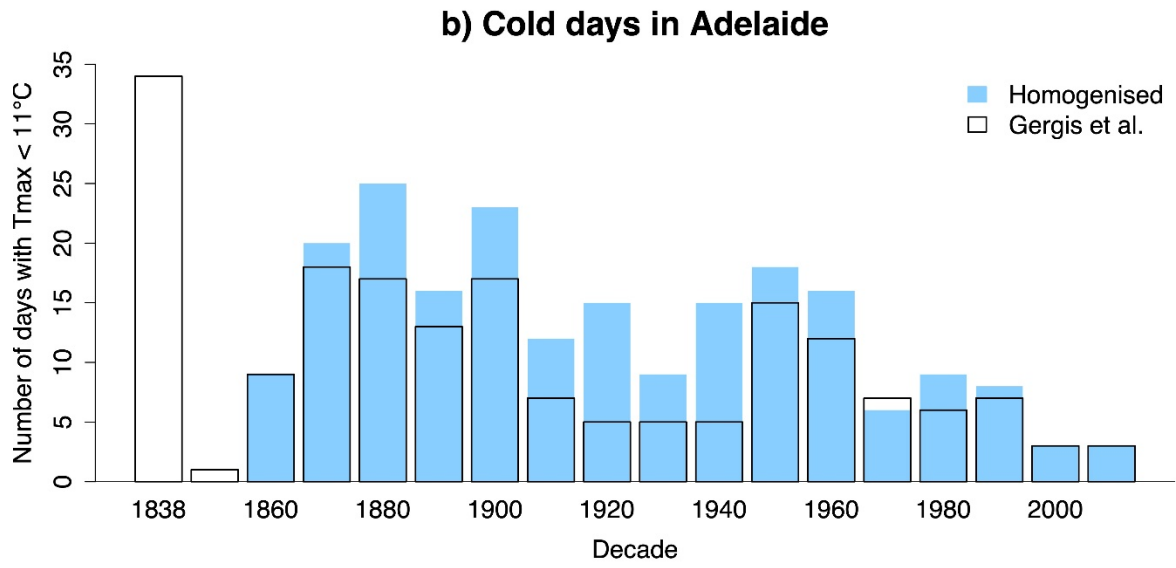




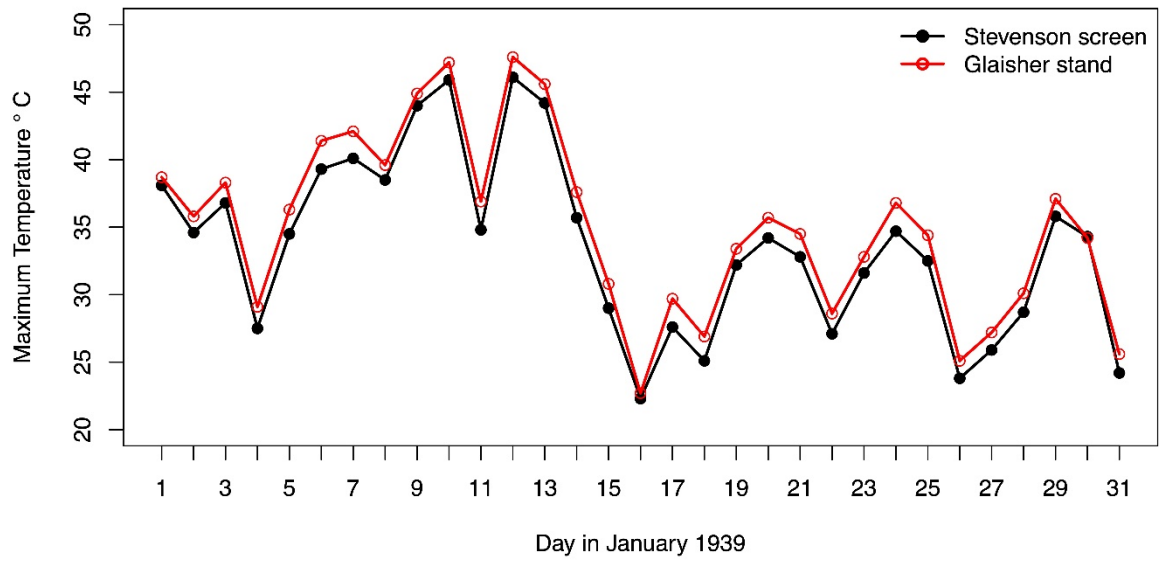
### a) Heatwaves in Adelaide



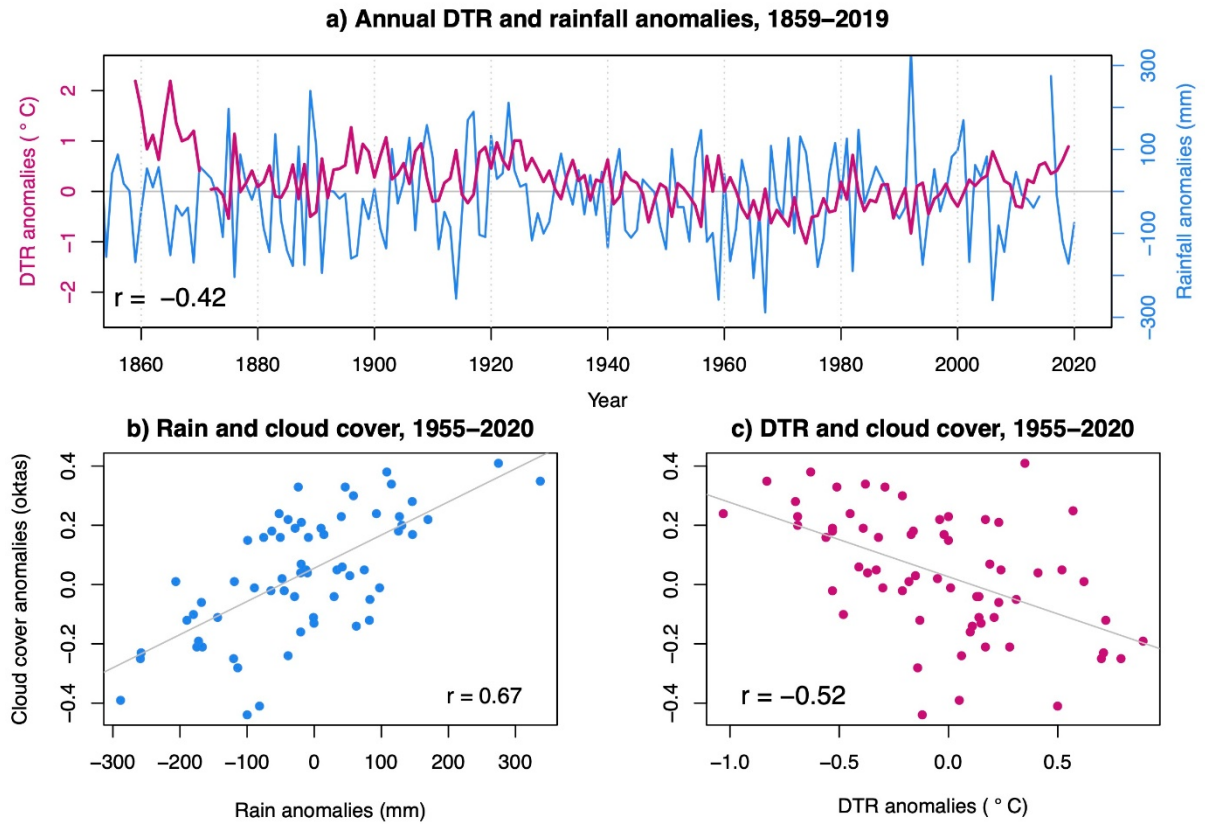
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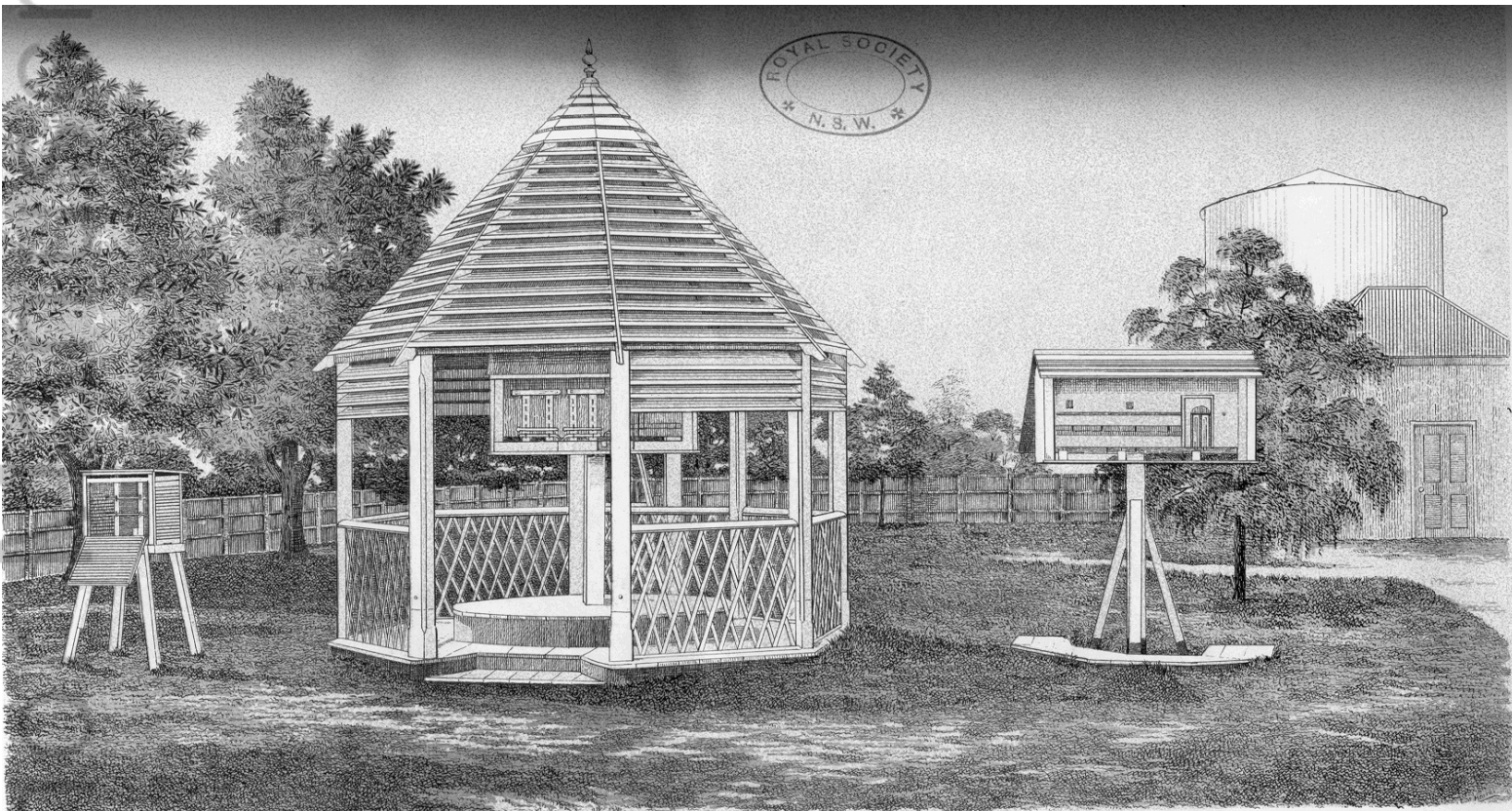
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THE THERMOMETER HOUSES AT THE ADELAIDE OBSERVATORY.

R. F. IRIDGE, Govt. Printer, Ad.

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# DAILY MAX AND MIN

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DATE	1921		1922		1923		1924		1925		1926		1927		1928		1929	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
1	85.6	63.8	79.1	59.9	81.2	64.6	75.6	49.9	62.8	53.8	57.0	48.1	65.4	51.2	66.8	53.7	68.3	45.7
2	80.9	62.1	66.5	63.4	77.8	58.3	78.2	52.8	60.8	45.4	66.8	50.3	68.0	49.2	66.0	55.8	75.8	50.1
3	88.8	69.8	69.6	58.5	81.2	55.5	72.5	58.7	64.7	42.4	65.7	56.0	65.2	48.3	66.2	48.9	79.5	54.9
4	89.5	66.2	70.8	50.1	83.8	62.3	80.8	60.6	69.8	46.8	62.8	53.3	63.1	48.2	67.8	46.7	71.8	61.4
5	86.6	66.6	62.7	55.8	72.2	60.8	65.6	55.8	71.0	46.6	65.8	50.0	66.0	43.6	65.4	48.9	65.2	52.9
6	71.8	60.9	61.5	48.6	72.9	52.6	65.2	46.9	74.2	47.5	69.6	49.8	71.7	47.9	64.2	42.8	60.5	49.0
7	62.0	47.6	62.8	52.1	68.5	56.1	63.3	51.8	74.4	48.9	63.0	52.8	75.8	55.9	71.1	49.1	60.0	45.7
8	64.3	44.8	63.6	47.8	65.8	52.4	65.0	47.8	67.3	57.6	62.8	44.4	82.6	49.4	74.8	47.0	60.9	47.4
9	65.8	52.6	63.6	52.8	66.5	57.4	67.0	41.4	60.7	54.1	59.3	43.1	76.3	65.3	79.0	53.1	60.9	48.9
10	70.3	44.9	64.1	52.9	67.7	53.9	72.6	42.9	65.8	53.7	59.2	44.5	70.3	50.1	60.8	54.9	61.6	42.4
11	73.1	50.8	65.9	56.3	70.7	60.3	76.2	44.8	67.2	50.8	63.4	47.2	67.8	56.7	62.3	44.6	63.8	45.0
12	72.4	55.1	62.2	49.5	74.3	56.8	77.8	52.6	55.6	52.2	58.1	46.1	63.9	41.0	60.8	53.2	69.0	54.6
13	77.3	56.9	62.8	45.8	72.0	55.9	60.9	56.7	61.9	53.9	60.0	46.4	68.9	48.8	59.6	52.3	73.1	52.5
14	76.7	56.8	61.8	46.9	75.0	59.2	60.8	45.2	61.2	52.9	61.6	46.6	74.2	47.8	64.3	54.4	76.4	50.6

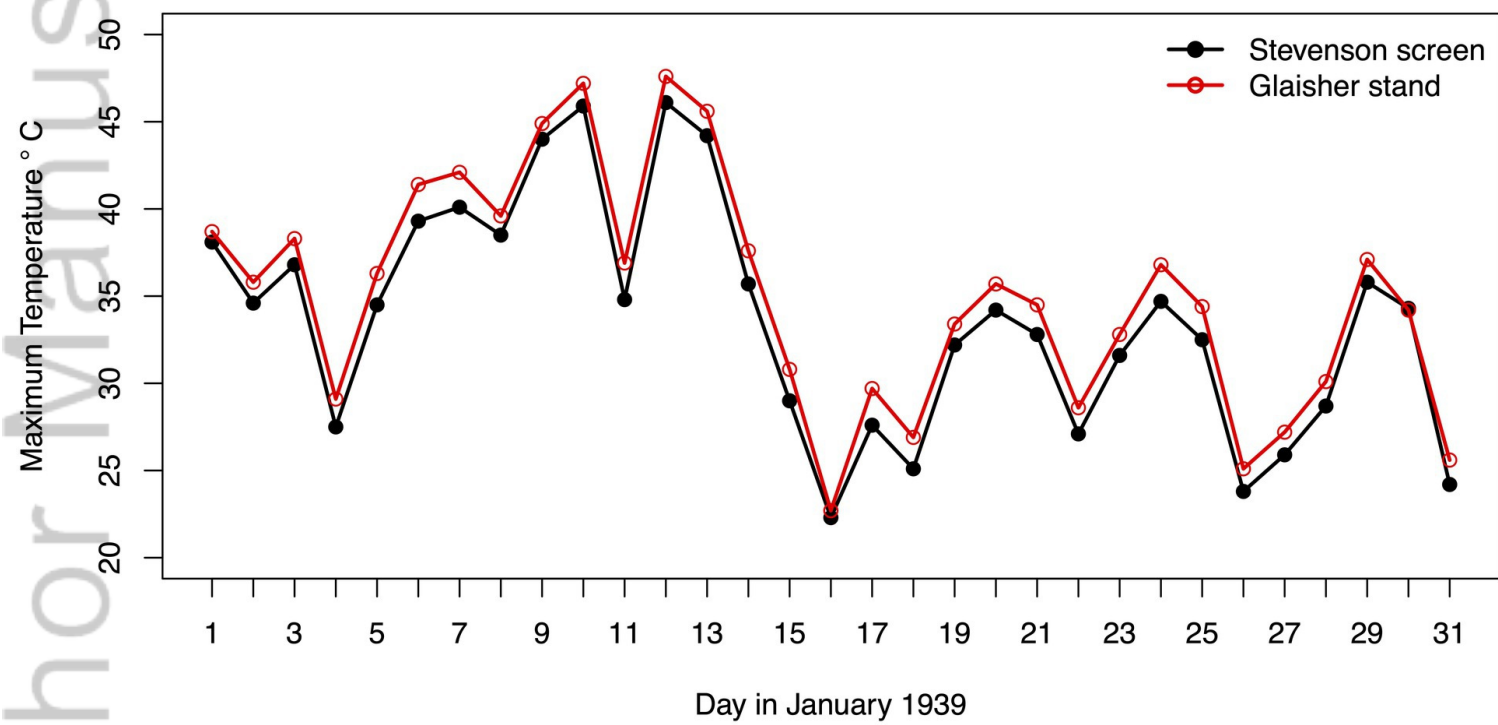
JOC\_7385\_Adelaide paper - figure 2.jpg

The world's longest known parallel temperature dataset: a comparison between daily Glaisher and Stevenson Screen temperature data at Adelaide, Australia, 1887–1947

Linden Ashcroft, Blair Trewin\*, Mac Benoy, Darren Ray, Catherine Courtney

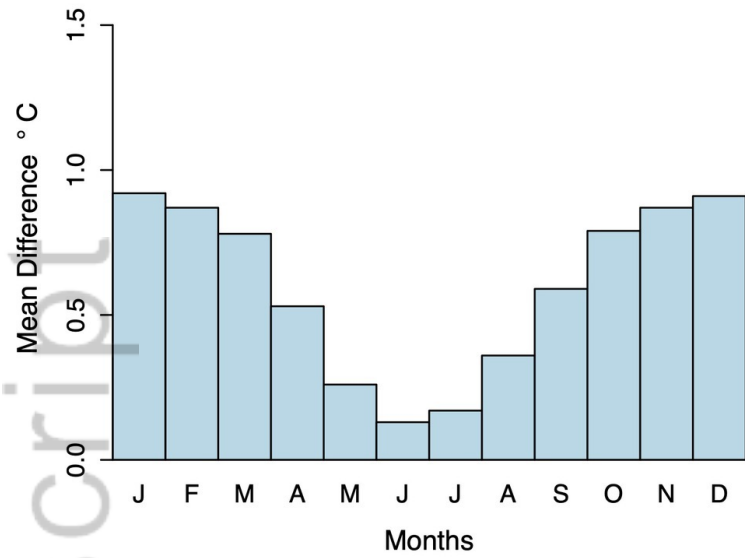
We examine the world's longest known sets of parallel temperature observations: daily temperature data for Adelaide, South Australia, recorded using two different thermometer screens for the 60 years from 1887 to 1947. The data then contribute to a 160-year continuous temperature record, one of the longest in the southern hemisphere.



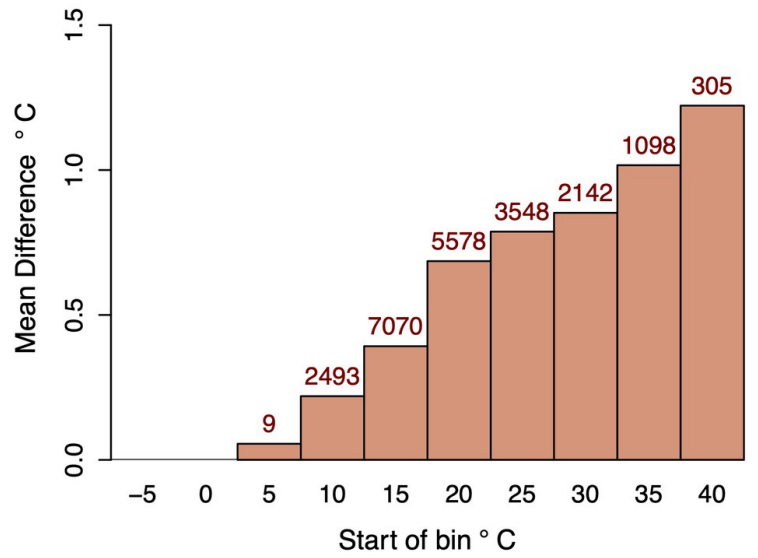


JOC\_7385\_Fig9\_Jan1939\_hw\_tmax\_comparison.jpg

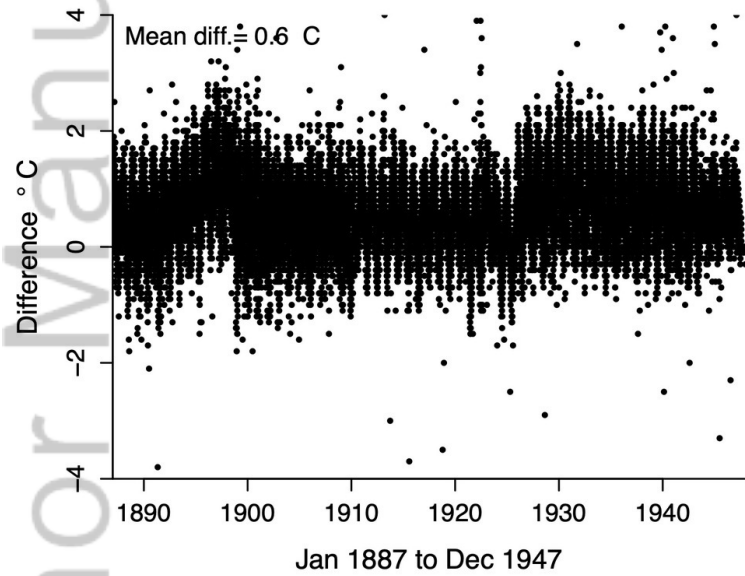
a) Difference by month



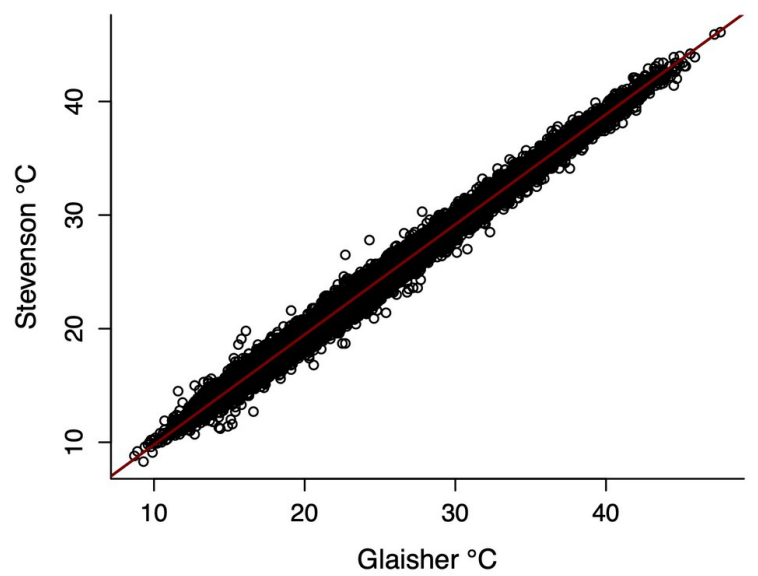
b) Difference in 5 ° C bins



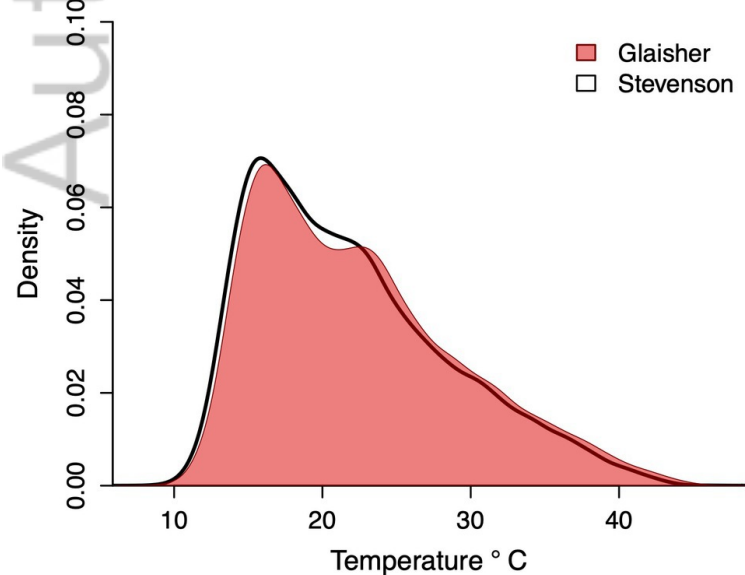
c) Daily differences



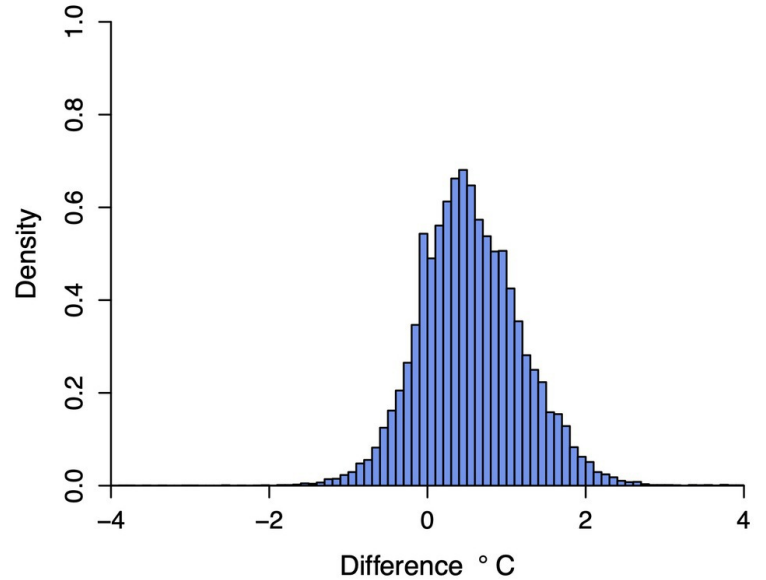
d) Glaisher vs Stevenson (RMA regression)



e) Maximum temp. distribution

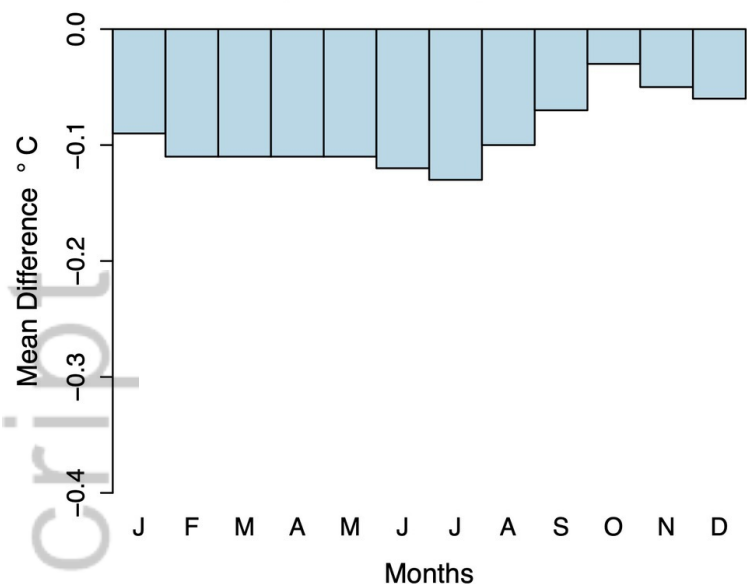


f) Distribution of differences

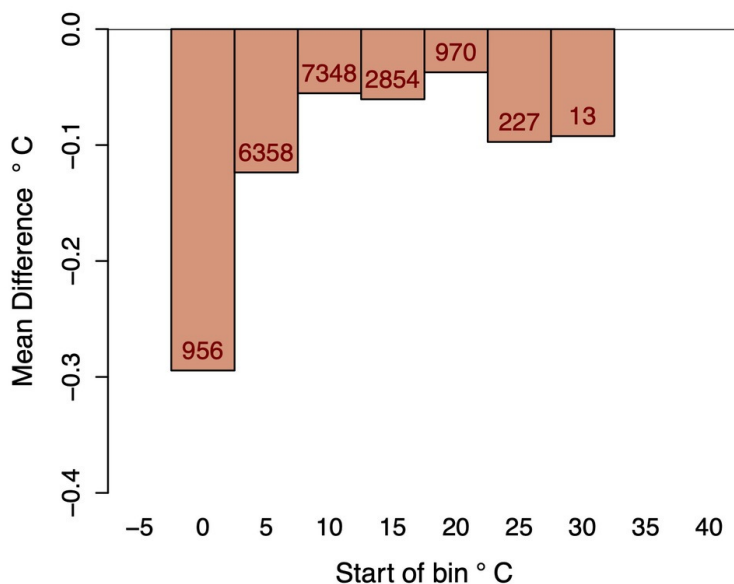


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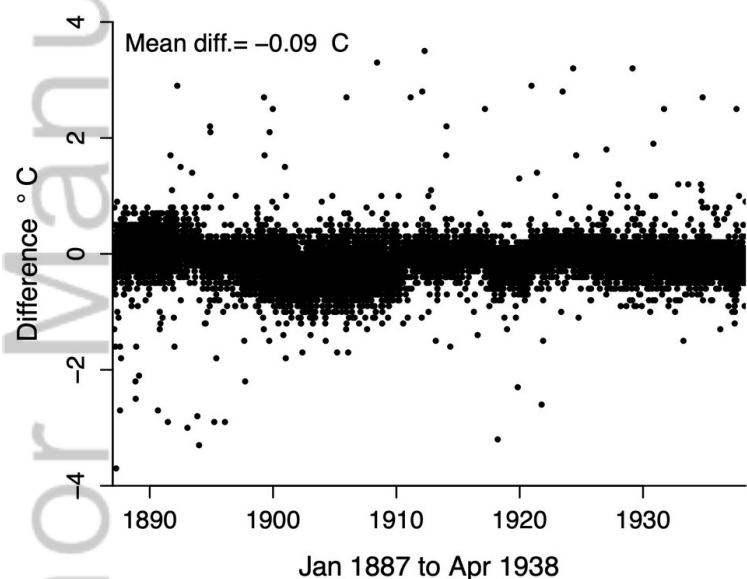
a) Difference by month



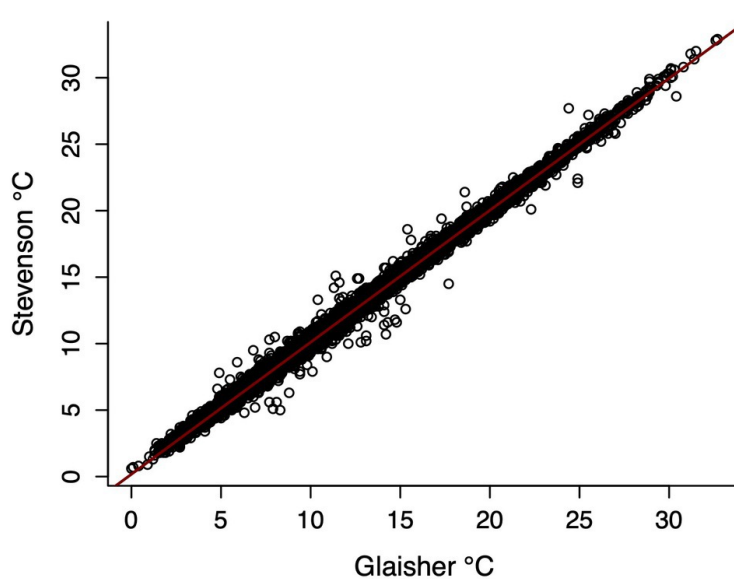
b) Difference in 5 ° C bins



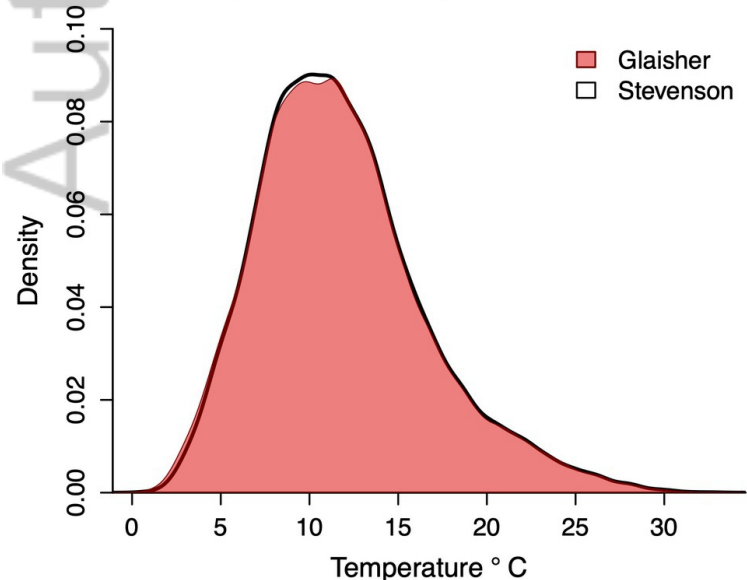
c) Daily differences



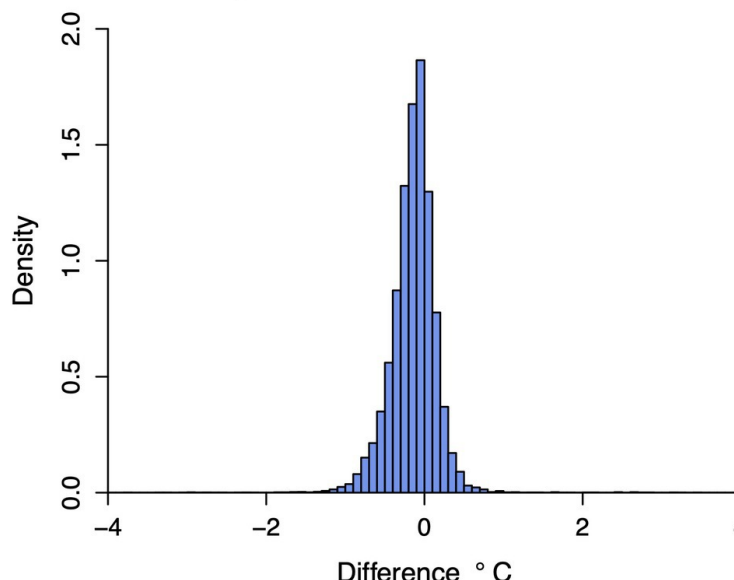
d) Glaisher vs Stevenson (RMA regression)

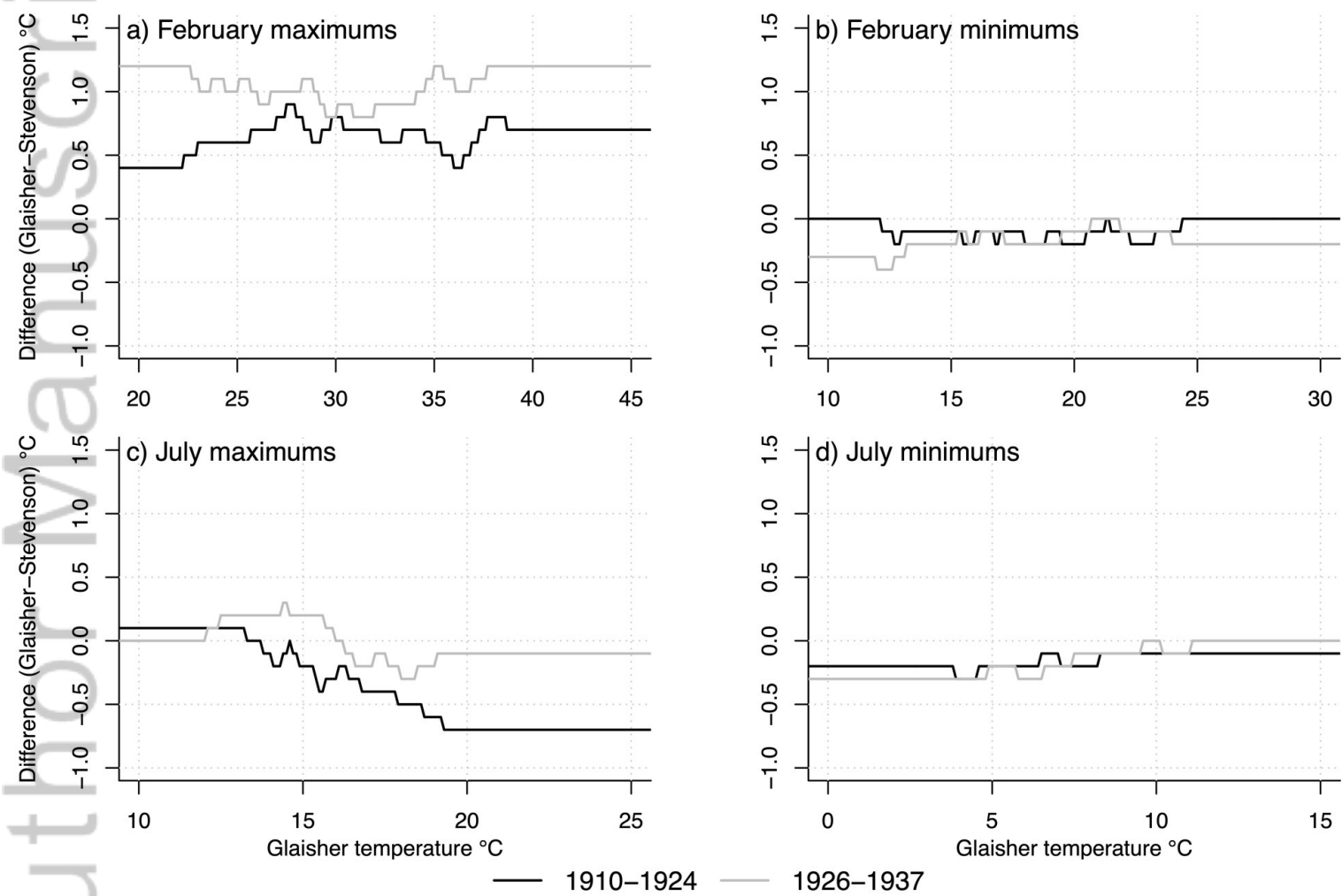


e) Minimum temp. distribution

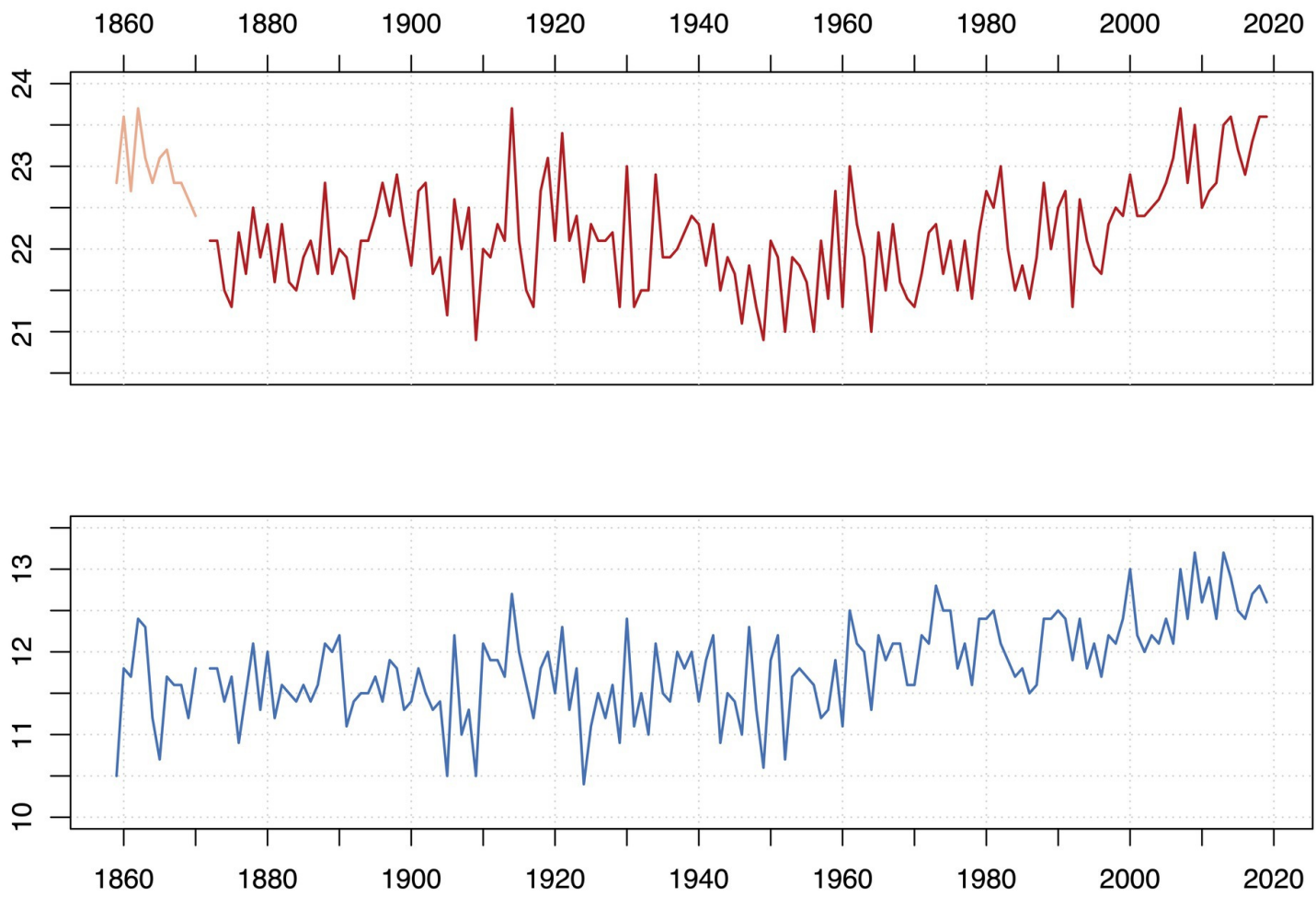


f) Distribution of differences



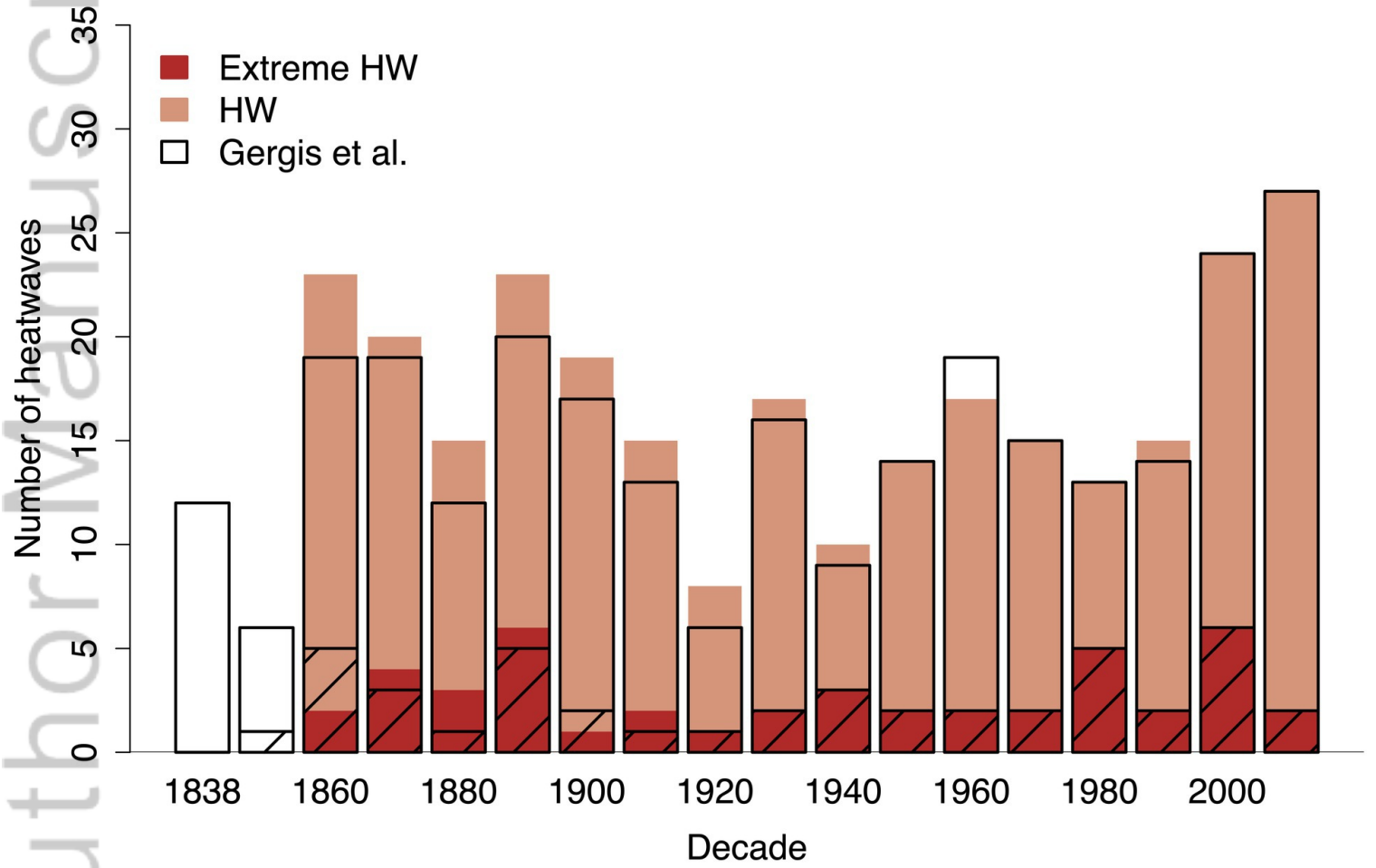


JOC\_7385\_Fig 5. Transfer\_functions\_2020-10-08.jpg



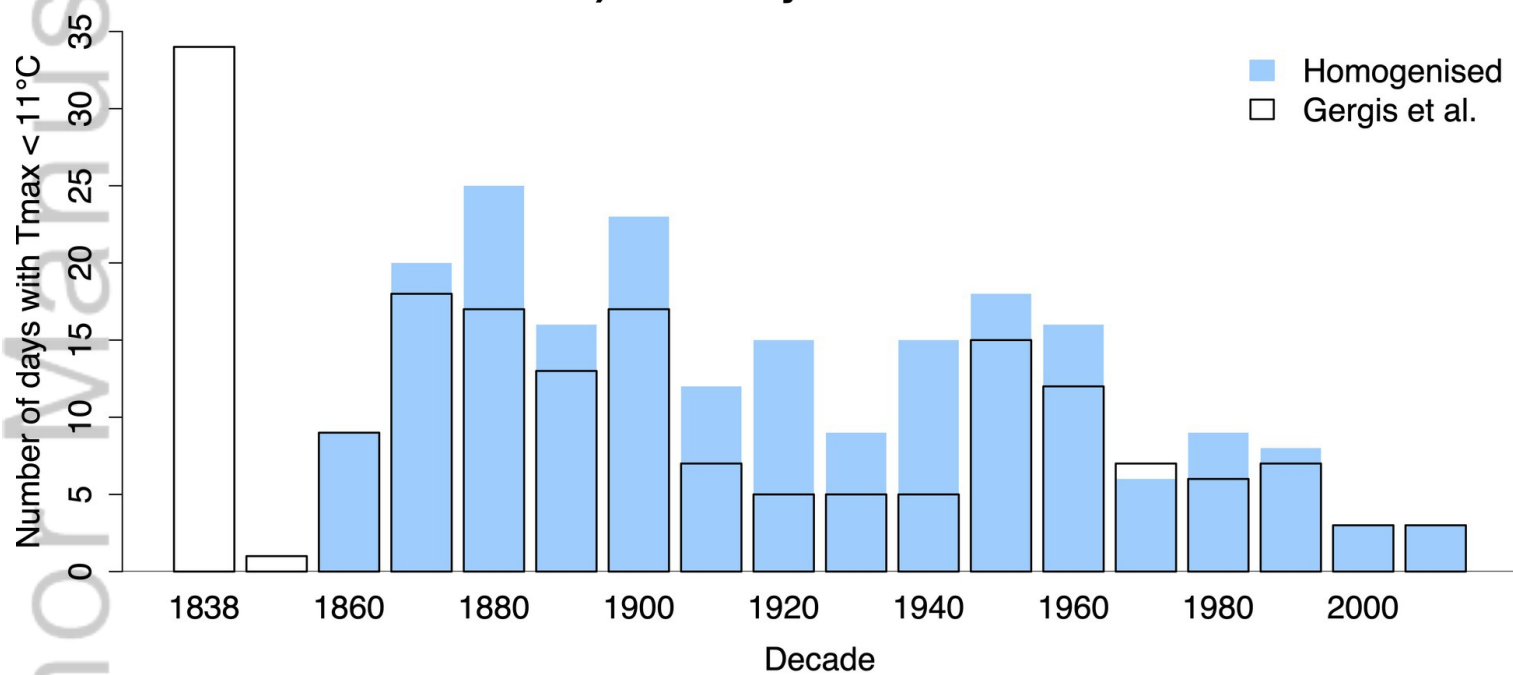
JOC\_7385\_Fig 7. Adelaide\_annual\_1859-2019\_2021-07-21.jpg

### a) Heatwaves in Adelaide



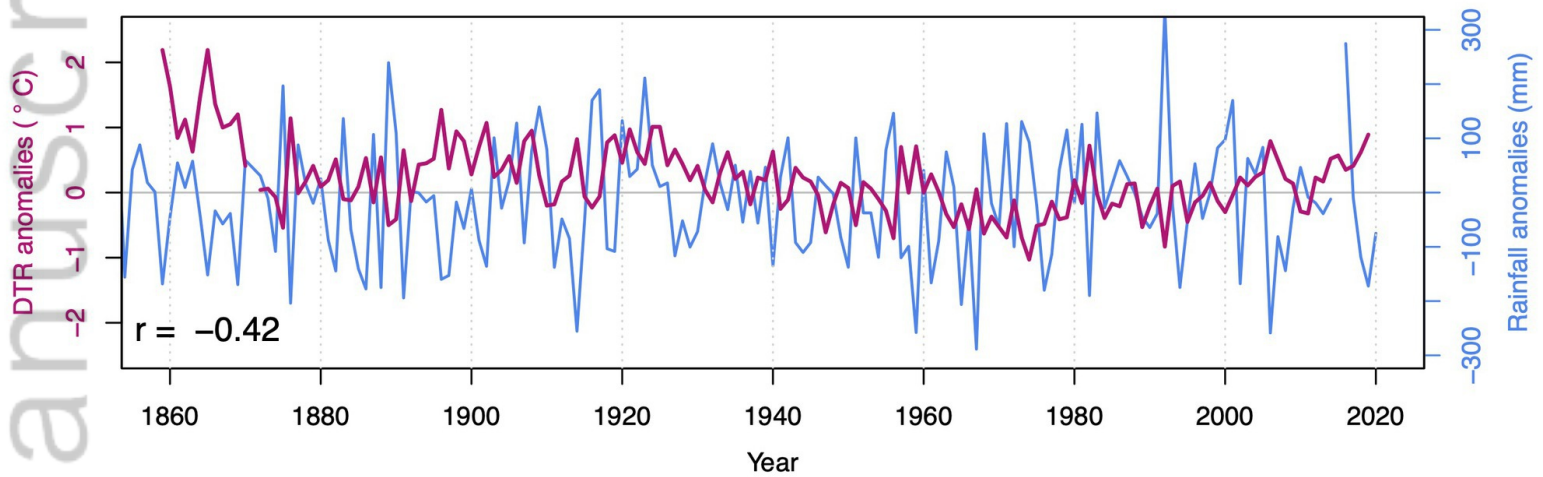
JOC\_7385\_Fig 8a. Heatwaves in Adelaide.jpg

### b) Cold days in Adelaide

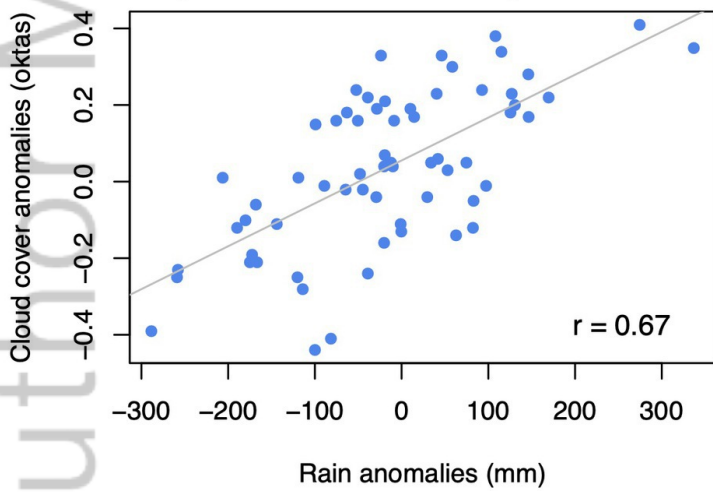


JOC\_7385\_Fig 8b. Instrumental\_snowday\_counts\_homog\_2021-07-21.jpg

**a) Annual DTR and rainfall anomalies, 1859–2019**



**b) Rain and cloud cover, 1955–2020**



**c) DTR and cloud cover, 1955–2020**

