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A historical climate dataset for southwestern Australia, 1830–1875

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Abstract

Southwestern Australia is a high priority area for climate research as there has been a significant, anthropogenically-influenced winter rainfall decline detected in the region since 1970. Here we present the oldest daily historical climate dataset for Perth, southwestern Australia, to provide an extended record for analysing pre-industrial climate variability and extremes from the region. This newly digitised record contains sub-daily observations of temperature, barometric pressure, wind direction and weather remarks, including rain days, from 1830–1875.

Following quality control and homogeneity adjustments, we demonstrate that the historical dataset reliably resolves modern characteristics of Perth's weather and climate variability, including the seasonal cycle and the ability to capture daily extremes like storm and heatwave events. We compare covariations in temperature, pressure, wind and rain days to cross-verify our historical dataset against modern observations for Perth. We also use the historical dataset, modern Bureau of Meteorology observations, the Twentieth Century Reanalysis, and historical documents to further validate our results. The multivariate method introduced in this study demonstrates that using multiple variables and data sources is a useful approach to reconstruct past variability, extremes and their societal impacts from historical observations.

This is the first long instrumental record to be developed for southwestern Australia; an important region for observing pre-industrial Indian and Southern Ocean variability and extremes. The new record from Perth provides 19th century data from a data sparse region of the Southern Hemisphere that can now be compared with daily observations from South Africa, New Zealand and southeastern Australia. This comparison will improve the understanding of contemporary changes in Southern Hemisphere atmospheric circulation.

Keywords: Australia, Perth, historical climatology, temperature, pressure, extremes

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1. Introduction

Historical weather records are fundamentally important for understanding contemporary changes in the climate system (Brönnimann *et al.*, 2019; Brönnimann *et al.*, 2020). Daily meteorological observations provide an opportunity to examine past climate variability and place recent extremes into a longer context (Ashcroft *et al.*, 2019; Gergis *et al.*, 2020).

Since 2006 there have been concerted international efforts to recover and digitise historical weather observations, co-ordinated through the International Atmospheric Circulation Reconstructions over the Earth (ACRE) program (Allan *et al.*, 2011). The main aim of this initiative is to improve reconstructions of global historical weather conditions primarily through the development of the Twentieth Century Reanalysis product (Compo *et al.*, 2011; Slivinski *et al.*, 2019). This product reconstructs synoptic conditions using sub-daily surface pressure observations as input and observed monthly sea surface temperatures and sea ice conditions as boundary conditions (Compo *et al.*, 2011; Slivinski *et al.*, 2019), allowing the dynamical conditions of past extremes to be examined in greater detail (Slivinski *et al.*, 2021).

To date, the majority of historical instrumental records have been located in continental Europe (Brönnimann *et al.*, 2020), with fewer records available from equatorial and sub-tropical regions of the world (Nash and Adamson, 2014). The current lack of long-term climate records from the Southern Hemisphere limits scientific understanding of long-term climate variability in the Pacific, Indian and Southern Oceans which impacts regions like Australia, New Zealand, South Africa and South America (Gergis and Henley, 2017). Given the global and regional impacts associated with the dynamical features of the El Nino–Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM) (Risbey *et al.*, 2009), recovering daily weather observations from Southern Hemisphere regions remains the priority for data recovery efforts (Ashcroft *et al.*, 2014a; Lorrey and Chappell, 2016; Picas *et al.*, 2019; Copernicus Climate Change Service, 2020; Gergis *et al.*, 2020; Picas and Grab, 2020).

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In recent years there has been substantial progress in recovering historical weather records from Australia (Gergis and Ashcroft, 2013; Ashcroft *et al.*, 2014a; Ashcroft *et al.*, 2016; Gergis *et al.*, 2018). However, to date these efforts have largely been restricted to the colonial centres of south-eastern Australia. Very little effort has been focused on Western Australia, primarily because of the inability of key research groups to access hardcopy material from historical archives. Recently there has been a concerted effort to digitise a range of historical material, including the National Library of Australia's Trove digitised newspaper database, which contains colonial meteorological tables and weather reports of extremes events from many regions, including Western Australia (National Library of Australia, 2020).

In 2017, the National Archives of Australia imaged sixteen handwritten weather journals containing sub-daily meteorological observations of temperature, barometric pressure, wind direction and weather remarks from the Swan River colonial settlement in Perth (National Archives of Australia, 2020) (Figure 1). As outlined in Table 1, these observations span 16 April 1830 to 31 December 1875, making them the earliest weather observations available from Western Australia, and some of the earliest available from the Southern Hemisphere (Brönnimann *et al.*, 2020). Once homogenised and merged with modern data sources from the Australian Bureau of Meteorology (BoM) (http://www.bom.gov.au), this record will provide near-continuous sub-daily observations of meteorological conditions experienced in southwestern Australia since 1830. This will provide a valuable long-term context for assessing recently observed variability and extremes.

Perth is located in southwestern Australia, a small climatologically distinct temperate region on the edge of a large, arid continent influenced by the vast ocean masses of the surrounding Indian and Southern oceans (Timbal *et al.*, 2006). The climate of the region is primarily influenced by the seasonal movement of the sub-tropical ridge of high atmospheric pressure associated with the descending branch of the Hadley cell located at approximately 30°S (Timbal *et al.*, 2006; Bates *et al.*, 2008; Larsen and Nicholls, 2009).

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Perth's location in the prevailing Southern Hemisphere westerly wind belt is the primary influence on the region's climate (Larsen and Nicholls, 2009; Nguyen *et al.*, 2015). Southwestern Australia's rainfall is highly seasonal with up to 80% of the rain falling during the cool season months from April to October (Bates *et al.*, 2008) when the westerly storm track reaches its most northerly extent as the subtropical ridge contracts equatorward (Bureau of Meteorology, 2008). During summer when the westerlies migrate poleward, easterly winds bring hot and dry conditions to the Perth region (Bureau of Meteorology, 2008). The strong land–sea contrast during the warm season results in a fresh south-westerly sea breeze known locally as the 'Fremantle Doctor', providing relief from summer heat (Bureau of Meteorology, 2008).

While large-scale atmospheric circulation is the dominant driver of regional climate (Smith and Timbal, 2012), there are other local factors that influence Perth's climate. Offshore, the Leeuwin Current, which transports warm water southward from the tropical Indian Ocean, increasing rainfall over southwestern Australia (Timbal *et al.*, 2006). These warm sea surface temperature conditions off southwestern Australia contrast to other locations at similar latitudes on the west coasts of landmasses like Africa or South America that have cold ocean currents flowing equatorward, resulting in double the rainfall received in these other locations of the Southern Hemisphere (Timbal *et al.*, 2006). In terms of local topography, the city of Perth is located on a relatively flat coastal plain between the Indian Ocean and the low elevation Darling Range to the east of Perth (Bureau of Meteorology, 2017). Modest orographic uplift is provided by the Darling Escarpment, which runs in a north–south direction at an elevation of approximately 200 metres above sea level, increasing rainfall in the Perth region where the majority of water storage dams are located (Smith and Power, 2014; Bureau of Meteorology, 2017).

Southwestern Australia is a high priority area for climate research as there has been a significant, anthropogenically-influenced winter rainfall decline detected in the region since the late 20th century (Cai and Cowan, 2006; Timbal *et al.*, 2006; Nicholls, 2010; Delworth and Zeng, 2014). There has been a 20% decline in May–July rainfall in the region since 1970 (relative to the 1900–1969 average),

with the reduction increasing to around 28% since 2000 (Bureau of Meteorology and CSIRO, 2020). This trend is largely associated with a reduction in the number of observed cold fronts and low pressure systems, which are the most important weather systems for rainfall in southwestern Australia, particularly during the cool season (Bureau of Meteorology and CSIRO, 2020).

The reduction in rainfall since the 1970s has already contributed to a 70% decline in runoff into water storages, leading to a greater reliance on groundwater and desalination of sea water to secure Perth's drinking water supply (Petrone *et al.*, 2010). These declines are also relevant for agriculture as Western Australia is estimated to produce over 30% of Australia's total winter grain crop and around 40% of the average annual Australian wheat crop; with these crops mainly grown in the inland areas in the southwest of the state (Pook *et al.*, 2011). While the rainfall decline has been primarily attributed to large-scale circulation changes influencing rain bearing systems (e.g. Hope *et al.*, 2006) and anthropogenic changes in greenhouse gases and ozone (e.g. Timbal *et al.*, 2006; Delworth and Zeng, 2014), other factors including land clearing, soil moisture–vegetation dynamics, and declining ground water levels have also contributed to a substantial reduction in surface runoff (Bates *et al.*, 2008; Petrone *et al.*, 2010; Smith and Power, 2014). There is high climate model agreement that this drying trend will likely persist, especially in the cooler months between April and October (Hope, 2006; Smith and Power, 2014; Hope *et al.*, 2015; Bureau of Meteorology and CSIRO, 2020). As such, a long-term understanding of natural variability from this region is important for adapting to future anthropogenically-driven climate change.

Given the significant impacts of sustained rainfall declines in southwestern Australia on water resources and agricultural productivity in key areas like the Central Wheatbelt of Western Australia (Petrone *et al.*, 2010; Pook *et al.*, 2011), there is a clear need for longer instrumental datasets to better understand the long-term changes in rainfall variability. Recovering other meteorological variables such as atmospheric pressure will help clarify the local synoptic conditions and teleconnections for modes of climate variability that influence the region (Nicholls, 2010; Pook *et al.*, 2011).

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Daily instrumental records are also important for providing extended, direct estimates of natural climate variability in southwestern Australia that help distinguish the anthropogenic contribution to recently observed trends and extremes (Timbal *et al.*, 2006; Delworth and Zeng, 2014). For example, early instrumental observations are valuable for validating other datasets like palaeoclimate reconstructions (O'Donnell *et al.*, 2018), which provide estimates of multi-decadal variations that predate the start of instrumental records. Daily instrumental records are also very useful for cross checking extremes like heatwaves, cold outbreaks or heavy rainfall events noted in historical documents like newspapers and other colonial records of the time (Ashcroft *et al.*, 2019; Gergis *et al.*, 2020).

Although there can be considerable data quality issues associated with analysing historical weather observations (e.g. Nicholls *et al.*, 1996; Trewin, 2010), the use of multiple variables and data sources helps improve the reliability of results in the pre-1900 period (Gergis *et al.*, 2018; Ashcroft *et al.*, 2019; Gergis *et al.*, 2020). Alongside quality control and statistical data homogenisation processes, adopting a multi-variate approach to internally verify each variable against others available from the record makes it possible to corroborate evidence for the occurrence and severity of past climate conditions (Ashcroft *et al.*, 2014b).

For example, when considering the plausibility of a historical heatwave, high temperature observations in a record can be independently verified in atmospheric pressure observations, and expected wind directions that prevail during contemporary heatwaves in the region. In addition, consulting historical documents like newspapers and colonial reports allows extreme events to be verified independently, as well as describing the societal impacts of these extreme events (Gergis *et al.*, 2020). In this way, verifying early instrumental observations using multiple variables and data sources helps reduce the uncertainties associated with reconstructing past climate variability and extremes from historical records (Gergis *et al.*, 2020).

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The aim of this study is to present the oldest daily weather records for the Swan River colonial settlement of Perth, southwestern Australia, taken shortly after first European settlement of the region in 1829. Our objectives are to:

1. Introduce a new historical dataset of near-continuous, sub-daily meteorological observations of temperature, pressure, rain days and wind for Perth covering the 1830–1875 period
2. Detail the data quality control and homogenisation methods applied to the new historical dataset
3. Demonstrate the new historical dataset's ability to resolve key features of the contemporary climate of southwestern Australia, including the seasonal cycle and daily extremes.

2. Data

2.1. Historical instrumental observations

According the National Archives of Australia's (2020) online catalogue, sixteen volumes of handwritten weather journals exist, beginning shortly after the arrival of the first contingent of colonial settlers at the Swan River settlement area (modern day Perth) in 1829 (see National Archives of Australia catalogue for record PP430/1). The series predates the first official meteorological observations which commenced in the Perth Botanical Gardens in 1875 near the modern day Supreme Court Gardens (National Archives of Australia, 2020). Little information is known about exactly where the Swan River observations were taken, however on 5 July 1843 it is noted that the thermometer was relocated to 'outside the Survey Office on a southern aspect'. There is also reference to observations being taken in the colonial hospital or 'colonial dispensary' from July–September 1842 (volume 3 series PP430/1), but the exact location of the meteorological instruments is unknown. We believe that these observations were taken very close to the Perth Botanical Gardens (Figure 1).

The identity of the observer(s) is also unspecified, but consistent and descriptive weather remarks and occasional mentions of astronomy suggest they were very observant. In fact, remarks in later journals even identify the names of specific cloud types. Changes in handwriting are infrequent but they do occur for periods up to a few weeks. There is also little information on the instruments used

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to take the temperature and pressure observations. However, on 23 May 1863 it was noted that a Troughton and Simms thermometer replaced the old instrumentation. Temperature observations were then made using both the old and new thermometer for six weeks, suggesting the observer attempted to quantify the bias introduced by the malfunctioning thermometer. Unfortunately, the lack of metadata currently available for this record means that the thermometer exposure conditions remain uncertain.

In total, the sixteen volumes of handwritten journals spanning 1830–1875 contain over 50,000 fixed-time observations of temperature, barometric pressure, wind direction and weather remarks including rain days. The daily record is near-continuous; however as seen in Table 1, observations are missing in the periods May 1836–August 1837 and November 1851–December 1853. Although the majority of the observations were taken at the Survey Office, a set of multi-year overlapping journals were also present in the collection from September 1837– February 1850 (see Table 1). The overlapping set contains parallel fixed-hour observations suggesting they were taken at the same location, however a lack of metadata for the record means that the possibility of another observing site during this period cannot be ruled out. These journals tend to be much neater and the time and frequency of observations largely does not change (twice daily pressure observations and four times daily temperature observations).

Based on the similarity of the values in the overlapping period, we suggest that two sets of weather journals were maintained – an ‘original’ journal for in situ observations and a neater ‘transcribed’ journal, where select observations from the ‘original’ journals were copied across to. Unfortunately, we were only able to locate the transcribed journals for the two time periods of September 1837–December 1844 and January 1845–February 1850. Although at times these periods overlap with the ‘original’ journals, sometimes they also fill gaps in the ‘original’ journals, such as September 1837–August 1845 and August 1847–September 1849. During a three-month overlapping period from July–September 1842, observations were also taken at the colonial hospital, thought to be approximately

500 metres from the survey office. Note that these are the only observations located for the hospital site.

The number of weather observations made per day varies across the weather journals, with some inconsistencies noted between variables (Table 1). For example, during the 1840s, up to six temperature observations a day were made. This contrasts to pressure observations, wind direction and weather remarks which were primarily noted twice each day. The observation time also varies across the record, but predominantly the morning observations were taken at 1000 and the afternoon at 1600, although 0900 and 1500 observations are present in some parts of the record (e.g. 1830–1836, 1837–1844 and 1842). As was common practice until the mid-1970s, meteorological observations in Australia were not made on Sundays (Viney and Bates, 2004), with the latest observation made on Saturday at 1300.

In addition to the fixed-time temperature observations, pairs of 'interval' temperature observations were also available for much of the record (1830–1863). A page from October 1860 (volume 11, series PP430/1) has a column title that describes the interval temperature observations as 'Range of Temperatures' rather than the usual 'Temperatures'. It may be that the interval temperature observations represent the maxima and minima between the fixed-time observations or that they represent the maxima and minima of the day. Further analysis is required to confirm this hypothesis, but was beyond the scope of the current analysis, so the interval observations were not analysed in this study.

2.2. Modern instrumental observations and reanalysis data

Sub-daily temperature and pressure observations from the Australian Bureau of Meteorology meteorological stations of Perth Regional Office (BoM station number: 009034; 1942–1992) and Perth Metro (BoM station number: 009225; 1994–2019), were used to verify the ability of the historical observations to reproduce features of Perth's modern climate.

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The time of observation varies between the two Bureau of Meteorology stations. The Perth Regional Office station typically observed temperature and pressure every three hours, while the Perth Metro station observes temperature hourly and pressure every three hours. As there are no overlapping observations between the Perth Regional Office and Perth Metro stations (missing values for the year 1993), we were not able to homogenise the record into a continuous series from 1942 until present. We compared the seasonal and daily cycles of both stations (results not shown) however, due to their differences, we opted not to combine them.

Consequently, we use both records to validate the observations of the historical record. For example, we predominantly use the Perth Regional Office record (1942–1992), as it is currently the longest time series available for this location. However, we use the Perth Metro station (1994-2019) to examine the quality of the historical temperature record (Section 3) as both records made temperature observations at 1000 and 1600. In contrast, the Perth Regional Office station made observations at 0900 and 1500.

While there are no other nearby instrumental temperature data that overlap with the historical temperature observations available from 1830–1875, there are some pressure data for Perth from the 19th century. These data were extracted from the International Surface Pressure Databank (ISPD) version 4.7 (Cram *et al.*, 2015). A continuous dataset was not available, however pre-20th century observations for ISPD station ID: 9034 covering 1840–1846 and 1879–1905 were used for comparison with our newly recovered 19th century pressure observations. The ISPD record's temporal resolution is inconsistent; in some instances, there are twice-daily observations, while for other parts of the record entire months are missing. In total, there are 7,674 pressure observations for IPSD station ID: 9034. Other observations were available from the ISPD for the 19th century; however, most were very short records, and likely observations from ships which docked at Perth for a short period of time. It is worth noting that the station ID for the ISPD pressure record is the same as the Perth Regional Office station (009034), although it is currently unknown whether they are in

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fact the same station, or a composite of pressure records from unknown sites within the broader region of southwestern Australia.

To investigate the synoptic conditions associated with particular extreme events we follow the approach of Gergis *et al.* (2020) and use the ensemble mean of the 20th Century Reanalysis version 3 (20CRv3; Slivinski *et al.*, 2019). This version contains recently recovered surface pressure observations from the 19th and early 20th century from Australia (Ashcroft *et al.*, 2014a; Ashcroft *et al.*, 2014b), potentially improving its regional performance over this period (Slivinski *et al.*, 2019; Slivinski *et al.*, 2021).

3. Data quality control and homogenisation

An integral component of analysing historical meteorological observations involves conducting comprehensive quality control and homogenisation procedures to flag spurious data that may undermine the utility of a dataset for reliable climate analysis (Peterson *et al.*, 1998). Historical climate data must be closely examined for erroneous values which can be hallmarks of non-climatic influences (Trewin, 2010). The largest issue with historical observations relates to the availability of adequate station metadata that contain specific details needed to determine discontinuities (Peterson *et al.*, 1998; Trewin, 2010). These changes include station moves, changes or malfunctions in instrumentation, changes in the ambient environmental conditions like buildings and/or surrounding vegetation, new observers, and any changes in the time of observation (Peterson *et al.*, 1998; Trewin, 2010). Assessing the quality of digitised historical climate data is essential for identifying: 1) errors in the digitisation process, 2) systematic biases (inhomogeneities), and 3) errors resulting from the method of observation (Ashcroft *et al.*, 2018). In this section, we detail our methods used to examine these three potential sources of bias.

Transcription errors stemming from the digitisation of handwritten records is common. To keep digitising errors to a minimum, the same two digitisers were used to transcribe alternate journals. Both digitisers keyed the year 1830 to assess the readability of the records, and identify any patterns

in their digitisation errors. The digitised observations were checked for agreement with the original journals by visually and statistical verifying outliers and comparing overlapping data sources when available.

When analysing historical meteorological observations, it is important to determine which values are simply transcription errors to minimise the chance of inadvertently removing genuine extreme values from the record. In this study, we follow the approach of Ashcroft *et al.* (2018) and use the Universal Quality Control (UQC) software (http://www.c3.urv.cat/softdata.php) to examine the statistical quality of the temperature observations, as well as the RHTESTv4 software (https://github.com/ECCC-CDAS/RHtests) to assess homogeneity of the pressure observations (detailed in section 3.2).

Despite our best efforts to remove spurious values, it is important to acknowledge that there are inherent limitations to historical data associated with non-standard instrument exposure and the lack of detailed station metadata to confirm the possible nature and cause of statistically defined inhomogeneities. To try and address this, we conduct a multi-variate comparison of all available variables to corroborate potential evidence for the variability and extremes observed in a single variable from the 19th century record.

Note that all imperial measurements were converted to modern units to compare historical observations with contemporary climate records. For temperature, Fahrenheit temperature observations were converted to degrees Celsius. For pressure, the original pressure readings were recorded in inches of mercury (In Hg) so were converted into hectoPascals (hPa) using the standard conversion (hPa= (In Hg) x 33.86).

3.1 Temperature

3.1.1 Detecting transcription issues

We use a range of visual and statistical techniques to detect potential transcription errors in all temperature observations available from 1830–1875. Plotting 1000 and 1600 observations revealed

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clearly erroneous values such as a value above 200°F or one less than 10°F. To identify less obvious transcription errors, 1000 and 1600 observations beyond ± 3 standard deviations from monthly means were flagged. This identified 25 statistical outliers, one of which was found to be a true digitisation error.

As noted in Section 2.1, we digitised two sets of weather journals; an 'original' set and a 'transcribed' set (see Table 1). The period of overlap (1843–1847; 1849–1850) provided an opportunity to examine the agreement between the overlapping years. In doing so we identified 54 revisions or omissions related to unclear handwriting. In cases where the two journals disagreed, the value in the 'original' journal was used.

In an unbiased data set, one would expect an even distribution in the last digit of a temperature observation. However in Australia weather stations, it has been found that values ending in .0 and .5 are overrepresented (Trewin, 2010). For temperature, we found an obvious inclination for the last digit to be '0' or '5', and a slight tendency towards even numbers. Given the inherent precision issues associated with historical observations, the impact of this practice was not considered a significant issue for examining relative rather than strictly absolute variations contained in the data set.

3.1.2 Statistical quality control

After completing the above analysis to identify transcription errors, we then follow the approach of Ashcroft *et al.* (2018) and implement the Universal Quality Control (UQC) software (Universitat Rovira i Virgili, 2014 - http://www.c3.urv.cat/softdata.php). The UQC software performs a number of quality control checks (Table 2) on a sample of sub-daily observations. As the observing times vary throughout the record, we only examine the statistical quality of timestamps that contained at least 100 observations. That is, we only examine the observations made at 0900, 1000, 1100, 1200, 1300, 1500, 1600 and 1700 to minimise the introduction of analytical biases in the dataset.

The only statistical errors (Table 2) which the UQC software detected were outliers which coincide with the period just before the thermometer was replaced. As mentioned in section 2.1, the

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thermometer was replaced on 23 May 1863 in response to it malfunctioning. This was evident from temperatures that were considerably higher (up to 5 standard deviations) than the rest of the record.

To correct this issue, we followed the approach of Gergis *et al.* (2020) and applied a simplified version of the quantile matching technique introduced by Trewin (2018). Every fifth percentile (5th, 10th, 15th … 95th) was computed for both the reference period and the target period that were corrected. A transfer function, using both sets of percentiles, was then constructed based on which bin an uncorrected value falls within.

For this we needed to determine when the thermometer began malfunctioning, noting that there was no metadata indicating when this may have occurred. To do this we examined: the outliers detected by the UQC software, daily temperature anomalies, and daily z-scores to identify each observation's departure from the mean (not shown). The biases associated with the malfunctioning thermometer begin to be obvious during the year 1862. As the precise date could not be identified, we take a conservative approach of correcting the temperature observations from 1 January 1862.

As shown in Figure 2, the application of the quantile matching technique results in temperature observations that are much cooler, and more consistent with earlier observations within the record. The observations are still warmer than after the thermometer is replaced, however the exact model of the new thermometer is likely to be different to the one that it replaced, which may explain the absolute difference between the two sets of observations. It is important to note that there may still be non-climatic features in the period 1 January 1862–23 May 1863 which we have not corrected for. The approach we have taken is a cautious one that tries not to 'over correct' in an attempt to retain genuinely extreme values.

As noted in Section 2.1, the thermometer was moved on 5 July 1843 to 'outside the Survey Office on a southern aspect'. As expected, this relocation caused the temperature observations from this date until the date the thermometer was replaced (23 May 1863) to be markedly cooler than the rest of the record. To correct this bias, we again implemented the quantile matching technique detailed above.

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The monthly means presented in Section 4 demonstrate how closely the historical morning and afternoon observations resemble observations from a modern weather station after this correction, suggesting our adjustment to the record was appropriate.

3.2 Barometric pressure

3.2.1 Detecting transcription errors

To identify potential transcription errors we followed the approach of Alexander *et al.* (2010) and used a probability density function (PDF) based method to detect 'extreme pressure events'. We computed daily average pressure and then estimated a PDF from the difference between subsequent observations. The 1st and 99th percentiles of the PDF were then used to define 'extreme' events. These events may represent genuine storm events or digitisation errors which arise from the incorrect transcription of the original observations or errors in the original observation. In the majority of instances, the 'extreme' events identified were transcription errors which were corrected by consulting the original weather journals. This method is less applicable for variables like temperature which exhibit significant day-to-day variation. This is why we opted not to use it to identify transcription errors in the temperature observations. While this test is effective for identifying digitization errors, it is unable to detect inhomogeneities, so the pressure observations were subjected to the homogeneity analysis detailed in section 3.2.2.

3.2.2 Testing homogeneity

To test the homogeneity of the historical pressure data we implemented the commonly used RHTestv4 (Wang and Feng, 2013; available online from https://github.com/ECCC-CDAS/). The RHTestv4 software uses two methods to detect and correct change points in a timeseries: the penalised maximal t test (PMT) and the F test. If no changepoints are detected, then a time series is considered homogenous.

The decision regarding which test to apply was based on the availability of a reference station or correlated dataset. As there are currently no reference stations to assess the inhomogeneities of this

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dataset against, we implemented the F Test (Wang, 2008a; 2008b). In the absence of extensive metadata for the record, we only searched for 'Type 1 changepoints'. These are changepoints that are statistically significant and do not need to be corroborated with station metadata.

We assessed the homogeneity of both daily and monthly surface pressure averages. We found that the pressure observations are predominately homogenous with only one Type 1 changepoint detected in the daily series (Figure 3), and two Type 1 changepoints detected in the monthly series (not shown).

The RHtestv4 package also contains a Quantile-Matching (QM) algorithm which homogenises a timeseries, removing the Type-1 changepoints (Wang *et al.*, 2010; Vincent *et al.*, 2012). We used this algorithm to internally homogenise the historical pressure data and used this series for all subsequent analysis.

It is important to note that data homogenisation is ideally conducted using a reference series that is both highly correlated and overlaps with the timeseries that is being examined (Peterson *et al.*, 1998; Venema *et al.*, 2012). Unfortunately, such a series does not yet exist for comparison with our 19th century Perth observations. As such, the homogenised pressure data presented here should be interpreted cautiously, providing an estimate of relative rather than absolute variations in the record.

3.3 Rainfall

In the absence of quantitative rainfall observations, rain days were tallied from the remarks section of each journal to develop a categorical rainfall proxy. Values were normalized relative to the maximum possible of five rain remarks per day identified in the record. This allowed a relative rainfall scale to be used to determine 'light', 'moderate' and 'heavy–very heavy' rain conditions for the Perth region over the 1830–1875 period (Figure 4). For example, the highest number of rain days are observed during the mid 1840s, mid 1850s, and early-mid 1860s (Figure 4).

To cross check the rain day results, we compare the number of rain days with average daily pressure conditions. As seen in the upper panel of Figure 4, there is a clear tendency for wetter days to correspond with lower barometric pressure conditions associated with storm events. The average

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daily pressure of the wettest days falls within the first quintile of the pressure data, while the average daily pressure of days with no rain is indistinguishable from the average daily pressure of the whole record. This may reflect the intrinsically moisture limited region of southwestern Australia and, potentially, the sampling of a particularly dry period as noted above.

The month of June 1868 appears to have been an exceptionally wet month when 23 rain days were reported. Many remarks made during this month described conditions as 'heavy' or 'much' rain, with a comment exclaiming 'Rain! Rain! Rain!' was made on July 3 1868. This was the only time throughout the series exclamation marks were used, highlighting the observer's amazement and rarity of these conditions. On this same day, the *Perth Gazette and W.A. Times* newspaper reported Perth's major waterway the Swan River was 'fresh down to its mouth, a fact we believe almost unprecedented so early in the season'. Rainfall data from the same newspaper reported that 13.91" (353.3 mm) fell in June 1868. Given the unusual nature of this period, we investigate this very wet month further in a case study provided in section 5.1.

It is clear from the lower panel of Figure 4 that heavy rainfall is far less common than light-moderate rain in the region over the 1830–1875 period. Dry periods are noted in the late-1830s through to the early 1840s, and late 1850s. This may reflect the semi-arid conditions that exist directly adjacent to the temperate coastal location of Perth, or the real presence of protracted dry periods at our study site during the 19th century. Interestingly, the late 1830s-mid 1840s is a pronounced period of drought in south-eastern Australia as identified from early instrumental, documentary and palaeoclimate records (Fenby and Gergis, 2013; Gergis and Ashcroft, 2013). Evidence of protracted dry conditions from southwestern Australia provides a first line of instrumental evidence that this may have been a period of widespread drought across southern Australia (Ashcroft *et al.*, 2016).

3.4 Wind

Wind direction from the historical record was analysed to help infer past atmospheric circulation conditions and verify the barometric pressure and temperature observations. Wind roses (Figure 5)

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are constructed to show the frequency of wind direction observations in both the historical and a modern record. The morning observations contain more variability than the afternoon observations in both the modern and historical observations. Morning wind directions in the historical record were consistently observed from the south-west and north-east. In contrast, the historical afternoon observations were clearly dominated by south-westerly winds, with other wind directions making up a much smaller fraction of the total observed wind direction.

3.5 Covariation analysis

To further verify the historical wind observations, we also examine them in parallel with temperature and pressure conditions observed during stormy conditions (Figure 6). To isolate stormy periods within the record, we implemented the PDF method of Alexander *et al.* (2010) detailed in section 3.1.2. This approach uses sharp changes in subsequent pressure observations to identify periods of atmospheric instability. We extract the days that coincide with sharp spikes or declines in daily pressure observations that are equal to or greater than the 99th percentile or equal to or lower than the 1st percentile. We average the temperature and pressure observations for those days to assess covariations in pressure and temperature, along with the most common wind direction.

To test the ability of the record to track the development and abatement of storms we calculate these averages for a period of five days before and after peak storminess. Figure 6 shows the expected decline in atmospheric pressure and temperature in the lead up to a storm and the increase in pressure and temperature once the storm has passed. Storms in Perth typically originate in the south-west, a feature that is consistent with the results seen in the historical dataset for Perth.

Finally, to see if the historical record is capable of recreating the north-easterly to easterly flow that is associated with extreme temperatures in this region (Pezza *et al.*, 2012), we examined the wind observations coincident with extreme temperature events that were in the top 99th percentile. In the morning of these extreme temperature events, the wind direction that was most commonly observed was north east, followed by easterly winds. In the afternoon this shifts, when the most common

direction is south-westerly. As in the storm example presented above, these results show that the historical record captures the dynamical signature associated with extreme weather events in Perth.

4. Comparison of historical observations with modern records

To assess whether the 19th century rescued historical temperature and pressure observations can reproduce the main features of Perth's contemporary climate, we conduct several comparisons between the historical record and modern meteorological observations.

We compared the seasonal cycle of the historical temperature observations, after the issues outlined in section 3 were adjusted, and that of the Perth Metro station (ID: 009025). Original, uncorrected values are also presented for comparison. As seen in Figure 7, the seasonal cycle present in the 1000 and 1600 monthly historical temperature observations reproduce the modern season cycle seen in contemporary Perth. That is, high temperatures are observed during the November–March warm season and cool temperatures during April–October. The 19th century morning observations are consistently cooler than the modern 1000 monthly temperatures observed during the 1994–2019 period across all months. This difference is similar in magnitude to the 1ºC of warming that has been observed in Australia since the mid-20th Century (Bureau of Meteorology and CSIRO, 2020), but may also reflect remaining cool biases that exist in temperatures recorded in non-standard thermometer screens due to sub-standard air circulation (Nicholls *et al.*, 1996).

The corrected 19th century 1600 observations display the tendency to over-estimate warm season temperatures, and slightly colder cool season temperatures. This is likely to reflect issues associated with the non-standard exposure of the 19th century thermometers compared with modern Stevenson screen temperature observations (Nicholls *et al.*, 1996). As seen in Figure 7, a cool bias is more pronounced in the uncorrected temperatures suggesting sustained exposure issues in the 19th century dataset. Note that for this analysis only, the Perth Metro station data (ID: 009025) spanning the 1994–2019 period was used instead of the longer Perth Regional Office (ID: 009034) as the Perth Metro

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station contained temperature observations for 1000 and 1600 which directly matched the observation time of the 19th century temperature record.

Figure 8 highlights another systematic bias in the seasonal cycle contained in the historical pressure observations. A high pressure bias is clearly seen when compared to the pressure observations obtained from the Perth Regional Office station (ID: 009034) from 1942–1992. Less pronounced differences are seen between the historical pressure observations and the 19th century station data extracted from the ISPD, with less divergence noted during cool season months, especially from June–August. This may suggest similarities in the instrumentation and exposure of the two 19th century datasets. The prevalence of low pressure outliers particularly during April–June is seen across all three records suggesting that the historical observations are able to capture seasonal storm conditions typical of the region, even though the absolute value of these observations are offset by a relative bias compared with modern values.

As seen in Figure 5, the Bureau of Meteorology's modern wind roses for annually averaged 0900 conditions over the 1944–2016 period, easterly and north-easterly flow dominates the morning wind conditions in the Perth region. While the 19th century observations do display significant north-easterly flow, the results indicate some inconsistencies compared with modern observations.

In contrast, the Bureau of Meteorology's modern wind roses for annually averaged 1600 afternoon conditions in Perth are primarily influenced by south-westerly to westerly winds over the 1944–2016 period (Figure 5). This feature is colloquially referred to as the 'Fremantle Doctor', which describes the cooling effect of the afternoon sea breeze that occurs during summer months in southwestern Australia in response to increased land–sea temperature contrasts that develop from hot inland conditions and cooler air flowing from the adjacent Indian and Southern Oceans. The most striking feature of the 1600 historical wind observations is the very clear capture of this south-westerly flow, suggesting that the 19th century observations are able to record this characteristic feature of Perth's modern climate.

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4.1 Covariation analysis

To further assess how well the historical dataset matches modern observations, we investigate the covariations present in the modern and historical observations by comparing temperature and pressure in both datasets. We do this analysis to see if the historical record recreates the known relationship between these variables in Perth, Australia. For example, stable atmospheric conditions are often associated with hot and dry weather with northerly and easterly prevailing winds, while storm conditions are characterised by sudden changes in atmospheric pressure, cold temperatures and southerly and westerly wind flow (Hope *et al.*, 2006).

First we examine the covariation of pressure and temperature. Figure 9 examines the relationship between monthly temperature and pressure observations in Perth's 19th century (1830–1875) and modern climate (1942–1992). In addition, Table 3 provides the seasonal and annual correlation coefficients between the historical and modern records. As noted above, we observe a high pressure bias in the scatterplot of the historical observations presented in Figure 9. While the absolute values between the historical and modern records differ, the overall trend between the two variables is characterised by a strongly negative relationship in austral autumn and spring and a weaker relationship in austral summer and winter. The signal is dominated by low pressure indicated by a negative correlation (representing a relationship between low atmospheric pressure and high temperatures) in the transition seasons of autumn (March–May) and spring (September–November), also seen in Table 3.

5. Case studies

Based on the analyses presented in sections 3 and 4, we conclude that the 19th century observations are a good estimate of past climate conditions experienced in Perth. In a final assessment of the historical record, we provide a 'proof of concept' analysis testing the ability of the 19th century observations to resolve daily extreme events. We use daily pressure and temperature fields extracted from the Twentieth Century Reanalysis version v3 (20CRv3; Slivinski *et al.*, 2019) to explore the

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dynamical conditions associated with a winter storm and summer heatwave identified in the year 1868. This also allowed newly-identified extremes in Perth's extended climate record to be verified using synoptic maps generated from the independent 20CRv3.

To further cross-verify the synoptic conditions associated with the event, the National Library of Australia's Trove historical newspaper database (National Library of Australia, 2020) was searched to the verify the societal impacts of these two extremes experienced in Perth. This helped assess the ability of the historical observations and reanalysis product to accurately represent the meteorological conditions associated with daily extremes experienced in southwestern Australia.

5.1 Storm event: 14–19 June 1868

As outlined in section 3.3, the analysis of rain day counts suggested that very heavy rainfall was noted for the month of June 1868 in the historical record. As seen in Figure 10, a significant storm passed over the Perth region from 14–19 June 1868. The synoptic maps indicate deep low-pressure conditions over southwestern Australia, consistent with cold front activity that characterises the westerly storm track that influences southern Australia (Hope *et al.*, 2006). A sequence of strong cold fronts appears to have crossed the region, resulting in a corresponding drop in temperatures of approximately 5^{o}C relative to the 1950–2005 average as estimated by the 20CRv3. The lowest temperature reading is registered on 16 June when 59^{o}F [15^{o}C] was recorded at 1600. The wind direction observations indicate that south-westerly wind prevailed during the event as the front passed through. The remarks mention 'heavy squalls with rain' starting on 15 June, with 'heavy showers' and a 'fresh breeze' recorded until 19 June when conditions appear to have eased.

An analysis of newspaper records for this event (Table 4) verifies that the June 1868 storm brought significant rains and damaging winds. *The Inquirer and Commercial News* reports ships that were 'driven ashore', as well as damage to coastal infrastructure. It appears the rainfall associated with this storm was the most amount of rain this colonial settlement had received since they arrived in 1829. *The Perth Gazette and West Australian Times* wrote of abundant rainfall stating: '…all fears had been

set at rest by abundant falls of rain, which speedily caused the earth to put on a green livery; the lambing had been very good, and for the first time since the country has been occupied, it was hoped to shear a clean clip of wool, free of dust and grass seeds'. The severity of this storm is well supported by three independent sources – documentary, 20CRv3 and 19th century instrumental records – indicating that our multivariate method is effective at capturing significant storm events using historical records.

5.2 Heatwave event: 28–30 December 1868

As seen in Figure 11, a significant heatwave affected the Perth region from 28–30 December 1868. The 20CRv3 pressure field displays a pressure dipole with the dominance of high pressure south of Australia, and low pressure south of New Zealand. In Perth, significant heatwaves are commonly associated with a prolonged heat trough extending from the southern Indian Ocean towards the Great Australian Bight (Pezza *et al.*, 2012); a pattern observed in the 20CRv3 fields in Figure 11. This results in strong, near-stationary high-pressure conditions that can lead to the sustained advection of warm air from inland areas, causing a prolonged and significant increase in temperatures (Pezza *et al.*, 2012; Hirsch *et al.*, 2019).

Temperature anomalies in the Perth region were likely to have been 6–8°C above the 1950–2005 average as estimated by the 20CRv3, representing a significant heatwave event for southwestern Australia. The wind remarks report the dominance of north-easterly winds during the day, shifting south-westerly during the afternoon, corresponding very well with the wind direction results presented in Figure 5. Specific mention of 'thunder during the day' is noted on 28 December 1868 with an additional temperature reading of 101°F [38.3°C] inserted at 1500. The maximum temperature noted in the weather journal appears on 30 December when 102.5°F [39.2°C] was recorded at 1600. On 31 December 1868, a cold front appears to have come through with south-westerly winds dropping the temperature to 81°F [27.2°C] by 0900.

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As seen in Table 5, historical newspaper reports over the period suggest that 'oppressively hot' conditions were experienced during this event. For example, on 30 December 1868, *The Inquirer and Commercial News* reported 'The weather for the last week has been extremely hot, land winds prevailing'. Bushfire conditions were reported on 6 January 1869, with damage to agricultural crops also noted. Interestingly, *The Inquirer and Commercial News* noted a temperature observation of 100ºF [37.8ºC] on 30 December 1868. This is comparable to the 1600 observation of 102.5ºF [39.2ºC] recorded in the instrumental temperature record. These historical newspaper reports provide an important source of independent verification for the heatwave recorded in Perth 19th century temperature record and synoptic features resolved in the independent 20CRv3 dataset.

6. Discussion and conclusion

We have presented the oldest daily historical climate dataset for Perth, southwestern Australia. The new record contains sub-daily observations of temperature, pressure, wind and rain days spanning 1830–1875. While the record is near-continuous, observations are missing from May 1836–August 1837 and December 1851–November 1853. The reasons for the missing data during this period are currently unknown. Following quality control and homogeneity adjustments, we demonstrate that the dataset reliably resolves modern characteristics of Perth's weather and climate variability, including daily extreme events like storms and heatwaves. The multivariate method introduced in this study demonstrates that multiple variables and data sources, including historical documents, are useful records for reconstructing past variability, extremes and societal impacts.

Of significance, this is the first long instrumental record to be developed for southwestern Australia; an important region for observing Indian and Southern Ocean variability. Perhaps most importantly, the new historical record from Perth provides 19th century data from a data sparse region of the Southern Hemisphere, that may be compared with comparable daily weather records from Cape Town, South Africa (Picas *et al.*, 2019; Picas and Grab, 2020), Northland, New Zealand (Lorrey and

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Chappell, 2016), and the capital cites of south-eastern Australia (Ashcroft *et al.*, 2019; Gergis *et al.*, 2020).

While the development of this historical daily dataset for Perth is significant, it is important to note that overlapping observations with modern records are needed to serve as a reference station to homogenise the 19th century dataset for a more precise comparison with modern records. As noted in section 3, there are biases in the temperature and pressure observations that currently limit the record's ability to resolve the absolute value of past weather and climate conditions. Until a period of overlap with modern records is available, the record will remain unhomogenised, so can only offer insights into relative climate variations experienced during the 19th century. Nonetheless, given the lack of records available for this region of the world, the historical dataset still offers valuable insights into the past climate variability and extremes experienced in the dynamically important sub-tropical region of the Southern Hemisphere that has experienced a clear anthropogenically-forced rainfall decline since the late 20th century (Cai and Cowan, 2006; Timbal *et al.*, 2006; Nicholls, 2010; Delworth and Zeng, 2014).

While monthly temperature observations are available from 1876–1930 from the Bureau of Meteorology's Perth Gardens station (ID: 009097), daily observations have not been digitised for this site. A citizen science effort is planned to digitise 21 volumes of daily observations for the Perth Gardens from 1880–1900 held by the National Archives of Australia (record PP430/2). The catalogue notes a critical gap in the daily observations stating: 'Volumes for the period 1876–1879 are missing from the series although rainfall records 1876–1879 are present in series 5 of this accession'. As the record presented in this study ends in December 1875, an overlap with daily modern observations for the Perth Gardens site remains elusive.

At present the location of daily observations for the 1876–1879 period from Perth is unknown, but may be found in historical newspapers that were often published weekly, or monthly abstracts of daily meteorological conditions. However, it is worth noting that monthly temperature, barometer, rainfall and rain day observations for the Perth Botanic Gardens appear in a historical compilation of

meteorological observations by Western Australia's former Government Astronomer W. Ernest Cooke from 1876–1899 (Cooke, 1901). This will provide an opportunity to develop a near continuous monthly dataset from 1830 until present. Numerous other records are known to exist for Western Australia (see Cooke, 1901), but have not been recovered or digitised.

A concerted research effort is required to build off this preliminary analysis to demonstrate the need to recover valuable instrumental data from this data sparse region of the Southern Hemisphere. Rescuing 19th century weather observations from Australia has the potential to allow the development of key instrumental reference series that can be used in the long-term analysis of Southern Hemisphere climate on daily–multi-decadal timescales. The observations we have recovered can now be used to examine variations in circulation patterns across the southern Indian Ocean and, in conjunction with recovered data from other mid-latitude regions of the Southern Hemisphere (Ashcroft *et al.*, 2014a; Lorrey and Chappell, 2016; Picas *et al.*, 2019; Gergis *et al.*, 2020; Picas and Grab, 2020), can shed light on large-scale hemispheric variability.

The incorporation of historical observations from the Australian region will also help improve data coverage in global datasets like the Twentieth Century Reanalysis that can be used to better resolve the dynamics of past weather and climate variability and extremes (Slivinski *et al.,* 2021). This will allow a detailed analysis of the circulation changes being experienced in the sub-tropical regions of the Southern Hemisphere that are already showing sensitivity to anthropogenically-driven climate change.

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References

Alexander, L. V., Uotila, P., Nicholls, N. and Lynch, A. (2010). A New Daily Pressure Dataset for Australia and Its Application to the Assessment of Changes in Synoptic Patterns during the Last Century. *Journal of Climate* **23**: 1111-1126.

Allan, R., Brohan, P., Compo, G., Stone, R., Juerg Luterbacher, J. and Brönnimann, S. (2011). The International Atmospheric Circulation Reconstructions over the Earth (ACRE) Initiative. *Bulletin of the American Meteorological Society*: doi: 10.1175/2011BAMS3218.1.

Ashcroft, L., Coll, J. R., Gilabert, A., Domonkos, P., Brunet, M., Aguilar, E., Castella, M., Sigro, J., Harris, I., Unden, P. and Jones, P. (2018). A rescued dataset of sub-daily meteorological observations for Europe and the southern Mediterranean region, 1877–2012. *Earth System Science Data* **10** (3): 1613-1635.

Ashcroft, L., Gergis, J. and Karoly, D. J. (2014a). A historical climate dataset for southeastern Australia, 1788–1859. *Geoscience Data Journal* **1** (2): 158–178.

Ashcroft, L., Gergis, J. and Karoly, D. J. (2016). Long-term stationarity of El Niño—Southern Oscillation teleconnections in southeastern Australia. *Climate Dynamics* **46** (9–10): 2991-3006.

Ashcroft, L., Karoly, D. J. and Dowdy, A. J. (2019). Historical extreme rainfall events in southeastern Australia. *Weather and Climate Extremes* **25**: https://doi.org/10.1016/j.wace.2019.100210.

Ashcroft, L., Karoly, D. J. and Gergis, J. (2014b). Southeastern Australian climate variability 1860–2009: a multivariate analysis. *International Journal of Climatology* **34** (6): 1928–1944.

Bates, B. C., Hope, P., Ryan, B., Smith, I. and Charles, S. (2008). Key findings from the Indian Ocean Climate Initiative and their impact on policy development in Australia. *Climatic Change* **89** (3): 339-354.

Brönnimann, S., Allan, R., Ashcroft, L., Baer, S., Barriendos, M., Brázdil, R., Brugnara, Y., Brunet, M., Brunetti, M., Chimani, B., Cornes, R., Domínguez-Castro, F., Filipiak, J., Founda, D., Herrera, R. G., Gergis, J., Grab, S., Hannak, L., Huhtamaa, H., Jacobsen, K. S., Jones, P., Jourdain, S., Kiss, A., Lin, K. E., Lorrey, A., Lundstad, E., Luterbacher, J., Mauelshagen, F., Maugeri, M., Maughan, N., Moberg, A., Neukom, R., Nicholson, S., Noone, S., Nordli, Ø., Ólafsdóttir, K. B., Pearce, P. R., Pfister, L., Pribyl, K., Przybylak, R., Pudmenzky, C., Rasol, D., Reichenbach, D., Řezníčková, L., Rodrigo, F. S., Rohr, C., Skrynyk, O., Slonosky, V., Thorne, P., Valente, M. A., Vaquero, J. M., Westcottt, N. E., Williamson, F. and Wyszyński, P. (2020). Unlocking pre-1850 instrumental meteorological records: A global inventory. *Bulletin of the American Meteorological Society*: https://doi.org/10.1175/BAMS-D-19-0040.1.

Author Manuscript

Brönnimann, S., Martius, O., Rohr, C., Bresch, D. N. and Lin, K.-H. E. (2019). Historical weather data for climate risk assessment. *Annals of the New York Academy of Sciences* **1436** (1): 121-137.

Bureau of Meteorology (2008). *Climate of Australia*, Bureau of Meteorology, Melbourne, Australia, 214pp.

Bureau of Meteorology (2017). Perth: Geographic information, Australian Bureau of Meteorology, Accessed at: http://www.bom.gov.au/water/nwa/2017/perth/regiondescription/geographicinformation.shtml.

Bureau of Meteorology and CSIRO (2020). State of the Climate 2020. Australian Bureau of Meteorology, Melbourne, Australia. Accessed at: http://www.bom.gov.au/state-of-the-climate/.

Cai, W. and Cowan, T. (2006). SAM and regional rainfall in IPCC AR4 models: Can anthropogenic forcing account for southwest Western Australian winter rainfall reduction? *Geophysical Research Letters* **33** (24).

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., Gleason, B. E., Vose, R. S., Rutledge, G., Bessemoulin, P., Brönnimann, S., Brunet, M., Crouthamel, R. I., Grant, A. N., Groisman, P. Y., Jones, P. D., Kruk, M. C., Kruger, A. C., Marshall, G. J., Maugeri, M., Mok, H. Y., Nordli, Ø., Ross, T. F., Trigo, R. M., Wang, X. L., Woodruff, S. D. and Worley, S. J. (2011). The Twentieth Century Reanalysis Project. *Quarterly Journal of the Royal Meteorological Society* **137** (654): 1-28.

Cooke, W. E. (1901). *The climate of Western Australia from meterological observtions made during the years of 1876–1899*, W.M. Alfred Watson, Government Printer, Perth, Australia.

Copernicus Climate Change Service (2020). Copernicus Climate Change Service (C3S) Data Rescue Service, UK Met Office, Accessed at: https://datarescue.climate.copernicus.eu.

Cram, T. A., Compo, G. P., Yin, X., Allan, R. J., McColl, C., Vose, R. S., Whitaker, J. S., Matsui, N., Ashcroft, L., Auchmann, R., Bessemoulin, P., Brandsma, T., Brohan, P., Brunet, M., Comeaux, J., Crouthamel, R., Gleason, B. E., Groisman, P. Y., Hersbach, H., Jones, P. D., Jónsson, T., Jourdain, S., Kelly, G., Knapp, K. R., Kruger, A., Kubota, H., Lentini, G., Lorrey, A., Lott, N., Lubker, S. J., Luterbacher, J., Marshall, G. J., Maugeri, M., Mock, C. J., Mok, H. Y., Nordli, Ø., Rodwell, M. J., Ross, T. F., Schuster, D., Srnec, L., Valente, M. A., Vizi, Z., Wang, X. L., Westcott, N., Woollen, J. S. and Worley, S. J. (2015). The International Surface Pressure Databank version 2. *Geoscience Data Journal* **2** (1): 31-46.

Delworth, T. L. and Zeng, F. (2014). Regional rainfall decline in Australia attributed to anthropogenic greenhouse gases and ozone levels. *Nature Geoscience* **7** (8): 583-587.

Fenby, C. D. and Gergis, J. (2013). Rainfall variations in south-eastern Australia Part 1: consolidating evidence from pre-instrumental documentary sources, 1788–1860. *International Journal of Climatology* **33** (14): 2956-2972.

Gergis, J. and Ashcroft, L. (2013). Rainfall variations in south-eastern Australia Part 2: a comparison of documentary, early instrumental and palaeoclimate records, 1788–2008. *International Journal of Climatology* **33** (14): 2973–2987.

Author Manuscript

Gergis, J., Ashcroft, L. and Garden, D. (2018). Recent Developments in Australian Climate History. *The Palgrave Handbook of Climate History*. S. White, C. Pfister and F. Mauelshagen. London, Palgrave Macmillan UK**:** 237-245.

Gergis, J., Ashcroft, L. and Whetton, P. (2020). A historical perspective on Australian temperature extremes. *Climate Dynamics* **55**: 843–868.

Gergis, J. and Henley, B. J. (2017). Southern Hemisphere rainfall variability over the past 200 years. *Climate Dynamics* **48** (7): 2087-2105.

Hirsch, A. L., Evans, J. P., Di Virgilio, G., Perkins-Kirkpatrick, S. E., Argüeso, D., Pitman, A. J., Carouge, C. C., Kala, J., Andrys, J., Petrelli, P. and Rockel, B. (2019). Amplification of Australian Heatwaves via Local Land-Atmosphere Coupling. *Journal of Geophysical Research: Atmospheres* **124** (24): 13625-13647.

Hope, P., Grose, M. R., Timbal, B., Dowdy, A. J., Bhend, J., Katzfey, J. J., Bedin, T., Wilson, L. and Whetton, P. H. (2015). Seasonal and regional signature of the projected southern Australian rainfall reduction. *Australian Meteorological and Oceanographic Journal* **65** (1): 54-71.

Hope, P. K. (2006). Projected future changes in synoptic systems influencing southwest Western Australia. *Climate Dynamics* **26** (7): 765-780.

Hope, P. K., Drosdowsky, W. and Nicholls, N. (2006). Shifts in the synoptic systems influencing southwest Western Australia. *Climate Dynamics* **26** (7): 751-764.

Larsen, S. and Nicholls, N. (2009). Southern Australian rainfall and the subtropical ridge: Variations, interrelationships, and trends. *Geophysical Research Letters* **36** (L08708): DOI: 10.1029/2009GL037786.

Lorrey, A. M. and Chappell, P. R. (2016). The "dirty weather" diaries of Reverend Richard Davis: insights about early colonial-era meteorology and climate variability for northern New Zealand, 1839–1851. *Climates of the Past* **12** (2): 553-573.

Nash, D. J. and Adamson, G. C. D. (2014). Recent Advances in the Historical Climatology of the Tropics and Subtropics. *Bulletin of the American Meteorological Society* **95** (1): 131-146.

National Archives of Australia (2020). Meteorological observations, Swan River Settlement Area (Series PP430/1). National Archives of Australia, Accessed at: https://www.naa.gov.au.

National Library of Australia (2020). Trove Digitised Newspapers. National Library of Australia, Accessed at: http://trove.nla.gov.au/newspaper/.

Nguyen, H., Lucas, C., Evans, A., Timbal, B. and Hanson, L. (2015). Expansion of the Southern Hemisphere Hadley Cell in Response to Greenhouse Gas Forcing. *Journal of Climate* **28** (20): 8067-8077.

Nicholls, N. (2010). Local and remote causes of the southern Australian autumn-winter rainfall decline, 1958–2007. *Climate Dynamics* (34,): 835–845.

Author Manuscript

Nicholls, N., Tapp, R., Burrows, K. and Richards, D. (1996). Historical thermometer exposures in Australia. *International Journal of Climatology* **16**: 705-710.

O'Donnell, A. J., Cook, E. R., Palmer, J. G., Turney, C. S. M. and Grierson, P. F. (2018). Potential for tree rings to reveal spatial patterns of past drought variability across western Australia. *Environmental Research Letters* **13** (2): 024020.

Peterson, T. C., Easterling, D. R., Karl, T. R., Groisman, P., Nicholls, N., Plummer, N., Torok, S., Auer, I., Boehm, R., Gullett, D., Vincent, L., Heino, R., Tuomenvirta, H., Mestre, O., Szentimrey, T., Salinger, J., Førland, E. J., Hanssen-Bauer, I., Alexandersson, H., Jones, P. and Parker, D. (1998). Homogeneity adjustments of in situ atmospheric climate data: a review. *International Journal of Climatology* **18** (13): 1493-1517.

Petrone, K. C., Hughes, J. D., Van Niel, T. G. and Silberstein, R. P. (2010). Streamflow decline in southwestern Australia, 1950–2008. *Geophysical Research Letters* **37** (11).

Pezza, A. B., van Rensch, P. and Cai, W. (2012). Severe heat waves in Southern Australia: synoptic climatology and large scale connections. *Climate Dynamics* **38** (1): 209-224.

Picas, J. and Grab, S. (2020). Potential impacts of major nineteenth century volcanic eruptions on temperature over Cape Town, South Africa: 1834–1899. *Climatic Change*.

Picas, J., Grab, S. and Allan, R. (2019). A 19th century daily surface pressure series for the Southwestern Cape region of South Africa: 1834–1899. *International Journal of Climatology* **39** (3): 1404-1414.

Pook, M. J., Risbey, J. S. and McIntosh, P. C. (2011). The Synoptic Climatology of Cool-Season Rainfall in the Central Wheatbelt of Western Australia. *Monthly Weather Review* **140** (1): 28-43.

Risbey, J. S., Pook, M. J., McIntosh, P. C., Wheeler, M. C. and Hendon, H. H. (2009). On the remote drivers of rainfall variability in Australia. *Monthly Weather Review* **137**: 3233-3253.

Slivinski, L. C., Compo, G. P., Sardeshmukh, P. D., Whitaker, J. S., McColl, C., Allan, R. J., Brohan, P., Yin, X., Smith, C. A., Spencer, L. J., Vose, R. S., Rohrer, M., Conroy, R. P., Schuster, D. C., Kennedy, J. J., Ashcroft, L., Bronnimann, S., Brunet, M., Camuffo, D., Cornes, R., Cram, T. A., Dominguez-Castro, F., Freeman, J. E., Gergis, J., Hawkins, E., Jones, P. D., Kubota, H., Lee, T. C., Lorrey, A. M., Luterbacher, J., Mock, C. J., Przybylak, R. K., Pudmenzky, C., Slonosky, V. C., Tinz, B., Trewin, B., Wang, X. L., Wilkinson, C., Wood, K. and Wyszynski, P. (2021). An evaluation of the performance of the 20th Century Reanalysis version 3. *Journal of Climate*: DOI: 10.1175/JCLI-D-20-0505.1.

Slivinski, L. C., Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Giese, B. S., McColl, C., Allan, R., Yin, X., Vose, R., Titchner, H., Kennedy, J., Spencer, L. J., Ashcroft, L., Brönnimann, S., Brunet, M., Camuffo, D., Cornes, R., Cram, T. A., Crouthamel, R., Domínguez-Castro, F., Freeman, J. E., Gergis, J., Hawkins, E., Jones, P. D., Jourdain, S., Kaplan, A., Kubota, H., Le Blancq, F., Lee, T.-C., Lorrey, A., Luterbacher, J., Maugeri, M., Mock, C. J., Moore, G. W. K., Przybylak, R., Pudmenzky, C., Reason, C., Slonosky, V. C., Smith, C., Tinz, B., Trewin, B., Valente, M. A., Wang, X. L., Wilkinson, C., Wood, K. and Wyszyn'ski, P. (2019). Towards a more reliable historical reanalysis:

Author Manuscript

Improvements for version 3 of the Twentieth Century Reanalysis system. *Quarterly Journal of the Royal Meteorological Society*: https://doi.org/10.1002/qj.3598.

Smith, I. and Power, S. (2014). Past and future changes to inflows into Perth (Western Australia) dams. *Journal of Hydrology: Regional Studies* **2**: 84-96.

Smith, I. N. and Timbal, B. (2012). Links between tropical indices and southern Australian rainfall. *International Journal of Climatology* **32** (1): 33-40.

Timbal, B., Arblaster, J. M. and Power, S. (2006). Attribution of the Late-Twentieth-Century Rainfall Decline in Southwest Australia. *Journal of Climate* **19** (10): 2046-2062.

Trewin, B. (2010). Exposure, instrumentation, and observing practice effects on land temperature measurements. *Wiley Interdisciplinary Reviews: Climate Change* **1** (4): 490–506.

Trewin, B. (2018). Bureau Research Report No. 032. The Australian Climate Observations Reference Network – Surface Air Temperature (ACORN-SAT) version 2. Australian Bureau of Meteorology. 67pp.

Venema, V. K. C., Mestre, O., Aguilar, E., Auer, I., Guijarro, J. A., Domonkos, P., Vertacnik, G., Szentimrey, T., Stepanek, P., Zahradnicek, P., Viarre, J., Müller-Westermeier, G., Lakatos, M., Williams, C. N., Menne, M. J., Lindau, R., Rasol, D., Rustemeier, E., Kolokythas, K., Marinova, T., Andresen, L., Acquaotta, F., Fratianni, S., Cheval, S., Klancar, M., Brunetti, M., Gruber, C., Prohom Duran, M., Likso, T., Esteban, P. and Brandsma, T. (2012). Benchmarking homogenization algorithms for monthly data. *Clim. Past* **8** (1): 89-115.

Vincent, L. A., Wang, X. L., Milewska, E. J., Wan, H., Yang, F. and Swail, V. (2012). A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis. *Journal of Geophysical Research: Atmospheres* **117** (D18).

Viney, N. R. and Bates, B. C. (2004). It never rains on Sunday: the prevalence and implications of untagged multi-day rainfall accumulations in the Australian high quality data set. *International Journal of Climatology* **24** (9): 1171-1192.

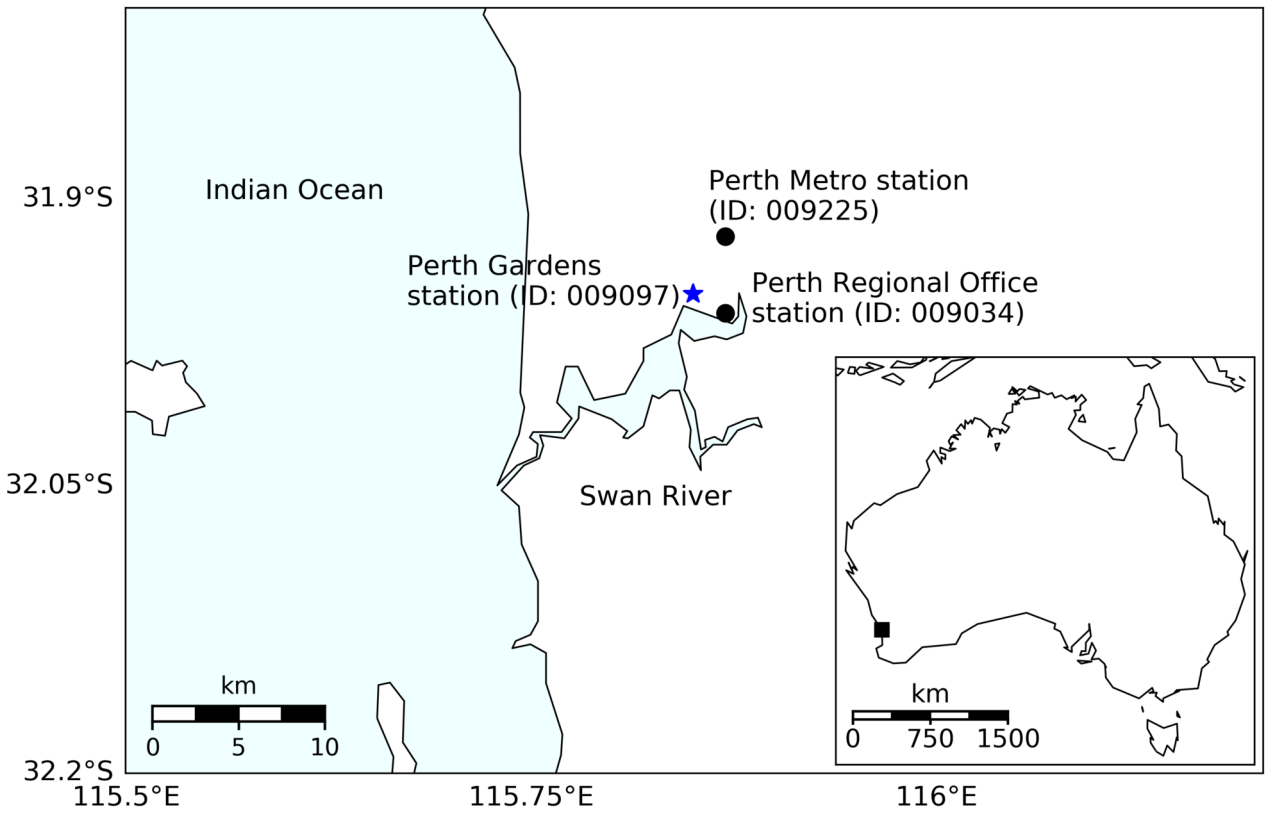
Wang, X. L. (2008a). Accounting for Autocorrelation in Detecting Mean Shifts in Climate Data Series Using the Penalized Maximal t or F Test. *Journal of Applied Meteorology and Climatology* **47** (9): 2423-2444.

Wang, X. L. (2008b). Penalized Maximal F Test for Detecting Undocumented Mean Shift without Trend Change. *Journal of Atmospheric and Oceanic Technology* **25** (3): 368-384.

Wang, X. L., Chen, H., Wu, Y., Feng, Y. and Pu, Q. (2010). New Techniques for the Detection and Adjustment of Shifts in Daily Precipitation Data Series. *Journal of Applied Meteorology and Climatology* **49** (12): 2416-2436.

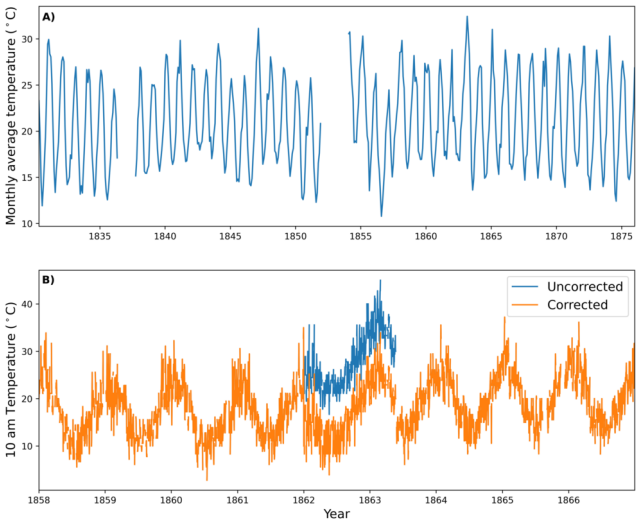
Wang, X. L. and Feng, Y. (2013). RHtestsV4 User Manual. Atmospheric Science and Technology Directorate, Science and Technology Branch, Environment Canada, Toronto. 29 pp., Accessed at: http://etccdi.pacificclimate.org/software.shtml.

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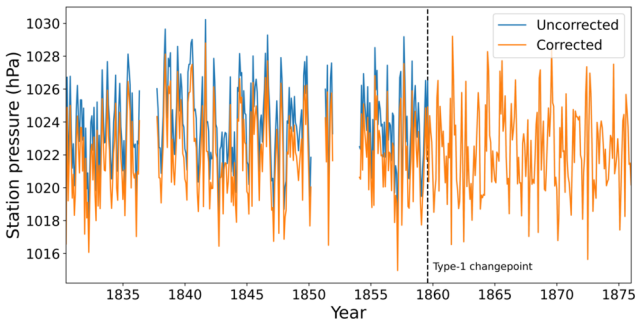
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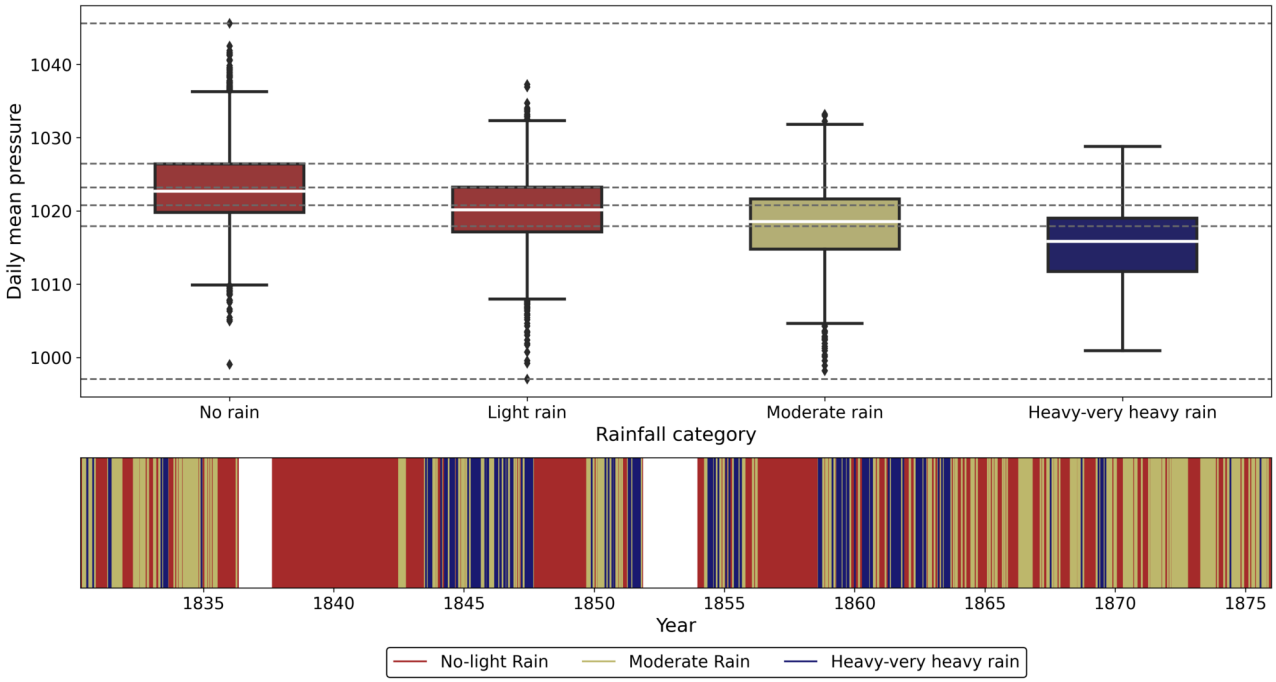
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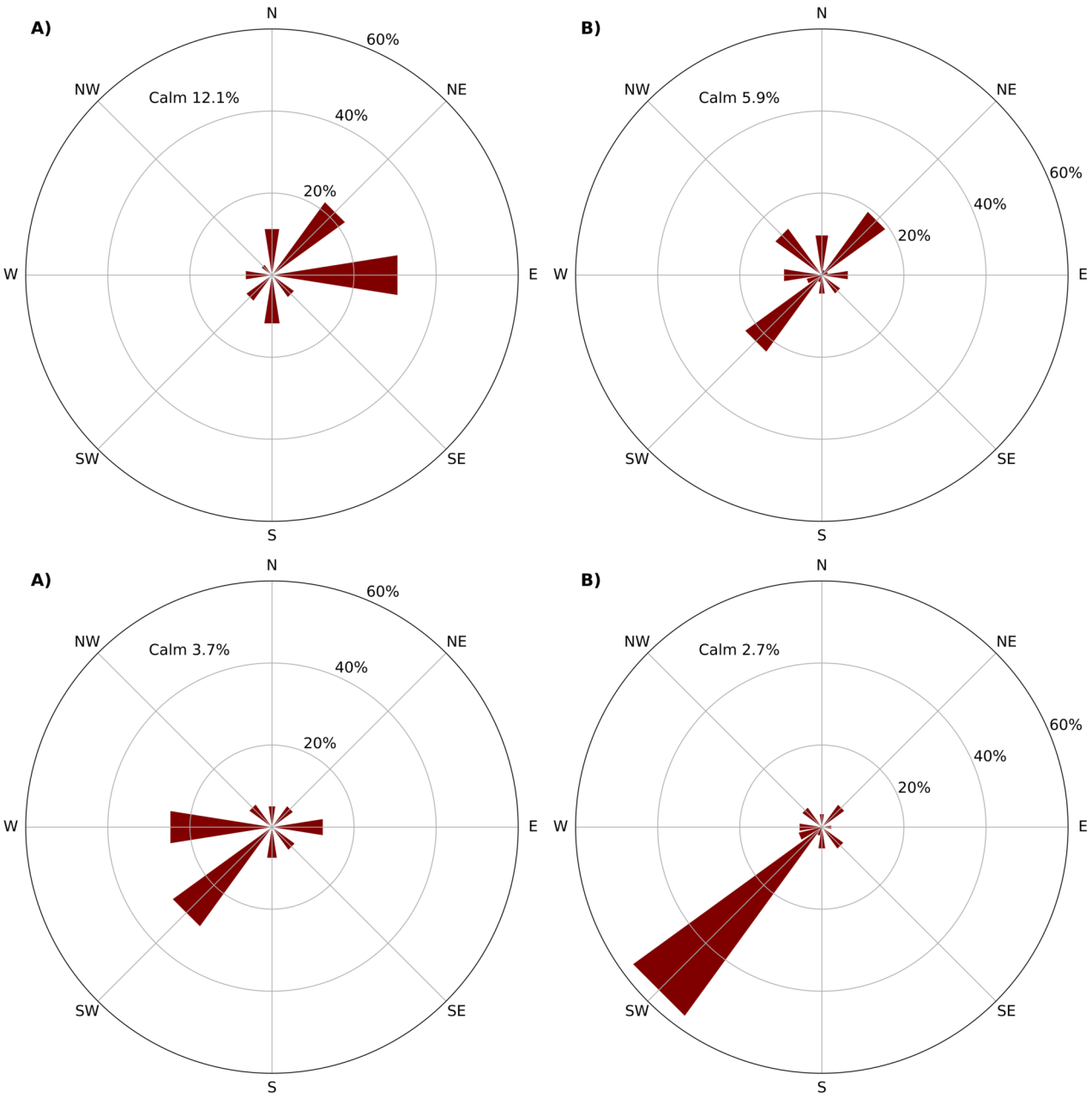
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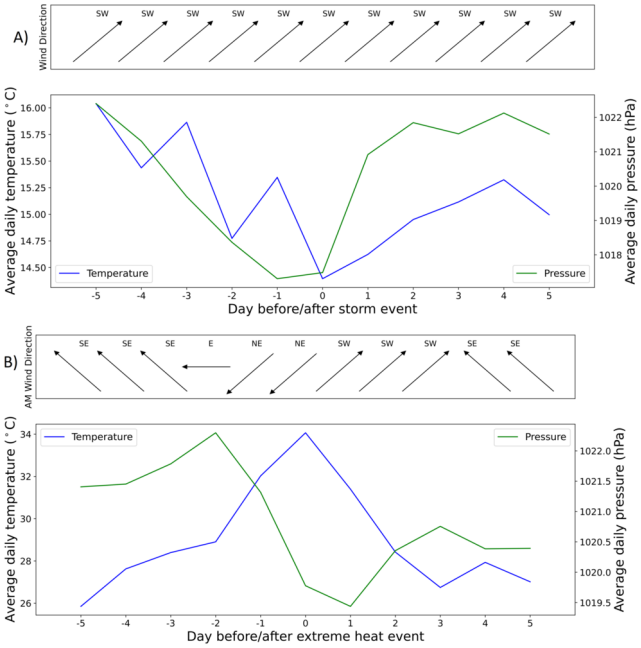
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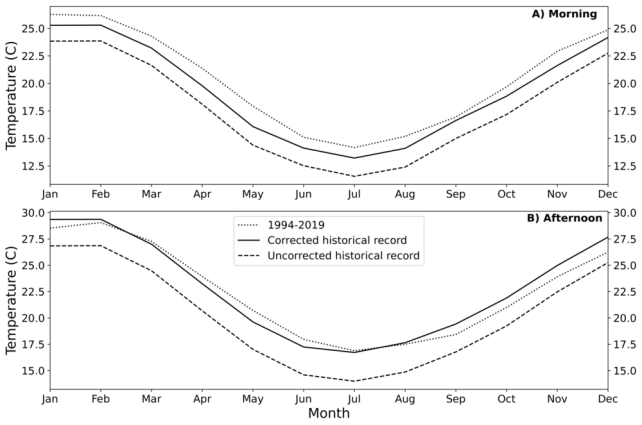
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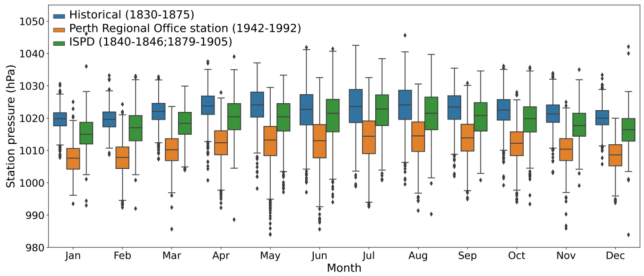
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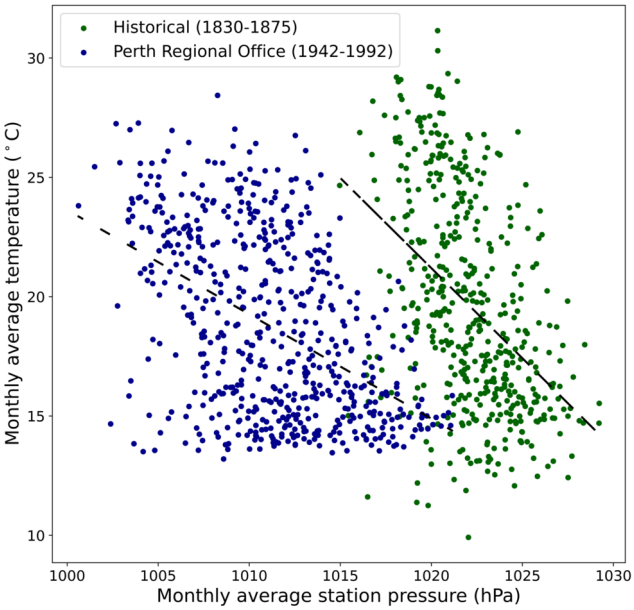
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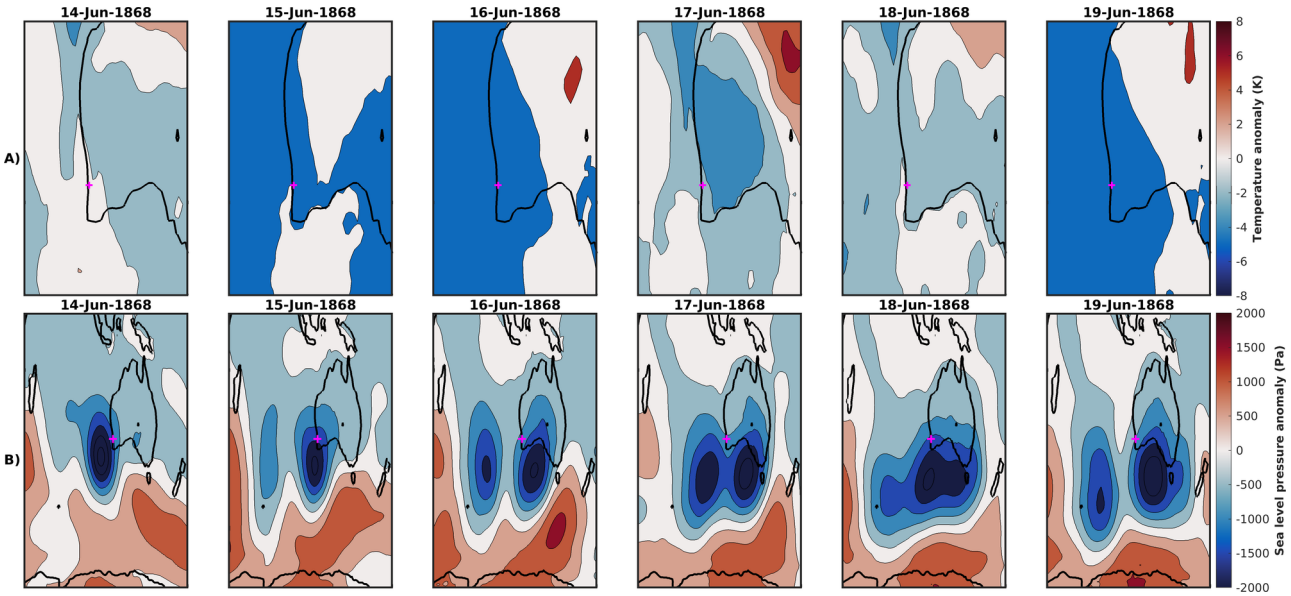
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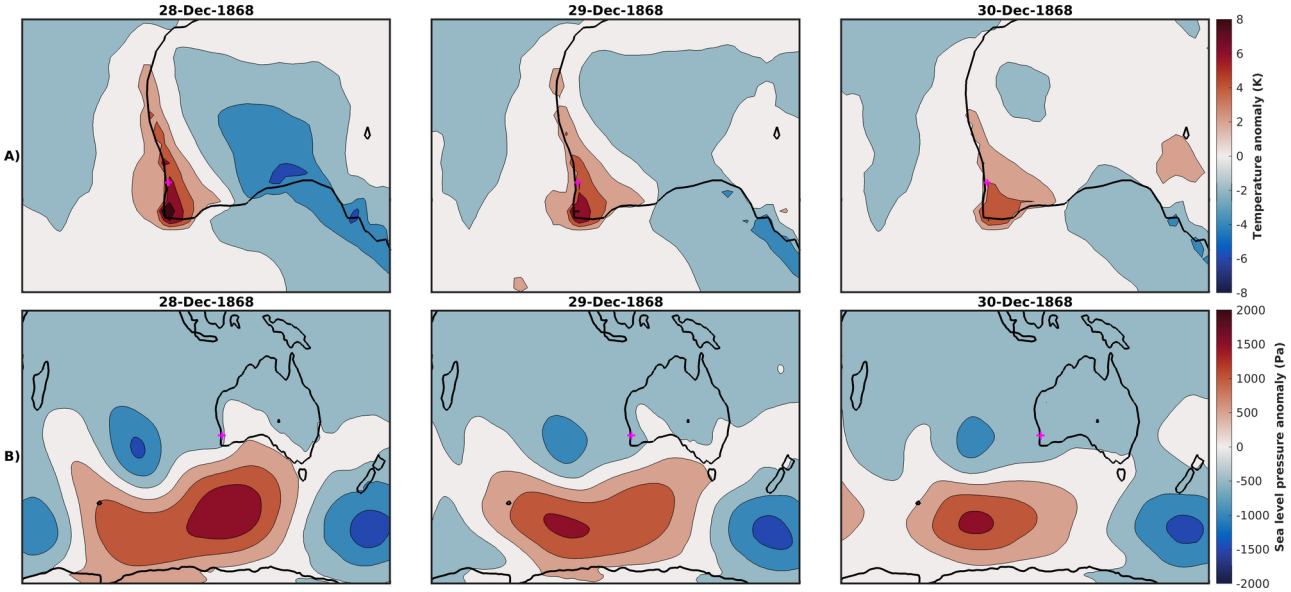
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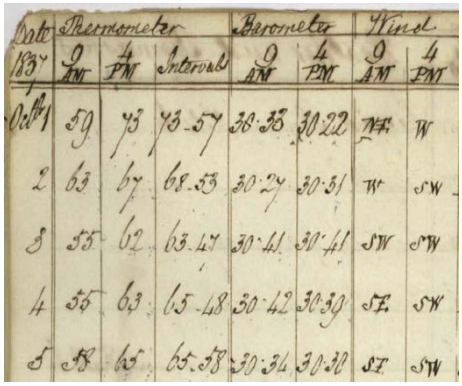
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A historical climate dataset for southwestern Australia, 1830–1875

Joëlle Gergis*, Zak Baillie, Stefan Ingallina, Linden Ashcroft and Tessa Ellwood

Southwestern Australia has experienced detectable anthropogenic climate change since 1970. Here we introduce the first long-term historical instrumental record to be developed for southwestern Australia; an important region for observing pre-industrial Indian and Southern Ocean variability and extremes. The new record from Perth provides 19th century data from a data sparse region of the Southern Hemisphere that can now be compared with daily observations from South Africa, New Zealand and southeastern Australia, improving hemispheric estimates of pre-industrial climate variability.



Date 183?	Thermometer 9 AM	Thermometer 4 PM	Thermometer Intervals	Barometer 9 AM	Barometer 4 PM	Wind 9 AM	Wind 4 PM
Oct 1	59	73	73-57	30·35	30·22	NE	W
2	63	67	68-53	30·24	30·31	W	SW
3	55	62	63-47	30·41	30·41	SW	SW
4	56	63	65-48	30·42	30·39	SE	SW
5	58	65	65-38	30·34	30·30	SE	SW

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Table 1. Data coverage of the sixteen volumes of handwritten weather journals from the Swan River colonial settlement in Perth (National Archives of Australia Series PP430/1) spanning April 1830– December 1875. Details of the date range and the most frequent morning and afternoon observing times on weekdays as measured at the Survey Office and Colonial Hospital. Note that the 'interval sets' are thought to be the approximate range of daily maxima and minima temperature observations.

Journal Number	**Start**	**End**	**Morning Observation**	**Afternoon Observation**	**Interval Sets**
Survey Office (Original)					
1	April 1830	May 1833	9am then 10am	3pm then 4pm	1
2	June 1833	April 1836	10am then 9am	3pm then 4pm	1
5	June 1843	August 1845	10am	4pm	2
6	August 1845	August 1847	10am	4pm	2
8	September 1849	November 1851	10am	4pm	2
9	January 1854	April 1856	10am	4pm	2
10	April 1856	August 1858	10am	4pm	2
11	August 1858	April 1861	10am	4pm	2
12	April 1861	July 1863	10am	4pm	2
13	July 1863	February 1866	10am	4pm	0
14	February 1866	October 1869	10am	4pm	0
15	October 1869	May 1874	10am	4pm	0
16	May 1874	December 1875	10am	4pm	0
Survey Office (Transcribed)					
4	September 1837	December 1844	9am then 10am	4pm	1
7	January 1845	February 1850	10am	4pm	1
Colonial Hospital					
3	July 1842	September 1842	9am	3pm	0

Table 2. A list of the quality control checks that the UQC automatic quality control software conducted on the historical temperature record. The software is available at: http://www.c3.urv.cat/softdata.php

UQC test	Description
Date order check	Check for errors in calendar date order
Data repetitions	Check for duplication of entire months
Impossible values	Check for values which are physically impossible
Duplicate values	Flag instances of at least 10 consecutive duplicate values
Monthly mean of absolute increments	Flag months which contained increments above the climatic normal
Unexpected distribution	Flag months whose distributions include a second peak
Climatic outliers	Check for values that are beyond the climatic normal
Sudden changes	Flag values which are significantly different to adjacent values

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Table 3. Correlation between pressure and temperature observations in historical (1830–1875) and modern Perth observations (Perth Regional Office station (1942–1992; ID: 009034)). Statistically significant correlations (p value <0.05, significant using the Student's two-tailed t test) are marked in bold.

Data source	**Summer (Dec –Feb)**	**Autumn (Mar–May)**	**Winter (Jun–Aug)**	**Spring (Sep–Nov)**	**Annual (Jan–Dec)**
Perth Regional Office meteorological station (1942–1992)	-0.06	**-0.20**	0.11	**-0.24**	**-0.48**
Historical Perth record (1830–1875)	-0.06	**-0.29**	0.06	**-0.25**	**-0.44**

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Table 4. Newspaper accounts of the significant storm event in Perth, 14–19 June 1868. Data accessed from the National Library of Australia's Trove newspaper database (National Library of Australia, 2020).

Date	Source	Comments
17-06-1868	The Inquirer and Commercial News (Perth, WA: 1855-1901) p.3 Guildford (WA).	'The weather has been very unsettled, but quite suitable for the farmers and graziers. The early crops are making great progress and give general satisfaction to all.'
17-06-1868	The Inquirer and Commercial News (Perth, WA: 1855-1901) p.3, Fremantle.	'For the last four days the weather has gradually become more and more unfavourable for discharging vessels in the harbour. To-day the Sea Spray was driven ashore, and it is expected that this evening and night will witness other vessels in a similar strait. Monday evening, June 15. The Albert is ashore this morning, and some damage is done to the Watering Jetty. The other vessels are riding safely so far. The gale still continues, but not so violently.'
19-06-1868	The Perth Gazette and West Australian Times (WA: 1864-1874) p. 3 Events of the Month.	'A very heavy fall of rain occurred in Perth on the evening and night of Monday last, which from appearances we should suppose also extended far inland as well as along the coast. The rain gauge on Tuesday Morning returned rather more than an inch and a quarter.'
19-06-1868	The Perth Gazette and West Australian Times (WA: 1864-1874) p.2 Summary for the Mail.	'We have excellent intelligence from the North Settlement, more generally known as Nicol Bay, where so far as the country is concerned all fears had been set at rest by abundant falls of rain, which speedily caused the earth to put on a green livery; the lambing had been very good, and for the first time since the country has been occupied, it was hoped to shear a clean clip of wool, free of dust and grass seeds…And on the night of the 13th the wind began to rise and continued until it settled into a heavy gale from the N.W., which lasted until the afternoon of the 17th when it moderated at W. by S. and the barometer rose again as high as 30-10, but as before only maintained its position for a few hours and again fell to 29-70, the wind veering round to N.W. blowing in heavy squalls yesterday morning.'
24-06-1868	The Inquirer and Commercial News (Perth, WA: 1855-1903) p.3 York (WA).	'…Weather for the last week or ten days has been very wet and stormy; the glass some few days ago was lower than it has been for many years, and it is generally thought we shall have a severe winter. Lambing and ploughing, the all-engaging topics of the day, are nearly over, and both alike promise to be conducive of good results for the future. The average drop of lambs is estimated at from 95 to 98 per 100 ewes. This is undoubtedly an exceptional yield, and has, coupled with the favourable accounts by last mail of the home wool market, roused the sheep owners from the fit of despondency into which they had, through recent disasters, given way… Unfortunately, the weather was unfavourable…'
10-07-1868	The Perth Gazette and West Australian Times (WA:1864-1874) p.2 Register of Temperature at Leschenault near Bunbury from 1st to 30th June 1868.	'Register of Temperature at Leschenauult near Bunbury from 1st to 30th June 1868. Maximum rainfall in 12 hours – night of 14th….3 inch 3-10ths.'

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Table 5. Newspaper accounts of the significant storm event in Perth, 14–19 June 1868. Newspaper accounts of the heatwave event in Perth 28–30 December 1868. Data accessed from the National Library of Australia's Trove newspaper database (National Library of Australia, 2020).

Date	Source	Comments
30-12-1868	The inquirer and Commercial News (Perth, WA: 1855-1901) p.3 Local and General News.	'The weather for the last week has been extremely hot, land winds prevailing, scarcely any change.'
02-01-1869	The Herald (Fremantle, WA: 1867-1886) p.3, The Weather.	'The weather has been strangely irregular for this season of the year. In the early part of the month, it was unreasonably cool, but quite suddenly it changed and the weather has for the last week been intensely hot.'
06-01-1869	The Inquirer and Commercial News (Perth, WA 1855-1901) p.3, York.	'The weather for the past ten days has been intensely hot, and the thermometer on Wednesday last' (30-12-1868), 'Stood at 100 degrees in a (comparatively speaking) cool room. Bushfires are also making their dreaded appearance in many directions; a very large one broke out a few days ago near Mr. Warton's Beverley, finding its way into that gentleman's field of corn, about 20 acres, totally destroying the whole.'
06-01-1869	The Inquirer and Commercial News (Perth, WA: 1855-1901) p.3, Events of the Month.	'The weather has been oppressively hot.'