A historical perspective on Australian temperature extremes

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Abstract

Global temperature increases are most clearly detected in the shifting distribution of extreme events. Australia's warming climate has resulted in significant changes in the frequency of temperature extremes, with a general increase in heatwaves and a reduction in the number of cold days. Here, we present the longest historical analysis of daily Australian temperature extremes and their societal impacts compiled to date. We use a newly consolidated early instrumental dataset and a range of historical sources for the South Australia region of Adelaide—the nation's driest state, containing the most heatwave-affected city in Australia—to investigate any changes in the characteristics of daily temperature extremes back to 1838. We identify multidecadal variability in heatwave and snow event frequency with a peak in the early 20th century, with an overall decrease in cold extremes and an increase in heatwaves in the region over the 1838–2019 period. Documentary and instrumental records show a decrease in the number of snow events in Adelaide, and a clear increase in the number of heatwaves since the late 20th century. To gain dynamical insight into historical extremes in South Australia, detailed case studies are presented to compare the synoptic characteristics of historical hot and cold extremes and their impacts. We place a particular emphasis on lesser-known events of the pre-1910 period and rare low-elevation snowfall. Significantly, this is the first study to provide long-term evidence for a reduction of low-elevation snow events and cold outbreaks in Australia. Finally, a discussion of the value and limitations of using historical instrumental and documentary data to assess long-term changes in Australian temperature extremes and their potential to improve future climate change risk assessment is provided.

Keywords: Australia, Adelaide, temperature, extremes, heatwaves, cold extremes, snow, historical climatology

1. Introduction

Australia is a country that experiences significant temperature variability and extremes (Bureau of Meteorology, 2008a). Australia's mean surface air temperature has increased by 1.1°C since 1910, with most of the warming occurring since the 1970s (Bureau of Meteorology and CSIRO, 2018). Extended instrumental temperature records for south-eastern Australia show that this recent warming is the most significant since at least 1860 (Ashcroft *et al.*, 2012), and a reconstruction of Australasian temperatures by Gergis *et al*. (2016) concluded that 1985–2014 was the warmest 30-year period experienced over the past 1,000 years.

This strong regional warming trend has resulted in changes in the frequency of temperature extremes, as average minimum and maximum temperatures have increased (CSIRO and Bureau of Meteorology, 2015). There are now more high-temperature extremes occurring on daily to inter-annual timescales (Reisinger *et al.*, 2014; CSIRO and Bureau of Meteorology, 2015). In particular, there has been a significant increase in the frequency, duration and magnitude of heatwaves, many of which had major societal impacts including severe effects on human health (Nairn and Fawcett, 2013; Coates *et al.*, 2014; Bureau of Meteorology and CSIRO, 2016; Perkins-Kirkpatrick *et al.*, 2016).

At the same time, the number of cold extreme events across the country has declined, with high temperature records being broken at three times the rate of low temperature records (CSIRO and Bureau of Meteorology, 2015). Frost occurrence in southern Australia is a partial exception to this, as a trend towards drier winters has led to small increases in clear nights and frost in some regions (Dittus *et al.*, 2015; Crimp *et al.*, 2016). However, this signal is localised, with the national annual pattern dominated by the warming of minimum temperatures (CSIRO and Bureau of Meteorology, 2015).

Snowfall is also associated with cold extremes in Australia. Large snow depths in Australia's alpine zone often accumulate enough to support winter tourism and water resource management, while at lower elevation, parts of rural southern Australia occasionally experience short-lived snow events.

The impacts of low-level snow events are usually minor, but they can cause disruption and damage. For example, the depth of snow associated with an event in July 1900 in New South Wales led to the collapse of verandas and lightly constructed buildings in Bathurst and adjacent localities (Shepherd, 1982). To date, analyses of long-term trends in snow occurrence are confined to alpine snow, where notable declines in light snow days and lower elevation snowfalls have been reported (CSIRO and Bureau of Meteorology, 2015; Fiddes *et al.*, 2015).

There have been limited attempts to assess both the physical characteristics and societal impacts of historical Australian temperature extremes in the pre-20th century period (e.g. Coates, 1999; Callaghan and Power, 2014; Coates *et al.*, 2014). Coates *et al*. (2014) reported that between 1844 and 2010, extreme heat events resulted in over 5,332 deaths in Australia. They estimated that over 4,555 heat-related fatalities occurred since 1900, exceeding the combined total of deaths from all other natural hazards (Coates *et al.*, 2014). Aside from the fatalities associated with the devastating January–February 2009 heatwave, which killed 432 people in South Australia and Victoria, the most prominent events in their analysis included 435 deaths from October 1895–January 1896 across many parts of Australia, and the exceptional heat of January 1939 that resulted in 420 fatalities in New South Wales, Victoria and South Australia (Coates *et al.*, 2014). The authors report that South Australia — the nation's driest state, containing the most heatwave-affected Australian city — had the highest historical heat-related death rate of any state or territory, with up to 12.5 deaths annually per 100,000 people from 1907 to 2010 (Bureau of Meteorology, 2008a; Coates *et al.*, 2014).

The recent severity of Australian temperature extremes and their major societal impacts (e.g. Arblaster *et al.*, 2015; Climate Council *et al.*, 2017) have prompted interest in understanding the long-term context of recently observed extremes. In recent years there has been a concerted effort to consolidate Australia's pre-20th century instrumental, documentary and palaeoclimate record to provide extended estimates of past temperature and rainfall variability. Particular focus has been on south-eastern Australia, the nation's most densely populated region (e.g. Gallant and Gergis, 2011;

Ashcroft *et al.*, 2012; Gergis *et al.*, 2012; Fenby and Gergis, 2013; Gergis and Ashcroft, 2013; Timbal and Fawcett, 2013; Ashcroft *et al.*, 2014; Callaghan and Power, 2014; Allen *et al.*, 2015; Ho *et al.*, 2015; Gergis *et al.*, 2016; Ashcroft *et al.*, 2019). These studies provide an opportunity to examine recent climate variability and extremes from a longer perspective afforded by precisely-dated records that sometimes span centuries into the past.

While most research efforts using historical information have focused on rainfall variability and drought conditions, climate change is in fact most clearly statistically detectable in Australian temperature records (e.g. Karoly and Braganza, 2005; CSIRO and Bureau of Meteorology, 2015), as Australian rainfall has multiple complex influences on its variability (CSIRO and Bureau of Meteorology, 2015). Research into pre-20th century temperature variations from newly consolidated early instrumental data and the accessibility of online historical resources from Australia (e.g. Benoy, 2011; Ashcroft *et al.*, 2014; National Library of Australia, 2019; Peachfield, 2019) offers the opportunity to examine societal and environmental impacts such as agricultural losses and deaths experienced in local regions in the past, highlighting areas of historical vulnerability to both hot and cold temperature extremes.

In this study, we capitalise on a newly consolidated early instrumental dataset and a range of historical sources available for the Adelaide region to examine temperature extremes back to 1838. We select this area as our study region for a number of reasons. Firstly, it is the most heatwave-affected city in Australia and, like other areas of southern Australia, can experience cold extremes that generate frost and low level snow caused by cold outbreaks transporting cool sub-Antarctic air masses from the Southern Ocean (Bureau of Meteorology, 2008a). Secondly, Adelaide is one of the few areas of Australia where the availability of long-term daily temperature observations makes the analysis of extreme temperatures possible (Ashcroft, 2013; Ashcroft *et al.*, 2014). Finally, rich documentary records are available from the region from the early 19th century (Hunt, 1918; Benoy, 2011; National

Library of Australia, 2019; Peachfield, 2019), providing an excellent opportunity to assess the validity of results seen in early instrumental temperature records.

In attempting this analysis, we note the limitations associated with both documentary and instrumental historical climate information. For example, documentary records tend to emphasise extreme conditions as these were generally the most important events experienced by the recorder (Jones, 2008). As such, it is critically important to cross-check documentary accounts with instrumental data wherever possible for mutual verification. In this study we assess whether some of the temperature events that appear extreme in the instrumental observations are recorded as such in the documentary record, and vice versa. While there is a recognised bias in documentary records as the role of human perception influences historical accounts of weather and climate events (Jones, 2008; Fenby, 2012), they are the only way we can attempt to quantify the past societal impacts of temperature extremes — information that is not available from instrumental observations.

Like all geographical regions of the world, there is not a uniform distribution of population throughout any given area, which results in inherent data bias in historical climatology. Regions with higher population densities tend to cluster around regions with favourable environmental characteristics such as good supplies of potable water, navigable harbours and ports, and/or rich agricultural soils. Therefore, in this study the 'Adelaide region' refers to the coastal city of Adelaide and the surrounding settled agricultural districts of the southeast of the state mentioned in historical records (Figure 1).

Similarly, issues such as non-standard thermometer exposure, site changes, discontinuities and other inhomogeneities associated with 19th-century instrumental temperature records also limit our ability to provide absolute precision when reconstructing past temperature variability and extremes (Nicholls *et al.*, 1996; Trewin, 2010). Although we address data quality issues in the record where possible (see section 2.1), a lack of comprehensive metadata for the historical temperature observations means that unknown biases or errors may still exist in our analysis. Despite this, it is still possible to gain insight into the relative rather than absolute changes seen between historical and modern temperature observations. In fact, the advantage of our approach is that the availability of historical documentary records provides an opportunity to 'ground truth' whether extremes recorded in instrumental temperature observations are erroneous values or genuine events that caused notable societal consequences recorded in the newspapers or other historical documents of the time.

In light of these factors, our study aims to assess the ability of Adelaide's early instrumental temperature records to reliably capture extreme events by using documentary records for independent verification. To assess the feasibility of using historical instrumental temperature observations for extreme event analysis research, we confine the historical comparison to the pre-1910 period. This corresponds to the start of Australia's high quality, daily temperature record (Trewin, 2013) and is the period where documentary record sources are available and/or more easily compiled. We adopt a conceptual framework that uses documentary sources to verify events that pass hot and cold extreme event definition thresholds based on historical instrumental records. This approach places more confidence in the quantitative observations that are less subjective than qualitative narrative accounts, as they provide a direct, albeit imprecise, measurement of historical temperatures.

Following the pre-1910 comparison of instrumental temperature extremes with documentary records, we assess modern and 19th century temperature trends using the full length of all daily temperature records currently available for Adelaide. This provides an opportunity to evaluate if Australia's warming climate has resulted in notable changes in the frequency of heatwaves and cold extremes in the Adelaide region of South Australia since 1838. In summary, the aims of our study are to:

1. Identify temperature extremes over the 1838–2019 period for the Adelaide region

2. Compare pre-1910 historical temperature extremes identified from early instrumental data with documentary sources from the Adelaide region

3. Provide descriptive case studies of significant temperature extremes from the 1838–1910 period, highlighting notable societal and environmental impacts

4. Conduct a preliminary trend analysis of historical heatwaves and low elevation snow days in the Adelaide region over the 1838–2019 period; and

5. Assess the suitability of historical sources for examining Australian temperature extremes.

2. Data

2.1. Instrumental temperature observations

The instrumental data used in this study are derived from a range of historical and modern sources (Table 1). Note that our goal here is not to provide a complete and homogenised temperature record for Adelaide from European colonisation to the present. Instead, we are examining whether early instrumental data in their original state — with rudimentary quality control and minimal opportunities to identify and correct for non-climatic influences — can be used in the identification of extreme temperature events. Consequently, we have only applied a basic adjustment procedure (detailed below) to combine the historical temperature observations into a single dataset, rather than conduct a comprehensive homogeneity assessment.

Although Adelaide was officially proclaimed as Australia's first free colony on 28 December 1836, weather observations for the region do not begin until 1 January 1838 (Rogers, 2011). The early observations of surgeon and public servant William Wyatt from 1838 to 1847 provide a rare insight into the weather experienced during the early settlement of Adelaide (Rogers, 2011). Wyatt's daily register contained three times daily temperatures as well as weather descriptions presumably taken at his home between Grenfell and Pirie streets in central Adelaide (Rogers, 2011). He additionally recorded maximum and minimum temperatures from 1841 to 1844, although Ashcroft *et al*. (2014) show that the minimum temperature data in particular are unreasonably high. Unfortunately, very little extra information has so far been uncovered about the observation method or thermometer exposure used by Wyatt.

Newly recovered daily observations from the West Terrace Observatory in Adelaide (Ashcroft *et al.*, 2020) enabled us to examine temperature variability from 1856 to the start of the Bureau of Meteorology's official West Terrace record (Bureau of Meteorology station number 23000) that begins in 1887. The newly rescued data come from a thermometer housed in a Glaisher thermometer stand at the same site from 1856 to 1948, rather than a Stevenson screen, which is the modern standard (Trewin, 2010). Detailed homogenisation of this valuable daily record is currently underway (Ashcroft *et al.*, 2020), however previous analysis of monthly averages by Nicholls *et al.* (1996) suggests that average temperatures recorded in the Stevenson screen during the overlapping 1887–1942 period are lower than in a Glaisher stand, with discrepancies noted in maximum and minimum temperatures with different seasonal biases (Nicholls *et al.*, 1996). The Glaisher screen monthly minima were observed to be approximately 0.2ºC cooler than Stevenson screen observations (Nicholls *et al.*, 1996), while the maximum temperatures ranged from around 0.2ºC warmer in winter to nearly 1°C warmer in summer in the Glaisher stand compared to the Stevenson screen observations.

We use data from the most recent sources as soon as they became available, meaning data from Adelaide (West Terrace, Bureau of Meteorology station number 23000) were used from 22 February 1887 to 1 February 1977, and data from Adelaide (Kent Town, Bureau of Meteorology station number 23090) from 2 February 1977 to the present. A simplified quantile matching technique based on that used by Trewin (2018) was then applied to combine the different datasets into a near-continuous series. The daily distributions of each dataset during their overlapping period are compared by calculating the difference between them for every fifth percentile. For example, the value of the 5th percentile for Kent Town was compared to the 5th percentile for West Terrace, and then the 10th percentile, and so on. The transfer function employed by Trewin (2018), based on these differences, was then used to adjust all of the data from the older dataset. This approach is first applied to the West Terrace data, comparing it with the Kent Town observations for 1977 to 1979, and then compared the adjusted West Terrace data to the Glaisher stand record for 1887 to 1937. Unlike Trewin

(2018), this process is applied using all daily data rather than looking at each month separately, and used absolute values rather than anomalies.

While we have not taken into account additional inhomogeneities that undoubtedly exist in such long records, we argue that this basic combination reduces the impact that changing data sources has on the analysis of extreme event identification. The vast majority of extreme events analysed here were in fact identified in both the quantile-mapped data and the raw data, suggesting that the adjustments had very little impact on the results of our study.

As there are currently no overlapping digitised data sources to compare to William Wyatt's daily weather record over the 1838–1847 period, no adjustments were applied to this record. Based on the quality assessment from Ashcroft *et al.* (2014), the unadjusted historical maximum temperatures are likely to overestimate the magnitude of maximum temperature extremes, particularly during warmer months, and underestimate the magnitude of minimum temperature extremes in the earliest part of our analysis. That is, the hot extremes for this period may be hotter and the cool extremes may be warmer than events identified using modern Stevenson screen exposures. As such, absolute temperature values for the 1838–1847 period should be treated cautiously.

The Bureau of Meteorology's homogenised temperature record for Adelaide from Version 2 of the Australian Climate Observation Reference Network – Surface Air Temperature data product (ACORN-SAT; Trewin, 2018) is used for additional analysis of post–1910 extreme events (Section 5). The Adelaide ACORN-SAT record is made up of data from West Terrace and Kent Town, but has been examined in great detail using statistical methods and metadata to identify and remove non-climatic inhomogeneities.

Finally, to investigate circulation features associated with our temperature extreme case studies presented in section 4, we use the ensemble mean of the 20th Century Reanalysis version 2c (20CRv2c, Compo *et al.*, 2011) provided by the US National Oceanographic and Atmospheric Administration (NOAA) Earth System Research Laboratory (https://www.esrl.noaa.gov/psd/). The

20CRV2c is a reanalysis product developed using sub-daily surface pressure observations as input and observed monthly SSTs and sea ice conditions as boundary conditions (Compo *et al.*, 2011). Surface pressure and temperature fields available over 1851 to 2012 allow us to independently evaluate the results obtained using historical temperature observations for Adelaide, while providing insight into the dynamical features that may have resulted in the temperature extremes identified here.

2.2. Documentary records

A range of documentary records are used to verify any potential hot and cold extremes indicated by the historical temperature observations in the pre-instrumental 1839–1910 period. The National Library of Australia's Trove digitised newspaper database (https://trove.nla.gov.au) was searched for accounts of heatwaves and a range of cold extremes including snow and frost events in the Adelaide region. Note that South Australia's first newspaper *The Adelaide Chronicle and South Australian Advertiser* was first published in December 1839, so does not overlap with our earliest instrumental observations which begin on 1 January 1838. Another gap in data coverage occurs after *The South Australian Chronicle and South Australian Literary Record's* final edition (18 May 1842) and the beginning of the *Adelaide Observer* on 1 July 1843. This creates a break in newspaper coverage from 19 May 1842– 30 June 1843. We also made use of the Charles Todd Folios which contain newspaper articles independently collated for the 1879–1909 period (Benoy, 2011; https://met-acre.net/MERIT/).

Alongside the Trove newspaper analysis, a number of additional documentary records to examine snow events were also compiled. The snow records for 1841 to 1917 are taken from Bureau of Meteorology's 'Results of Rainfall Observations' (Hunt, 1918). Occurrences of snow were tabulated separately, and the details of the records appeared to rely heavily on newspaper reports of the day. For the 1965 to 2008 period, the Bureau of Meteorology's *Monthly Weather Reviews: South Australia* are used to identify days with occurrence of snow (Bureau of Meteorology, 2008b). Over the course of this series, snow information appeared under either 'Phenomena' or 'Noteworthy events'. There were format changes over the years, so homogeneity is uncertain. As low elevation snow occurrence is a distinct phenomenon and is a rarity in South Australia, these events are well captured in documentary records, as they would have been very noteworthy events for people in the area.

We also consulted a detailed amateur enthusiast website 'South Australian Snow' (Peachfield, 2019), in which newspapers articles and other sources reporting snow in South Australia are compiled. It includes extensive information for the earliest decades based primarily on Trove newspaper searches. Note that the Bureau of Meteorology compilations were used as our primary resource, with Peachfield (2019) used to supplement some additional events that appeared well documented but absent from the other records.

2.3. Palaeoclimate data

For further independent verification of the temperature conditions experienced in the Australian region, we use the Principal Component Regression version of the Australasian temperature reconstruction of Gergis *et al.* (2016). In that study, Australasia is defined as the land and ocean areas of the Indo-Pacific and Southern Oceans, bounded by 0º–50ºS and 110ºE–180º. The reconstruction uses twenty-eight temperature sensitive palaeoclimate records from the region to estimate warm-season (September–February) combined land and ocean temperature of Hadley Centre/Climatic Research Unit, version 3 (HadCRUT3v) (Brohan *et al.*, 2006; Rayner *et al.*, 2006) over the 1838–2016 period of overlap with the historical temperature observations from Adelaide. Although it is a warm season reconstruction so is directly comparable to hot extremes, the presence of cool summer conditions is at least a general indication of the conditions experienced during a given year. As there are no palaeoclimate temperature reconstructions available specifically for South Australia, the estimates of Gergis *et al.* (2016) are used as they currently provide the only annually-resolved, statistically robust temperature estimates available for mainland Australia.

3. Historical temperature extremes

3.1. Hot extremes

In this study, heatwaves are defined as three or more consecutive days with maximum temperatures (Tmax) above 34ºC (95ºF and above) and with minimum temperatures (Tmin) above 20ºC (76ºF and above). Heatwaves are defined as 'extreme' if the Tmax of at least three of those days reached more than 35ºC and the Tmin did not drop below 25ºC. If Tmax and Tmin are not available, as is the case for William Wyatt's daily meteorological diary, we used 1500 temperatures in lieu of Tmax and 0900 and 2100 temperature for Tmin. This definition is based on the combined hot days and tropical nights (CHT) heatwave definition from Fischer and Schär (2010), as discussed in Perkins and Alexander (2013), and captures both above average daytime and overnight temperatures as this is a key factor in the impact of heatwaves on human health. A lower threshold of 34ºC rather than 35ºC for Tmax and a two-stage definition was used so we could identify a complete heat event, rather than several extreme days within a single event. The approach of testing different definitions and thresholds allowed us to capture the same events present in overlapping data sources.

Table 2 lists the heatwaves identified from the combined instrumental data for 1838–2019. A documentary analysis of the extreme heatwaves was then undertaken using the National Library of Australia's Trove newspaper database searching for the keywords of 'weather, hot, heat, temperature, thermometer, or meteorology' for all South Australian newspaper titles to verify the events identified by the instrumental temperature observations.

As seen from Table 2, thirty-seven extreme heatwaves were identified in the instrumental record between 1838 and 1910. Twenty-eight heatwaves area identified using the documentary record, with the nine 'missing' events occurring during the earliest part of the record from 1839–1843. This is likely to reflect underlying issues with the documentary record during the 19th century. For example, *The Adelaide Chronicle and South Australian Advertiser* was first published on 10 December 1839 until 20 May 1840 as a weekly publication usually with only four printed pages. This might suggest restrictions to the newsprint that was available during the early years of the colony, so perhaps weather information was omitted due to space restrictions.

The second newspaper, *The South Australian Chronicle and South Australian Literary Record* is only available from 27 May 1840, and is also a weekly, four-page publication until 18 May 1842. *The Adelaide Observer* then begins on 1 July 1843, leaving a gap in newspaper coverage from June 1842–June 1843, a period that contains three of our identified events. Furthermore, the lack of newspaper coverage from January 1839 until November 1839 also fails to capture a heatwave identified in the instrumental temperature record from 14–16 February 1839. Together, these factors are likely to account for the low agreement during the earliest part of the analysis (1839–1843). In contrast, there are no missed events during the 1856–1910 period (contained in the Glaisher and modern West Terrace temperature observations), representing 100% accuracy for instrumentally-identified heatwaves in the documentary record. See supplementary Table S1 for detailed documentary comparisons of each instrumentally-defined heatwave and their impacts.

Figure 2 compares the number of heatwaves and extreme heatwaves for each decade over the 1839–2019 period. The 1839–1850 period contains the highest number of extreme heatwaves, with nine events. However, it should be noted that Ashcroft *et al.* (2014) identified a warm bias in the Wyatt observations, so the high frequency of extreme heat events seen in in the early period (lighter bars in Figure 2) is likely to be a result of inadequate thermometer exposure. Unfortunately, there are currently no other digitised instrumental records to compare to during this period, so absolute values inferred from this analysis must be treated with caution.

The late 19th–early 20th century (1870s with 21 heatwaves, 1890s with 18 heatwaves and 1900s with 19 heatwaves) and the late 20th–early 21st century (2000s with 21 heatwaves and 2010s with 25 heatwaves) stand out as the periods with the highest number of total heatwaves. This contrasts to the 1850s, 1940s and 1910s, which contained the lowest number of heatwaves. In particular, some notable but previously underexplored extreme heatwaves occurred in the 1890s. These are examined further in section 4.1.

3.2. Cold extremes

3.2.1. Cold events

In this study a cold extreme is defined as a day, or series of consecutive days, with a Tmax (or 1500 temperature value for Wyatt's records) of 11ºC (51ºF) or less in the combined temperature record. This is approximately the 0.1th percentile, and allowed us to identify a manageable number of cold extremes to compare to documentary accounts. Maximum temperatures in Adelaide are considered a better representation of regional cold conditions than minimum temperatures, as the latter can be more affected by local conditions such as Adelaide's coastal location. We then undertook a documentary analysis of cold extremes using the National Library of Australia's TROVE newspaper database searching for the keywords of 'winter, weather, cold, snow, temperature, thermometer, meteorology, or frost' for all South Australian newspaper titles to verify the events identified by the instrumental temperature observations.

Table 3 lists eighty-one cold extremes that were identified in the instrumental record between 1838 and 1910. Seventy-two of these events were verified using documentary records. Like the heatwave analysis, eight of the nine 'missing' events in the historical documents occurred during the 1843–1846 period when there are noted issues with the newspaper coverage. In contrast to the early period, there is only one missed event (22 June 1894) observed during the 1856–1910 period, representing a 99% agreement between instrumental and documentary accounts of historical cold extremes identified using the historical temperature readings from West Terrace. Supplementary Table S2 provides detailed documentary evidence of each instrumentally-defined cold extreme. It is notable that although cold events were selected based on maximum temperature, cold conditions described in the documentary records are as least as likely to refer to severe frost — generally associated with low overnight temperatures — as they are to daytime cold (as evidenced by low elevation snow occurrence).

Similar to the heatwave analysis, the lack of agreement of cold events that occurred during 1843–1846 is likely to reflect underlying issues with the documentary record during the early 19th century. However, it is also possible that instrumental exposure issues associated with minimum temperature extremes may contain a cold bias, despite Ashcroft et al. (2014) finding a warm bias in the monthly means of the Wyatt record. It is also possible that people originally used to Northern Hemisphere climates had a higher tolerance for cold weather, compared with their limited experience of extreme heat, so cold events may have been under reported (Duncan and Gregory, 1999; Rogers, 2011; Beattie *et al.*, 2014).

Figure 3 shows that the 1840s, 1870s, 1880s and 1900s were the coldest decades in Adelaide's extended temperature record. There were thirty-four extreme cold days during the 1840s, and eighteen recorded during the 1870s. The 1880s and 1900s both contained seventeen cold extremes. Once again, it should be noted that the high number of cold extremes recorded during the 19th century may reflect the thermometer exposure cold bias noted above. That said, the independently compiled snow days discussed below suggest that the 1870s and 1880s contained the highest number of snow days recorded outside of the 1900s and 1910s. Furthermore, Figure 4, which provides independent palaeoclimate estimates of Australasian temperature variability, identifies the 1830s, 1840s and 1900s as particularly cold decades. In fact, the 1830s and 1840s are the coldest decades reconstructed since first European settlement in 1788 (Gergis *et al.*, 2016).

3.2.2. Snowfall events

Next, we consider further cold events as represented by observations of snowfall in our study area. The compilation of snow events recorded in Hunt (1918) for the period 1841 to 1917 is used in this case, allowing some analysis in the reverse direction, i.e. where we anchor on the documentary record and then compare with the instrumental observations. Hunt (1918) tabulates single days or small numbers of consecutive days (usually two or three) along with descriptions of snow. In this study, each of these days are counted as 'snow days'. We note that it is not always completely clear if Hunt's dates refer to the day that the snow fell, or the day that snow was first observed lying, introducing a possible timing error of plus one day. Also, it is likely that a single event that occurred at night and continued into the morning of the next day will be counted as two snow days, whereas a similar event with different timing would only generate a single snow day. Additional snow days recorded in the analysis of Peachfield (2019) but not in Hunt (1918) were added to the compilation where the documentation appeared sound.

We also use the *Monthly Weather Review: South Australia observations for 1965 to 2008* (Bureau of Meteorology, 2008b) to create a more recent record that may be compared with the earlier snow day chronology. As before, a snow day is recorded where a date is given and snow recorded. Peachfield (2019) was again consulted for possible additional events in this period, and for 2009 to 2016, when it is the only source. Note that the intervening period 1917 to 1964 is not covered, or poorly covered, in the sources we are using, so is not considered further here. The 1911–1917 data could have been omitted for an exact comparison of pre-and post 1910 data sets, but instead we choose to include the full length of the valuable historical data available.

Figure 5 shows the number of snow days in the Adelaide region identified per decade from these documentary sources from 1841 to 2016. One hundred and seventy-six snow days were identified during 1841–1917 – more than twice as many as the number of cold days identified using instrumental data alone. Of these, 38 were added based on Peachfield (2019), mainly for the period before 1870 (10 days), and post 1900 (25 days). For the 1965–2019 period, 71 snow days were identified, of which 19 were supported by Peachfield (2019) only (eleven days post-2008, for which it was the only source).

Table S3 contains detailed descriptions of snow conditions provided by Hunt (1918) for all of the events in the early period for which some mention is made of lying snow to highlight the more significant events. As seen in this table, some events have detailed information about depths of lying snow and geographical locations affected, as well as reactions of residents to the snow conditions (e.g. snowballing). Figure 1 displays the generalised geographical extent of all snow occurrences (falling or lying) in South Australia for 1841–1917 based on the observations recorded in Hunt (1918). Snow has been seen from the Northern Flinders Ranges south to Mt Gambier, and as far west as the Eyre Peninsula.

Figure 5 also shows variation over time in snow occurrence by considering snow days per decade for all decades under analysis. It is clear that snow occurrence was exceptionally high in the decades of the 1900s and 1910s – more than four times more frequent than other decades. This result agrees strongly with the cold conditions independently identified using palaeoclimate temperature estimates presented in Figure 4. These decades clearly contribute strongly to the increased snow conditions observed in the early period, but notably the decades of the 1870s and 1880s are also snowier than any other decade (except for the 1900s and 1910s).

The additional days drawn from Peachfield (2019) disproportionately affect the 1900s and 1910s, but their deletion would not remove the dominance of these decades in the record. As described in section 3.2.1, this period contained a very high number of cold extremes independently identified using instrumental temperature observations, so is very likely to be indicative of cold conditions experienced during the early 20th century. The low number of snow days observed in the 1840s and 1850s is presumably somewhat affected by European settlement being less extensive at that time, suggesting that the frequency of snow days in the early period may be biased low.

4. Case studies

Having presented the long-term frequency of Adelaide's temperature extremes, we now explore the dynamic conditions behind selected pre-1910 temperature extremes. Synoptic maps for six hot and cold extremes that occurred in the lesser-studied pre-1910 period are compared to daily pressure and temperature fields extracted from the 20th Century Reanalysis version 2c (20CRv2c, Compo *et al.*, 2011). This allows newly-identified extremes in Adelaide's extended temperature observations to be verified using synoptic maps generated from independent temperature values calculated in 20CRv2c. Importantly it also allows an opportunity to further cross-verify the synoptic conditions that may have led to the societal impacts noted in the newspaper analysis presented in Tables S1–S2. This is relevant for assessing the ability of historical temperature extremes and reanalysis products over the Australian region experienced in the region to accurately capture potential changes in the meteorology behind temperature extremes.

This study focuses on the relatively undescribed pre-1910 period as it encompasses the Little Ice Age (LIA). This period is a globally cool interval generally agreed to have a start date around A.D. 1300, but its termination date ranges in different studies from 1850 to as recently as the early 20th century in Australasia (Schaefer *et al.*, 2009; Abram *et al.*, 2016; Gergis *et al.*, 2016; Lorrey and Chappell, 2016). To date, this period remains poorly described using instrumental and documentary records from the region, although limited studies are starting to emerge as data rescue efforts continue (e.g. Gergis *et al.*, 2009; Ashcroft *et al.*, 2014; Ashcroft *et al.*, 2016; Lorrey and Chappell, 2016). We also seek to examine the nature of lesser-known heatwaves that are reported to have had significant societal impacts in the Adelaide region, an area known today for its high risk of extreme heatwaves (Coates *et al.*, 2014).

4.1. Heatwaves

4.1.1. Heatwave of 25–30 January 1858

The heatwave of 25–30 January 1858 registered six days above 40ºC, with a maximum temperature of 46.8ºC recorded at West Terrace in the Glaisher stand on 26 January (adjusted value used in our analysis: 46.6ºC). Minimum temperatures were also very high, remaining close to 32ºC from 26–28 January. On 6 February 1858, the *Adelaide Observer* reported: 'Ordinarily we should leave it to a meteorological journal to chronicle the range of the thermometer and the moisture of the atmosphere just as the majority of persons would leave to meteorological observers the task of ascertaining such particulars. But when the heat has been so intense as to become the principal topic of conversation in every circle…during the previous week [late January], it is certain no subject has been so frequently or so anxiously discussed…we are certain there is no one here who has permitted the weather to pass unheeded lately'.

'Frightfully hot' conditions were reported in the *Adelaide Times on* 30 January 1858: 'The intense heat of the weather is the all-absorbing topic; in fact, how could it be otherwise… within the last week the mortality has been frightful in the extreme'. As detailed in Table S1, many heat-related deaths were reported, with at least nineteen children and several adults dying from 'excessive heat'. A letter to the editor of *The South Australian Register* on 1 February 1858 also called for changes to summer work hours for labourers to prevent heat related deaths, saying 'At present they are periling life and health by the practice of working during the hours of midday… Already lives have been lost; health is being fearfully sacrificed'.

Figure 6 shows the average synoptic conditions associated with the 25–30 January 1858 heatwave. The surface pressure field indicates a high pressure system to the south of Tasmania, however it should be noted that direct pressure observations from the land areas of Australia incorporated in the 20^{th} Century Reanalysis are limited during the mid 19th century, which are likely to be reflected in the simulated magnitude and spatial pattern seen in Figure 6. However, the spatial structure of the temperature anomalies generated by the reanalysis for this event is very similar to conditions commonly observed during modern heatwaves in south-eastern Australia, where a large region from western South Australia to eastern Victoria is affected. Anomalies of up to 8ºC above the 1981–2000 average are estimated by the reanalysis, supporting the historical instrumental and documentary data. Although data sparsity is an issue during this period, the high spatial coherence of temperature across Australia, even when limited observations are available, is well known (e.g. Gergis *et al.*, 2016).

4.1.2. Heatwave of 12–16 February 1895

Between October 1895 and January 1896, 435 heat related deaths were recorded in South Australia, Victoria, New South Wales, Queensland and Western Australia (Coates *et al.*, 2014), making it a period worth investigating. According to our temperature observations, no extreme heatwaves were experienced in Adelaide during this time, although standard heatwaves were observed in January, February and March of 1896. However, our data suggest that Adelaide experienced a severe heatwave earlier in 1895, from 12–16 February. During this event, there were six days with maximum temperatures over 37ºC, with 40.8ºC observed on 12 February in the Glaisher stand and 40.3ºC in the Stevenson Screen (adjusted value used in analysis: 41ºC). On 15 February the *South Australian Register* reported 'the fierce heat of the sun seems to penetrate through almost any thickness of wall' and numerous bush fires which 'obscured the sky with dense clouds of smoke, almost justified the impression that the colony was to have another visitation like that of the historic Black Thursday [6 February 1851]'. There were also reports of the need to replace formal British clothing for a 'more sensible style of dress' and improved passive cooling of houses. In an attempt to tolerate the heat 'a fair number of people have had their roof whitened with more or less permanent paint or wash, while a few have lined their ceilings with seaweed'.

Despite the mortality figures noted by Coates *et al*. (2014) above, curiously only a handful of specific mentions of heat-related fatalities – often referred to as a 'sudden death' from 'heat apoplexy' – were noted in our analysis of this event unlike other events e.g. 25–30 January 1858, 4–6 February 1876, 26–30 December 1897 and 14–19 January 1908 (Table S1). This may reflect issues with text correction of the newspapers for this year limiting the retrieval of newspaper accounts for this event, or the potential influence of newspaper editorial practices that downplayed the impacts of extreme heat to avoid deterring new migrants to the area. In fact, an editorial piece published on *South Australian Register* on Friday 15 February 1895 suggested that heath related deaths associated with the extreme conditions of February 1847 had been ‘frightfully exaggerated’ saying they were ‘struck with the contrast in journalism then and now’.

As seen in Figure 7, the 12–16 February 1895 heatwave was associated with an anticyclone in the Tasman Sea with an intense monsoonal trough over much of the continent. This generated a north-easterly pressure gradient over south-eastern South Australia, including the Adelaide region. High pressure systems located in such a position in the Tasman Sea are known to transport hot air from inland Australia over southern coastal regions, generating very hot weather. This pattern is commonly associated with prolonged heatwave conditions in south-eastern Australia (Pezza *et al.*, 2012; Perkins-Kirkpatrick *et al.*, 2016). During this event, temperature anomalies were up to 8ºC above the 1981–2000 average as estimated by the reanalysis, although the spatial extent was not as widespread at the 25–30 January 1858 event.

4.1.3. Heatwave of 26–30 December 1897

An extreme heatwave was experienced in Adelaide region from 26–30 December 1897. Maximum temperatures recorded in the Glaisher stand were above 40ºC for all five days of the event, including a maximum of 43.8ºC recorded on 28 December (the Tmax recorded that day in the Stevenson Screen was 42.3ºC, adjusted value used: 43ºC). Minimum temperatures remained well above 23ºC, only dropping to 31.2ºC on 29 December (31.8ºC in the Stevenson Screen, adjusted value: 31.5ºC). There are many newspaper accounts of major impacts ranging from heat related deaths, agricultural damage, animals dying in the zoo, bushfires, to burning hot pavements scorching the soles of people’s shoes. For example, on 29 December the *South Australian Register* reported: ‘When the mercury reaches its ‘century’ [37.8ºC] there must be a really uncomfortable experience for everyone. One such day can be struggled with; but six of them in a fortnight, three in succession—that is a thing to bring limpness to all mankind’. On 31 December 1897 the *South Australian Register* wrote ‘This has been the hottest December known in the colony. Those who have lived in Adelaide during the last week will believe it. They have reason to know it, but the figures are worth placing on record if only to tempt the weather to attempt to break the record of 1897. May Heaven preserve us from being here when the 'scorchers' try to add a few degrees to the total'.

As detailed in Table S1, numerous deaths were reported, with heat stress also noted: 'a large number of children…were brought round by sponging the body and applying ice to the head'. Extreme heat also took its toll on animals: 'The hot weather has had a most disastrous effect upon the animals at the Zoo, and several valuable animals have been lost…Mr Minchin says he has never seen the carnivores in such a state of distress. They will not eat anything and are reduced to a state of weakness which is pitiful to observe. On Thursday be placed bags in front of the various cages and houses, and the caretakers spent their time hosing them in order to reduce the temperature'.

Figure 8 displays dominance of high pressure to the south and east of Australia based on a composite of the synoptic conditions experienced between 26–30 December 1897. A 'blocking high' configuration occurs when a strong, near-stationary high-pressure systems essentially 'blocks' the west to east transport of cold fronts across southern Australia. This leads to the sustained advection of warm air from inland areas, causing significant warming (Pezza *et al.*, 2012). As seen in Figure 9, temperature anomalies in the Adelaide region were likely to have been up to 8°C above the 1981–2000 average, representing a very significant heatwave event for the region.

4.2.Cold extremes

As outlined in section 3.2, the coldest and snowiest periods identified in our analysis occurred during the 1870s until the 1910s. This period is during the Little Ice Age interval, which ended as late as the early 20th century in Australasia (e.g Abram *et al.*, 2016; Gergis *et al.*, 2016). Accordingly, we investigate three prominent cold extremes from this period to analyse in more detail local conditions experienced as part of this globally-recognised cold interval.

4.2.1. Cold outbreak of 23–24 July 1879

According to Peachfield (2019), this event is notable in Adelaide's historical record of snow events for its widespread geographical coverage and local persistence of snow cover. As detailed in Table S2 and Table S3, and seen in Figure 9, snow was reported from the southern Mount Lofty Ranges, the mid north of South Australia, and the Flinders Ranges. For example, the *Evening Journal* published on Friday 25 July 1879 reported: 'The Flinders Range presented a beautiful appearance yesterday. The tops were covered with snow for 30 miles from south of Mount Remarkable to north of Mount Brown. At noon today snow was still on the summit of Mount Remarkable'. On Thursday 24 July 1879 *The Express and Telegraph* stated: 'There was a heavy fall of snow on the Mount Lofty Ranges early on Thursday morning… in the neighbourhood of that township the ground was covered with snow, which, in some places lay at least a foot deep. The roofs of the houses and all vegetation were white with it, reminding old people of the appearance of houses and trees in England during the winter season'.

According to the Glaisher stand record from West Terrace in Adelaide, observed maximum temperatures reached 8.4ºC on 23 July (adjusted value: 8.1ºC), with a minimum of 5.3ºC (3.8ºC). The following day, the minimum temperature fell to just 4.4ºC (2.9ºC) with a high of 9.7ºC (9.4ºC). As seen in Table S2, there are various newspaper reports describing conditions as 'bitterly cold', 'exceedingly cold' and even 'the coldest known by the oldest residents [of the township of Burra]'.

The synoptic conditions for this event provided in Figure 9 show a pressure dipole over the Southern Ocean and a deep trough across much of Central Australia. As noted by Peachfield (2019), these conditions lead to the south-easterly to easterly winds, which are unusual for a cold outbreak. More typically cold outbreaks over southern Australia are associated with a more northerly pressure dipole: a surface anticyclone to the west and cyclone to the east leads to strong southern geostrophic winds, forcing cold advection and the equatorward movement of high-latitude air (Ashcroft *et al.*, 2009).

4.2.2. Cold outbreak of 29 August 1905

A newspaper account from Sydney describes a widespread snowfall event on 29 August 1905, with *The Register* published on 31 August 1905 reporting: 'There was a recurrence of wintry conditions yesterday, and today snow has fallen over the highlands from the Queensland border right down to the Victorian border, and also over portions of the western slopes [of New South Wales]. The falls have been uniformly light, except in the Monaro country, where up to 18 [inches] has been recorded, but have been remarkable for the large area covered'.

In South Australia, very extensive snowfalls were reported from the Mount Lofty Ranges to the Flinders Ranges, as seen in Figure 10. According to Adelaide's *Evening Journal* published on Wednesday 30 August 1905: 'Snow fell in numerous localities, but in no place more heavily than on the Mount Lofty Ranges… the present fall is easily a record. Old residents of the ranges, who have been bred and born there, say that they remember nothing like the present visitation. The country was transformed into a wonderful world of white'.

The severity of the event caused transport delays in the area of Hallett, in the mid-north of South Australia, with *The Express and Telegraph* reporting on Wednesday 30 August 1905: 'Many of the inhabitants of this locality were taken by surprise on arising this morning to see everything covered with a white mantle. Snow must have been falling for some time, for at about 7 o'clock the ground was already covered. The Broken Hill express [train] was 35 minutes late, through waiting for passengers, who jumped out at every station and indulged in the good old English game of snow balling. It is still snowing heavily'.

During this cold outbreak, observations from West Terrace recorded a maximum temperature of 10.4ºC on 29 August (10.1ºC in the Glaisher stand, adjusted value used for analysis: 10.4ºC), with a minimum of 4.8ºC (4.9ºC in the Glaisher stand, adjusted value: 3ºC). According to newspaper reports compiled by Peachfield (2019), 'a cold change from the south came up, with rain, hail, and snow' resulting in apparent temperatures that felt ‘as if it was at freezing point all day, there being a bitter cold wind from the south’.

A more typical synoptic pattern for these types of events is seen for this cold outbreak of 29 August 1905, with the expected anti-cyclone–cyclone dipole over the Australian region (Figure 10). The very deep low-pressure system over Tasmania combined with high pressure over south-west Western Australia, establishes a strong west to east pressure gradient over South Australia, leading to strong southerly geostrophic winds.

4.2.3. Cold outbreak of 22 June 1908

As described from Table S2 and Table S3, the winter of 1908 was particularly cold, resulting in a cluster of cold extremes including snowfall from June to August 1908. In particular, there was a major snow event that occurred on 22 June 1908. As seen in Figure 11, the synoptic conditions again indicate the anticyclone–cyclone dipole of a classic cold outbreak. A very deep low is centred over Tasmania, with relatively high pressure located to the west, generating a strong south-westerly flow over the South Australia.

On Monday 22 June 1908 *The Express and Telegraph* reported: ‘When the Adelaide citizens went out into the open and "looked towards the hills" on the eastern horizon the cause, of the abnormal frigidity of the atmosphere was explained. For miles the contour of the mountains was outlined in shining white… But if the spectacle was a fine one as seen from the city, the sight in the midst of the hills was indescribably grand. The brilliant white of the snow was over everything, trees, plains, valleys, houses, and hedges being covered with the fleecy flakes. Many people made a special journey from Adelaide by train, carriage, or motor to revel in the unwonted delight of gazing on such a wide expanse of real snow, and all who did so felt that their trouble was amply rewarded by the panorama of loveliness spread out before their enraptured eyes. Even residents in the hills were delighted, for the fall was heavier and more general than any they had previously witnessed’.

According to the *Burra Record* published on Wednesday 1 July 1908 from Mount Bryan on 28 June 1908: ‘Jack Frost is still playing a cool game out this way. Since the snowstorm [22 June] the air has been particularly keen, and old residents say it is the coldest few days that they remember. Snow is still to be seen several feet thick on the Razorback Ranges, and patches here and there along the creeks on the flat’. These accounts and the map of settled snow reports seen in Figure 11 suggest the snowfall was widespread and persistent.

During this cold outbreak, temperature observations from the West Terrace Stevenson Screen recorded a maximum temperature of 10.2ºC on 22 June (10ºC in the Glaisher stand, adjusted value used for analysis: 10.2ºC), with a minimum of 3.8ºC (3.7ºC in the Glaisher stand, adjusted value: 2ºC). Extensive newspaper accounts published in the *Chronicle* on 27 June 1908 refer to ‘the piercing cold of the atmosphere’ and ‘intense cold’ in Adelaide when the ‘maximum thermometer reading was 52 [11.1ºC], but twice during the day, when heavy hailstorms came up, the temperature lowered to 43 [6.1ºC]’.

5. Comparison of historical and modern temperature extremes

Combining instrumental data and documentary information allowed the identification of extreme heat and low-elevation snow events experienced in Adelaide since European settlement. We now consider possible changes in the frequency, intensity or timing of these events compared to modern records.

Figure 2 shows that heatwaves have become more frequent in the Adelaide region since 1838. The decade 2010–2019 has the highest count of heatwaves of any decade in the record, and this analysis does not include the extensive heatwaves of December 2019 (Bureau of Meteorology, 2019). Similar results are obtained if we examine the 1910–2019 period using the homogenised ACORN-SAT dataset (Figure S1). However, a significant increase in the number of extreme heatwaves during 1839–2019 is not observed. It may seem that there is in fact a decrease, given the high number of extreme events identified in the earliest part of the record. However, exposure issues associated with the historical observations (Ashcroft *et al.*, 2014) indicate that the high counts of extreme heatwaves in the early part of the record must be treated with caution, so no definitive conclusions can be drawn.

Figure 12 shows that there is no clear change in the overall average length of heatwaves over the 1839–2019 period. The average length of a heatwave is approximately four days per decade, a result also observed in the ACORN-SAT dataset (Figure S2). However, it is worth noting that much longer events can occur. For example, the historical temperature observations show identified extreme heatwaves of up to 10 days in Adelaide from 4–11 February 1866, 1–8 January 1910, 28 February–9 March 1989, 8–17 March 2008, 27 January–3 February 2009 and 8–15 November 2009.

In contrast, the cold event analysis suggests that there has been a decrease in the number of snow days since European settlement. With the exception of the 1950s and 1960s, the post-1910 period contains notably fewer cold extremes than the 19th century–early 20th century. This corresponds with the marked warming trend observed in Australasia since the mid-20th century (Figure 4).

To evaluate this further, Figure 13 presents the snow day and cold day occurrences in days per year over the seasonal cycle and between 1841–1917 and 1965–2016. In both periods, cold event frequency peaks in July (0.7 days per year in 1841–1917, and 0.5 days per year in 1965–2016), with occurrences ranging from April to November. In the documentary analysis, it is notable that in both periods early spring (September) is snowier than early winter (June), perhaps reflecting a marine influence on the temperature of cold outbreaks. Interestingly, the instrumental data do not show as many events in the late autumn and early spring, suggesting that documentary records are more sensitive at capturing localised snow events. The slight increase in documentary snow days observed for the month of May during the 1965–2016 period may be an artefact of this feature, particularly given that a similar increase is not seen in the instrumental data.

Figure 13b clearly shows that there is a markedly lower rate of snow day occurrence in the later period, particularly from August to October, where the rate is more than halved. Overall, the 1965–2016 period contains 1.3 days snow days per year, compared to 1841–1917 when 2.3 days per year were recorded. A valuable extension of this analysis would be to compare the date of first snowfall to identify shifts in the snow season over time. Currently Nash and Grab (2010) is the only other study of historical winter conditions in the Southern Hemisphere, so a detailed comparison with their observations from South Africa would be a logical target for future work.

Both the documentary and instrumental records from 1841–1917 and 1965–2016 shown in Figure 13 come from different sources so we are uncertain if they can be reliably compared. However, the strong difference in snow day and cold day frequency is at least suggestive that Australian warming of 1.1ºC since 1910 and a southward shift of storm tracks over southern Australia (CSIRO and Bureau of Meteorology, 2015; Bureau of Meteorology and CSIRO, 2018) may have reduced the occurrence of low-level snow events and cold outbreaks in the Adelaide region.

To test the reliability of this comparison, an additional analysis was conducted using the instrumental temperature data (West Terrace 1858–1917, and Kent Town 1965–2016) to calculate average snow day temperature (Figure 14). All snow days in this period were used (except an outlier 'snow day' of 26ºC on 3 April 2001, which falls outside the typical cool season).

As expected, snow day temperature is well below the climatological mean in each month, and lowest in June and July where it averages approximately 12ºC. Some days had cold maximum temperatures on adjacent days that may better capture snow weather conditions (when the day before, it may suggest that the snow fell overnight, or when the day after, it may indicate that warm weather preceded a rapid change which brought the snow). Use of colder adjacent days would reduce the average snow day temperature by a few tenths of a degree. Exclusion of the additional snow days based only on Peachfield (2019) would also reduce the snow day temperature slightly.

However, the most notable result in Figure 14 is that there appears to be little difference in snow day temperature between 1858–1917 and 1965–2016, which suggests that snow occurrence as observed in the two periods represents similar regional temperature conditions. This strengthens the argument for the apparent decline in snow day frequency in the later period being real, rather than an artefact of the underlying data. However, it is possible that West Terrace and Kent Town, although located at similar elevations and within close proximity of each other, have different exposures to cold outbreak conditions that may affect this comparison.

6. Discussion

As outlined in sections 3 and 4, there is remarkably good agreement between Adelaide's historical temperature observations and independent historical documents. In fact, the major discrepancies occur during the earliest part of the record from 1839–1843 when there are gaps in the newspaper coverage and the instrumental data are of uncertain quality. Considering hot extremes, it is also possible that the newspapers intended to downplay the true variability of the weather and climate of South Australia during the early years of the colony to avoid deterring new arrivals (Rogers, 2011). This was part of a technique Australian historians refer to as 'puffery', a 19th century promotional writing strategy which included exaggerated claims to entice migrants into new colonies like South Australia (Rogers, 2011).

The same bias issue does not appear to apply to the reporting of cold extremes. Instead, it is clear from Table S2 that reports of snow, frost, hail and heavy rain events often appear together. This can make it difficult to distinguish a single phenomenon from the newspaper records, despite the fact that frost and low-level snowfall are caused by different meteorological conditions.

This study demonstrates the value and complexity, of using historical observations for assessing long-term temperature extremes for comparison with modern extremes. While there are many similarities in the results calculated from historical and modern observations, early instrumental heatwave data must be treated with caution due to thermometer exposure issues. Interestingly, documentary records are better at capturing 'edge of season' low-level snowfall events, perhaps reflective of microclimate conditions experienced in regions outside of the city of Adelaide. Snow likely fell more in outlying regions because they had higher elevation than the location of the weather station in central Adelaide.

In addition to reports of meteorological phenomena, there are also plenty of reports of significant frost events and their impacts on agricultural crops and livestock noted in Table S2. For example, *The Register* reported on Wednesday 29 July 1908: 'Delamere July 28. A severe frost experienced here on Sunday morning [26 July] caused much damage to potato crops and gardens generally. There was frost on Monday night [25 July]. It is feared that the frosts will check the crops and feed… Green's Plains, July 28, the principal frost experts are of opinion that the past week puts up the freezing record for the district. Dams have been occasionally frozen over, and from tanks and troughs a quarter of an inch or more of surface water could be removed in solid frost. Tomato plants are at a standstill, melons have been nipped in the bud, and early morning potatoes are now no more seen.' These accounts suggest that it may be possible to refine this analysis to specifically target frost events in future work. However, comparing Adelaide's minimum temperatures with documentary records of regional frost was deemed outside of the scope of the current 'proof of concept' analysis to assess the feasibility of examining daily temperature extremes from Australian historical records for the first time.

Independently verifying temperature conditions experienced in Adelaide using palaeoclimate data (Figure 4) highlighted the potential to discern regional impacts of the globally-recognised Little Ice Age cool period (Schaefer *et al.*, 2009; Abram *et al.*, 2016; Gergis *et al.*, 2016; Lorrey and Chappell, 2016). In particular, the prevalence of cold extremes and snow days noted during the 1840s, 1870s, 1880s, 1890s, 1900s and 1890s presented in Figures 3 and 5, corresponds to cool intervals seen in the Australasian temperature reconstruction shown in Figure 4.

As noted in section 3.2, the 1830s and 1840s are the coldest decades reconstructed since first European settlement in 1788 (Gergis et al., 2016). Unfortunately, the Adelaide temperature record begins in 1838 and currently has a break in its coverage from 1848–1856. However, instrumental weather observations recovered from northern New Zealand from 1839–1844 and 1848–1851 indicate cooler winter temperatures and an increase in southerly and westerly circulation influences (Lorrey and Chappell, 2016). The authors also report a snow event that occurred from 30–31 July

1849 in northern New Zealand, an area where snow fall is extremely rare (Lorrey and Chappell, 2016).

These new results from Adelaide on the Australian mainland, together with the record from northern New Zealand, provide emerging evidence from Australasia that the Little Ice Age was associated with cold extremes in the region. Future work could be directed at comparing historical temperature observations from Australia with palaeoclimate reconstructions of the Southern Annular Mode (SAM) (Villalba *et al.*, 2012; Abram *et al.*, 2014; Dätwyler *et al.*, 2018), as this circulation feature is associated with temperature extremes including cold outbreaks and heatwaves in the region (e.g. Hendon *et al.*, 2007; Marshall *et al.*, 2014). However, currently available SAM reconstructions for the 19th century are largely annual means with strong trends in specific seasons (Jones *et al.*, 2016), which may preclude the assessment of SAM conditions that are most evident on weekly–monthly timescales. Assimilating more daily weather observations from Australasia into the 20th century reanalysis products (e.g. Compo *et al.*, 2011; Slivinski *et al.*, 2019) will lead to improvements in the ability to investigate synoptic conditions associated with historical extremes, providing an opportunity to improve future climate risk assessment (Brönnimann *et al.*, 2019).

7. Conclusions and recommendations

This study has clearly demonstrated the value and potential of using historical observations and documentary records to examine temperature extremes and their societal impacts in Australia. While there are irresolvable issues associated with determining the absolute magnitude of historical temperature extremes from early temperature observations, independent reanalysis data, documentary and palaeoclimate records provide an additional way of verifying conditions experienced during these high impact events. We recommend using multiple data sources to help reconstruct a more reliable and complete interpretation of individual events and their societal impacts than is possible using historical instrumental observations alone. The case studies presented in Section 4 demonstrate that there is excellent potential to reconstruct past extremes and their synoptic drivers. This provides opportunities to use pre-industrial extremes to force climate model simulations of future extremes occurring on the background of a warming climate.

Extending Adelaide's temperature record back to 1838 indicates that the warming trend observed in Australia has resulted in a decrease in cold extremes and an increase in heatwaves in the region. The most prominent feature of the cold extremes analysis is the peak in snow days during the 1840s and late 19th–early 20th century, providing regional evidence of the global-scale cool period of the Little Ice Age. The extended analysis presented here suggests that there has been a notable decline in snow day frequency, consistent with the decreasing trend reported in the number of cold extremes observed since 1910 (CSIRO and Bureau of Meteorology, 2015). Our results also show that while there has been an increase in the overall number of heatwaves, no real trend in the average length of heatwaves was observed. Like Coates *et al.* (2014), we report that there have been significant heatwaves in Adelaide's past that have resulted in heat-related deaths. This suggests that there is potential to use historical estimates of significant heatwaves to better estimate the future risk of Australia's deadliest natural hazard (Coates *et al.*, 2014).

This study demonstrates a method for analysing historical daily temperatures that can be applied to other regions of Australia with sparse historical observations. While there are some small-scale efforts to recover and digitise daily historical weather observations (Ashcroft *et al.*, 2016), geographical and temporal data gaps exist (Ashcroft *et al.*, 2014; Ashcroft *et al.*, 2019). However, a group of volunteers from the Australian Meteorological Association have recently imaged a historical weather journal containing daily temperature and pressure observations from Adelaide spanning 1 April 1843 and 5 December 1856 (https://met-acre.net/MERIT/), which would bridge the gap in observations from 1 January 1848 until 1 November 1856 noted in Table 1. Importantly, it will provide overlap with William Wyatt's observations between 1 April 1843 and 31 December 1847, allowing the extreme heatwaves discussed in section 3.1 to be verified. Once digitised and homogenised, these observations will provide the link needed to establish the longest continuous daily temperature record in Australia, and indeed one of the longest in the Southern Hemisphere.

Despite the field's clear potential, current efforts to digitise valuable historical weather observations are primarily done by volunteers or very small research teams with limited resources. A larger, adequately funded initiative would help researchers in the emerging field of Australian historical climatology to demonstrate its practical value for future climate change risk assessment (Allan *et al.*, 2011; Brönnimann *et al.*, 2019). Finally, we strongly advocate a multidisciplinary approach to climate extremes research to ensure that physical climate factors are considered alongside estimates of societal vulnerabilities such as population exposure to extreme heatwaves. This will help emergency management services to better adapt and respond to future climate risks associated with Australia's warming climate.

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Table 1. Historical and modern instrumental temperature data used in this study, 1838–2019.

Period	**Data source**	**Details**	**Access**
1 Jan 1838–31 Dec 1847	William Wyatt's diary (34.93°S, 138.60°E, 47 m above sea level)	• Temperature observations taken at 9am, 3pm and 9pm, with Tmax and Tmin data available for 1841–1844 • Daily descriptions of weather including frost occurrence • Original values in °F • Very little metadata, observations presumed to be taken at Wyatt St in Adelaide	Original data available at State Records of Adelaide (Rogers, 2011).
2 Nov 1856–31 December 1920	Observations made in a Glaisher stand at Adelaide West Terrace Observatory (34.93°S, 138.58°E, 29 m above sea level)	• Maximum and minimum temperatures with 1.96% of missing data for Tmax and Tmin • Original values in °F	Provided by South Australian office of the Bureau of Meteorology (Ashcroft et al., in preparation)
21 Jan 1887–28 Feb 1979	West Terrace (Bureau of Meteorology station number 023000, 34.93°S, 138.58°E, 29 m above sea level)	• Maximum and minimum temperatures recorded with 0.16% missing data for Tmax, 0.24% missing data for Tmin • Observations taken in a standard Stevenson screen • Original values in °F until September 1972 (Australian Bureau of Meteorology, 2012)	Provided by Bureau of Meteorology, available at http://www.bom.gov.au/climate/data/
1 Feb 1977–31 August 2019	Kent Town (Bureau of Meteorology station number 023090, 39.92°S, 138.62°E, 48 m above sea level)	• Maximum and minimum temperatures recorded in °C with 0.04% missing data for Tmax and Tmin	Provided by Bureau of Meteorology, available at http://www.bom.gov.au/climate/data/

Table 2. Extreme heatwave events in Adelaide, 1839–2019 from William Wyatt's daily meteorological diary (1838–1847), West Terrace Glaisher observations (1856–1887), Bureau of Meteorology station Adelaide West Terrace (station number 023000, 1887–1979), and Bureau of Meteorology station Kent Town (station number 023090, 1977–2019). Events in bold are > 5 days. Events in italics do not formally reach the extreme heat wave threshold, but were considered noteworthy. An Asterisk (*) denotes an extreme heatwave that was not verified using independent documentary records. Details of all instrumental–documentary record agreements are provided in Table S1.

Pre-1910 heatwaves	**Comments**	**Post-1910 heatwaves**	**Comments**
*1839-02-14 to 16		_1910-01-01 to 08_	
		1927-01-09 to 14	**The 12th Tmin only peaked at 24.8ºC, but with a Tmax of 34.9ºC**
* **1839-12-28 to 1840-01-03**		**1934-03-08 to 14**	**No temperatures below 20ºC from 13–19)**
*1840-01-16 to 18			
* 1840-12-16 to 18		**1940-03-07 to 13**	**No temperatures below 20ºC from 7–13**
* _1841-02-09 to 13_	_1500 Temp peak was recorded as 92ºF/33ºC on the 12th, but Tmax was 94ºF. Tmin was also 86ºF/30ºC on the 12th)_	**1943-01-27 to 02-01**	
* 1841-12-10 to 13		**1951-01-26 to 31**	
* _1842-02-27 to 1841-03-01_	_Questionable as 02-28 and 03-01 have identical data_	1955-01-23 to 27	
* 1843-01-03 to 07		1961-01-24 to 28	
1844-02-12 to 17		1967-02-02 to 07	
1847-02-22 to 26		**1968-02-14 to 20**	
_1847-12-26 to 31_	_1500 Temperature was above 28.8ºC/84ºF, while 0900 and 2100 temps stayed above 26ºC/79ºF_	1970-02-06 to 09	
1858-01-25 to 30	**Tmax above 40°C and Tmin above 20°C from the 25th to the 30th**	1971-02-15 to 20	

1860-01-03 to 06	3rd Tmin almost reached the threshold as well	**1972-02-06 to 12**	
1860-02-23 to 28	*Six days with Tmax above 35°C and Tmin above 21°C*	1972-02-26 to 29	
1866-02-04 to 11	Eight days with Tmax above 34°C (above 39°C from 4 to 9) and Tmin above 20°C	1973-01-18 to 23	
1872-02-28 to 03-07	*Extreme heatwave days for 02-28, 02-29 and 03-01, and 05-03 to 07-03, with slight relief from 03-02 to 03-04 but nights still ~20°C and Tmax above 38°C.*	**1982-01-18 to 24**	
1873-01-17 to 19		1985-03-10 to 13	
1875-12-19 to 22		1989-01-25 to 28	
1876-01-26 to 30		**1989-02-28 to 1989-03-09**	
1876-02-04 to 06		**1993-01-31 to 04**	
1880-01-28 to 02-03	Seven days with Tmax > 37°C and Tmin > 23°C	1995-02-13 to 15	
1884-01-11 to 13		1997-02-17 to 22	
1887-01-07 to 10			
1890-01-17 to 20		**2000-01-11 to 17**	
1895-02-12 to 16			
1897-12-26 to 30		**2001-01-20 to 25**	
1898-01-31 to 02-04		2006-01-19 to 22	
1898-12-28 to 31		2007-02-16 to 18	
1899-02-07 to 13	*No temperatures below 20ºC from 07–13*	**2008-03-08 to 17**	
1899-12-31 to 1900-01-03		**2009-01-27 to 2009-02-03**	
1906-01-03 to 07	The 5th Tmin only reached 23.3ºC, but Tmax on that day was 43.4ºC	2012-01-01 to 03	**01-27 to 02-03 with no temperatures below 20ºC**
1908-01-03 to 07	No temperatures below 20ºC from 02–07	2014-01-13 to 17	
1908-01-14 to 19			

Table 3. Cold extremes events in Adelaide identified using instrumental temperature data detailed in Table 1 over the 1839–2019 period. Events in bold in the list below are particularly cold or noteworthy. An Asterisk (*) denotes a cold extreme that was not verified using independent documentary records. Details of all instrumental–documentary record agreements are provided in Table S2.

Pre-1910 cold extremes	Comments	Post-1910 cold extremes	Comments
1841-08-05	Snow, snow (P), Frost (Wyatt)	**1916-06-23**	**No Tmax above 13ºC from 21–25**
* 1843-07-20	Frost	1917-06-12	
* 1843-07-25	Frost	1917-08-21	
* 1844-07-02	Frost	**1918-07-13 and 1918-07-18**	**No Tmax above 13ºC between these dates**
* 1844-07-22 to 1844-07-25	Frost	1920-06-06	
1845-06-13	Frost, Frost	**1922-06-29**	**Tmax 8.3ºC, Tmax below 13ºC from 06-27 to 07-01**
1845-06-20 to 1845-06-22	Frost, Frost	1922-07-07	
1845-06-24 to 1845-06-27	**Frost 23/6/1845 reached a temp of 11.1ºC/52ºF, Frost**	1922-07-15	
* 1845-07-23	Frost	1927-07-21	
* 1845-08-16	Frost	**1931-07-11**	**No Tmax above 13ºC from 07-05 to 07-11, Tmax on the 11th 8.8ºC**
1846-07-02 to 1846-07-09	Snow, Snow(P), Frost	1933-07-17	
* 1846-07-12	Frost	1935-08-02	
* **1846-08-02 to 1846-08-08**	Snow (P), Frost	1936-07-07	
1858-07-13		1938-06-21	
1861-07-08		1940-07-09	
1862-06-28 to29		1942-06-03	
1864-08-19		1944-07-26	
1865-06-28		1948-07-26	
1865-07-09		1949-07-18	
1867-07-09		1950-08-19	
1867-07-27		1951-07-08	
1868-07-18		1951-07-16	
1870-07-19		1951-07-19 and 20	
1872-08-09 to 10		1951-08-09	
1873-07-17		1953-07-08	
1873-08-06		1953-08-04	
1874-06-27		1953-08-15	
1874-07-11		1956-06-06	
1874-07-31		1956-07-14 to 16	
1875-08-07		1957-09-15	
1876-06-16		1959-07-08	

1877-07-11		1960-08-11 and 12	
1877-09-22		1963-06-23	
1878-06-12		**1965-06-21**	**Tmax below 13ºC from 21–25**
1878-07-12		1965-07-10	
1879-07-02		1966-07-16	
1879-07-09		1966-07-19	
1879-07-23 to 24		1968-06-25	
1880-07-17		1968-07-01	
1880-08-07		1968-07-16	
1880-09-11		1968-07-21	
1881-07-13		1969-09-13	
1881-07-16		1970-07-18	
1882-07-10		1971-08-07	
1882-07-26		1977-07-23	
1882-07-28		1977-08-31	
1882-08-15		1978-07-26	
1883-07-08		1978-08-08	
1883-08-19		1979-07-21	
1884-05-12		1984-07-02	
1884-06-14		1985-08-06	
1885-06-13		1986-07-08	
1886-05-02			
1886-07-11		1987-07-26	
1887-06-12		1989-06-01	
1890-07-06	Frost	1989-07-22	
1890-08-05	frost	1990-06-24	
1891-07-09	frost	1990-07-05	
1893-07-07	frost	1991-07-08	
* 1894-06-22		1994-08-09	
1894-06-27	Frost	1996-07-11	
1894-07-11	Snow, snow (p)	1998-07-28	
1895-07-24	**No Tmax above 13ºC from 18–24 snow, snow(p) on 20th and 22dn**	1999-06-13	
1896-07-08 and 11		2003-08-10	
1898-06-20	**(Tmax of 9.1ºC) frost**	**2005-07-12 and 13**	**Tmax on the 12th 9.9ºC, no Tmax above 13ºC from 11–14**
1899-07-04 and 05	frost	2012-06-22	
1900-07-23		2014-07-09	
1900-08-16	**No Tmax above 13ºC from 13–16snow, snow (p)**	2016-07-12	
1903-07-11			
1903-07-13	Frost, snow (p)		
1904-06-28	No snow or frost?		
1904-06-30	Snow, snow (p)		
1904-07-12 to 14	Frost, Snow, snow (p) on 14th		
1905-08-29	Snow		
1906-08-27	Snow, snow (p)		

1907-07-08	Snow. Snow (p)		
1908-06-09	Cold		
1908-06-22	Snow, snow (p)		
1908-07-23	**Snow, snow (p)No Tmax above 13ºC from 22–28**		
1908-07-25	Frost, snow(p)		
1908-08-01	Snow, snow (p)		

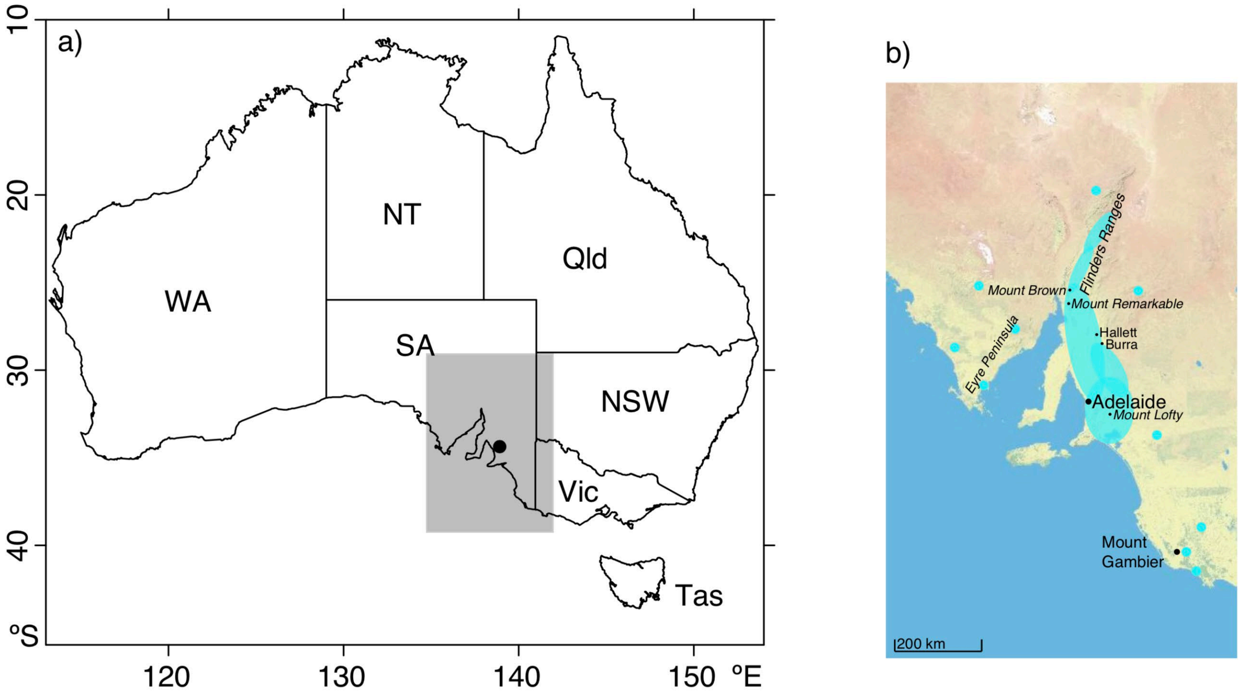

Figure 1. Adelaide region of Australia used in this study: (a) regional map of the study area (b) key towns and geographic locations referred to in the analysis. The Australian of Western Australia (WA), Northern Territory (NT), South Australia (SA), Queensland (Qld), New South Wales (NSW), Victoria (Vic) and Tasmania (Tas) are shown in (a), as well as the location of Adelaide (black circle). Light blue shading in (b) indicates the rough location of snow occurrence in Hunt (1918) for 1841–1917. Terrain features in (b) provided by Open Street Map/Leaflet/US National Park Service.

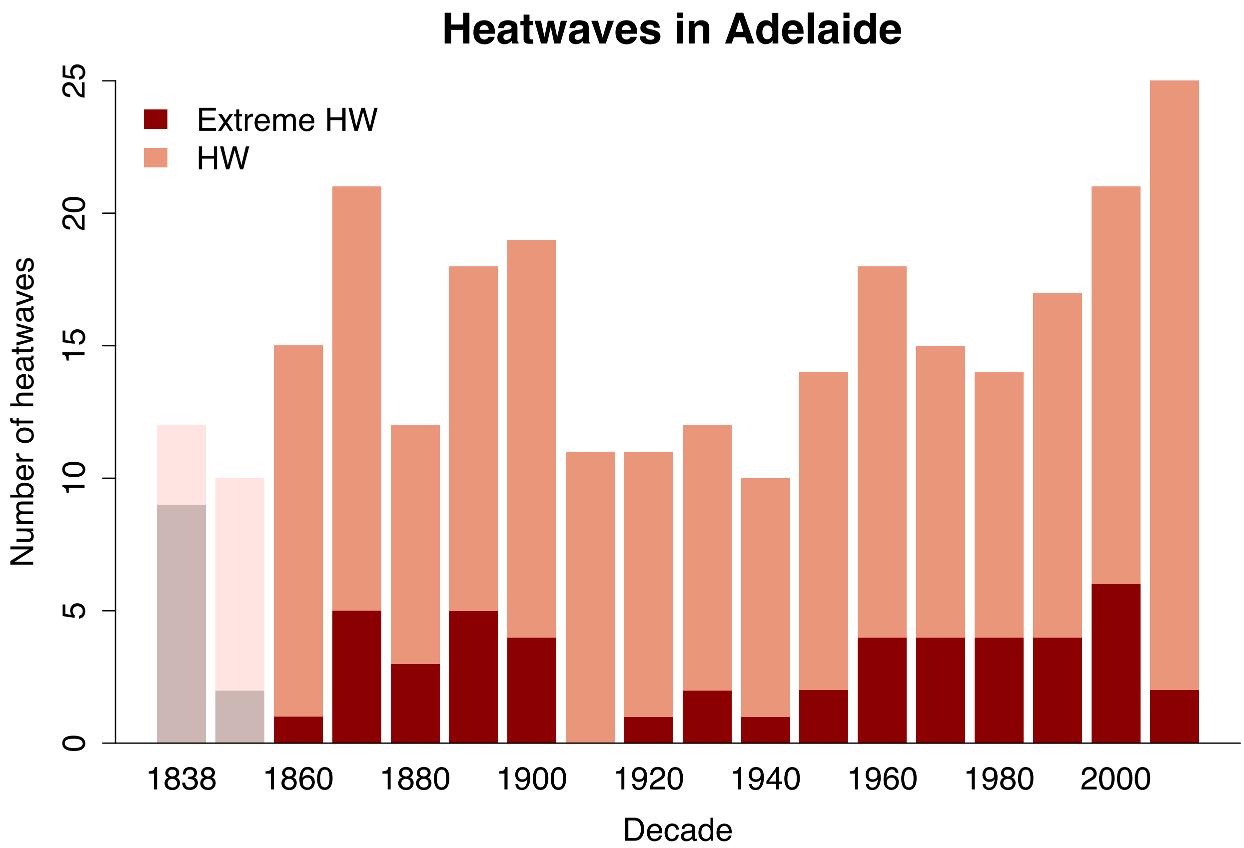

Figure 2. Number of heatwaves (pink) and extreme heatwaves (red) identified from the Adelaide region over the January 1838–August 2019 period. No digitised temperature observations are available from 1 January 1848– 1 November 1856, so these decades are shown in lighter shades. Note the first bar represents the 12-year period from 1838 to 1849.

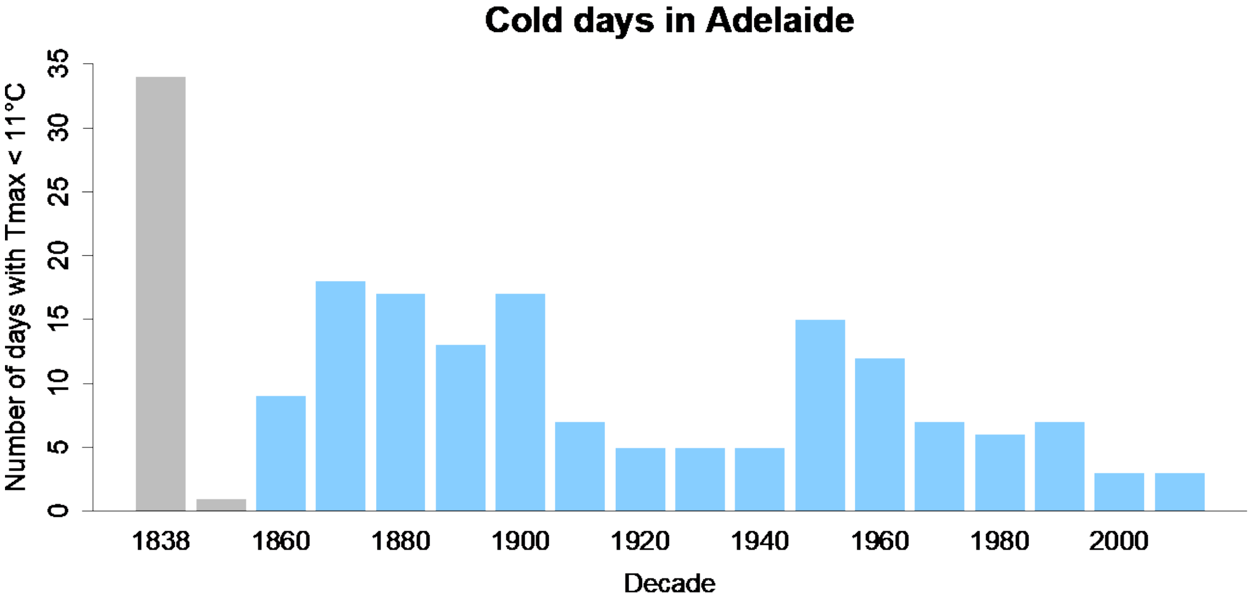

Figure 3. Number of extreme cold days (blue) identified from the Adelaide region over the January 1838–August 2019 period using instrumental data. No digitised temperature observations are currently available from 1 January 1848–1 November 1856, so these decades are shaded grey. Note the first bar represents the 12-year period from 1838 to 1849.

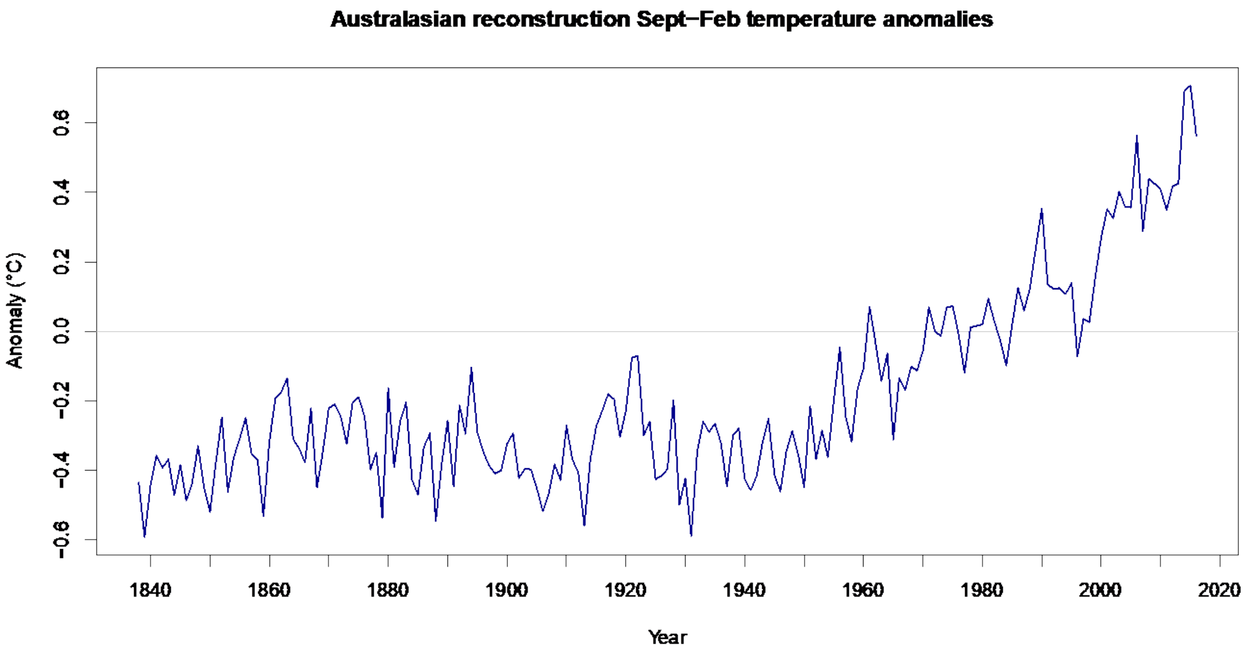

Figure 4. Reconstructed September–February Australasian HadCRUT3v temperatures, 1838–2016, relative to the 1961–1990 base period. Note that 2001–2016 data points are direct instrumental temperature observations, not palaeoclimate estimates. Updated from Gergis *et al.* (2016).

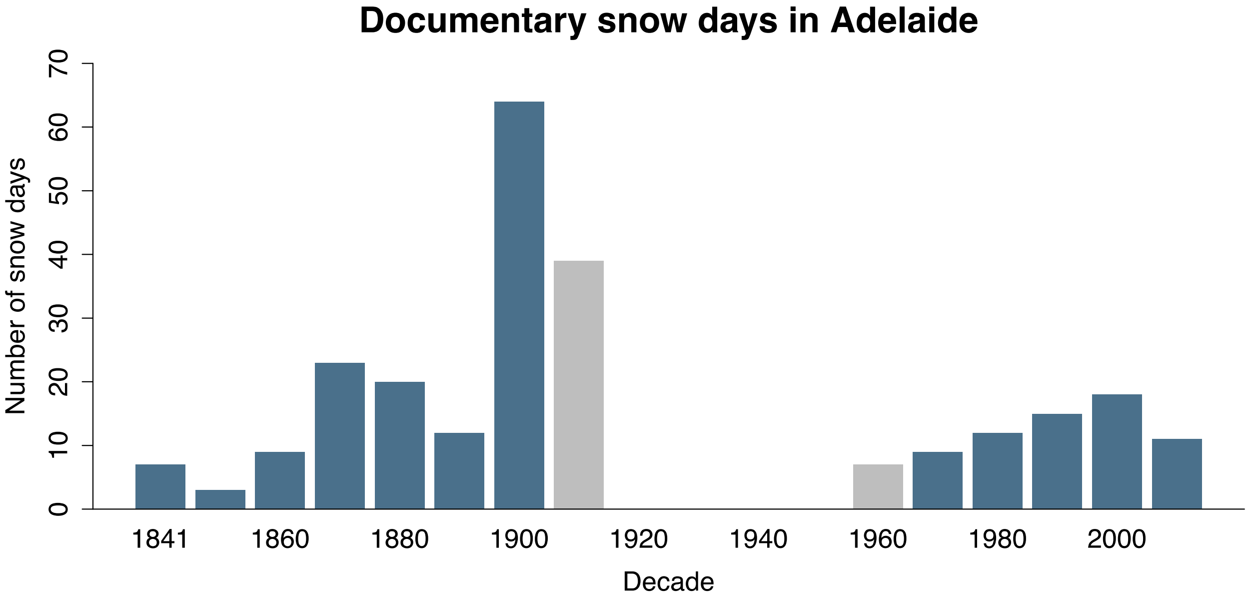

Figure 5. Number of snow days (both falling and settling snow) identified from the Adelaide region over the 1841–2016 period using documentary sources detailed in section 2.2. Decadal data are incomplete from 1920–1960, and the 2010s; as such, these decades are plotted in grey.

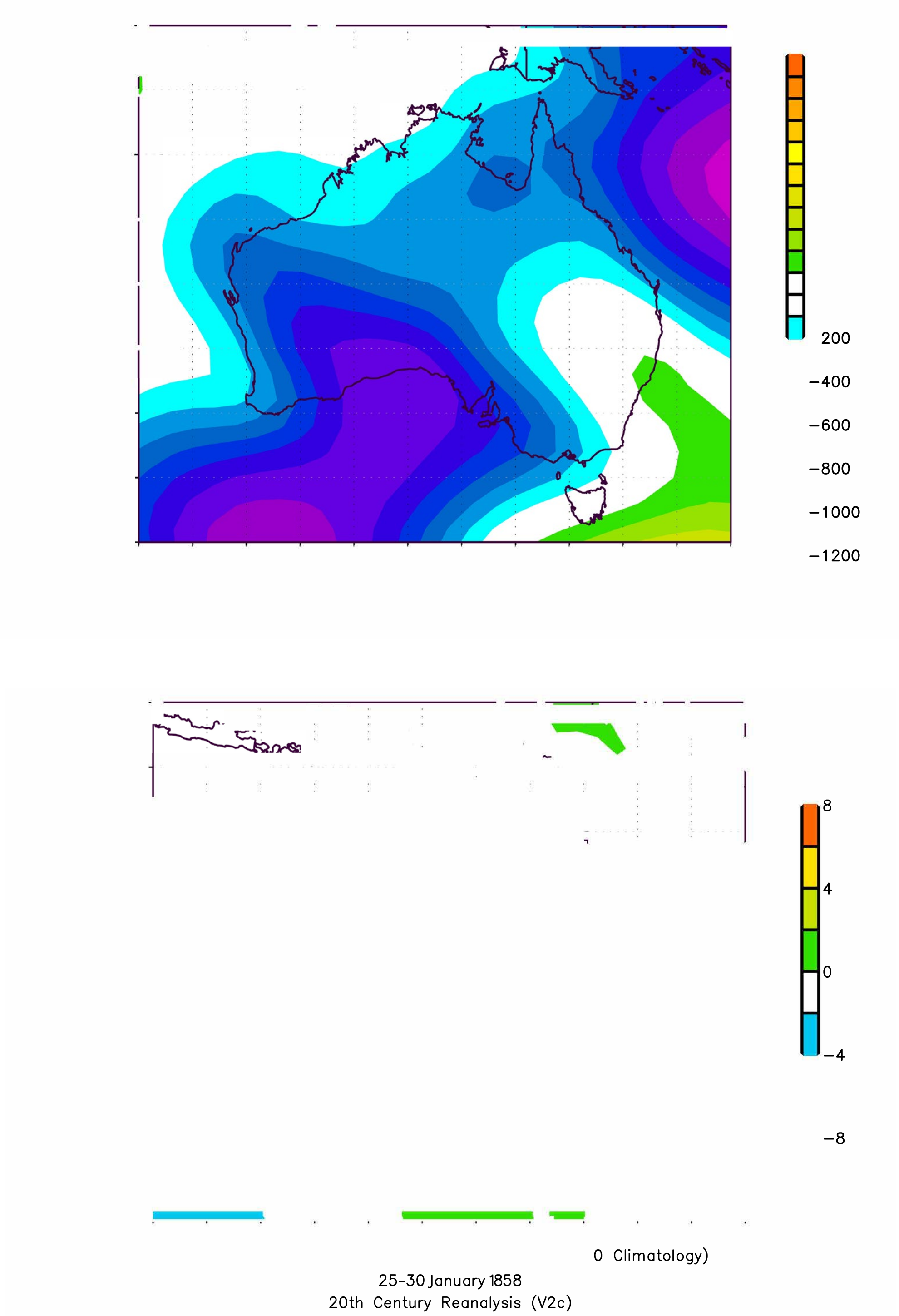

Figure 6. Sea level pressure (top) and 2m air temperature (bottom) anomalies associated with heatwave conditions of 25–30 January 1858. Data derived from 20th Century Reanalysis Version 2c provided by the NOAA Earth System Research Laboratory, Boulder, Colorado, USA, accessed from https://www.esrl.noaa.gov/psd/. Sea level pressure and 2m air temperature anomalies are given in Pascale (Pa) and Kelvin (K), respectively.

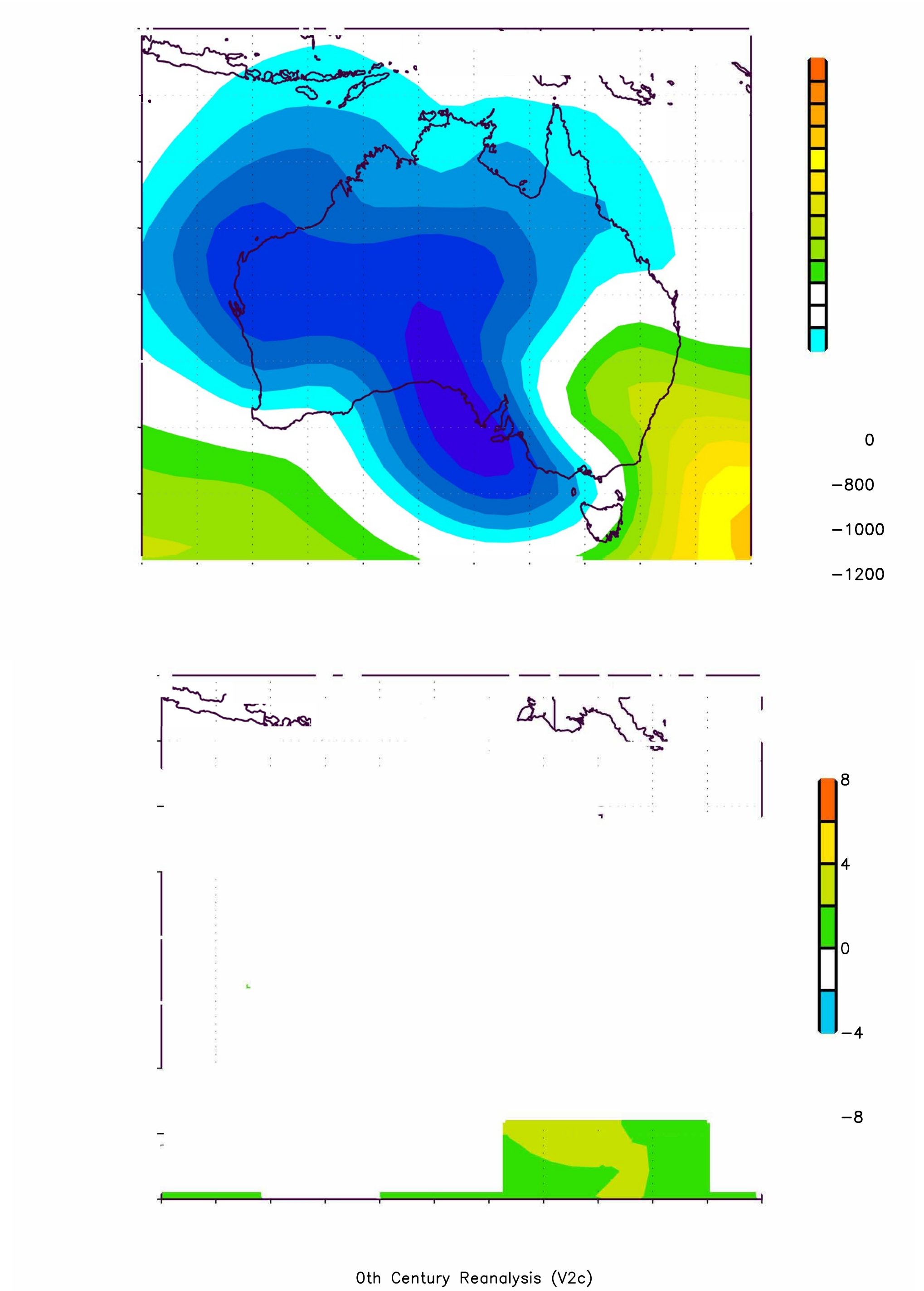

Figure 7. Sea level pressure (top) and 2m air temperature (bottom) associated with heatwave conditions of 12–16 February 1895. Data derived from 20th Century Reanalysis Version2c provided by the NOAA Earth System Research Laboratory, Boulder, Colorado, USA, accessed from https://www.esrl.noaa.gov/psd/. Sea level pressure and 2m air temperature anomalies are given in Pascale (Pa) and Kelvin (K), respectively.

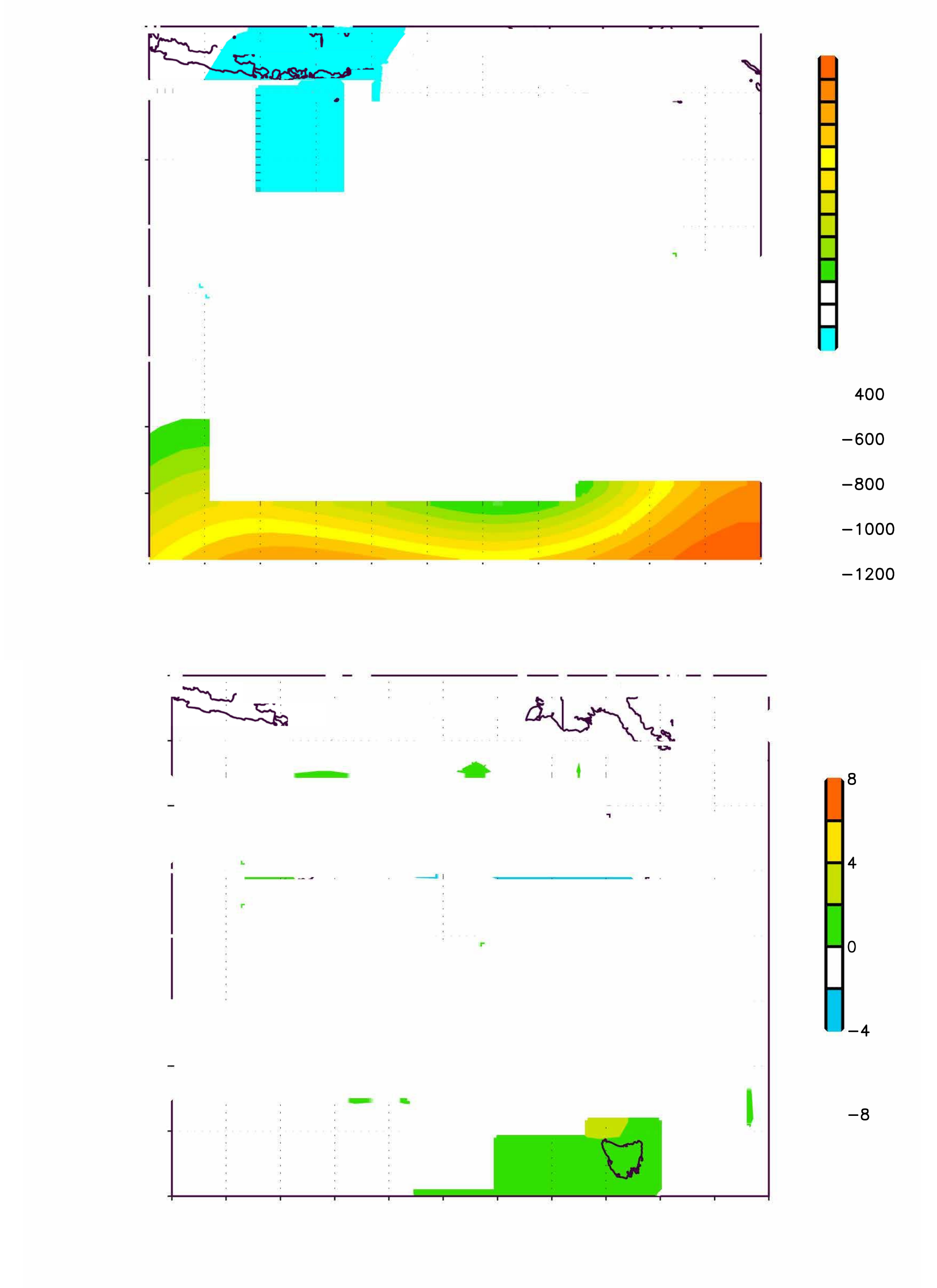

Figure 8. Sea level pressure (top) and 2m air temperature (bottom) associated with heatwave conditions of 26–30 December 1897. Data derived from 20th Century Reanalysis Version2c provided by the NOAA Earth System Research Laboratory, Boulder, Colorado, USA, accessed from https://www.esrl.noaa.gov/psd/. Sea level pressure and 2m air temperature anomalies are given in Pascale (Pa) and Kelvin (K), respectively.

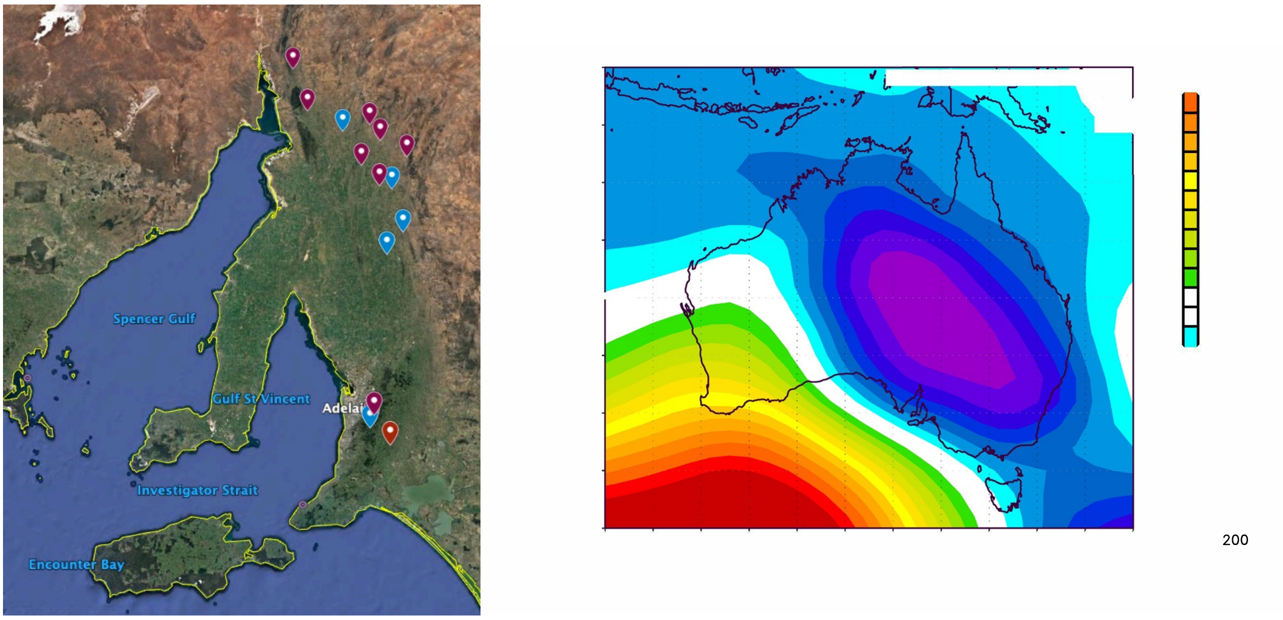

Figure 9. Snow event of 23–24 July 1879. Left: Historical reports of snow (blue pins), including reference to settled snow (red pins) on 20th July. Right: Sea level pressure anomalies for 19–20 July 1895. Data derived from 20th Century Reanalysis Version2c provided by the NOAA Earth System Research Laboratory, Boulder, Colorado, USA, accessed from https://www.esrl.noaa.gov/psd/. Sea level pressure anomalies relative to (1981–2010 base period) are given in Pascale (Pa).

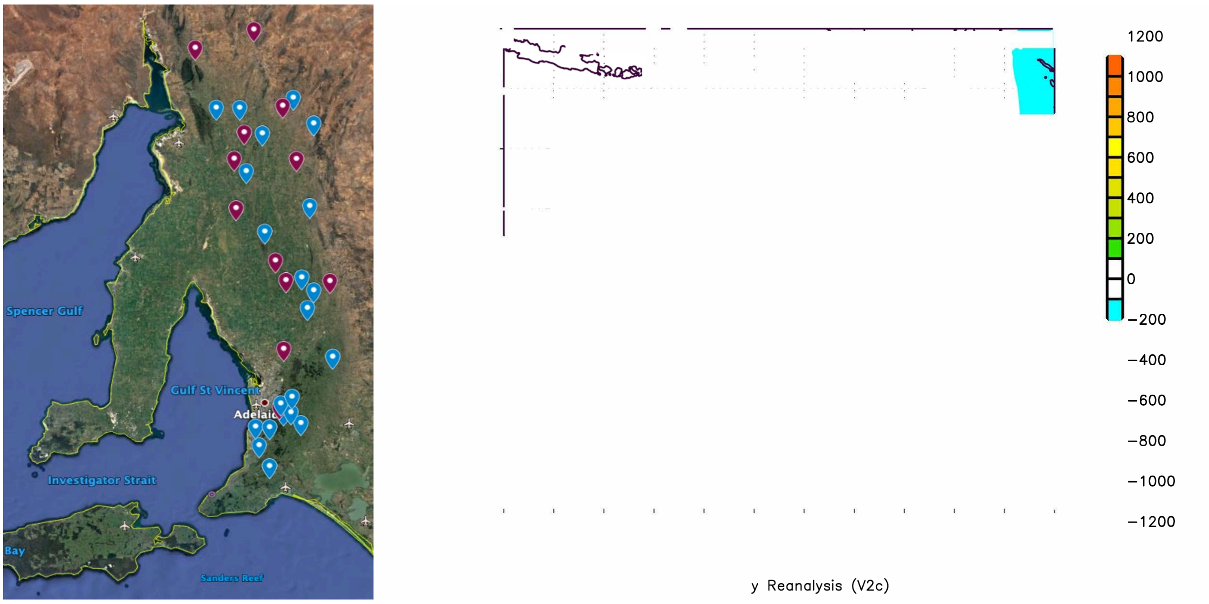

Figure 10. Snow event of 28 August 1905. Left: Historical reports of snow (blue pins), including reference to settled snow (red pins) on 29 August. Right: Sea level pressure anomalies for 28 August 1905. Data derived from 20th Century Reanalysis Version2c provided by the NOAA Earth System Research Laboratory, Boulder, Colorado, USA, accessed from https://www.esrl.noaa.gov/psd/. Sea level pressure anomalies (relative to 1981–2010 base period) are given in Pascale (Pa).

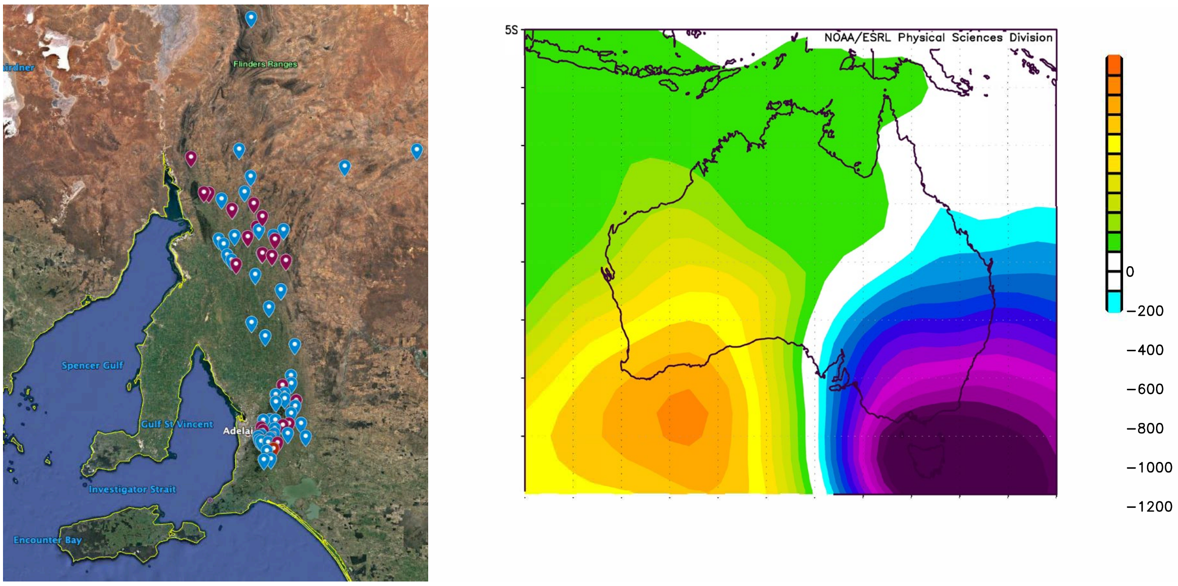

Figure 11. Snow event of 22 June 1908. Left: Historical reports of snow (blue pins), including reference to settled snow (red pins) on 22 June. Right: Sea level pressure anomalies for 22 June 1908. Data derived from 20th Century Reanalysis Version2c provided by the NOAA Earth System Research Laboratory, Boulder, Colorado, USA, accessed from https://www.esrl.noaa.gov/psd/. Sea level pressure (SLP) anomalies (relative to 1981–2010 base period) are given in Pascale (Pa).

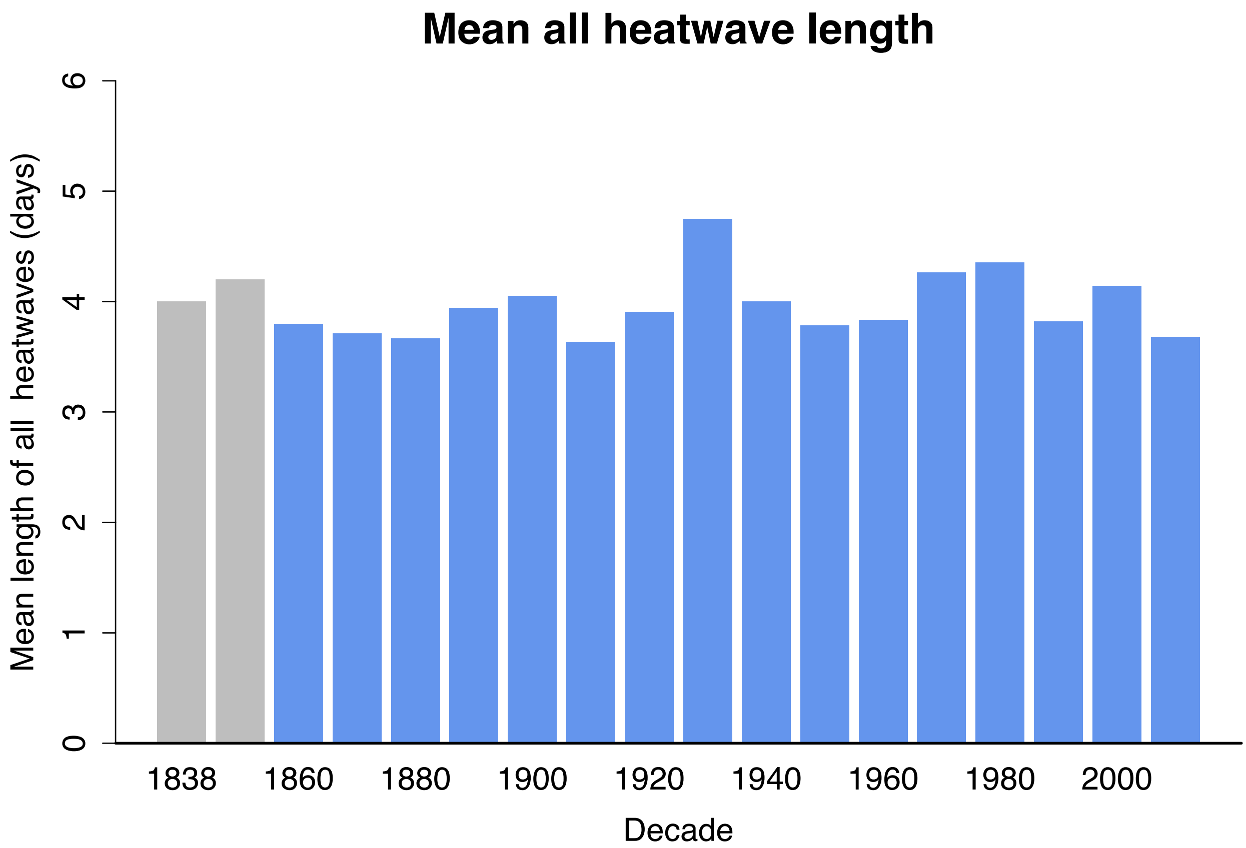

Figure 12. Mean duration of heatwaves identified from the Adelaide region over the 1838–2019 period. No digitised temperature observations are currently available from 1 January 1848– 1 November 1856, so these decades are shown in grey. Note the first bar represents the 12-year period 1838–1849.

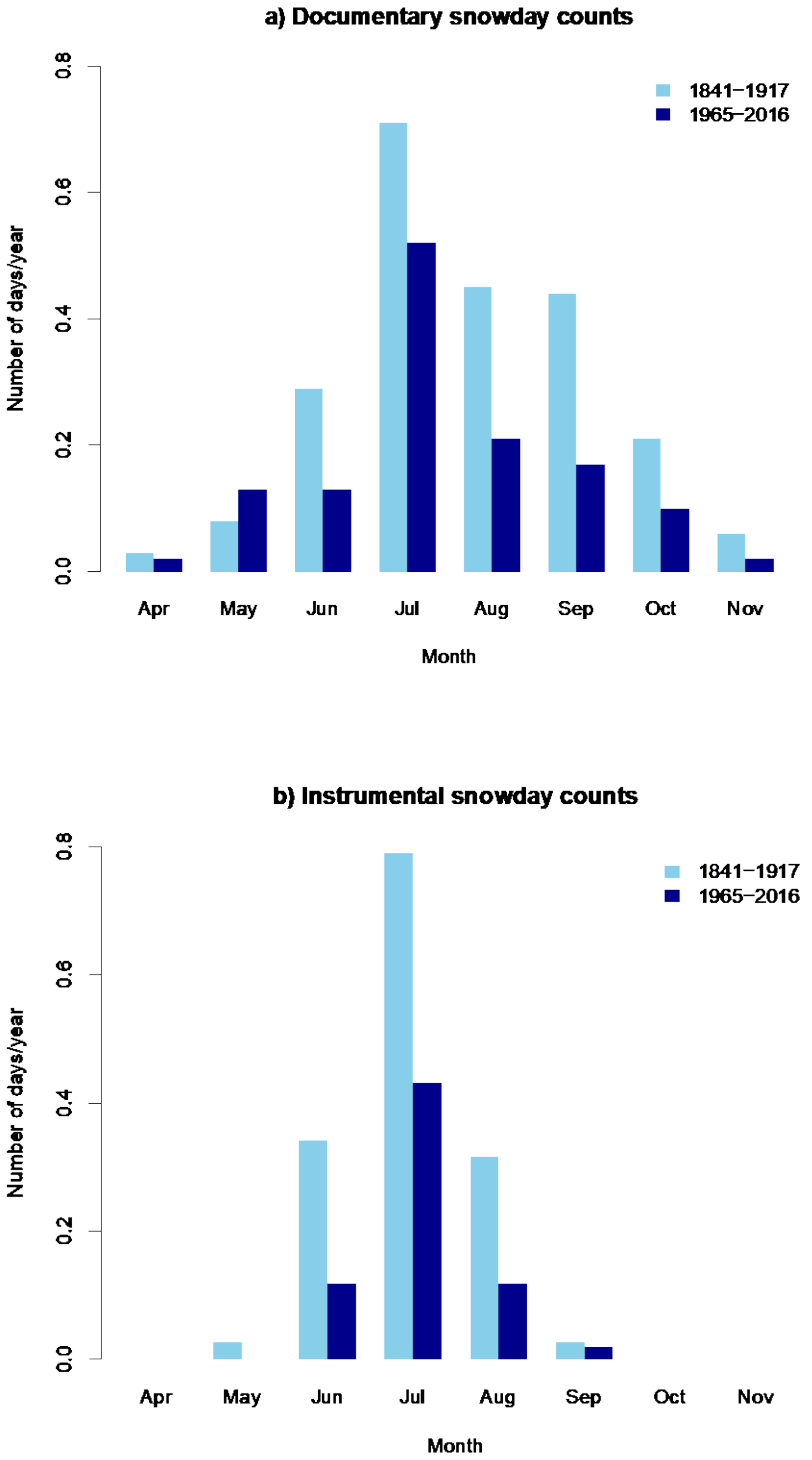

Figure 13. Average number of snow days per year identified in the a) documentary analysis and b) instrumental analysis identified from the Adelaide region from 1841–1917 (light blue) and 1965–2016 (dark blue) over the May–November period.

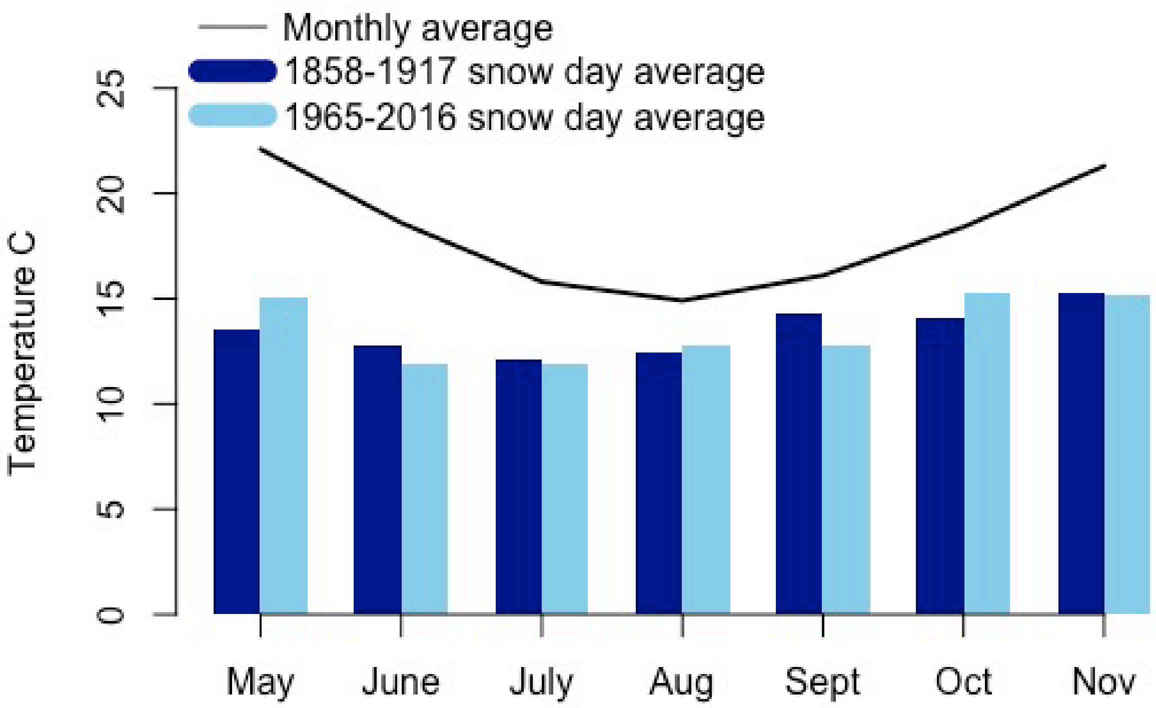

Figure 14. Comparison of maximum temperatures averaged for snow days identified in the documentary analysis identified from the Adelaide region from 1858–1917, using West Terrace data (dark blue) and 1965–2016 using Kent town data (light blue) over May–November months. Climatological average maximum temperatures West Terrace (all available records) are shown by black time series.