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ORIGINAL ARTICLE

A severe winter storm record for southwestern Australia, 1830–2024

Joëlle Gergis[1,2] · Jarrad Rowe[1,2] · Linden Ashcroft[1] · Zak Baillie[2] · Blair Trewin[3] · Rob J. Allan[4] · Tessa Ellwood[2] · Stefan Ingallina[3]

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Abstract
This study describes the development of the longest sub-daily pressure record available from Australia and the Southern Hemisphere. We present newly consolidated mean sea level pressure observations for Perth in southwestern Australia, spanning 1830–2024. After establishing the quality of the new sub-daily pressure record, we evaluate its ability to resolve severe storms, verifying them against the synoptic fields generated by the 20th Century Reanalysis and independent historical records. We calculate a severe storm index for Perth using extreme pressure changes to assess any long-term changes in austral winter (June–August) storm activity back to 1830. Our results show a 20.2% decrease in the number of winter storms influencing Perth since 1970, with the decline further strengthening to 30.9% since 1990. The most recent decade (2010–2019) shows the lowest number of storms compared with any other decade since 1830. A supporting analysis of Perth rain days since 1830 displays considerable inter-annual variability and a notable reduction in winter rainfall since the 1970s. These results provide further evidence of a drying trend across southern Australia previously attributed to anthropogenically-influenced shifts in westerly storm tracks and changes in storm characteristics. We also identify a protracted dry period between 1830–1846 that is more pronounced than the current rainfall deficit. This analysis suggests that twentieth and twenty-first century weather observations do not capture the range of natural variability and extremes recorded in pre-industrial records, implying that future weather and climate risk is likely to be underestimated in the Australian region.

Keywords Australia · Perth · Historical climate · Extremes · Pressure · Severe storms

1 Introduction

Southern Australia is one of several regions in the Southern Hemisphere that has experienced long-term, anthropogenically-influenced drying trends since the late twentieth century (Douville et al. 2021). Southwest Western Australia (SWWA) has recorded a 20% decrease in winter (May–July) rainfall since 1970, with a 24% rainfall decline recorded since 1994 (Bureau of Meteorology and CSIRO 2024). This drying trend in SWWA has been attributed to a reduction in the frequency of near-surface rain-bearing systems on the northern edge of the mid-latitude storm track (e.g. Pepler et al. 2019, 2021, 2026), an increase in atmospheric surface pressure over Southern Australia (e.g. Allan and Haylock 1993; Shaw et al. 2024), the strengthening of the sub-tropical ridge (Timbal and Drosdowsky 2013), and a weakening of the potential for storm growth (Osbrough and Frederiksen 2021). Anthropogenic stratospheric ozone depletion and increased greenhouse gas concentrations have been implicated as the drivers of these changes (e.g. Arblaster and Meehl 2006; Hope et al. 2006; Timbal et al. 2006; Timbal and Drosdowsky 2013; Delworth and Zeng 2014; Rauniyar et al. 2023; Shaw et al. 2024).

Southern Australia is influenced by mid-latitude storm tracks where annual rainfall is dominated by the passage of rain-bearing fronts and cut off lows, particularly during

✉ Joëlle Gergis
jgergis@unimelb.edu.au

1 School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Melbourne, Australia

2 Fenner School of Environment and Society, Australian National University, Canberra, Australia

3 Bureau of Meteorology, Melbourne, Australia

4 Institute for Environmental Research and Sustainable Development, National Observatory of Athens, Athens, Greece

the May–October cool season (Hope et al. 2006; Pook et al. 2011; Pepler et al. 2021; Pepler 2024). To date, studies of changes in westerly storm tracks have been mostly confined to analyses beginning in the mid-twentieth century when most reanalysis datasets begin. Research focused on longer timescales are mostly confined to the North Atlantic region of the Northern Hemisphere where long-term station pressure observations are available (Alexander et al. 2010). In Australia, only a handful of studies have sought to develop sub-daily station-based pressure datasets to support the investigation of long-term changes in synoptic pressure conditions (Alexander and Power 2009; Alexander et al. 2010; Gergis et al. 2023). For example, Alexander et al. (2010) report a significant reduction in the rain-bearing systems affecting southern Australia since the beginning of the twentieth century, with synoptic patterns featuring a marked trough south of the mainland associated with reductions in severe storms in southeastern Australia, and rainfall declines in the four Australian cities of Sydney, Melbourne, Adelaide and Perth.

While monthly pressure records are generally available for many locations across Australia, and in gridded form back to 1850 through the HadSLP2 dataset (Allan and Ansell 2006) with relatively robust trends in the Australian region back to the late nineteenth century (Timbal and Hope 2008), there is a lack of digitised sub-daily pressure observations for the first half of the twentieth century, including all Australian capital cities except Darwin and Hobart (Gergis et al. 2023). Although previous data rescue efforts by the Bureau of Meteorology (BoM) were undertaken in the 2000s (Clarkson et al. 2001), this focused on stations which had substantial amounts of undigitised daily maximum and minimum temperature data, and therefore omitted most capital cities (whose daily temperatures were already digitised) as well as a substantial number of Western Australian stations whose daily temperature data had been digitised in a separate earlier project. As a result, sub-daily pressure observations for most Australian capital cities are not digitised prior to 1955, resulting in very few long-term stations with digitised sub-daily observations before that date, with even fewer extending into the nineteenth century (Alexander et al. 2010; Ashcroft et al. 2014; Gergis et al. 2023). Despite colonial-era weather records being available in undigitised paper format held by the National Archives of Australia as far back as the early-mid nineteenth century in capital cities like Adelaide and Perth (Gergis et al. 2023), the earliest sub-daily pressure observations available in digital format from the BoM are from the inland town of Deniliquin in western New South Wales starting in September 1859 (Bureau of Meteorology 2026a). Despite the best efforts of the Atmospheric Circulation Reconstructions over the Earth (ACRE) (https://www.met-acre.net/), ACRE MERIT (http://www.met-acre.net/MERIT/AMETA.html) and Climate History Australia (https://climatehistory.com.au), daily to sub-daily southern Australian lighthouse weather records from the mid to late nineteenth century are still at various stages of recovery, imaging, digitisation and quality control (Breaksea Island and Point King in Western Australia; Cape Borda, Cape Jaffa, Cape Martin, Corny Point, Tipara Reef, and Troubridge Shoal in South Australia; and Cape Wickham in Bass Strait).

Some of the longest, continuous sub-daily pressure observations from Australia are from the Cape Otway lighthouse on the southern coast of the state of Victoria beginning in 1865. Alexander and Power (2009) developed a severe storm index using these twice-daily in situ surface pressure observations available between 1865 and 2006 which showed a 40% decline in the annual number of severe storms since the mid-nineteenth century. They suggest that this decline in storminess could be due to a poleward shift in rain-bearing weather systems reaching southern Australia, noting the domination of systems associated with fluctuations in the Southern Annular Mode with a lesser influence of El Nino Southern–Oscillation (ENSO). While this significant decline in storminess is consistent with observational and climate modelling studies, they note that the results inferred from their pre-1907 analysis requires verification from other long-term pressure datasets.

This study presents the development of new, sub-daily pressure observations for Perth in southwestern Australia to provide a basis for further evaluating long-term changes in southern Australian weather and climate variability. Building off the data rescue efforts presented by Gergis et al. (2023), this study bridges the previously reported gap between nineteenth century sub-daily pressure observations and modern instrumental records available for Perth from the Bureau of Meteorology from 1942 (Gergis et al. 2023). We describe the development of a globally significant sub-daily pressure dataset from Perth beginning in 1830, which is currently the longest available sub-daily pressure record for Australia and the Southern Hemisphere (Picas et al. 2019; Gergis et al. 2023; World Meteorological Organization 2026).

We begin by outlining the quality control, homogenisation and adjustment processes required to develop a near-continuous mean sea level pressure (MSLP) dataset for Perth back to 1830. Next, we verify the quality of the new MSLP record from Perth using two lighthouse records from Cape Leeuwin and Cape Otway, an independently derived rain days index for Perth, and a tree-ring based rainfall reconstruction from Lake Tay in southwestern Australia (Fig. 1). Following Alexander and Power (2009), we develop a severe winter storm index for Perth and compare our results with those observed from Cape Otway in southeastern

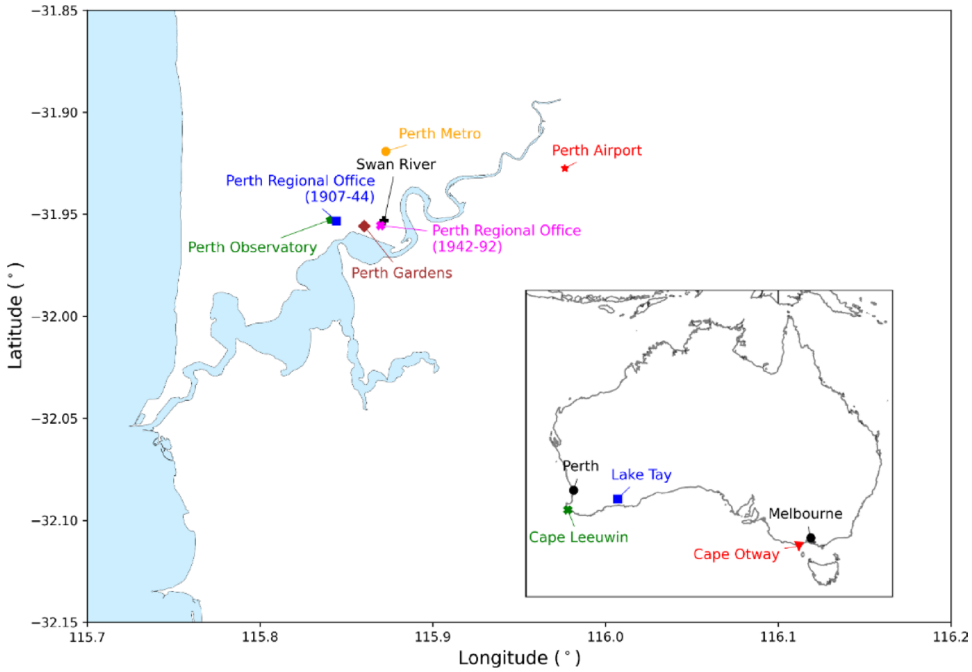


Fig. 1 Locations of historical and modern stations used to develop the long term mean sea level pressure (MSLP) record for Perth, Western Australia, from 1830–2024. Details of each station used in this study are provided in Table 1

Australia. We use the 20th Century Reanalysis data (Slivinski et al. 2021) and independent historical records (Hunt 1929; Benoy 2011; National Library of Australia 2026) to investigate case studies of severe storms identified in the newly recovered pressure observations from the previously missing 1909–1941 period (Gergis et al. 2023). Finally, we assess any long-term changes in austral winter storm activity influencing southwestern Australia since 1830. Although Aldridge and Christensen (2025) have identified several nineteenth century tropical cyclones for southwestern Australia, summer systems such as tropical cyclones are outside the scope of the current analysis focusing on trends in winter storms.

2 Data

2.1 Raw pressure observations for Perth, 1830–2024

Sub-daily pressure observations for Perth are available from the six stations seen in Fig. 1 and Table 1, with the earliest barometer readings recorded at the Swan River colonial settlement from May 1830 (Gergis et al. 2021). Historical pressure observations for the Swan River site were taken twice a day, with morning observations mostly read at 10:00 and afternoon readings at 16:00. Nonetheless, 09:00 and 15:00 observations are also present in some parts of the Swan River record, allowing comparison with the Perth Gardens (1880–1900), Perth Observatory (1897–1908), Perth Regional Office (1907–1992), Perth Airport (1944–2024) and Perth Metro (1994–2024) stations. The primary focus of the latest data recovery effort was to bridge the gap between sub-daily observations available from the Swan River, Perth Gardens and Perth Observatory sites consolidated by Gergis et al. (2023) before 1909, and the start of the BoM's digitised sub-daily pressure readings from 1942 for the Perth Regional Office (BoM Station number 009034). To do this, we conducted a major digitisation effort to recover sub-daily 'As Read' barometer readings, dry bulb temperature and attached thermometer readings for the Perth Regional Office registers contained in the National Archives of Australia K994 series between the years 1907 and 1944.

To consolidate the pressure observations into a single homogenised pressure record for Perth, a number of analytical processes outlined in Fig. S1 were applied to the dataset. To combine the newly digitised historical material with existing pressure observations for Perth, we recovered and compared two years of parallel observations in the overlapping periods from January 1907 to December 1908 with the Perth Observatory observations (Gergis et al. 2023) and April 1942 to March 1944 from the Perth Regional Office, in line with best practice (Trewin 2010). Note that the homogenisation of the Perth Gardens and Perth Observatory was possible due to the parallel observations available between the years 1897–1900 (Gergis et al. 2023). Unfortunately, a gap in the continuity of the sub-daily pressure record for Perth is still present from the end of the Swan River record in 1876 until the start of the Perth Gardens observations in 1880. Nevertheless, monthly observations are available from Perth Gardens during the four-year period between 1876–1879 (Cooke 1901), providing a continuous

Table 1 Summary of available historical pressure data for Perth, Western Australia, 1830–2024. Note that the newly-digitised Perth Regional Office dataset recovered for the 1907–1944 period is an extension of the Bureau of Meteorology's existing Perth Regional Office dataset (ID: 009034) previously only available digitally from 1942. In cases where clear metadata were not available, the Fortin Barometer constant was applied. Additionally, in cases where the cistern barometer type was unknown, an average of the constants of the Kew-Pattern and Fuess Cistern barometers was applied as recommended by the World Meteorological Organization (2024)

Pressure data availability for Perth, Western Australia, Australia										
Source	Origin	Latitude (°)	Longitude (°)	Barometer height (m)	Start	End	Barometer type	Temporal resolution	Observation times	Gaps
Swan River	National Archives of Australia (series number: PP430/1)	31° 57′ 11″ S	115° 52′ 19″ E	14.3	May 1830	Dec 1875	Fortin	Sub-daily	00:00, 06:00, 07:00, 08:00, 09:00, 10:00, 11:00, 12:00, 13:00, 14:00, 15:00, 16:00, 17:00, 18:00, 19:00, 20:00, 22:00	1836-04-28 to 1837-09-01, missing 491 days 1851-11-04 to 1854-01-01, missing 789 days
Perth Gardens (BoM Station Number: 009097)	National Archives of Australia (series number: PP430/2)	31° 57′ 11″ S 31° 57′ 11″ S 31° 57′ 21″ S	115° 52′ 20″ E 115° 52′ 20″ E 115° 51′ 37″ E	14.3 18 14.3	Jan 1880 Jan 1885 Jul 1887	Dec 1884 Jul 1887 Dec 1900	Kew Pattern Kew Pattern Kew Pattern	Sub-daily	07:00, 09:00, 12:00, 15:00	No gaps> =31 days
Perth Gardens Monthly (BoM Station Number: 009097)	Cooke (1901)	31° 57′ 11″ S 31° 57′ 11″ S 31° 57′ 21″ S	115° 52′ 20″ E 115° 52′ 20″ E 115° 51′ 37″ E	14.3 18 14.3	Jan 1876 Jan 1885 Jul 1887	Dec 1884 Jul 1887 Dec 1899	Kew Pattern Kew Pattern Kew Pattern	Monthly	09:00 and 15:00	No gaps> =1 month
Perth Observatory	Hathi Trust: https://babel.hathitrust.org/cgi/pt?id=uc1.c2999442	31° 57′ 10″ S	115° 50′ 26″ E	60	Jan 1897	Dec 1908	Fortin	Sub-daily	09:00, 15:00, 21:00	No gaps> =31 days
Perth Regional Office	National Archives of Australia (series number: K994)	31° 57′ 12″ S 31° 57′ 12″ S 31° 57′ 12″ S	115° 50′ 39″ E 115° 50′ 39″ E 115° 50′ 39″ E	60 64 64	Jan 1907 Apr 1942 Oct 1942	Mar 1942 Sep 1942 Mar 1944	Fortin Fortin Kew-Pattern	Sub-daily	09:00, 15:00, 21:00	No gaps> =31 days
Perth Regional Office (BoM Station Number: 009034)	Australian Bureau of Meteorology	31° 57′ 12″ S 31° 57′ 20″ S	115° 50′ 39″ E 115° 52′ 11″ E	64.9 19.5	Jan 1942 Jul 1967	Jun 1967 Apr 1992	Kew-Pattern Kew-Pattern	Sub-daily	00:00, 02:00, 03:00, 05:00, 06:00, 08:00, 09:00, 11:00, 12:00, 14:00, 15:00, 17:00, 18:00, 20:00, 21:00, 23:00	No gaps> =31 Days

Table 1 (continued)

Pressure data availability for Perth, Western Australia, Australia										
Perth Airport (BoM Station Number: 009021)	Australian Bureau of Meteorology	31° 56′ 29″ S 31° 56′ 29″ S 31° 56′ 29″ S 31° 56′ 29″ S 31° 56′ 29″ S 31° 55′ 43″ S 31° 55′ 39″ S 31° 55′ 39″ S 31° 55′ 39″ S 31° 55′ 39″ S	115° 57′ 55″ E 115° 57′ 55″ E 115° 57′ 55″ E 115° 57′ 55″ E 115° 57′ 55″ E 115° 58′ 30″ E 115° 58′ 35″ E 115° 58′ 35″ E 115° 58′ 35″ E 115° 58′ 35″ E	31 31 31 31 31 20.3 20 20 20 20	May 1944 Jul 1951 Jan 1990 Apr 1993 Jun 1994 Oct 1997 Oct 2003 Jun 2007 Feb 2012 Jan 2019	Jun 1951 Dec 1989 Mar 1993 Jun 1994 Oct 1997 Oct 2003 Jun 2007 Feb 2012 Jan 2019 Ongoing	Kew-Pattern Kew-Pattern-1983 Kew-Pattern-1948 Vaisala PA11A-561,174 Vaisala PA11A-R5110008 Vaisala PA11A-R5110008 Vaisala PA11A-R5110008 Vaisala PA11A-433,545 Vaisala PTB330B-G2970057 Vaisala PTB330B-J4030021	Sub-daily	00:00, 00:08, 00:27, 01:00, 02:00, 03:00, 03:02, 03:04, 03:08, 03:14, 04:00, 05:00, 06:00, 06:09, 06:10, 07:00, 08:00, 09:00, 09:03, 09:06, 09:12, 10:00, 10:21, 11:00, 11:35, 12:00, 12:09, 12:24, 13:00, 14:00, 15:00, 15:01, 15:05, 15:06, 15:08, 15:15, 16:00, 17:00, 18:00, 18:03, 19:00, 19:28, 20:00, 21:00, 21:03, 21:07, 21:10, 21:14, 22:00, 23:00	1944-06-27 to 1944-08-04, missing 39 days 1945-01-21 to 1945-04-04, missing 74 days 1945-04-29 to 1951-01-22, missing 2094 days 1951-02-05 to 1951-03-08, missing 31 days
Perth Metro (BoM Station Number: 009225)	Australian Bureau of Meteorology	31° 55′ 9″ S 31° 55′ 9″ S 31° 55′ 9″ S 31° 55′ 9″ S 31° 55′ 9″ S	115° 52′ 22″ E 115° 52′ 22″ E 115° 52′ 22″ E 115° 52′ 22″ E 115° 52′ 22″ E	25.4 25.4	Jan 1994 Dec 2007 Mar 2008 Jul 2011 Apr 2012	Dec 2007 Mar 2008 Jul 2011 Apr 2012 Ongoing	Vaisala PA11A-428,206 Vaisala PA11A-653,256 Vaisala PA11A-667,126 Vaisala PA11A-653,247 Vaisala PTB330B-G2970058	Sub-daily	00:00, 01:00, 02:00, 03:00, 04:00, 05:00, 06:00, 07:00, 08:00, 09:00, 10:00, 11:00, 12:00, 13:00, 14:00, 15:00, 16:00, 17:00, 18:00, 19:00, 20:00, 21:00, 22:00, 23:00	No gaps > = 31 days
Monthly Pressure Dataset by Fogt et al. (2016)	United States' University Corporation for Atmospheric Research (UCAR) research data archive data set ds570.0	N/A	N/A	N/A	Jan 1876	Dec 2018	N/A	Monthly	N/A	No gaps > = 1 month

monthly pressure record back to 1854, with only two minor gaps previously noted between 1836–1837 and 1851–1853 (Gergis et al. 2021, 2023).

2.2 Metadata for reducing pressure observations to mean sea level pressure

To develop a long-term mean sea level pressure (MSLP) record for Perth, it was necessary to convert the raw 'As Read' barometer readings using the method provided by the World Meteorological Organization (2024). An overview of this method is provided in Fig. S1. The guidelines recommend that 'As Read' barometer observations are calibrated to 0°C and reduced to sea level (World Meteorological Organization 2024). These calibrations aim to standardise the influence of temperature and elevation, allowing pressure observations across regions to be compared (World Meteorological Organization 2024). It is important to note that 'As Read' pressure readings are not the same as station pressure or MSLP. As noted in Fig. S1, height, latitude, barometer type and temperature are required to calculate station pressure from the uncorrected 'As Read' barometer readings before converting to MSLP. For a given record, height, latitude and the barometer type were treated as constants unless a specific change in observational practice was noted in the available metadata. All changes in observational elevation, location, or instrumentation are given in Table 1.

As detailed in the method provided by the World Meteorological Organization (2024), attached thermometer temperature observations (T_{att}) are preferred when converting station pressure readings into MSLP, as these observations are measured from a thermometer directly attached to the barometer. Unfortunately, attached thermometer readings are not always available in historical records. In these instances, standard dry bulb temperatures (T_{db}) for the Perth station were used in the reduction calculations instead. It should be noted, however, the barometer may have been placed in a different location to the dry bulb thermometer. Our analysis showed the Pearson's (r) correlation between the Perth Regional Office's T_{att} and T_{db} on a sub-daily level from 1907 to 1941 is strongly positive (r = 0.90 significant at the 99% level), implying that most of the variability captured by T_{att} throughout the day is also captured by T_{db}. The strong correlation also suggests that where T_{att} is unavailable for the calculation of MSLP, T_{db} is an acceptable substitution for the development of an extended MSLP record for Perth.

To investigate the influence of the attached thermometer values (T_{att}) and dry-bulb temperature values (T_{db}) on the derivation of MSLP, we used both datasets to reduce the pressure observations to MSLP between the years 1907 and 1941 when no statistical inhomogeneities influenced the dataset (Fig. S2). The influence of using T_{db} instead of T_{att} is most pronounced during the summer months where the difference in MSLP calculated using T_{att} or T_{db} can be more than 1hPa on average during the day (Fig. S2). However, given we are exploring winter storms, this difference has minimal impact on the current study.

Analysis of the available metadata in Table 1 indicated that the type of barometer used for pressure readings varied over the 194 years of observations available for Perth. We identified the use of three analogue barometers (Fortin, Fixed Cistern Kew Pattern and Fixed Cistern Feuss) and two digital barometers (Vaisala PA11A and Vaisala PTB330B), with analogue readings used until 1993 before switching over to digital measurements. The Fortin and Fixed Cistern barometers used until the 1990s measure the distance between two mercury levels on the barometer to calculate the pressure in inches of Mercury (inHg) (World Meteorological Organization 2024). The Vaisala barometers are modern state-of-the-art digital barometers that register pressure with extreme accuracy and long-term stability, even under extreme changes in pressure (Vaisala 2024).

Alongside changes in instrumentation, shifts in observing locations that influenced factors such as elevation also needed to be determined and accounted for in the MSLP calculations (see Table 1). For example, the Swan River and Perth Gardens sites were located at approximately 14–18 m above sea level, in contrast to the Perth Observatory and Perth Regional Office (pre-1967) located at a higher elevation of approximately 60–65 m above sea level. Similarly, the Perth Airport site (BoM Station Number: 009021) is further inland than the coastal location of the current Perth Metro station (BoM Station Number: 009225). Given that the nineteenth century sites are in closer proximity to Perth Metro (see Fig. 1), this record was used as the reference station to develop the long MSLP record detailed in Sect. 4.

3 Data quality control and homogenisation

In preparation for the development of a long term, sub-daily pressure dataset for Perth, it was necessary to conduct thorough quality control and homogenisation processes on each of the individual records shown in Fig. 2 using the methods outlined in Fig. S1. Quality control (QC) is the process of flagging or adjusting weather observations to remove measurement errors in individual observations due to factors such as transcription errors or instrument faults, while homogenisation is aimed to remove non-climatic differences across or within datasets (Trewin et al. 2020; World Meteorological Organization 2024). Following the QC methods applied by Gergis et al. (2023) on the temperature and pressure datasets for Swan River, Perth Observatory and Perth

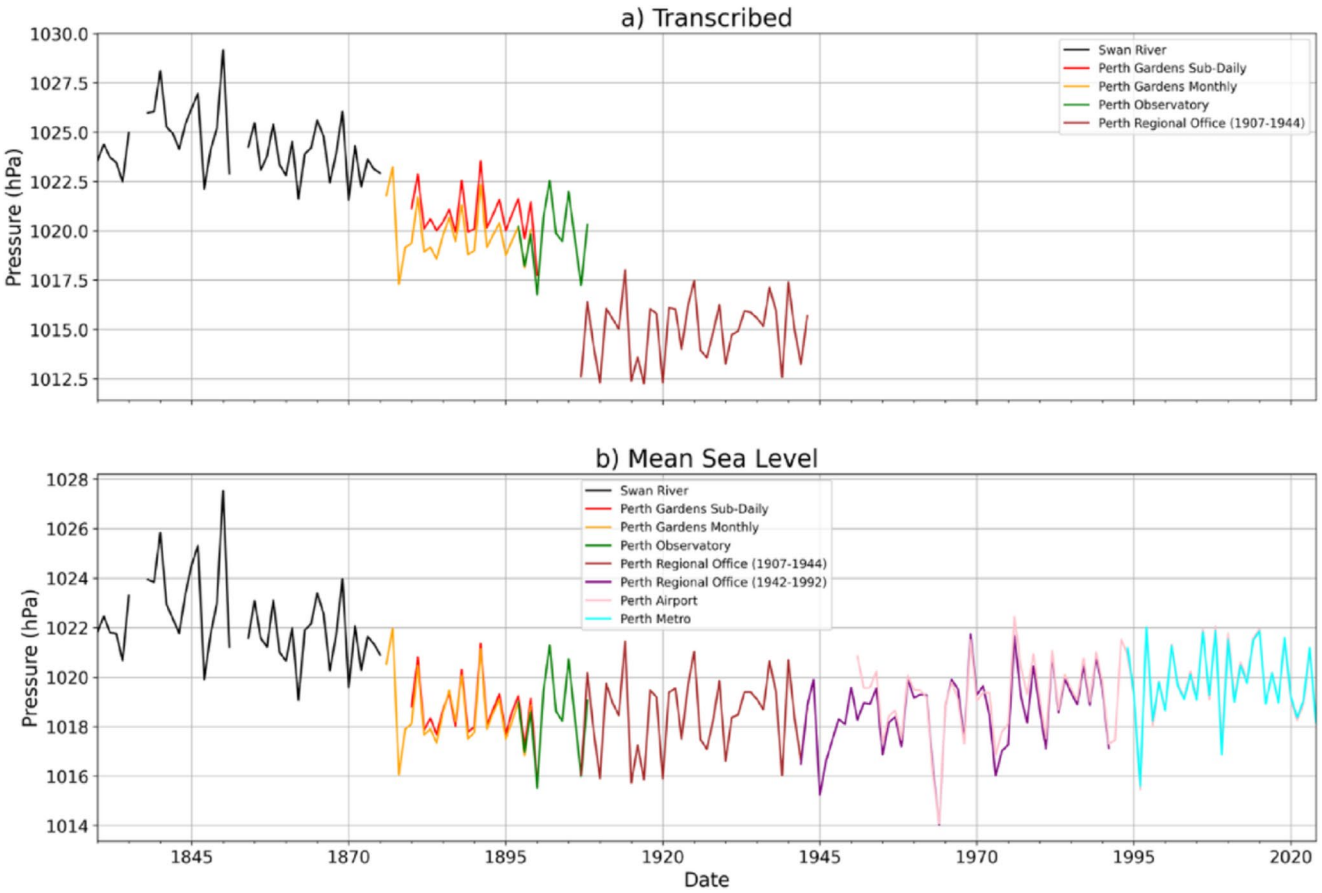


Fig. 2 Austral winter (June–August) averaged pressure (hPa) datasets used to develop the near-continuous, long-term pressure record for Perth from 1830–2024. a) 'As Read' transcribed pressure, b) shows the corrections by reducing the 'As Read' pressure to MSLP

Gardens observations, we applied the QC tools outlined in Table 2 to the newly-transcribed Perth Regional Office temperature and pressure datasets for the 1907–1944 period.

To identify transcription errors, we applied the University of Rovira i Virgili's C3 Centre for Climate Change Uncertainties in Ensembles of Regional Reanalysis Automatic Quality Control (C3-UERRA AQC) methods on Perth Regional Office's sub-daily pressure observations (Ashcroft et al. 2018; Gergis et al. 2023; C3 Centre for Climate Change 2024). This involved identifying, manually checking against original hand-written observations, and adjusting physically implausible outliers such as 150hPa readings, instances where ten or more identical values occurred successively, or significant outliers when sudden, possibly non-climatic jumps in pressure occurred. Out of the 120 potential errors identified in the transcribed Perth Regional Office sub-daily pressure record (see Table S1), 85% were associated with transcription errors and 15% were errors made by the original observer.

To combine the individual pressure records shown in Fig. 2, first we applied a Percentile-Matching (PM) algorithm used in the development of BoM's ACORN-SATv2 (Trewin 2013; Trewin et al. 2020). The PM algorithm outlined in Table 2 was applied to two-year overlapping periods of sub-daily pressure, generating a 5th to 95th percentile range which allowed the historical observations to be appropriately scaled to the distribution of modern records (Trewin et al. 2020). Pressure values that fell outside the 5th to 95th percentile range were subtracted or added to the tails of the corrected distribution, respectively (Trewin et al. 2020). For periods with no overlap with the modern record, we applied the simple mean adjustment scaling method detailed in Table 2 to allow a comparison of the historical observations to the modern record (see Fig. S1).

Next, historical pressure observations were homogenised using the RHTest software outlined in Table 2. The RHTest process checks for non-climatic shifts and inhomogeneities by applying quantile-matching adjustments and mean adjustments on the datasets to identify potential breakpoints in the record (Wang 2008a; 2008b; Wang et al. 2010; Vincent et al. 2012; Wang and Feng 2013; Gergis et al. 2023). To remove any non-climatic biases in the observations, we applied the penalized maximal F test and adjusted clear statistical breakpoints not supported by metadata (Type 1

Table 2 Methods used to assess statistical quality and homogeneity of historical pressure observations in this study

Name of method	Quality Control Description	Variables	Temporal resolution	Reference
UQC	Universal Quality Control software performing several quality control checks on the temperature sub-daily observations to identify non-climatic values	Temperature	Sub-daily	Ashcroft et al. (2018); Gergis et al. (2023); C3 Centre for Climate Change (2024)
SLP-snowQC	Sea-Level Pressure–Snow Quality Control performs several quality control checks on pressure sub-daily observations to identify non-climatic values	Pressure	Sub-daily	C3 Centre for Climate Change (2024)
Name of Method	**Homogenisation Description**	**Variables**	**Temporal resolution**	**Reference**
RHTest	Detects and adjusts sudden changes between distributions which may be non-climatic. To remove any non-climatic biases in the observations, the penalized maximal F test was used (Type 1). Changepoints that were clearly supported by the metadata were also adjusted (Type 0)	Pressure	Sub-daily, Monthly	Wang (2008a; 2008b); Wang et al. (2010); Vincent et al. (2012); Wang and Feng (2013); Gergis et al. (2023)
Percentile Matching (PM) Algorithm	Applied onto a 2-year overlapping period, generating a 5th to 95th percentile range which would adjust the historical record to a modern record. Any pressure values outside the 5th and 95th percentiles would be subtracted or added to the tails respectively	Pressure	Sub-daily, Monthly	Trewin (2013); Trewin et al. (2020)
Mean Adjustment Scaling Algorithm	The historical anomaly for each month is calculated by averaging sub-daily pressure values. To scale the historical observations to the modern record, we calculate the 30-year climatological mean for each month of the modern record. This value is then added to the sub-daily anomaly for any non-overlapping historical observations	Pressure	Sub-Daily, Monthly	This study
Name of Method	**Storm Identification Description**	**Variables**	**Temporal resolution**	**Reference**
Alexander and Power (2009)	Identifies large, abrupt pressure differences in pressure tendencies between 09:00 to 15:00 (6-Hour) and 15:00 to $09:00^{+1}$ (18-Hour) each day. Each tendency above (below) the 99th (1st) percentile is used to identify potential storms	Pressure	Sub-Daily	Alexander and Power (2009)

breakpoints) that did not fall within the distribution of the pressure observations. Type 0 breakpoints are those that were clearly supported by the metadata.

As seen in Fig. S1, the RHTest was first applied on the monthly average of each available sub-daily hour (e.g. the monthly 09:00 value) and then applied to the monthly-averaged dataset (e.g. the monthly average of all sub-daily observations) to further identify any genuine non-climatic shifts. When an inhomogeneity was flagged, we assessed all available metadata to identify whether the shift was likely to be non-climatic. If the shift was supported by metadata, such as a note in the original weather journal describing any changes in instrumentation or observational practices, the adjustment was applied to the sub-daily dataset using the monthly adjustment value for the corresponding observation time. Any shifts that were not supported by clear metadata were left uncorrected, as there was not enough evidence to confidently conclude they were inhomogeneities rather than part of the natural variability contained in the record.

4 Development of sub-daily MSLP record for Perth, 1830–2024

To develop a consolidated, long-term pressure record for Perth, it was necessary to convert the original 'As Read' barometers readings to mean sea level pressure (MSLP) observations using the standardised guidelines developed

by the World Meteorological Organization (2024). Table 1 outlines the metadata used to convert 'As Read' barometer readings to MSLP, with the key equations as follows:

$$B_1 = B_a + C_T \tag{1}$$

$$C_T = -0.000163 * (B_a + X) * T \tag{2}$$

where T is temperature (°C), B_a is 'As Read' pressure (hPa), B_1 is pressure corrected to temperature T (hPa), X is the adjustment made by the barometer type (Fortin = 0hPa, Cistern = 39hPa, Fuess Cistern = 31hPa and Kew-Pattern Cistern = 47hPa) and C_T is the pressure correction at temperature T (hPa) (World Meteorological Organization 2024). Once temperature was adjusted, we adjusted the gravity using the ratio in Eq. 3:

$$B_{Local} = B_1 * \left[\frac{G_{Local}}{G_{Average}}\right] \tag{3}$$

where B_{Local} is local pressure (hPa), B_1 is pressure corrected to temperature T (hPa), G_{Local} is local gravity (cms^{-2}), $G_{Average}$ is average gravity set to 980.665 cms^{-2} (World Meteorological Organization 2024). The pressure derived following the application of Eq. 3 was the local station pressure recorded at the latitude and height of the barometer. A final step converted the local pressure to MSLP as shown by Eq. 4:

$$B_{MSLP} = B_{Local} * e^{\left(\frac{H*9.81}{287*(T+273.15)}\right)} \tag{4}$$

where B_{MSLP} is Mean Sea Level Pressure (hPa), B_{Local} is local pressure (hPa), H is Height of the Barometer (m), T is temperature (°C) (World Meteorological Organization 2024).

When calculating MSLP, height and latitude are the most important variables in the adjustment as they impact the gravity component of Eqs. 3 and 4. Uncertainties in the elevation and latitude of historical observations or changes in instrumentation can influence the final MSLP calculation and lead to erroneous values. The impact of the type of temperature measurement used for Eqs. 1 and 2 were also considered. As discussed in Sect. 2.2, we investigated the impact of Dry Bulb Temperature (T_{db}) and Attached Thermometer (T_{att}) observations on the calculation of the MSLP from the 'As Read' pressure observations and found the influence of the temperature series used to be minimal (see Fig. S2). Therefore, whenever T_{att} observations were available, we favoured their use over T_{db} due to the thermometer being attached to the barometer to minimise uncertainties in the MSLP calculation.

To ensure that MSLP could be calculated for all sites seen in Fig. 2, it was essential to understand all the elements that may impact the conversion from 'As Read' pressure to MSLP. The 'As Read' pressure was a variable measured across all datasets used in this study. However, pressure observations recorded at the Perth Observatory between 1897–1908 had already applied the temperature (Eq. 2) and MSLP (Eq. 4) corrections as noted by Cooke (1906): 'The Barometer is… reduced to 32degF and mean sea-level. It is not reduced to mean gravity'. Fortunately, the gravity correction (Eq. 3) is a ratio between two gravity values, allowing us to apply Eq. 3 after Eq. 4.

Inhomogeneities in a MSLP record can occur for a number of reasons. The most common relate to changes in station elevation, instruments or observation time. While changes in station elevation should be accounted for when calculating MSLP, in some cases the station elevation changes without metadata being updated or undocumented MSLP conversion factors being changed. Another scenario that occasionally occurs is that the documented station elevation, and hence MSLP conversion factors, are changed as the result of a re-survey but the instrument has not physically moved. This makes it important to assess the homogeneity of the long-term MSLP record before undertaking climatological analysis.

To develop the consolidated long-term pressure record seen in Fig. 3, the Perth Metro station was selected as the reference station that all other datasets were calibrated to. Although the Perth Airport station is the reference station used in the ACORN-SATv2 temperature dataset for Perth (Bureau of Meteorology 2026b), it is located further inland from the nineteenth century stations which are closer to the coast (see Fig. 1). Accordingly, pressure observations from Perth Airport were only used between 1992–1993 before the Perth Metro readings are available from 1994.

As detailed in Table 1, the nineteenth century Perth observations were sampled at various times during the day. For the Swan River record, most observations were taken at 10:00 and 16:00, with the early part of the Perth Gardens record sampled observations at 07:00 and 12:00. To combine Perth's pressure observations into a single series, it was necessary to interpolate observations from Swan River and the start of the Perth Gardens record to the modern sample times of 09:00 and 15:00 using linear regression. Using Perth Metro as the reference station, we calculated 22 linear regressions that allowed the readings taken before noon to be interpolated to 09.00 and afternoon readings observed after 12:00 to 15:00. An overview of the interpolation process is outlined in Fig. S1.

As there is no overlap between the Swan River and Perth Gardens pressure observations, it was not possible to homogenise the sub-daily dataset between 1830–1875.

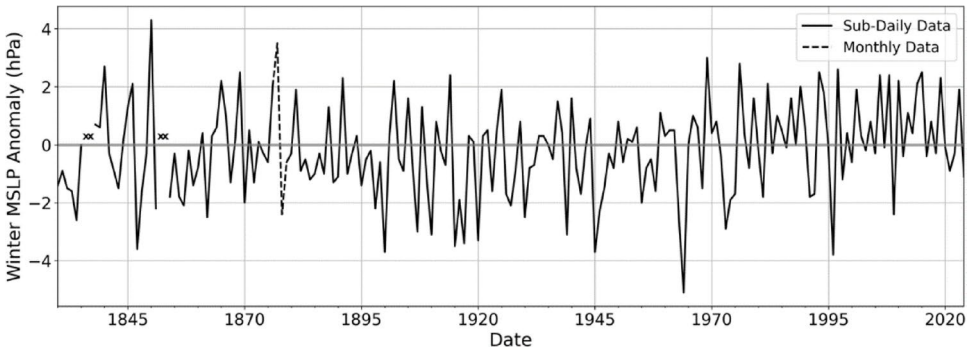


Fig. 3 Homogenised 09:00 and 15:00 averaged austral winter (June–August) MSLP record for Perth, 1830–2024. Solid lines indicate sub-daily pressure with dashed lines indicating periods when only monthly observations are available. Note that a two-year overlap was used by the percentile matching algorithm to develop a continuous, homogenised record, with Perth Metro used as the reference station. For the non-overlapping 1830–1875 period, a mean-adjusted scaling algorithm was used (see Table 2) to scale historical observations to the modern record. Note that no data are available between 1836–1837 and 1852–1853, resulting in two short gaps in the record indicated by crosses (x). Anomalies calculated from a 1961–1990 base period

To allow a comparison of relative (rather than absolute) variations in the non-overlapping 1830–1875 portion of the Perth pressure record we applied a mean adjustment scaling method (Table 2) that scales the anomalies of two 'floating' sections of the Swan River records (1830–1851 and 1854–1875) to the monthly means of the percentile-adjusted 1876–1905 period. The sub-daily anomalies of both sections of the Swan River record were calculated by first averaging each month over the length of the record and then subtracting the sub-daily pressure from the respective monthly mean. We then add the sub-daily anomaly back onto the corresponding monthly mean of the 1876–1905 period to proportionally scale each sub-daily pressure reading to the Perth Gardens monthly mean. This allowed the early nineteenth century Swan River pressure observations to be scaled with the continuous monthly record, providing a long-term record of sub-daily pressure variations in Perth since 1830 (Fig. 3). Note that the monthly pressure observations are continuous back to 1854 and the sub-daily measurements from 1880 due to the data gaps noted in Table 1.

Application of the RHTest on the extended Perth MSLP dataset (1830–2024) allowed us to identify and correct seven Type 0 breakpoints (supported by metadata) and Type 1 breakpoints (not supported by metadata) listed in Table S1. These inhomogeneities include a notable non-climatic shift in the Perth Regional Office record at the start of 1942. A difference was observed between the newly-digitised record and the BoM's official Perth Regional Office record at this time (Fig. S3), prompting us to search the original weather registers held at the National Archives of Australia. We found a metadata note indicating a barometer change at the start of April 1942. This inhomogeneity in Perth Regional Office's pressure record was associated with a change in the barometer height noted in the original weather journals from 197ft (60m) in March 1942 to 210ft (64m) in April 1942 (Table 1). This breakpoint was identified through comparison of the newly-digitised Perth Regional Office dataset from 1907–1944 with the three overlapping years in BoM's existing dataset for the Perth Regional Office record available between 1942–1992 (see Fig. S3). A further inspection of the metadata also identified that six months after the height change in April 1942, the Fortin barometer was replaced with a Kew-Pattern Cistern barometer (Trewin, pers comm, 2025) resulting in a Type 0 breakpoint noted in Table S1.

Our results also show that the 1880s contained non-climatic biases that impacted the homogeneity of the record. Although the RHTest identified the inhomogeneities associated with the interpolation of the pressure observations to 09:00 and 15:00 values during the 1880s, it failed to detect the impacts associated with the elevation changes noted in the metadata during this time (see Table 1). It was therefore necessary to manually insert breakpoints for 09:00 observations in January 1885 and July 1887 and 15:00 values in January 1880 and July 1887 to correct the remaining non-climatic biases present in the record during this period (Fig. S4).

To homogenise the continuous monthly pressure record available back to 1854, it was also necessary to fill the sub-daily measurements missing for the 1876 to 1879 period with monthly values available from the monthly Perth Gardens dataset (see Fig. S1). The non-climatic biases present in the monthly Perth Gardens observations were then corrected using the RHTest (see Table S1), before being combined with the remainder of the continuous record using the Percentile-Matching Algorithm using the two-year overlap available between January 1880 and December 1881. Fig. S4 provides a schematic detailing each stage of this homogenisation process.

While the development of the long-term Perth pressure record allows us to investigate pressure changes since 1830, only the post-1854 observations can be considered homogenous. Ideally, the process of homogenisation involves the use of a nearby reference series (e.g. Trewin 2010), but this is not possible given the sparsity of Australia's nineteenth century data network, especially in Western Australia where station density is limited. While the analysis presented here has sought to identify and reduce the impact of non-climatic breakpoints in the historical observations, it is possible that minor inhomogeneities may still remain in the record. As detailed in Sect. 3, various factors limited our ability to homogenise the entire pressure dataset. The novel scaling method applied to the non-overlapping Swan River observations is an extension of our previous work (e.g. Gergis et al. 2020, 2021, 2023), allowing us to infer relative rather than absolute changes in historical weather and climate extremes. Nonetheless, given that the Perth record between 1830–1875 are some of the oldest known sub-daily pressure observations in the Southern Hemisphere, the relative (rather than absolute) changes in the pressure record provides valuable insights into early nineteenth century weather and climate variability. To assess the quality of the newly-developed long term MSLP record for Perth, next we verify our results with two long lighthouse pressure records from Cape Leeuwin and Cape Otway, independent rain days calculations for Perth, and a palaeoclimate dataset.

5 Verification of sub-daily MSLP record for Perth, 1830–2024

5.1 Verification with Cape Leeuwin and Cape Otway lighthouse records

To verify any trends present in the newly extended MSLP record for Perth, we compare our results against two other long pressure stations: Cape Leeuwin in southwestern Australia and Cape Otway in southeastern Australia (Fig. 4). Given that both sites are located in the westerly storm track, similar pressure systems pass over southwestern and southeastern Australia, albeit with a lag of approximately three days (Hope et al. 2010). Importantly, the development of an extended pressure record from Perth allows for the first long-term analysis of MSLP trends and variability in the westerly storm track across southern Australia, extending the analyses provided by Hope et al. (2010) and Alexander and Power (2009). For this analysis, Cape Leeuwin and Cape Otway pressure datasets were subjected to similar quality control methods applied to the Perth record. The metadata provided in Table S2 allowed us to identify and correct non-climatic shifts using the RHTest, where Cape Leeuwin had two breakpoints and Cape Otway had three breakpoints corrected (see Table S1). These records provided two additional homogenised long-term southern Australian MSLP datasets for comparison with Perth's newly-extended pressure record.

To assess the quality of the newly-digitised pressure observations for the Perth Regional Office, first we compare the Perth dataset with pressure data from Cape Leeuwin, 300km south of Perth. As seen in Fig. 4, the full 1907 to 2024 period of overlap displayed a strongly positive correlation of $r=0.93$ (significant at the 99% level), with the correlation rising to $r=0.96$ over the newly transcribed 1907–1944 period. A slight weakening of the correlation between the two sites is seen in Fig. 4 between 1940 and 1960. This may reflect some missing sub-daily data at Cape Leeuwin in the winters of 1939 and 1942, micro-climatic differences between the exposed lighthouse location and central Perth and other undocumented inhomogeneities that still may be present in either of the pressure records. Notably, both Perth and Cape Leeuwin display a positive trend in MSLP beginning in the 1960s. Our results indicate that the new pressure observations from Perth match variations noted from a nearby independent station, confirming that the same dynamical systems influencing Perth are also experienced at Cape Leeuwin. It also suggests that our extended MSLP record for Perth is likely to provide a good estimation of pressure fluctuation experienced over southwestern Australia since 1830, with the mid-twentieth century increase in pressure a common feature of both records.

To verify the pre-1907 period of the new MSLP record for Perth and examine any widespread pressure trends across southern Australia, next we compare our results to Cape Otway, the only other long-term, continuous pressure record available in southern mainland Australia (Alexander and Power 2009). A moderately positive correlation of $r=0.66$ was observed over the 1861–2024 period of overlap, with our newly digitised pressure record for Perth (1907–1944) increasing to $r=0.74$, with both correlations significant at the 99% level. Unlike Cape Leeuwin which displays a consistently strong positive correlation with Perth MSLP, the 31-year running correlation with Cape Otway shown in Fig. 4 shows considerable variability, likely to be reflecting differences in some of the weather systems influencing southwestern and southeastern Australia (Jin et al. 2025). A distinct weakening of the correlation between the two records is seen during the 1880s and 1890s. This reflects known issues in the Cape Otway record during this time which could not be resolved, despite an inspection of metadata contained in the original weather journals accessed at the National Archives of Australia. Nonetheless there is good agreement between the Cape Otway and Perth MSLP

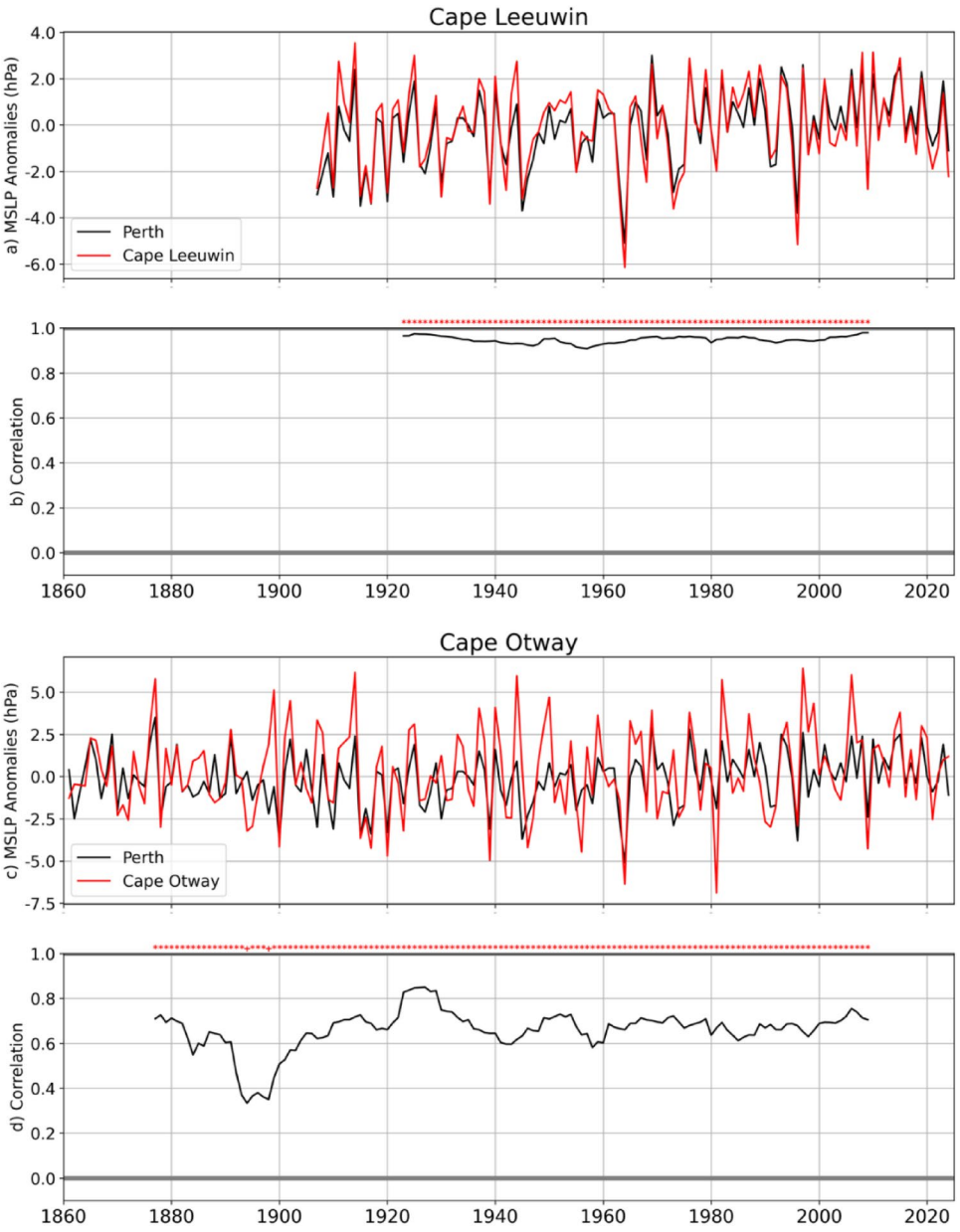


Fig. 4 **a** Comparison of average sub-daily austral winter (June–August) MSLP anomalies calculated between Perth (black) and Cape Leeuwin (red) for 1907–2024 period of overlap. **b** 31-year running Pearson's r correlation calculates the average sub-daily winter pressure anomalies between Perth and Cape Leeuwin from 1910 to 2024. **c** Average sub-daily winter pressure anomalies for Perth's (black) and Cape Otway (red) pressure records for overlapping 1861–2024 period. **d** 31-year running Pearson's r correlation calculates the of average sub-daily winter pressure anomalies between Perth and Cape Otway from 1861 to 2020. Plus (+) indicates significance at the 90% level, with an asterisk (*) denoting significance at the 95% level. Note anomalies are calculated from a 1961–1990 base period

records, with both records indicating a positive trend in MSLP variability from around 1920 onwards.

5.2 Long-term variability of Perth MSLP–rainfall relationship

As outlined in the introduction, a significant decline in south-western Australia cool season rainfall has been observed since the 1970s (Hope et al. 2010; Gergis et al. 2023; Bureau of Meteorology and CSIRO 2024). This trend is associated with an increase in mean sea level pressure, a poleward shift of baroclinic instability and a weakening of the mid-latitude storm tracks that influence rain-bearing frontal systems along southern Australia (Arblaster and Meehl 2006; Hope et al. 2006; Timbal and Drosdowsky 2013; Nguyen et al. 2015; Frederiksen et al. 2017; Fogt and Marshall 2020). However, the lack of long term meteorological records from the region makes it difficult to contextualise the nature of recently observed trends, variability and extremes (Gergis et al. 2023).

Having developed an extended pressure record for Perth back to 1830, next we verify whether the post-1970 rainfall decline is consistent with natural variations observed in the extended MSLP and rainfall records developed in this study (Fig. 5). We examine changes in austral winter (June–August) rainfall, the season where the most significant decline has been observed (Hope et al. 2010; Gergis et al. 2023; Bureau of Meteorology and CSIRO 2024). Given

the lack of quantitative rainfall data available before 1880 (Gergis et al. 2021), we use rain days to examine indicative rainfall variability over the full 1830–2024 period. To directly compare the modern, quantitative rainfall record available from 1880 with historical rain day observations (1830–1875), we convert the modern daily rainfall totals into a simple categorical rain days index (Fig. 5). Following Gergis et al. (2023), a threshold of 0.4mm was used to define a rain day in Perth's modern records to closely match the seasonal distribution of the pre-1880 dataset. Note that while the use of a total rain day index allows us to extend the analysis back to 1830, we are unable to capture the change in the rainfall amount per rain day.

For the 1880–2024 period when continuous pressure and rainfall data are both available for Perth, we also calculated a Pearson's (r) correlation to determine the nature of the relationship between winter MSLP and rainfall anomalies. A strongly negative correlation of r=–0.72 (significant at the 99% level) was identified between winter MSLP and rainfall in Perth, confirming the previously-reported low pressure–high rainfall relationship (Gergis et al. 2023). Although a strongly negative correlation (significant above the 95% level) persists throughout the record, considerable interannual–interdecadal variability is also noted in Fig. 5. The MSLP–rain days relationship is slightly weaker and more variable during the nineteenth century. The 1900–1950 period stands out as the most sustained above average rainfall period since 1830, corresponding with a stable period of strongly negative correlation between MSLP and rainfall. In particular, the newly-digitised 1907–1944 sub-daily pressure observations missing from Gergis et al. (2023) display a sustained period of low pressure in the MSLP record that is associated with a predominately wet period (Fig. 5).

Although the previously reported winter rainfall decline beginning in the 1970s is clearly observed in Fig. 5, it confirms our earlier finding for the full cool season (April–October) that the modern rainfall decline is not as pronounced as the dry conditions observed in Perth during the early nineteenth century (Gergis et al. 2023). As seen in Fig. 5, a prolonged dry period is noted from 1830–1850, with the driest year observed in the winter (JJA) of 1840 when there were 29 fewer winter rain days than the 1961–1990 average. Considering the extended April–October cool season shown in Fig. S5, the deficit recorded in 1840 falls to 49 fewer rain days than the 1961–1990 base period.

A prolonged drought was also noted during most of the 1860s and 1870s, corresponding to a time of increased MSLP. Notably, very few wet recharge years are observed

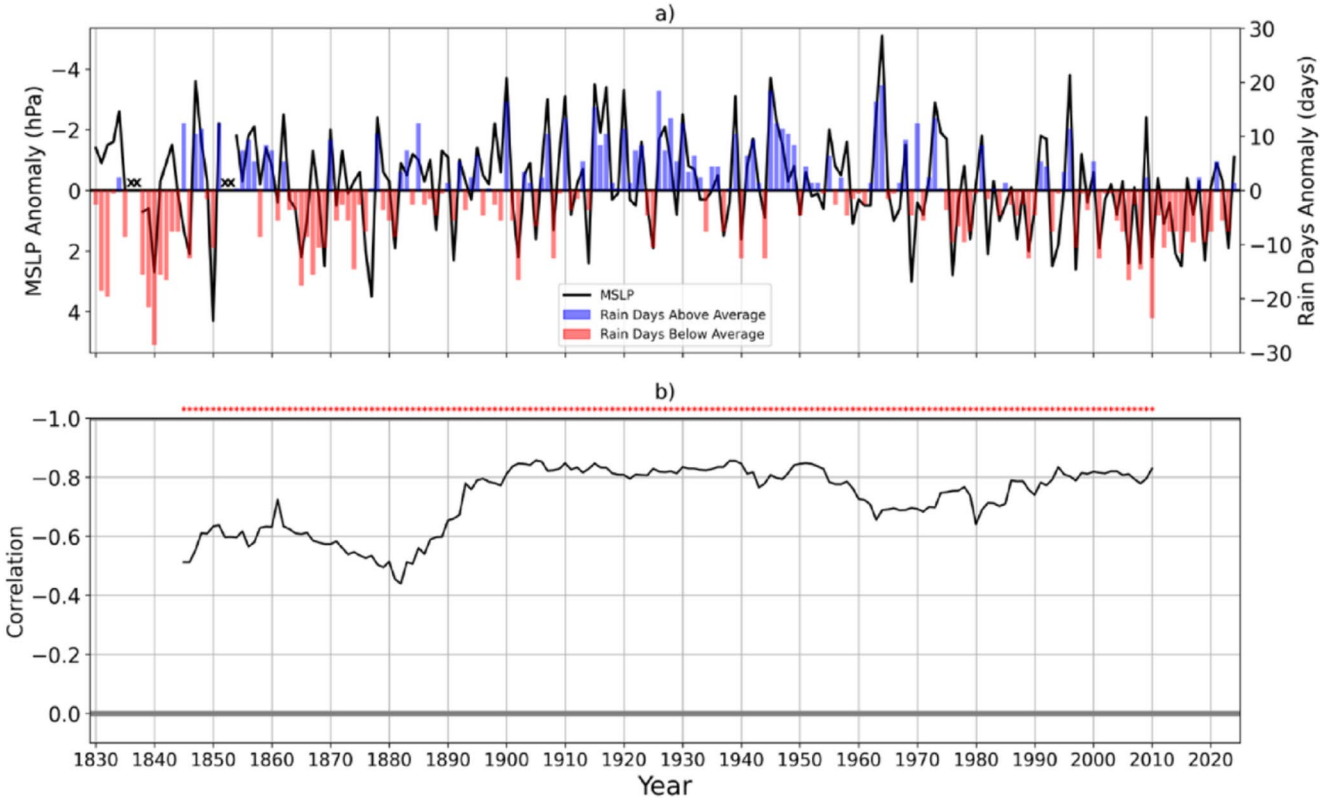


Fig. 5 **a** Comparison of Perth June–August (JJA) MSLP anomalies with the total JJA rain days, 1830–2024. Note that anomalies are calculated using a 1961–1990 base period, and the MSLP anomalies have been inverted for ease of comparison. **b** 31-year running Pearson's r correlation calculated between Perth's winter pressure and rain days. Plus (+) indicates significance at the 90% level, with an asterisk (*) denoting significance at the 95% level. Crosses (x) indicate missing data

in the post-1970 period, associated with an increase in MSLP in the region. The strength of the MSLP–rainfall relationship has fluctuated considerably, suggesting other factors may be influencing the southwestern Australian climate. These might include variations associated with the Southern Annular Mode, tropical interactions originating in the Indian and Pacific oceans (e.g. Hope et al. 2010; Gergis et al. 2023), or changes in the sub-tropical ridge associated with anthropogenic warming in the region (e.g. Delworth and Zeng 2014; Nguyen et al. 2015). Given the influence of large-scale climate drivers on regional climate, further analysis of the long-term variability of Southern Hemisphere teleconnections should be a priority for future research.

5.3 Verification with Western Australian rainfall reconstruction

To further verify the nineteenth century climate variations noted in the extended rain day and MSLP records for Perth, next we compare our results with a tree-ring based March–September rainfall reconstruction from the Lake Tay area of SWWA (Cullen and Grierson 2009). This palaeoclimate record was developed from a site located at 33° 1′ 57″ S (see Fig. 1) which is similar to the latitude of Perth (31° 57′ 8″ S), thus was considered suitable for comparison with our results (Pauline Grierson, pers comm, 2025). A weak positive correlation is observed between the Lake Tay rainfall reconstruction and the extended March–September cool season rain day index calculated for Perth (r = 0.20, significant at the 99% level), with the 31-year running correlation shown in Fig. 6 displaying considerable inter-decadal variability. High variability is also observed between March–September Lake Tay rainfall and Perth MSLP presented in Fig. S5, which displays relatively weak negative correlations for the 1830–2005 period of overlap (r = –0.25), significant at the 99% level).

These weak relationships may also reflect a combination of influences including the fact that Lake Tay is considerably further inland from the coastal city of Perth (approximately 630km to the east), non-climatological factors influencing biological records, the calculation of the rainfall reconstruction over an extended cool season and the spatial heterogeneity of rainfall. Furthermore, in the early part of the March–September period, rainfall at Lake Tay, and to some extent at Perth, largely originates directly or indirectly from tropical systems and is weakly connected or unconnected to the position of the mid-latitude storm track. These factors together may explain the relatively weak relationships noted here. However, to place these results into a broader context, we also calculated the correlation over the period

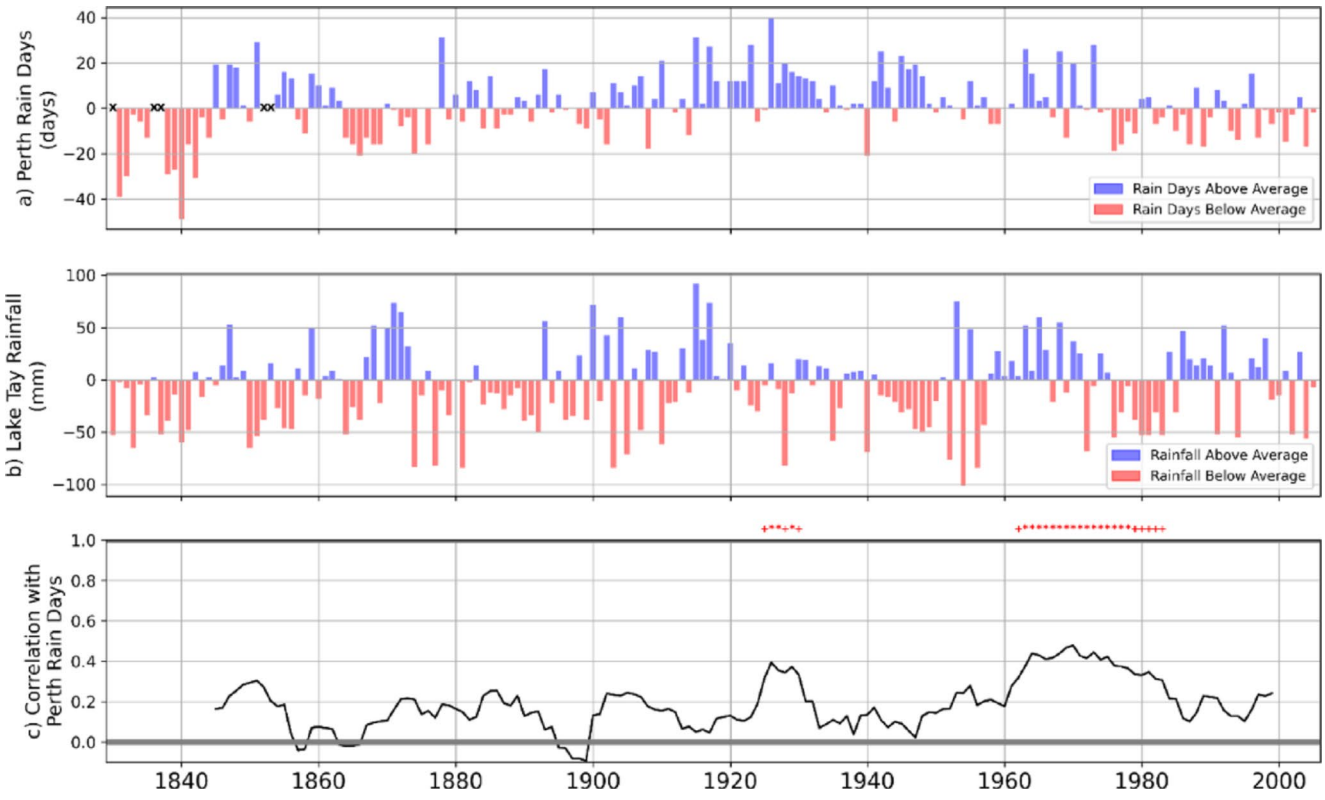


Fig. 6 **a** Perth's rain days, **b** Lake Tay tree-ring based rainfall reconstruction calculated over the March to September extended cool season, and **c** 31-year running correlation between Perth rain days and the Lake Tay rainfall reconstruction. Anomalies are calculated relative to the 1961–1990 base period. Plus (+) indicates significance at the 90% level, with an asterisk (*) denoting significance at the 95% level

of available data (1932−2024) between March–September Perth MSLP and rainfall at the nearest long-term Bureau of Meteorology observing site, Salmon Gums (012071, 80 km east of the Lake Tay site). As see from Fig. S5, the correlation between Salmon Gums and the extended MSLP record for Perth is also modest but significantly negative (r=–0.38, significant at the 99% level), with the relationship weakening notably in the post-1970 period.

As seen in Fig. 6, dry spells in the Perth rain day record only correspond to dry periods in the Lake Tay tree ring record episodically. However, Fig. S5 shows that high pressure is mostly significantly correlated with low rainfall at Lake Tay during the pre-1900 period, particularly during the 1840s, and from the 1870s until the 1890s. Despite these weak correlations, our results align with the findings of O'Donnell et al. (2021) who report that the 1828–1859 and 1876–1888 periods were the driest in southwestern Australia since 1350 in their tree-ring based rainfall reconstruction using samples from 300km north of Lake Tay. Interestingly, Figs. 5 and 6 also shows a pronounced drought in Perth and inland southwestern Australia during the 1830s and 1840s that surpasses the post-1970s rainfall decline observed in our results. This provides further evidence that modern weather records do not capture the full range of natural climate variability seen in longer records and that future drought risk in southwestern Australia is likely to be underestimated (O'Donnell et al. 2021).

6 Severe storm analysis, 1830–2024

As seen in Fig. 3, an increasing trend in winter MSLP is observable across southwestern Australia beginning in the mid twentieth century, persisting to 2024. This dominance of high pressure in winter is consistent with the results of Alexander and Power (2009) for Cape Otway in southeastern Australia, who suggested that shifts in westerly storm tracks resulted in a 40% reduction in the number of severe storms since the mid-nineteenth century.

To quantify the impact of this increasing pressure trend in southwestern Australia, first we calculate a winter (JJA) severe storm index to compare our results with the decline in storminess observed from Cape Otway in southeastern Australia. We follow the pragmatic approach of Alexander and Power (2009) who use the generic term 'severe storm' to refer to extreme low pressure values in historical pressure observations. We note that this term may differ from operational definitions used in modern weather forecasting that incorporate a more complete suite of variables than is possible from data sparse nineteenth century historical records.

To allow our results to be compared to those reported from Cape Otway, we followed the percentile analysis approach taken by Alexander and Power (2009) to define extreme pressure values. To identify possible significant winter storms, we calculated pressure differences on a sub-daily scale and isolated pressure deviations that fell outside the 1st and 99th percentiles of all 6-hour and 18-hour pressure tendencies for each month. This process identified 572 low pressure events which were then verified against the handwritten weather logs. To assess the sensitivity of our results to this stringent definition, we also applied a weaker 5th and 95th percentile threshold to the pressure observations. This returned 2119 potential events, which was nearly four times as many events to manually check, so was deemed too labour-intensive just for the sake of comparison. Since our study was targeting severe storms, and not just moderately extreme events, we proceeded with the 1st and 99th percentile thresholds for our pressure analysis.

Given that a pressure-only definition may not adequately capture severe storms with potentially significant societal impacts, we also cross verified the extreme pressure readings against the new rain day and rainfall dataset developed for Perth (Gergis et al. 2023). This identified a subset of 384 severe low pressure events that were also associated with rainy conditions. When quantitative rainfall observations are available from 1880 onward, the identification of storms was restricted to events associated with a rainfall total of at least 25 mm. While this threshold is somewhat arbitrary, it corresponds to daily winter rainfall above the 95th percentile so is representative of heavy rainfall events for this location. Because we are interested in analysing severe storms but do not have access to wind speed data throughout the record, instead we applied an additional rainfall criterion to identify potential social impacts such as flooding that may have been reported in historical documents. Storms identified in the pre-1880 pressure observations were verified by manually checking the original weather journals for supporting remarks referring to rainfall, gales, squalls or similar. Extreme pressure readings that were not supported by relevant comments in the original journals were omitted to avoid the potential inclusion of erroneous events (false positives). This method identified 141 severe storms that impacted Perth between 1830–2024 (available online at https://doi.org/10.5281/zenodo.17103389, with the twenty most extreme storms recorded since 1830 listed in Table 3.

A key goal of this study was to develop a long-term, daily MSLP record for Perth to allow pre-industrial weather extremes to be examined. The extension of high quality instrumental records provides a unique way of better quantifying past weather extremes that can then be used to assess future climate risk in a warmer climate (Brönnimann et al. 2019; Hawkins et al. 2023). Before evaluating any trends present in the Perth's long-term winter storm activity, first we demonstrate the ability of our new sub-daily pressure

observations to accurately resolve daily weather extremes using the ensemble mean of 20CRv3 dataset (Slivinski et al. 2021) by examining the synoptic systems associated with severe storms selected from Table 3. While low data availability affects the quality of 20CRv3 across Australia before the mid-twentieth century, previous analysis has shown it to skilfully capture extreme rainfall events back to the 1870s (Pepler et al. 2017; Gergis et al. 2020, 2021, 2023).

Given our previous verification of nineteenth century storms, for this analysis we selected three notable storms that fell within the newly-available pressure observations for the 1909–1941 period. Following our previous method, each storm event was cross-checked against independent historical storm and heavy rainfall lists compiled for Western Australia by Hunt (1929), the historical synoptic charts of Charles Todd compiled by the Bureau of Meteorology's Adelaide Regional Office volunteers (http://www.met-acre.net/MERIT/) and newspaper records accessed using the National Library of Australia's TROVE database (National Library of Australia 2026) that detailed significant societal impacts associated with each event.

6.1 Severe storm of 8–9 August 1909

A severe storm impacted Perth from 8–9 August 1909 (Storm ID #83), with the *Daily News* reporting 'some of the heaviest wind storms which have been known in the memory of the oldest inhabitant'. A notable feature of the system was the windy 'hurricane force' conditions described in the Argus newspaper on 9 August 1909 (however this is a journalistic description so is not equivalent to the Beaufort wind force scale). Nonetheless, the same day the *West Australian* reported that windspeeds reached 74km/hour (46 miles/hour). Hunt (1929) detailed considerable wind damage, noting 'most of the smaller trees lining the sidewalks were torn up by the roots'. In the coastal suburb of Fremantle, 'violent weather' damaged homes, tore off corrugated iron roofs resulting in flying sheets of iron damaging the telegraph lines.

There were also accounts of pea to 'pigeon-egg' sized hail and heavy rainfall inundating low lying areas including the Perth Racecourse. Rainfall records show that between 6–10 August, 91.2mm of rainfall was recorded (Table 3). Another significant storm impacted Perth from the 16–18 August, which produced 113.5mm of rain, and went on to contribute

Table 3 Top twenty most extreme winter (June–August) storms identified in Perth's sub-daily pressure record. Minimum pressure (hPa) and rainfall total (1880–2024) or journal remarks (1830–1879) also given for each event. Case studies discussed in Sect. 6 are bolded. A complete severe storm list (1830–2024) available online at https://doi.org/10.5281/zenodo.17103389

Start date	End date	Minimum Pressure (hPa)	Rainfall Total (mm) (1880–2024 events)	Journal Remarks (1830–1879 events)
1929–06–01	1929–06–01	989.8	31.8	–
1928-07-16	**1928-07-19**	**990.6**	**121.6**	**See case study notes in Sect. 6**
1927–06–16	**1927–06–19**	**991.1**	**98.9**	**See case study notes in Sect. 6**
1868–06–07	1868–06–10	991.4	–	Significant rain fell on 7 June. Squally conditions with heavy rainfall and stormy conditions on the night of 8 June. Continual heavy rain with heavy squalls until 10 June
1851–07–15	1851–07–17	991.7	–	Windy, squally and rainy conditions occurred on the 15 and 16 July. A fresh breeze with heavy showers occurred on 17 July
1908–07–05	1908–07–06	991.7	60.2	–
1840–07–07	1840–07–08	992.8	–	Heavy showers, strong gales and squally conditions
2003–08–11	2003–08–11	993.6	45.8	–
1968–06–12	1968–06–14	994.1	95.5	–
2010–07–09	2010–07–12	994.1	92.8	–
1935–07–07	1935–07–09	995.1	63.0	–
1995–06–06	1995–06–09	995.2	107.0	–
1907–07–28	1907–07–31	996.0	86.1	–
1830–06–30	1830–07–02	996.4	–	Rain and squally conditions
1831–06–21	1831–06–22	996.5	–	Rained significantly on the night of 21 June. 22 June experienced squally conditions and fresh gales
2021–07–27	2021–07–27	997.2	30.4	–
1868–06–15	1868–06–18	997.8	–	Squally conditions, strong breezes and heavy rainfall
1906–08–05	1906–08–06	997.8	46.5	–
1874–06–16	1874–06–17	998.0	–	Heavy rainfall with squally conditions occurred during the event. The event lasted until the morning of 17 June
1909–08–06	**1909–08–10**	**998.0**	**91.2**	**See case study notes in Sect. 6**

to severe flooding in southeastern Australia (Trewin 1999). These two winter storms combined accounted for ~ 20.6% of the total rainfall recorded for 1909. According to Hunt (1929), these conditions 'ensured a record season as the rains were even and widespread in their distribution and the downfall had penetrated far inland'.

Figure 7 and S6 show a significant low-pressure system impacted southwestern Australia during this event before moving eastward. According to an interview with the Commonwealth meteorologist, Mr E.B. Curlewis, published in the *West Australian* newspaper on 9 August 1909, this period of the 'most bleak and boisterous weather that has been experienced in Perth for some years' was associated with a persistent low pressure system centred over Breaksea Island, aligning with the synoptic conditions seen in the 20CRv3. Charles Todd's synoptic map seen in Fig. S7 also clearly captures the low pressure system. On 8 August, pressure readings in Perth reached a minimum of 998.0hPa at 3pm (Table 3). As seen in the extended synoptic analysis provided in Fig. S6, the low pressure system south of Perth slowly moved eastward, taking around five days to reach southeastern Australia. The low was then pushed out of the Great Australian Bight on 10 August as a high pressure system developed in the Indian Ocean.

6.2 Severe storm of 17 June 1927

On Sunday 19 June 1927, the front page of *The Sunday Times* featured the 'terrific wind and rain storm' that impacted Perth with a record wind speed of 80 miles per hour (128 km/hr) (Storm ID #91). As reported in the *Albany Advertiser* on 18 June, 'a storm of cyclonic strength swept Perth and Fremantle', which was not just journalistic hyperbole of the time – windspeeds of such high velocity are classified as a Category 2 tropical cyclone today (Bureau of Meteorology, 2026c). There are copious newspaper accounts of a powerful storm that caused extensive damage to buildings and infrastructure, with the *West Australian* reporting 'houses were unroofed and the crumpled sheets of iron flung away like paper. Balconies were torn down, fences and hoardings flattened and windows smashed by gusts of wind which rose to a velocity of 70 miles per hour [112 km/hr]'. There were also reports of disruption to 'shipping, railways, tramway, ferry and aeroplane services' as well as telegraph and electricity connections.

Extensive damage was also sustained on the coast, with South Fremantle and Cottesloe severely damaged. On 18 June 1927, the *Mirror* reported that the Hotel Cottesloe and Inglefinger's tea rooms were stripped of balconies and half roofed with other accounts of damage to the pier, seawall, bandstand and a local theatre in the waterfront area. Gale conditions were also experienced north of Perth, the

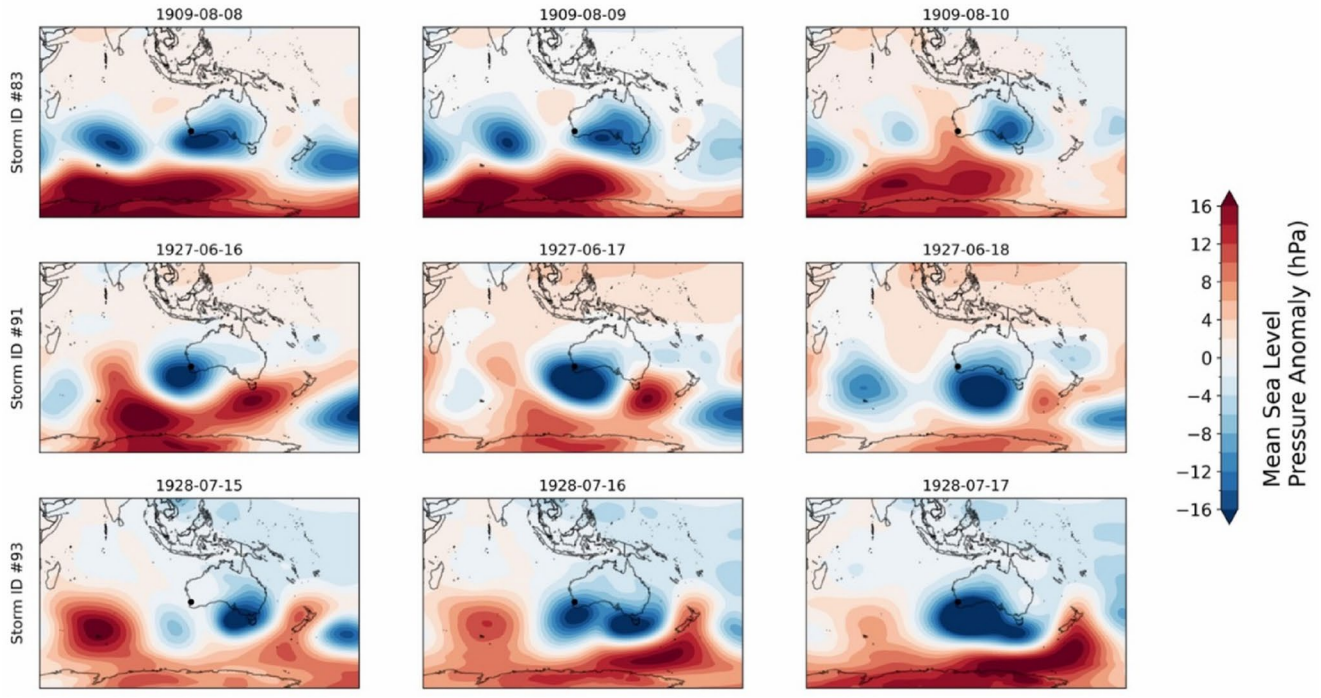


Fig. 7 Daily 20th Century Reanalysis Version 3 ensemble mean Mean Sea Level Pressure (MSLP) anomaly plots for the three winter storms that impacted Perth on 8–9 August 1909 (top), 17 June 1927 (middle) and 16–17 July 1928 (bottom). The left column indicates the day before the event (t = -1), the middle column is the day of the event (t = 0), and the right column is the day after the event (t = + 1). The red (blue) region indicates a region of higher (lower) than average June–August MSLP anomalies calculated from a 1961–1990 base period

Geraldton Express reporting that 'gigantic rollers coming well up on the foreshore' disrupting Geraldton's shipping operations in the harbour and damaging the railway line. The destruction also extended south of Perth, with the *Daily News* reporting flooded streets, badly damaged buildings, verandas and damage to the high school in the town of Bunbury.

As seen in Fig. 7 and the extended analysis of Fig. S6 the frontal system did indeed impact southeastern Australia in the days that followed the 17 June 1927 storm in Perth. The charts show a major polar outbreak surrounded by high pressure which may have increased the temperature gradient generated during this event resulting in very strong winds. Tightly spaced isobars associated with a steep pressure gradient are also clearly observed in the historical synoptic chart given in Fig. S8. The minimum pressure reading for the event was 991.1hPa recorded at 3pm on the 17 June, the lowest observed in our record since 1830 (Table 3).

6.3 Severe storm of 16–17 July 1928

As indicated by the 20CRv3 synoptic reconstruction shown in Fig. 7, a severe storm impacted Perth from 16–17 July 1928 (Storm ID #93), with significant damage reported in the newspapers. On 22 July, *The Sunday Times* reported the event as one of the 'most violent succession of storms Western Australia has experienced' with reports of 'violent gales accompanied with incessant heavy rain…with the result that a great deal of damage has been done'. Wind speeds of 93km/hour (58 miles/hr) were reported in Perth with journalists referring to the system as 'a hurricane'.

There was considerable damage reported to homes, businesses and infrastructure, with rooftops blown away by the strong winds and sections of the Great Southern railway line as far south as Albany were damaged by washouts and flooding caused by heavy rainfall. The Commonwealth Meteorologist reported approximately 64mm of rain fell in the city in 18 hours, a July record at the time. The newspaper mentions that the Swan River flooded inundating low lying areas from Fremantle on the coast to inland areas of Guildford in the northeast (near the modern day location of Perth Airport), with South Perth particularly impacted. There were also reports of heavy seas causing damage to ships further north in Geraldton, wrecking a fishing vessel and unmooring another ship from the harbour with passengers onboard.

Figure S6 shows that a series of cold fronts moved across southern Australia in the lead up to the storm. As noted in Table 3, the minimum sub-daily pressure reached a low of 990.6hPa at 3pm on 17 July 1928. An inspection of the original weather registers noted rainy conditions with a 'westerly gale' and hail throughout the day. A low pressure system spanning the Great Australian Bight during this event is also seen in the historical synoptic chart given in Fig. S9, with the high pressure prevailing over New Zealand possibly restricting the eastward transit of low pressure conditions. The synoptic maps also indicate the dominance of low pressure conditions in the Southern Ocean associated with a steep pressure gradient from the high pressure over eastern Australia, having a pronounced effect in the mid-latitudes on 17 July. Newspaper reports detailed impacts across South Australia and Victoria, with rough seas causing damage to a cargo ship and injuries to crew. These reports confirm that the vigorous frontal system reached southeastern Australia, suggesting stormy conditions were experienced across the entire southern coastline of Australia during this event.

7 Perth's long-term storm variability, 1830–2024

Having demonstrated the ability of our new sub-daily pressure record to resolve severe storms from Perth, finally we assess any long term changes in storm activity influencing southwestern Australia. Figure 8 shows the number of severe storms that impacted Perth for every decade since the 1830s. Figure S10 also shows the number of extreme pressure changes and rain days per decade to allow separate inspection of any trends present in the individual pressure and rainfall components of the severe storm record (which, as described in Sect. 6, combines both variables). Despite some missing data during the nineteenth century, many severe storms were observed during this period, with particularly stormy decades observed during the 1860s and 1890s. The early 20th Century was also characterised by high storm activity, peaking in the 1900s and 1910s. The stormiest decade was the 1960s when 28 severe storms were recorded, with the number of storms falling significantly from the 1980s onward. The lowest number of storms was observed in the most recent decade of 2010–2019, which only contained fourteen severe storms. Notably, the 2010s recorded considerably fewer events than dry decades such as the 1830s, 1850s and 1870s, although these decades have incomplete data so are likely to underestimate the true number of storms experienced during these periods.

Our results show a 20.2% decrease in the number of severe winter storms influencing Perth since 1970, with the decline further strengthening to 30.9% since 1990. Note that these values are calculated using an extended 1880–1969 base period where no missing data are present in the newly-extended Perth pressure record while maximising the sampling of pre-industrial variability. The notable decline in stormy conditions from southwestern Australia is in line with the results of Alexander and Power (2009) who

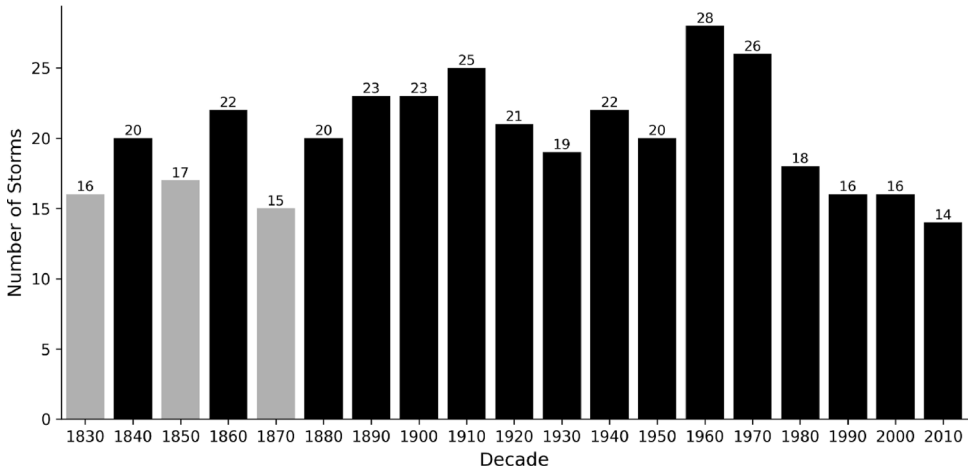


Fig. 8 Number of austral winter (June–August) severe storms in Perth for each decade from 1830–2019. Note that grey shading indicates missing data during the periods 1830–1839 (2 years), 1850–1859 (2 years) and 1870–1879 (4 years)

reported a 40% decrease in the annual number of severe storms since 1865 from Cape Otway in southeastern Australia. Differences in our results may reflect the base period used to calculate our results, regional differences between southeastern and southwestern Australia, differences in the seasonal window used to calculate changes in storm activity (total annual storms versus winter only storms), and the additional rainfall criterion used in the storm definition applied in this study. Nonetheless, both studies indicate a clear decrease in storm activity across southern Australia in recent decades.

The marked decline in storminess captured by our new pressure record for Perth is also reflected in reduced rainfall in the rain day and rainfall anomalies seen in Fig. 5 and S10. Using the same extended 1880–1969 base period used to assess recent changes in the pressure record, we report a 17.6% decline in Perth's winter (June–August) rainfall since 1970 and a 20.3% decline since 1990. These results are in close alignment with the 20% decrease in May–July rainfall reported across a broader region of southwestern Australia reported by the Bureau of Meteorology and CSIRO (2024) since 1970 and a 24% rainfall decline since 1994 (calculated using a 1900–1969 base period). The results seen in Fig. S10 suggest that the reduction in pressure extremes is more pronounced than the rainfall decline, implying that decrease in severe storms is not just influenced by decreasing rainfall. Our analysis confirms that a significant decline in rain-bearing systems is a robust feature of multiple variables that reflect the climatic changes observed in southwestern Australia since 1830.

8 Discussion and conclusion

This study describes the consolidation of the oldest sub-daily pressure observations available from Australian and the Southern Hemisphere. We present a newly homogenised mean sea level pressure record for Perth in southwestern Australia spanning 1830–2024. This extended pressure record contains sub-daily observations of surface pressure that bridge a previous gap between nineteenth century observations and the start of the Australian Bureau of Meteorology's digital holdings in 1942 (Gergis et al. 2023). Sub-daily observations are now available from 1830, with only three periods of missing data noted between 1836–1837, 1851–1853 and 1875–1879 (Table 1). While these gaps hamper the development of a continuous sub-daily pressure record before 1880, a continuous monthly pressure record for Perth is available back to 1854 making this the longest available for Australia and one of the longest observational sites in the world (Brönnimann et al. 2020).

Following rigorous quality control and data homogenisation processes, we verified the new pressure dataset for Perth against two long lighthouse records from Cape Leeuwin and Cape Otway, independent rain day observations for Perth, and a tree-ring based rainfall reconstruction from southwestern Australia. After establishing the quality of our new sub-daily pressure record for Perth, we evaluated its ability to resolve daily weather extremes. We examined three severe storms recorded in the newly-digitised 1909–1941 period verifying them against the synoptic fields generated by the 20th Century Reanalysis and independent historical records. The case studies of August 1909, June 1927 and July 1928 demonstrate the significant societal impacts of past storms that impacted Perth, providing unique opportunities to use pre-industrial events like these in warmer world experiments aimed at better quantifying future weather and climate risk (Brönnimann et al. 2019; Hawkins et al. 2023).

Using a combination of extreme pressure tendencies and rainfall data, we identified 141 severe storms that have impacted Perth since 1830. An assessment of long-term changes in austral winter (June–August) storm activity revealed a nineteenth century characterised by many storms, with the stormiest decade peaking in the 1960s before

declining notably from the 1980s. Overall, our results show a 20.2% decrease in the number of winter storms influencing Perth since 1970, with the decline strengthening to 30.9% since 1990. This decline in storminess is also supported by our analysis of rain days since 1830. While rain day counts show a notable reduction in winter rainfall in Perth since the 1970s (in agreement with the decreased frequency of extreme storms), the current rainfall deficit is not as pronounced as dry conditions observed during the 1830s and 1840s. Nonetheless, the post-1970 rainfall decline is more persistent and characterised by a complete absence of very wet years (rainfall > 90th percentile) since 2001 (Rauniyar et al. 2023), representing an overall reduction in variability. The modern decline in winter storms noted here is in line with the observed decrease in the number of low pressure systems and the total rainfall generated from deep lows influencing southern Australia during the cool season (e.g. Pepler 2024). Our findings are consistent with the aridification of sub-tropical locations noted globally (Douville et al. 2021).

Our results not only provide further evidence of a decrease in storminess and rainfall across southern Australia previously attributed to anthropogenically-influenced shifts in westerly storm tracks and changes in storm characteristics, but also suggest modern weather records do not capture the full range of natural variability and extremes recorded in historical observations. Given that the increasing trend in pressure and the decline in winter rainfall reported here are projected to continue across southern Australia (e.g. Hope et al. 2015; Polade et al. 2017), further development of long-term instrumental and palaeoclimate records from southwestern Australia (e.g. O'Donnell et al. 2021; Griffiths et al. 2022; McDonough et al. 2022; Priestley et al. 2023) may provide a basis for extending estimates of weather and climate extremes to help improve future climate risk assessment.

The conclusions inferred from the development of Australia's longest pressure record imply that future weather and climate risk is likely to be underestimated in the Australian region. The MSLP record for Perth introduced here provides an important foundation for assessing pre-industrial weather and climate variability from southern Australia with sub-daily resolution, extending the potential for attribution studies of anthropogenically-influenced weather extremes including severe storms and heatwaves. This newly extended MSLP record for Perth, alongside other recently-rescued observations for southern Australia (Gergis et al. 2023), can now be assimilated into forthcoming versions of the 20th Century Reanalysis to help resolve synoptic-scale weather variability and extremes in the Australia region. Our case study analysis also demonstrates the value of using historical material such as hand-drawn synoptic charts used in the pre-digital era to verify contemporary model-based datasets which still have incomplete regional data coverage in data sparse areas of the Southern Hemisphere, particularly in the pre-1955 period.

This study is an important contribution to the development of benchmark instrumental records needed to evaluate pre-industrial weather and climate variability of the Southern Hemisphere. The continuous length of sub-daily and monthly observations makes the Perth record a possible candidate for future inclusion in the World Meteorological Organization's global network of Centennial Observing Stations, which provides vital meteorological observations for monitoring long-term climate variability and change worldwide (World Meteorological Organization 2026). Ongoing data recovery efforts from Australia are needed to better understand the long-term behaviour of the major modes of Southern Hemisphere climate variability, especially changes in the sub-tropical ridge and the Southern Annual Mode and their influence on regional weather extremes including severe storms and heatwave conditions. Historical pressure observations should continue to be rescued from key locations of Australia to help resolve the dynamical conditions associated with extreme weather events that human societies will need to plan for as the planet continues to warm.

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Author contributions The study conception and design was led by Joëlle Gergis, with inputs from Jarrad Rowe, Linden Ashcroft and Blair Trewin. The data generated from this project was compiled by Joëlle Gergis, Jarrad Rowe, Tessa Ellwood, Zak Baillie, Stefan Ingallina and Rob Allan. Data analysis was performed by Jarrad Rowe under the guidance of Joëlle Gergis, Linden Ashcroft and Blair Trewin. Joëlle Gergis conducted the historical analysis for the severe storm case studies. The first draft of the manuscript was written by Joëlle Gergis with inputs from Jarrad Rowe, with all authors commenting on review drafts of the manuscript. All authors read and approved the final version of the manuscript.

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Data availability The dataset generated from this study is available in the following ZENODO repository: https://doi.org/10.5281/zenodo.17103389

Declarations

Competing interests The authors have no financial or non-financial interests to declare.

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