Received: 22 March 2019 | Revised: 23 July 2019 | Accepted: 9 August 2019
DOI: 10.1002/gdj3.80

DATA PAPER

Geoscience Data Journal RMetS WILEY

Meteorological observations for *Eversleigh* Station, near Armidale, New South Wales, Australia: 1877–1922

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Funding information
University of New England Heritage Centre; University of Newcastle Cultural Collections; Australian Academy of Science Moran Award for History of Science

Abstract
Historical weather observations on the daily scale are vital for the improvement of reanalysis products and the analysis of long-term variability of extreme events. While daily datasets extend for several centuries in parts of the Northern Hemisphere, the majority of historical data for the Southern Hemisphere are monthly averages or totals. In this paper, we describe a newly recovered dataset of ten daily meteorological variables for 1877 to 1922 from *Eversleigh*, a property in the New England region of New South Wales in Australia. Here, we present the full process of data rescue, from digitization to quality control and an assessment of homogeneity. We show that the majority of variables were recorded to a high standard and that the data are of general use for climate analysis. Forty years of daily temperature, cloud cover, wind, and pressure observations are now available for the New England Plateau, offering data that are more complete than any other records for the region in the Australian Bureau of Meteorology dataset. The *Eversleigh* dataset now provides an opportunity to gain more insight into the 19th century weather and climate of eastern Australia during a time of large interannual climate variability before the dominant impact of an anthropogenic warming signal.

KEYWORDS
Armidale, Australian climate, Belfield, data rescue, El Niño Southern Oscillation, meteorology

Dataset

Identifier: http://hdl.handle.net/1959.13/1387620

Creator: Belfield, Algernon and Cultural Collections, Auchmuty Library, University of Newcastle, NSW 2308 Australia

Title: Meteorological observations for Eversleigh Station, near Armidale, New South Wales, Australia: 1877–1922 (transcribed)

Publication year: 2018

Resource type: Dataset

Version: 1.0

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1 | INTRODUCTION

Long-term instrumental meteorological data are crucial for the understanding of natural climate variability and human-induced climate change (Brunet and Jones, 2011). Extended datasets assist in the identification of multi-decadal fluctuations and trends, identify past extreme weather and climate events, improve the development of atmospheric climate models, and assist in the validation and calibration of natural climate proxies that can extend our understanding of the earth's climate back hundreds of years (Gergis and Ashcroft, 2013; Allan *et al*., 2016; Ashcroft *et al*., 2019).

While many places in the Northern Hemisphere have access to daily datasets that stretch back several centuries (e.g. Slonosky, 2002; Camuffo and Bertolin, 2012), data in the Southern Hemisphere are generally only available from the early to mid-20th century (e.g. Morice *et al*., 2012). In Australia, the daily and monthly datasets currently used for the majority of climate research begin in 1900 for rainfall (Jones *et al*., 2009) and 1910 for temperature (Trewin, 2013). Before this time, there are not enough stations with digitized data to adequately represent the entire country. Additionally, temperature observations in particular were not taken in a standardized way (Nicholls *et al*., 1996).

Additional datasets for southeastern Australia extend back to the 1860s (Ashcroft *et al*. 2012, Ashcroft *et al*. 2014b; Timbal and Fawcett, 2013), and even cover the 1788–1860 period in some areas (Ashcroft *et al*., 2014a), but these are on the monthly scale only, prohibiting detailed studies of historical extreme weather events such as heatwaves, severe storms or frosts. Many stations with data for the pre-1900 period are also located along the coastal fringe. The climate of coastal regions is largely affected by local conditions, and so these early records may not fully capture changes in the role of large-scale circulation features that dominate Australia's climate, such as the phases of El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) or the Southern Annular Mode (SAM) (Risbey *et al*., 2009; Gergis and Ashcroft, 2013).

To get a more complete picture of past weather and climate in Australia, long-term inland series of observations on the daily scale are needed. A daily record spanning the second half of the 19th century would be particularly valuable, as it would provide a picture at higher temporal resolution of large swings between wet years of the 1870s and 1890s, and dry conditions around 1888, and through 1897–1903 (Garden, 2009; Gergis, 2018). This period covers several strong ENSO events and is generally considered to be before the majority of warming occurred in Australia (Australian Bureau of Meteorology and CSIRO 2018). Even more valuable would be a dataset taken by the same observer in the same location for an extended period, to minimize the impact of observer changes or site moves on the resultant record.

In this paper, we describe a newly recovered dataset that addresses all of these needs, if only for a small part of the country. In 2011, Richard Belfield found his grandfather Algernon's weather journals in a box in the attic. Algernon's diaries contain daily weather records for his farm *Eversleigh* in the New England region of New South Wales, from 1877 through to shortly before his death in 1922. His meticulous records include temperature, atmospheric pressure, rainfall, wind and cloud cover, as well as general weather comments.

We draw on the skills of an interdisciplinary team to assess the quality and value of Belfield's legacy for climate analysis. In Section 2, we introduce Algernon Belfield, to provide some context for his meteorological record within Australia's colonial scientific community. Section 3 describes the dataset, including metadata we have recovered. In Section 4, we conduct a detailed quality assessment of the observations, including a preliminary homogeneity assessment of some variables using neighbouring stations and reanalysis. We draw our conclusions in Section 5.

2 | BACKGROUND

To assess the quality of the dataset, it is useful to know a little about the observer who recorded the meteorological observations. Algernon Henry Belfield was born in the London suburb of Fulham in December 1838 and was educated at the prestigious Rugby Public School, where he won a number of academic awards (Thornton *et al*., 2018). He arrived in Sydney as an unassisted immigrant on 12 January 1857. Fourteen days later, he is recorded to have been at *Salisbury Court* south of Uralla in the New England region of New South Wales (Figure 1). In 1859, Henry Arding Thomas appointed him as an Overseer at *Saumarez*, a 40,000-hectare property south of Armidale, and in the following year, he was appointed Manager. In 1864, the northern portion of *Saumarez* was subdivided, and Belfield became the lessee/owner of 20,000 acres of what was to become known as *Eversleigh* (Figure 1).

His interest in scientific matters is evidenced by his active participation in the colony's official efforts, organized by the New South Wales Government Astronomer, H.C. Russell (Day, 2007; Douglas, 2007), to observe the 1874 Transit of Venus (Thornton *et al*., 2018). It was Russell who likely introduced Belfield to observing the weather at *Eversleigh*. The men had a semi-professional relationship for several decades, exchanging the occasional letter about astronomical observations, or methodologies for observing the weather (Thornton *et al*., 2018).

In handwritten logbooks, Belfield meticulously recorded meteorological information at 0900, local time, each day between July 1877 and June 1922 from his weather station (see Figure 2). He regularly communicated with the Sydney Observatory, to obtain replacement instruments and to provide monthly statistics of the observations he recorded (see Appendix S1). Given this communication and the detailed

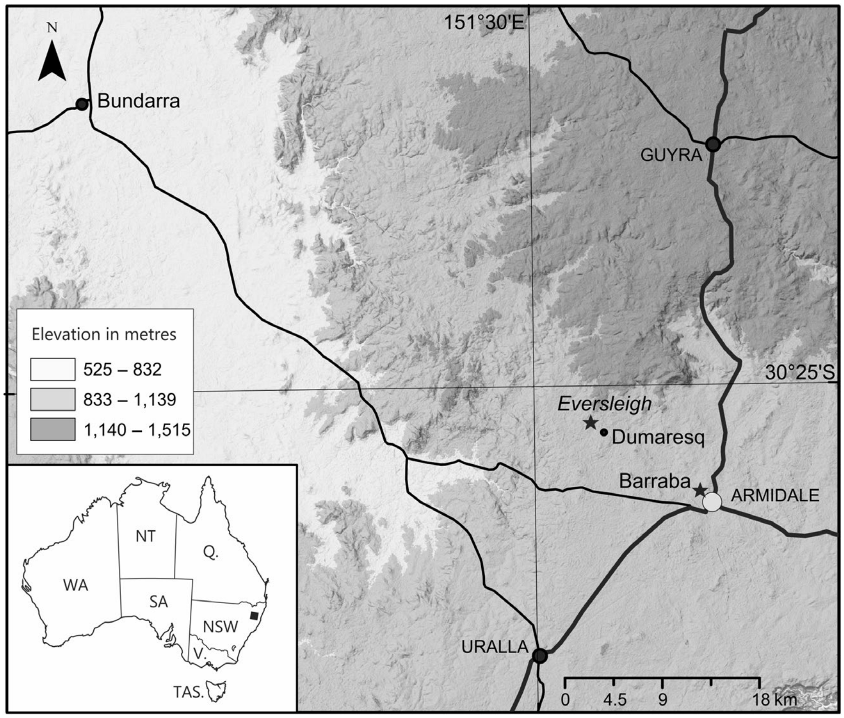

FIGURE 1 Map of NSW highlighting the locations of *Eversleigh* (star), near Armidale in New South Wales, Australia, also showing the terrain. The stations included on the map are included in the discussion below as part of the quality control analysis

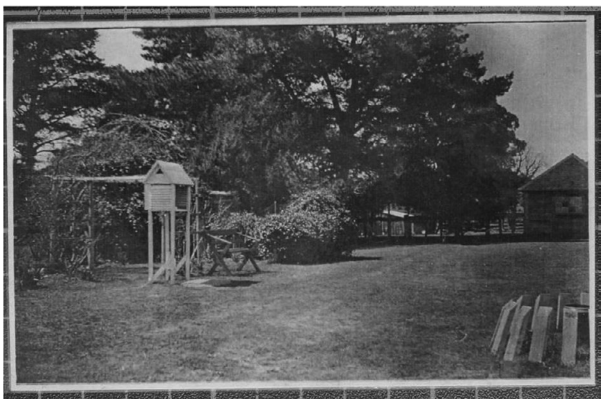

FIGURE 2 The location of the instrument shelter (similar to a Stevenson Screen but with a pitched roof) and rain gauge at *Eversleigh*. The photograph was taken in the early 1920s. Source: Belfield Family

nature of the letters between the two men (Belfield, .), it is likely that Russell provided his meteorological observation handbooks to Belfield (Russell, 1887) and that Belfield followed the recommended procedures carefully.

3 | DESCRIPTION OF THE DATASET

3.1 | Site metadata (available information and limitations)

The Australian Bureau of Meteorology (BOM) meteorological stations are generally accompanied by publicly available files containing metadata that describe features of the observation site and details of the site in situ environment: typically, site location, elevation, the type of instruments used, the observation routine or schedule, and an indication of the site's classification or specific network type. Importantly, the files contain a history of changes to the observing practices at the site (situation, location, nearby construction). The BOM does have daily rainfall data for *Eversleigh* for dataset used in this paper (1877 to 1920) and also monthly rainfall totals for 1877 to 1922. Monthly statistics for several other variables (maximum temperature, minimum temperature, cloud cover, atmospheric station pressure) from 1907 to 1922 are also available online for *Eversleigh* (BOM station number 056056). However, very little metadata are available online for the station.

The dataset used in this paper extends these records back to the middle of 1877, thus providing a 40-year continuous series of variables that are not generally available on the daily scale in the 19th century for Australia. The New South Wales Sydney Observatory Instrument Book entries about instrument exchange for the *Eversleigh* site (National Meteorological Library, MS 19) provide some useful information. The basic metadata we have found for *Eversleigh* are described in Table 1. Additional details about instruments from the New South Wales Instrument book are in Appendix S1. From visits to the farm, information from the Sydney Observatory's annual published rainfall reports, and using Google Maps, an approximation of the site latitude, longitude and elevation were determined The parameters measured by Belfield are given in Table 2, together with a quality assessment indicator we have determined based on the available metadata and using the quality control procedures described in the sections that follow.

The *Eversleigh* details in the New South Wales Instrument book (Appendix S1) state that the measurement period began on 21 June 1877, and the Belfield used a private barometer. This was located in the house on a wall, and evidence from Belfield's Estate papers suggests this was a good-quality mercury barometer. The rain gauge was located out in the open yard (Figure 2). It was baffled to minimize wind influence on rain collected, as suggested by Russell (1887). There is no indication that Belfield used an anemometer or wind vane during the period observations were collected. He initially recorded wind strength using a six-point scale (Russell, 1887), and so it was likely estimated by sight. He may have used a compass to estimate wind direction. The taller trees in the background (see Figure 2) may have caused local wind interference, which would have increased over time.

There is a statement in the Instrument book that Belfield visited the Observatory in 1889 to obtain a replacement for a broken thermometer. According to the Sydney Observatory logbook (Appendix S1), instruments were sent from the observatory to observation sites until 1915. Methods of shipment and transport during the measurement period meant several days could pass before replacement instruments were received, creating small gaps in the record. Belfield's instruments were returned to Sydney in August 1922, about 6 weeks after he died.

3.2 | Data books' description

Belfield recorded his observations in logbooks provided by the Sydney Observatory before 1908, and the Bureau of Meteorology from 1908 onwards (see Figure 3). These were formatted for recording meteorological data. However, on occasion, Belfield recorded his data on sheets of paper with hand-lined columns.

At the end of each month, Belfield compiled a monthly summary report which he included at the end of that month's daily records. While Russell, as the Government Astronomer, had a colony-wide network of weather observers that forwarded data on daily basis via telegraph, it is thought that Belfield was not one of these. Rather, it is likely that he forwarded his data after each month was complete. This assumption is based on the onerous nature of a daily 20 miles (32 km) round trip to a telegraph station (Post Office) in Armidale, and the fact that the *Eversleigh* data do not appear in daily tables published in Sydney newspapers from the late 1870s (Thornton *et al*., 2018).

Changes in procedure used to measure the weather parameters occurred after the Bureau of Meteorology commenced operation in 1908 (Day, 2007), and a new measurement instruction book was issued (Hunt and Commonwealth Bureau of Meteorology 1907). This contained considerably more detail in both siting of instruments and measurement methods and had some other important changes to observation practices. Some new monthly categories were added as follows: totalling days of dew, frost, fog, hail, thunder and lightning, and days of rain. These were recorded faithfully by Belfield. We believe Belfield continued to use a compass to determine wind direction. The instructions in 1907 stated that wind direction was to be recorded using 16 points directions rather than eight as previously recorded. The wind speed categories were also expanded to 12 (Beaufort Scale, Table 3), rather than six. Belfield conformed with both of these changes.

TABLE 1 Basic metadata for *Eversleigh* station details

Locality	New England Plateau, approximately 16 km from Armidale NSW, on a rural farming and grazing property owned by Algernon Belfield (Figure 1).
Latitude	30.443°S
Longitude	151.535°E
Altitude	1,090 m above sea level
Bureau of Meteorology (BOM) station number	056056 (daily rainfall and monthly climate summaries only)
Period of observations	21 June 1877–30 June 1922
Time of observations	0900 daily, determined by chronometer (although Belfield also had a sun dial).

3.3 | Data digitization

The records of meteorological observations from *Eversleigh* were scanned into pdf files and made available online (https://uoncc.wordpress.com/2011/03/09/climate-archive-to-help-predict-extreme-weather-events/). We used Internet-based crowd sourcing (https://theconversation.com/19th-century-weather-data-is-helping-climate-scientists-predict-the-future-57342) to call for volunteers to enter 1 year's worth of daily data into spreadsheets. The monthly summaries were entered into separate spreadsheet files. Twenty-five local and international volunteers were eventually chosen to enter the daily data, with five of the volunteers entering three or more years. Each volunteer was given a formatted spreadsheet to complete (similar to Ashcroft *et al*., 2018 and Vagge *et al*., 2019), a list of instructions, and access to a raw data book through the University of Newcastle file sharing system.

Since the main format of the daily data books and forms used changed in January 1908, two different logbook templates (for 1877–1907 and 1908–1922) had to be prepared and then combined into a single format for overall dataset use. Due to the small size and limited financial support for the project, each year of data was only digitized once; that is, the data were not double-keyed to assist in quality assessment (e.g. Ashcroft *et al*., 2018). However, as we show below, we found very few errors in the digitized data.

TABLE 2 Weather parameters measured at *Eversleigh* and quality evaluation based on data assessment

Parameter measured	Comments	Measurement assessment indicator[c]
Attached temperature to (Private) barometer[a]	ºF, attached to the barometer; used for calculation of pressure	C
Barometer readings	Inches of Mercury	A
Dry-bulb temperature[b]	0900, °F	B
Wet-bulb temperature	0900, °F	B
Maximum temperature (Tmax)	°F, Previous 24 hr	B
Minimum temperature (Tmin)	°F, Previous 24 hr	C
Rainfall	Points (hundredths of an inch), previous 24 hr to 0900	A
Wind direction	Compass direction estimate	C
Wind speed	Six- or 12-point wind scale	C
Cloud cover	Tenths of sky cover	A
Weather description	Brief written comments about conditions (irregular recording)	n/a

[a]The barometer was located inside the house.
[b]A white louvered box housed the thermometers, which was open on the south side, did not meet current Stevenson Screen requirements, but was acceptable at the time (see Figure 2).
[c]Quality assessment codes, modified from BOM standards (Trewin, 2010), are as follows: (A) Excellent, suitable for climatological analysis. (B) Very good, suitable for climatological analysis despite limited metadata. (C) Useable for meteorological analysis, some homogeneity and metadata limitations.

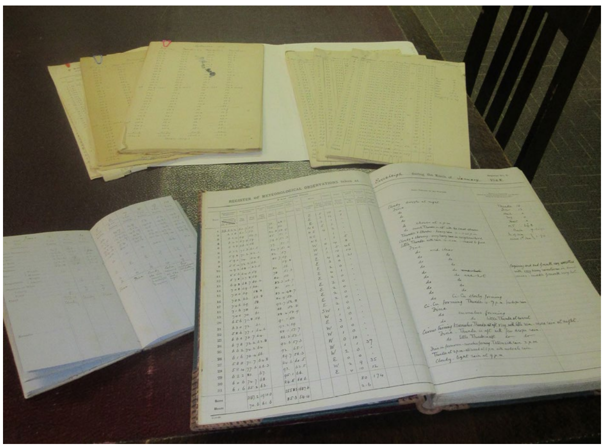

FIGURE 3 Examples of data books and pages used by Belfield to record weather observations

3.4 | Metric transformation

We transformed Belfield data from imperial to metric units using similar procedures to that of Ashcroft *et al* .(2018). All temperature observations were converted from degrees Fahrenheit to degrees Celsius using the standard equation, and rainfall data converted from points (100ths of an inch) to mm. Wind directions were transformed to compass degrees ranging from 0° (North) to 359°. Wind speed values were converted from wind strength categories to an approximation of wind speed following the World Meteorological Organization's Code 1100 (Da Silva *et al.*, 1995). Belfield originally used a 6-point wind strength scale from Russell (1887) before changing to a 12-point scale in April 1904, similar to the Beaufort scale suggested by the Bureau of Meteorology (Hunt and Commonwealth Bureau of Meteorology 1907). The date of this change was noted in Belfield's logbook. We mapped the initial 6-point scale onto the 12-point scale based on common descriptive terms and relative frequency of each scale value (Table 3). Belfield did not estimate wind speeds which were above the equivalent of 'gale force' wind speed in either scales. Such winds would be rare at an inland site, especially at 0900, except perhaps for the occasional gusts associated with thunderstorms (Australian Bureau of Meteorology).

The atmospheric pressure observations were converted from inches of mercury to hectopascals and reduced from station-level barometer readings to sea-level pressure using the Fortin pressure calculation (National Physical Laboratory, 2019) and the hypsometric equation, although similar results were obtained if the Fortin calculation was removed. Belfield recorded a standard barometer correction factor of −.004 inches inside the cover page of several years of his journal which we also applied as part of the reduction procedure. Letters from Belfield to Russell (Belfield, .) suggest that there was some confusion about how to best calculate altitude and derive sea-level pressure values, so it could be that an additional unknown calibration was also applied to the barometer readings.

We assumed that Belfield's barometer was a Fortin mercury barometer as many observations were recorded to three decimal places, a level of accuracy that is not attainable with other mercury barometers such as the Kew barometer (Srivastava, 2008). We used the attached thermometer readings as temperature input and estimated the acceleration due to gravity at *Eversleigh* to be 9.794 m s^{-2} based on its latitude of 30°S.

TABLE 3 Wind strength scales used by Belfield and their conversion to wind speeds

Russell number	Russell descriptor	Beaufort number	Beaufort descriptor	Wind speed approximation (m/s)
0	Calm	0	Calm	0.0
1	Very light	1	Light air	1.0
2	Light	2	Light breeze	2.6
		3	Gentle breeze	4.6
3	Moderate	4	Moderate breeze	6.7
4	Strong	5	Fresh breeze	9.3
5	Very strong	6	Strong breeze	12.3
		7	Near gale	15.4
		8	Gale	19.0
		9	Strong gale	22.6
		10	Storm	28.6
		11	Violent storm	30.9
6	Hurricane	12	Hurricane	35.0

Note: Belfield used the 6-point Russell scale until April 1904, before moving to the 12-point Beaufort scale.

4 | DATA QUALITY CONTROL AND ASSESSMENT

4.1 | Outliers and gross error identification

The crowd-sourced spreadsheet data were checked for quality and accuracy using a combination of manual and automatic inspection techniques, similar to other data rescue activities (e.g. Ashcroft *et al*., 2018; Vagge *et al*., 2019). Table 4 lists the important items we assessed. Initially, line graphs of the data on the daily scale were visually inspected, and individual peaks or troughs cross checked against the original numbers in the log books. Where appropriate, pairs of data parameters (i.e. maximum and minimum temperatures; dry- and wet-bulb temperatures) were graphed together and visually compared. We then subjected the data to additional testing using the RClimDex package with additional quality control checks from the Expert Team of Climate Change Detection and Indices (software and manual available at http://www.c3.urv.cat/softdata.php). The RClimDex-extraQC program provided additional tests for the maximum temperature, minimum temperature and precipitation data (Table 4).

Where discrepancies or incorrect values were identified, we checked the original data in the log books. On very rare occasions, temperatures in the original log books were entered in incorrect columns. After all data quality assurance checks were made, only 0.8% of the overall data had to be corrected or changed. There was also very good agreement between the monthly means calculated by Belfield and those we derived from the daily data ($r > .97$ for all variables). The high quality of these results to us is an indication of the dedication and interest that Belfield had for observing the weather at his property, as well as the reliability of our transcribers.

TABLE 4 Major items for consideration in quality assessment for the *Eversleigh* spreadsheet

Quality assurance checks
• Visual inspection of data for outliers ('peaks and troughs' of time series) • Comparison between monthly means calculated by Belfield and those derived from daily data • Intervariable comparison (maximum and minimum temperatures, wet- and dry-bulb temperatures, dry-bulb temperature and attached temperature) • Duplicate or impossible dates • Identification of wind direction values recorded when wind speed given as zero • Values outside the interquartile range for temperature and rainfall variables (RClimDex-extraQC) • Four or more consecutive identical values (RClimDex-extraQC) • Absolute Outliers: precipitation values greater than 200mm or temperature values greater than 50°C (RClimDex-extraQC) • Jumps: daily differences in maximum and minimum temperature greater than 20°C (RClimDex-extraQC) • Maximum temperature values less than minimum temperature on the same day (RClimDex-extraQC)
Additional items for consideration
• Interpretation of handwriting (i.e. 7 vs. 1) • Blank rainfall values indicating zero rainfall after 1907 • The impact of Algernon Belfield's illness on the data, 1921–1922 (reduced frequency of observations compared the rest of the dataset) • Instrument damage leading to missing data

4.2 | Data biases

An additional test of the quality of daily observations is to assess the last digit of every observation in its original units. Rounding issues such as a tendency towards values ending in

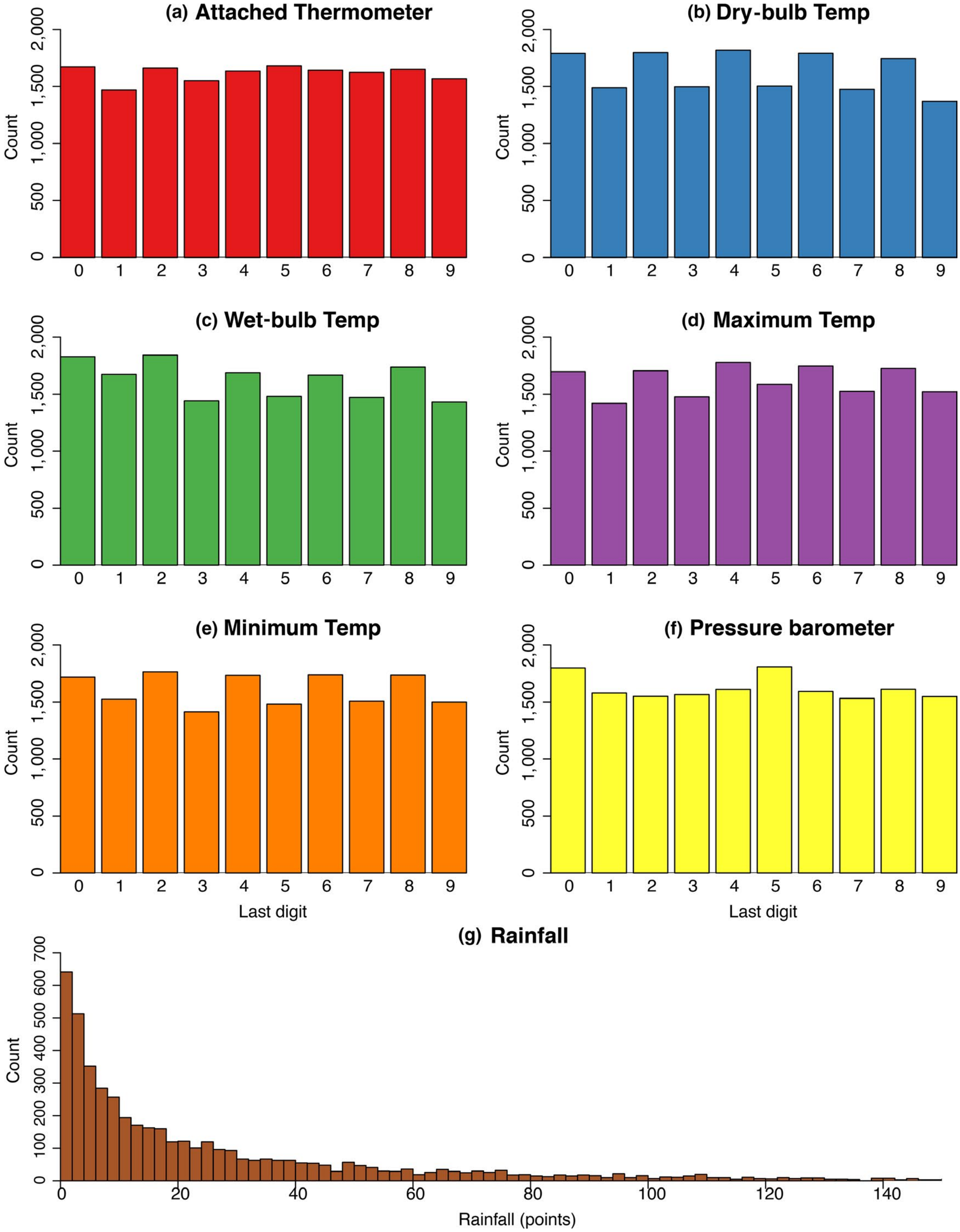

FIGURE 4 (a–f) Histograms of the second to last digit in a range of observations in the *Eversleigh* dataset. (g) Histogram of the *Eversleigh* rainfall observations (points)

0 or 5 are common in manually observed data, and large biases can indicate less than diligent observation practices (Trewin, 2010). Similarly, the distribution of daily non-zero rainfall observations should approximate a negative exponential distribution on an annual scale, with small amounts of rainfall being most common (Daly *et al*., 2007). If this is not the case, then light rainfall events may have not been recorded.

The *Eversleigh* data present a somewhat unusual case, as Belfield often recorded the atmospheric pressure to three decimal places in inches of mercury, and the temperature to one decimal place in °F (e.g. 29.305 mmHg and 83.4°F, instead of 29.30 mmHg and 83°F). This level of accuracy is uncommon in historical data sources, where pressure observations are generally given to two decimal places and temperatures rounded

TABLE 5 Annual, seasonal and monthly correlation between anomalies of related variables in the *Eversleigh* dataset

Variables	Ann	DJF	MAM	JJA	SON	Monthly
Rainfall/Cloud cover	**.82**	**.75**	**.74**	**.75**	**.68**	**.62**
Sea-level pressure/Rainfall	**−.48**	**−.34**	−.22	**−.41**	−.16	**−.18**
Tmax/Tmin	.04	.28	−.02	.15	.28	**.21**
Tmax/Rainfall	**−.62**	**−.63**	**−.67**	**−.34**	**−.54**	**−.43**
Tmin/Rainfall	**.33**	−.05	**.36**	**.63**	.16	**.3**
Dry-bulb temp/Wet-bulb temp	**.73**	**.58**	**.63**	**.87**	**.71**	**.72**
Dry-bulb temp/T_{max}	**.74**	**.81**	**.71**	**.76**	**.83**	**.81**
Dry-bulb temp/T_{min}	**.55**	**.56**	**.51**	**.63**	**.6**	**.56**

Note: Anomalies are calculated using mean values over the 1887–1922 period. Statistically significant correlations are bolded ($p < 0.05$ using the two-tailed Student's t test, taking autocorrelation into account when determining the degrees of freedom).

to the nearest degree due to the gradation of the instruments at the time (e.g. Ashcroft *et al*., 2014a). Plotting these very last digits of the *Eversleigh* data (not shown) revealed that while Belfield did have a high level of accuracy, the vast majority of the additional digits were 0. However, if we look at the second to last value of each observation (e.g. Figure 4), there is only a slight preference towards even values, and a small preference towards values ending and 0 and 5 in the case of the pressure data. The rainfall observations show a clear negative exponential distribution. These results provide further support to our hypothesis that Belfield was a very diligent observer.

4.3 | Intervariable comparison

Descriptive statistics and correlation analysis between related variables and relevant datasets were used to further assess the quality of the data results. To ensure a standard method of describing the data, annual, seasonal and monthly anomalies were calculated for each appropriate parameter, removing the mean value for the observation period. Table 5 summarizes the annual and seasonal correlations between the anomalies of related variables, and we delve into particular relationships below.

4.3.1 | Precipitation, atmospheric pressure and cloud cover

Figure 5 presents annual anomalies of previous 24-hour rainfall (determined at 0900), station-level pressure (hPa), derived sea-level pressure (hPa) and cloud cover (10ths) at 0900. It would be expected that periods of higher rainfall would also be periods of more cloud cover, and this is clear from the figures and the correlations in Table 5.

To determine whether the anomaly variations shown in Figure 5 are representative of more general periods of wet and dry conditions in southeast Australia, the results are compared with descriptive summaries from Gergis (2018). For the *Eversleigh* observation period, 1877 to 1922, Table 6 lists the known years of wet and dry conditions.

Years of lower rainfall and cloud cover (negative anomalies) presented in Figure 5 match the years showing dry anomalies in Table 6. The three strongest dry periods at *Eversleigh* are the 1888 Centennial Drought, the peak of the Federation drought in 1902, and the dry period in 1914–1915. Similarly, the major wet periods (positive anomalies in Figure 5), 1880, and the first half of the 1890s, are also listed in Table 6.

The expected relationship between pressure and precipitation is higher pressure (positive anomalies) with dry conditions and vice versa. The annual results compare very well to the periods listed in Table 6. Higher pressure anomalies occur during the Centennial Drought, the Federation Drought years, and the dry year in 1914. Lower pressure anomalies occur in the wet years of 1879–1880, the first half of the 1890s, and surrounding the dry period of 1914–1915. A comparison of station and derived sea-level pressure also shows good agreement for much of the period, with the largest differences in the early and later part of the record. The differences in the early part of the record may be due to incomplete correction factor information, while the latter is largely due to a step change in the attached thermometer reading (see below).

4.3.2 | Temperature

The temperature data measured at *Eversleigh* were divided into 24-hr (0900 to 0900) maximum and minimum for the previous day, and 0900 dry-bulb and wet-bulb temperatures.

Table 5 and Figure 6 indicate no significant relationship between maximum and minimum temperatures on an annual or seasonal scale. This is not unexpected, as the two variables can be affected by different large and local-scale processes (e.g. Trewin, 2012). Both variables however do show significant correlations with rainfall variability. Dry periods are largely associated with an above average diurnal temperature range with above average maximum temperatures and below average minimums, particularly during the cooler months, as clear skies lead to increased incoming short-wave

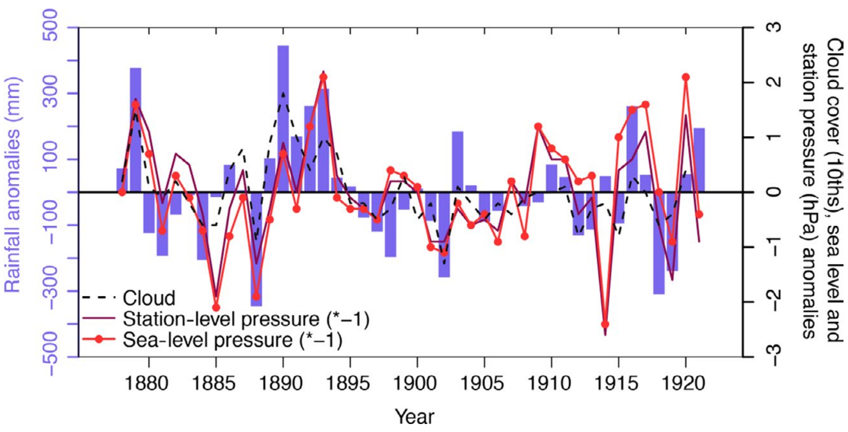

FIGURE 5 *Eversleigh* annual rainfall (blue bars, left y-axis), atmospheric pressure and cloud cover anomalies (lines, right y-axis), 1877–1922. Anomalies are relative to the full period. Note that the sea-level and station-level pressure values have been multiplied by −1 for ease of comparison

TABLE 6 Years or year periods of wet or dry in Southeast Australia between 1877 and 1922 as summarized by Gergis (2018)

Year or period	Dry or wet	Comments (from Gergis, 2018)
1876–1878	Dry	Short sharp drought
1880–1885	Dry	Moderate but prolonged drought
1888	Dry	Centennial Drought
1889–1895	Wet	Series of big rains
1896–1902	Dry	Federation Drought
1902–1913	Mixed	Mild wet and dry years
1914–1915	Dry	Short intense drought

radiation during the day and enhanced cooling at night (Jones and Trewin, 2000). The only exception to this is 1914, where warmer than average minimum temperatures result in a decrease in the diurnal temperature range. Wet periods on the other hand are, generally, associated with a reduction in the diurnal temperature range.

Comparing wet and dry years from Figure 5 with the temperature variability in Figure 6 reveals that for the most part, this relationship holds true. Dry years such as the Centennial Drought in 1888 and the Federation Drought are associated with an increase in the diurnal temperature range, whereas wet years such as 1879 and the early 1890s are associated with a decrease in the diurnal temperature range. Monthly analysis of 1888 in particular (not shown) indicates positive T_{max} anomalies and negative T_{min} anomalies for much of the year. This could be due to the extremely dry conditions experienced that year (Nicholls, 1997), or, given that the thermometer was replaced in early 1889, could suggest some quality issues with the instrument towards the end of its life.

The later part of the record does not show as clear a relationship between temperature and rainfall. Minimum temperature, in particular, seems to show an increasing trend that is not associated with rainfall variability. This finding, as well as a comparison between the *Eversleigh* minimum temperature and data from neighbouring stations (Section 4.4), suggests that there may be some quality issues with this variable.

Figure 7 presents the annual anomalies for wet-bulb, dry-bulb and attached thermometer temperatures at 9 a.m. local time, showing good agreement between them for most of the observation period. An examination of the daily values (not shown) suggests that the absolute wet- and dry-bulb values are more similar in the cooler part of the year than during the warmer months, in keeping with the temperature and humidity climatologies of the New England region (Australian Bureau of Meteorology,). Highly significant relationships are also clear between the dry-bulb temperature and maximum and minimum temperatures (Table 5).

The attached thermometer (indoor, attached to the barometer) temperatures show a clear jump in 1912, which has a flow on effect on the derived sea-level pressure values (Figure 5). Seasonal analysis (not shown) indicates that this step change is confined to the cooler months, particularly June–August, suggesting that a) the barometer (and attached thermometer) was moved closer to an internal heat source like a fire, or b) that Belfield changed the internal heating at *Eversleigh* in 1912.

Figure 7 indicates a positive trend of around 1°C in the 9 a.m. dry-bulb and wet-bulb temperatures from around 1895 to 1905, consistent with the increase in minimum temperature. The dry-bulb temperature in particular seems to show a step change around 1895 that is evident in Figure 7 and in seasonal difference plots, particularly during December–May (not shown). This step change, and the positive dry-bulb temperature anomalies around 1914 and 1915, may be associated with the onset of dry period, as a change in surface cover (i.e. from watered green grass to dry earth) can impact temperatures in the dry part of the year (Trewin, 2012). It may also indicate some drift in the quality of these observations, perhaps associated with changes in vegetation at the site that could lead to increased sheltering of instruments. The coincident positive trend in the minimum temperature data appears to

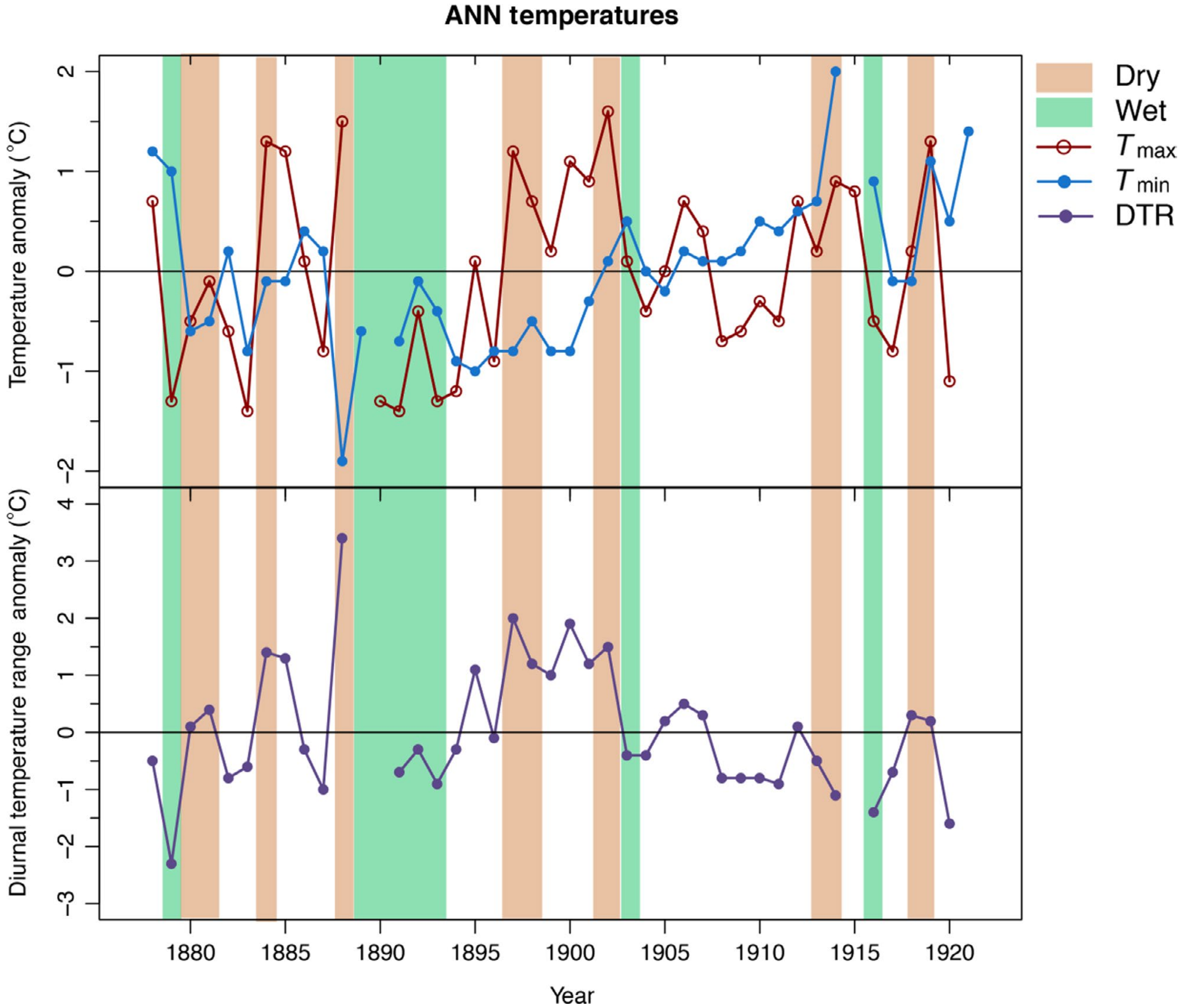

FIGURE 6 *Eversleigh* annual maximum (T_{max}, red) and minimum (T_{min}, blue) temperature anomalies (top figure), and diurnal temperature range (DTR, bottom) anomalies 1877–1922. Years with rainfall anomalies greater than or less than 100 m are marked in green and brown, respectively, to represent local wet and dry conditions

support this. There is no evidence of instrumentation issues with the wet-bulb or dry-bulb thermometers (Appendix S1).

4.3.3 | Wind speed and direction

A time series assessment of the wind observations revealed a dramatic change in 1908 with wind speeds dropping by around 1 m/s and a 40º change in wind direction. This is clear in Figure 8, with a reduction in northwesterly observations and an increase in calm and westerly wind observations. The newer requirement by the BOM to record wind in 16 compass directions rather than eight has likely created this change in the wind direction, although interestingly the change in wind speed measurements from a six-point scale to a 12-point scale occurred in April 1904 and there is actually an increase in cardinal observations during the second part of the observation period. These results also support the reality of gradual sheltering of the site over time, although the there may also be some quality issues in the *Eversleigh* wind observations due to a change in observation techniques. This is not overly surprising, as wind data are notoriously sensitive to changes in observing methods and local features (Jakob, 2010).

Overall, Table 2 ranks the quality of the measured meteorological data from excellent (A) to unsuitable for climatological analysis in their current form (C). All measured parameters are rated A or B except the wind data, attached thermometer and minimum temperature, which show a trend or step change that is at odds with the behaviour of other related variables. Most major anomaly variations in other variables can be related to periods of wet and dry shown in Table 3. This result indicates that the reasons for the variations in the annual anomalies are largely associated with natural changes in circulation patterns of climate (Gergis, 2018).

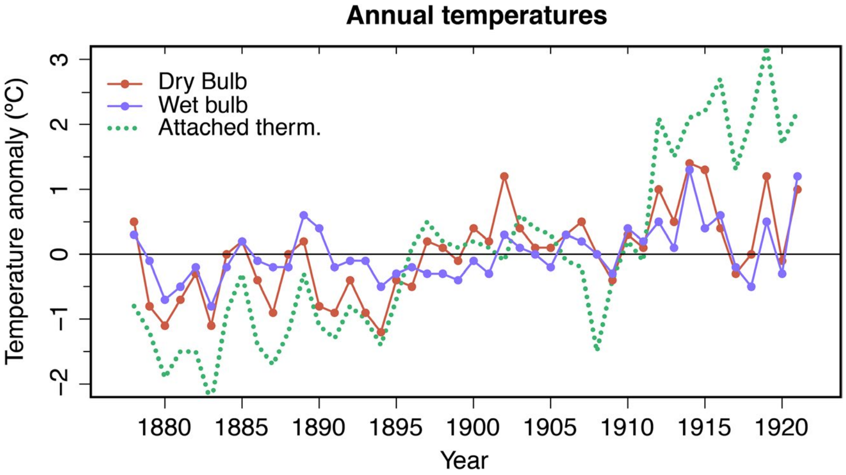

FIGURE 7 *Eversleigh* annual 9:00 a.m. dry-bulb, wet-bulb and attached thermometer temperature anomalies, 1877–1922

While some palaeoclimate studies suggest that the fingerprint of human-induced atmospheric warming can be seen in Australia at the start of the 20th century (Abram et al. 2016), further analysis would be required to determine whether the *Eversleigh* dataset is affected by increases in industrial greenhouse gas concentrations.

4.4 | Relationships to other datasets

Due to the lack of consistent measured data from other nearby locations during the 1877 to 1922 period, it is only possible to compare rainfall, and maximum and minimum temperatures from *Eversleigh* with neighbouring stations. Table 7 presents linear correlation R^2 results for annual rainfall totals between *Eversleigh* and the five nearest locations, all of which are on the New England Plateau (see Figure 1). These five datasets are all shorter in the time period than the *Eversleigh* data. Armidale is also the closest site to *Eversleigh* geographically, but is 200m lower in altitude. The highly significant correlation results (.70 to .81), despite the differences in stations' altitude, further show the representativeness and value of the *Eversleigh* measurements for the area.

Overlapping maximum and minimum temperature data were only available for Armidale, although these have been homogenized by Ashcroft *et al*. (2012). Figure 9 compares the seasonal cycle of the two stations, while Figure 10 shows the maximum and minimum temperature anomalies from the homogenized Armidale data and the *Eversleigh* dataset.

The seasonal cycles agree very well, although the *Eversleigh* maximum temperature cycle is slightly more elongated than that of Armidale. This could be due to genuine climatic differences between the two locations, with increased exposure leading to warmer summers and cooler winters, or may be an indication of slightly sub-standard instrument siting (Nicholls *et al*., 1996). However, based on our assessment, the *Eversleigh* observations are highly representative of the location. The minimum temperature curves are very similar, with *Eversleigh* consistently cooler than Armidale. This again could be due to the higher altitude and

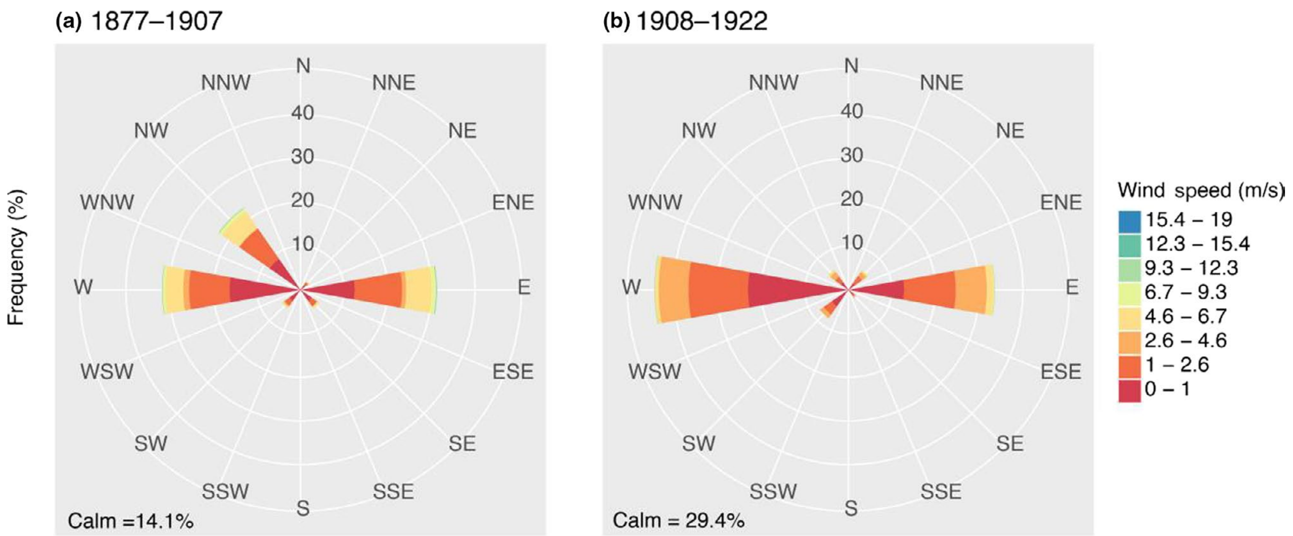

FIGURE 8 Wind roses of 0900 observations at Eversleigh for (a) 1877–1907 and (b) 1908–1922

TABLE 7 Correlations between annual rainfall at *Eversleigh* compared to five nearest Bureau of Meteorology stations (see also Figure 1)

Station	Altitude (m)	Approx distance/direction from Eversleigh	Period of record	Linear correlation R^2
Armidale (056002)	980	15 km SEbE	1882–1922	.81
Uralla (056034)	1,016	22 km SbW	1902–1922	.82
Barraba (054003)	500	90 km W	1882–1922	.71
Bundarra (056006)	610	56 km NWbW	1884–1922	.70
Guyra (056016)	1,320	29 km NNE	1887–1922	.84

local topography of *Eversleigh* leading to colder nights, or a symptom of instrument exposure that is more similar to a Glaisher thermometer stand, which is open on one side like Algernon's, than to a modern Stevenson screen.

Monthly and annual correlations between the two series are significant throughout the year, although minimum temperature observations are more highly correlated during the cooler months. Figure 10 shows the good agreement between the *Eversleigh* and Armidale maximum temperature, with an annual correlation of .54, and monthly correlations ranging from .44 (August) to .88 (September). The minimum temperatures however do not agree as well, particularly before the early 1900s. The annual correlation between the two is .37, with generally weaker correlations for the warmer months (.36 in January) and stronger in the cooler months (.77 in both May and September). Figure 10 shows a clear positive trend in the Eversleigh minimum temperature data between the late 1880s and early 1910s that is not present in the homogenized or raw Armidale data (raw data not shown). This suggests that there may be some quality issues in the minimum temperature data that need to be considered before conducting climatological analysis.

Finally, we also examined the correlations between monthly *Eversleigh* data and values from the nearest grid box of the 20th Century Reanalysis ensemble mean (Compo *et al*., 2011) during the 1882–1922 period when the ensemble mean becomes closer to observations over southeastern Australia (Ashcroft *et al*., 2014b). Correlations are significant for all variables but particularly high for mean sea-level pressure (.83) and maximum temperature (.52). Minimum temperature and rainfall correlations are weaker but still significant (.40 and .42, respectively), reflecting the possible inhomogeneity of the *Eversleigh* minimum temperature data as well as the greater spatial variability of both variables.

5 | CONCLUSIONS

In this paper, we have introduced a high-quality meteorological dataset from the *Eversleigh* property near Armidale, New South Wales, Australia. Parameters measured included atmospheric pressure; previous 24-hour rainfall and maximum and minimum temperatures; temperature, wet-bulb temperature and cloud cover at 0900; and wind direction and wind speed. The data were recorded by grazier Algernon Belfield between 1877 and 1922, at 0900 on virtually every day, in handwritten logbooks. He followed procedures established by the NSW State Astronomer between 1877 and 1907, and the newly created Australian Bureau of Meteorology between 1908 and 1922. Crowd-sourced volunteers entered the raw data into spreadsheets, which were then assessed for entry accuracy by three members of the research team. Belfield's dedication meant that only 0.8% of the data needed to be adjusted or corrected.

The final dataset was then assessed for quality using annual and seasonal anomalies (compared to the 45-year

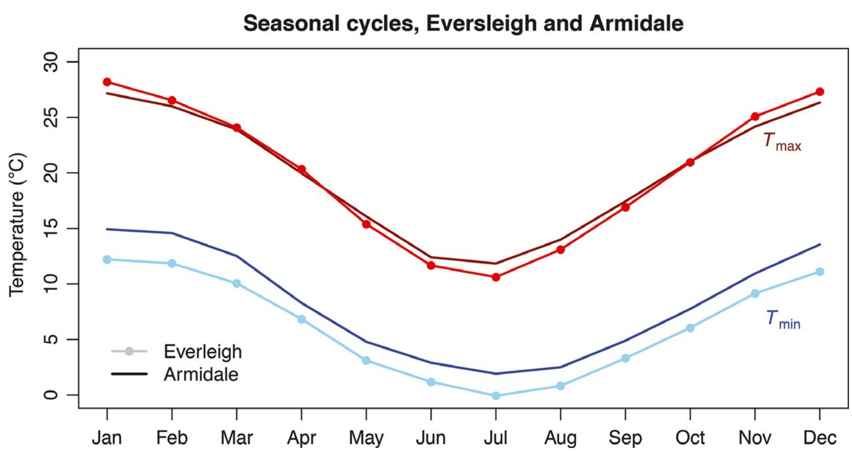

FIGURE 9 The average seasonal cycle of maximum and minimum temperatures for Eversleigh (1877–1922) and the homogenized Armidale (1860–1950)

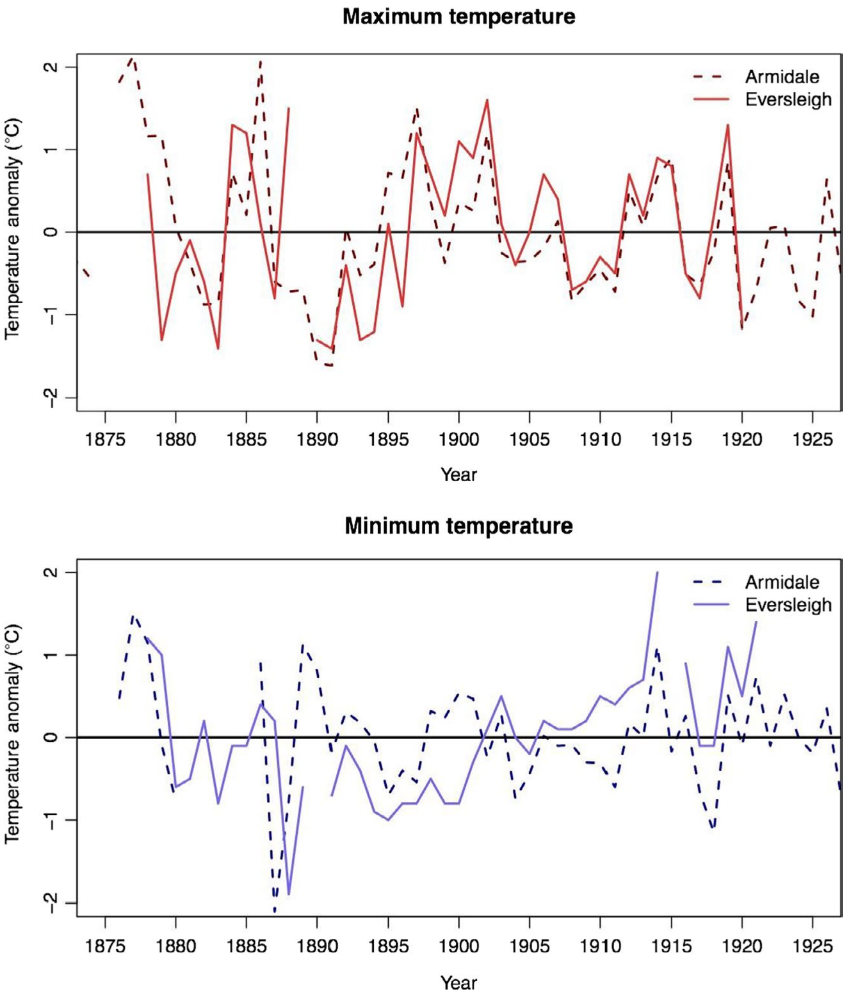

FIGURE 10 Maximum (top) and minimum (bottom) temperature anomalies for Armidale (dashed lines) and *Eversleigh* (solid lines), 1875–1925 using homogenized Armidale data from Ashcroft et al. (2012). Anomalies are relative to the 1877–1922 mean

average). The year-to-year anomaly variations were compared to known periods of wet and dry conditions as summarized by Gergis (2018), reanalysis data and homogenized historical observations of a similar region. The use of anomalies also allowed identification of measurement interferences due to outside influences, such as changes in measurement procedure.

All data except the wind measurements, attached thermometer and minimum temperature were considered of high enough quality to be used in the assessment of climate variability (rank A or B in Table 2). Periods of dry conditions, such as the Centennial Drought in 1888 and the Federation Drought from 1895–1903, and wet (the first half of the 1890s), were clearly seen in both the annual and seasonal anomalies of rainfall and temperature, although there are some remaining concerns about the quality of the maximum and minimum temperature data in 1888.

Wind direction was strongly affected by the change in procedures from 8 to 16 compass directions from 1908 onwards and may also have been influenced by vegetation growth interference. The minimum temperature observations, while diligently taken, appear to have a non-climatic positive trend for part of the observing period. The attached thermometer readings also suffer from a step change in 1912 largely confined to the cooler months, suggesting increased exposure to a heat source inside.

Despite these limitations, the *Eversleigh* data provide a valuable set of observations for the period before clear human influence on the climate system. The dataset, virtually complete on a daily basis over a 40-year period, offers a new and highly detailed insight into daily variability in a region of the world that is sorely lacking in historical weather data, but that shows strong co-variability with global climate drivers. To that end, the *Eversleigh* record has now been added to the International Surface Pressure Databank (ISPD, Cram *et al*., 2015) to further improve representation of Australian climate in the next generation of 20th Century Reanalysis (Compo *et al*., 2011). Future work will also use the newly recovered observations to assess the historical impact of large-scale circulation features on weather and climate extremes in the New England region.

ACKNOWLEDGEMENTS

We would like to thank Richard and Elspeth Belfield, descendants of Algernon Belfield, for access to the Weather data books, and for considerable support in developing this project. The scanning of the original data books and the organization of access for this project was supported by the University of New England Heritage Centre and the University of Newcastle Cultural Collections.

We also thank our 25 data entry volunteers, who provided excellent results and minimized our data correction tasks. We are very grateful to Blair Trewin, Katie Rosamond, the managing editor and two anonymous reviewers, whose valuable feedback helped improve this manuscript. The scanning of the original data books and the organization of access for this project was supported by the University of Newcastle Cultural Collections and the University of Newcastle Heritage Centre. Olivier Rey Lescure from the University of Newcastle provided the map for Figure 1. Dr Ashcroft was partially funded from the Australian Academy of Science Moran Award for History of Science.

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How to cite this article: Bridgman H, Ashcroft L, Thornton K, Di Gravio G, Oates W. Meteorological observations for *Eversleigh* Station, near Armidale, New South Wales, Australia: 1877–1922. *Geosci. Data J.*. 2019;6:174–188. https://doi.org/10.1002/gdj3.80