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A historical climate dataset for southeastern Australia, 1788–1859

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There is a significant lack of historical climate data in the Southern Hemisphere compared to the northern latitudes. To address this data scarcity and to improve understanding of regional climate variability, historical instrumental observations were recovered for southeastern Australian (SEA) for the 1788–1859 period. Instrumental observations of temperature, atmospheric pressure, rainfall and raindays were rescued from 39 archival sources, and examined to identify observer biases and inhomogeneities. The rescued data provide continuous information on SEA climate variability from 1826 to 1859, with short periods of observations identified between 1788–1791, 1803–1805 and 1821–1824. Quality control and homogenization of each data source indicates that the historical observations successfully capture regional interannual climate variability. The historical records exhibit high correlations between neighbouring observations and related climate variables. The instrumental observations also display very good agreement with documentary climate reconstructions, further verifying their quality. As an example of how this new historical dataset may be used, regional averages of the observations were calculated to estimate interannual climate variability across SEA from 1826 to 1859. Prolonged dry conditions were identified in various parts of the region during 1837–1843 and 1845–1852, while wet conditions were noted from 1836 to 1838, primarily in southern SEA. Anomalously cold periods were also identified in 1835–1836 and 1848–1849, in general agreement with temperature reconstructions from other regions of the Southern Hemisphere. This new dataset provides a valuable source of subdaily to monthly information on SEA climate variability for future climate analysis, palaeoclimate reconstruction verification and historical studies.

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Dataset

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Introduction

Extended datasets of instrumental meteorological observations are important for the study of climate variability, and the detection and attribution of anthropogenic climate change (Jones and Mann, 2004; Brázdil *et al.*, 2010). They are also vital for the verification and calibration of proxy climate data sources, such as palaeoclimate reconstructions (Brohan *et al.*, 2012) and documentary records (Brázdil *et al.*, 2010).

Historical meteorological records have been used in many regions of the Northern Hemisphere to examine multi-centennial changes in temperature (e.g., Manley, 1974), atmospheric circulation features (e.g., Jones *et al.*, 1997) and rainfall variability (e.g., Auer *et al.*, 2005). In contrast, the Southern Hemisphere is largely under-represented in the field of historical instrumental data research (Compo *et al.*, 2006; Gergis *et al.*, 2010a; Grab and Nash, 2010; Jones *et al.*, 2012; Nash and Adamson, 2014). Later colonial settlement dates and restricted geographical coverage means that most instrumental climate datasets for the southern latitudes begin in the early to mid-20th century (Garreaud *et al.*, 2009; Jones *et al.*, 2012; Trewin, 2013). There are only a few instrumental climate studies from individual towns or regions that include the 18th and 19th centuries (e.g., Können *et al.*, 1998; Gergis *et al.*, 2009; Farrona *et al.*, 2012).

This lack of historical instrumental data for the Southern Hemisphere severely limits understanding of long-term climate variability in the region, hampering efforts to isolate any anthropogenic or low-frequency natural variability that may have occurred (Power *et al.*, 1998; Compo *et al.*, 2011; Jones *et al.*, 2012). There is therefore a need to recover instrumental climate observations, to improve understanding of Southern Hemisphere climate variability (Gergis *et al.*, 2010a; Chappel and Lorrey, 2013).

Southeastern Australian (SEA) is one region of the Southern Hemisphere that has potential to provide long instrumental climate records. The area was settled by Europeans in 1788 (MacIntyre, 1999), and historical meteorological observations have been identified for many parts of the region extending back to the late 18th century (Russell, 1877; Gentilli, 1967; McAfee, 1981; Williams, 1984; Nicholls *et al.*, 2006; Gergis *et al.*, 2009; Gergis and Ashcroft, 2013).

Ashcroft *et al.* (2012, 2014) and Timbal and Fawcett (2012) have recently constructed SEA temperature, pressure and rainfall datasets covering 1860 to the present day. These networks provide an additional 50 years of historical information compared to the 20th and 21st century datasets currently used in Australian climate research (Jones *et al.*, 2009; Trewin, 2013). Rainfall reconstructions have also been developed for the European settlement period using palaeoclimate and documentary sources (Gergis *et al.*, 2012; Fenby and Gergis, 2013). Combined with early instrumental rainfall data, the reconstructions allowed for the first comparison of Australian instrumental, palaeoclimate and documentary rainfall records to span the full period of European settlement (Gergis and Ashcroft, 2013).

Despite these efforts, and several attempts to locate and digitise historical meteorological observations for SEA (McAfee, 1981; Reid, 1997), the majority of records have remained in archives, and have not been assessed for their meteorological value. Uncovering SEA climate data for the pre-1860 period extends the recently completed 1860 – present records, enabling a (discontinuous) instrumental analysis of SEA climate variability over the full period of European settlement in Australia. Historical instrumental records for the Australian region also provide a dataset for comparison with natural proxy and documentary climate reconstructions from other parts of the Southern Hemisphere (Neukom *et al.*, 2009; e.g., Nash and Grab, 2010; Grab and Nash, 2010; Neukom *et al.*, 2013).

This study locates, compiles and analyses instrumental meteorological observations for SEA from 1788 to 1859. The spatial and temporal coverage of the historical records are examined first, followed by an assessment of the quality of the historical data. Next, the rescued instrumental observations are combined to describe interannual eastern and southern SEA climate variability from the start of continuous observations in 1826 until 1860. The instrumental climate data are compared to documentary records of climate variability during the same period (Fenby and Gergis, 2013), expanding the Gergis and Ashcroft (2013) analysis of instrumental and documentary rainfall data for SEA.

It is not the aim of this study to reconstruct absolute temperature, pressure and rainfall values across SEA since European settlement in 1788. As the following sections will show, the quality of the historical observations before 1860 makes it difficult to assign precise values to a particular month or year during the first 72 years of European settlement, even after careful consideration of inhomogeneities (Slonosky, 2003; McGuffie and Henderson-Sellers, 2012). Instead, the goal here is to analyse the relative variability of the historical climate data to identify periods of warm, cool, dry and wet conditions across SEA prior to more widespread observations from 1860.

1. Historical data sources

Potential sources of historical instrumental climate data for SEA were identified from the detailed studies of Russell (1877), Gentilli (1967), McAfee (1981) and Williams (1984). These compilations describe the history of meteorological observations in Australia, and contain precise information on the existence and location of pre-1860 SEA climate data sources. The search for SEA historical records was limited to stationary, land-based temperature, rainfall and atmospheric pressure data, as these observations are the most commonly available (Nicholls *et al.*, 2006) and could be combined with the post-1860 datasets developed by Ashcroft *et al.* (2012, 2014). Rainday counts were also extracted from any weather remarks that accompanied daily instrumental data, to provide additional rainfall information.

Subdaily, daily and monthly observations were located, in the national and state libraries and archives of Victoria (VIC) and New South Wales (NSW), Australia. Subdaily and daily data were used to calculate monthly means for subsequent climate analysis. Only sources with more than 1 year of data were chosen for further examination, apart from several historically significant records, such as the first meteorological observations taken in the cities of Sydney and Melbourne (Reid, 1992; Gergis *et al.*, 2009). Several data sources had already been located and digitised by other researchers, and were obtained in digitised form only (see Table 1). Records from the London Royal Society also yielded a number of very early (pre-1830) sources (McAfee, 1981). Additional records were identified in the state archives of Tasmania (TAS) and South Australia (SA), but were not collected due to time and financial constraints.

Historical temperature observations were converted from degrees Fahrenheit to degrees Celsius, and rainfall observations were converted from inches to millimetres. Pressure observations were converted from inches of mercury to hectopascals, and station level pressure observations were then reduced to mean sea level pressure (MSLP) values using the hypsometric equation (Wallace and Hobbs, 2006). The hypsometric equation requires air temperature data, which are often taken as the temperature values from a thermometer attached to the recording barometer. If there were no published attached thermometer readings then external thermometer values were used, following Brohan *et al.* (2012).

A concerted effort was made to locate metadata about each historical record, such as the observatory location, instrument exposure and the name and occupation of the observer. This information is valuable for the assessment of the nature and quality of meteorological observations (Peterson *et al.*, 1998). For many sources, it was possible to determine the approximate location that the observations were taken using information from local historical societies. Some sources also provided comprehensive descriptions of the instruments used, or how the observations were taken. Many others, however, did not provide any information at all (see Table 1).

A total of 39 historical meteorological data sources were recovered for SEA (Table 1). The temporal and spatial coverage of the observations (Figures 1 and 2) largely reflect historical population settlement patterns in SEA. Records before the mid-1830s are limited to the Sydney region of NSW and penal colonies in TAS (known as Van Diemen's Land until 1856). Settlement, and consequently the spatial coverage of meteorological observations, slowly expand to the southern states of VIC and SA from the late 1830s (MacIntyre, 1999).

The occupations of each observer (Table 1) reveal the changing motivations behind meteorological observing in colonial SEA. Many of the observers were scientific men, indicating that they were familiar with meteorological theories of the time, and the need for consistent instrument exposure. A number of the pre-1860 observations come from astronomical observatories, showing the close ties between the studies of meteorology and astronomy in the colonial period (Home and Livingston, 1994; Golinski, 2007). The importance of meteorology for marine safety was also a contributing factor to the development of the SEA meteorological network, and a number of stations were set up to monitor coastal weather conditions (Gentilli, 1967; McAfee, 1981). The 18th and 19th century theories connecting climate and human health (e.g., Golinski, 2007) additionally encouraged doctors in SEA to take meteorological observations. It was not until the mid-1840s that farmer's observations emerged, showing an increasing awareness of the highly variable nature of the SEA climate, and the need to improve understanding of rainfall variability for agricultural success (Fenby and Gergis, 2013).

Figure 2 shows the temporal coverage of the recovered observations in each modern state of SEA. Continuous temperature and pressure observations are available from 1826 in Sydney, NSW, with additional isolated sources of data available for 1788–1791, 1803–1805 and 1822. The year 1822 presents a particularly interesting case study, as subdaily observations from short-lived stations along the eastern coast of SEA have been rescued for that year. Rainfall observations begin in 1832 in NSW, and are available for all subsequent years except 1839, when records from the Parramatta Observatory (source number 14 in Table 1) cease but observations at Port Jackson (source 23) have not yet begun. The number of raindays in the Sydney region can be obtained from July 1826, providing an additional source of rainfall information.

Rainfall records from TAS began in 1835, with observations from SA and VIC commencing in 1839 and 1840. Rainfall data also exist for Brisbane, Queensland (QLD), for 1840–1850. Pressure and temperature observations in the three southern states then began in late 1830s or early 1840s with a small gap in Victorian observations from 1852 to mid-1853. This includes a lack of Melbourne observations from 1852 until 1855, when official observations recommenced in the state capital city (Gentilli, 1967).

2. Data quality control and homogenization

All observational climate data require quality control and homogenization to ensure that the data are reflecting real climate variations rather than the influence of non-climatic factors (Peterson *et al.*, 1998). This is particularly the case for historical observations that have not been taken using modern standards and techniques (Brázdil *et al.*, 2010). The heterogeneous nature of historical SEA climate data meant that conducting quality control and homogenization required a certain amount of manual analysis. Clear errors were first removed, and sources of daily and fixed hourly data examined for observer bias. Next, detailed metadata were used in conjunction with data comparison and statistical analysis to adjust several inhomogeneities.

2.1. Quality control

Each data source was visually examined to identify any outliers or gross typographical errors that may have been made in the original observations or in the digitisation process. Errors were generally easily identified by a visual comparison of observations recorded

Table 1. Details of the 1788–1859 southeastern Australia historical climate data sources.

No	Source name	Observer occupation	State	City	Start date		End date		Frequency	Variable				Metadata availability
										T	P	R	RD	
1788–1799														
1	Bradley, William (HMS Sirius)	Naval officer	NSW	Sydney	January	1788	September	1788	Daily	1	1	0	0	3
2	Dawes, William	Astronomer	NSW	Sydney	September	1788	December	1791	Daily	1	1	0	1	3
1800–1820														
3	Sydney Gazette and New South Wales Advertiser	Unknown	NSW	Sydney	March	1803	May	1805	Daily	1	1	0	1	1
1821–1840														
4	Goulburn, Frederick	Colonial secretary	NSW	Sydney	May	1821	April	1822	Daily	1	1	0	1	1
5	Port Macquarie	Unknown	NSW	Port Macquarie	January	1822	December	1822	Daily	1	1	0	1	0
6	Hobart town	Unknown	TAS	Hobart	February	1822	December	1822	Daily	1	1	0	1	0
7	Sydney Hospital	Military officers	NSW	Sydney	April	1822	March	1823	Daily	1	1	0	1	1
8	Macquarie Harbour	Unknown	TAS	Macquarie Harbour	April	1822	January	1823	Daily	1	1	0	1	0
9	Parramatta	NSW Governor, amateur astronomer	NSW	Parramatta	May	1822	March	1823	Daily	1	1	1	1	1
10	Brisbane, Thomas	NSW Governor, amateur astronomer	NSW	Parramatta	May	1822	March	1823	Monthly	1	0	1	0	1
11	Sydney Gazette	Unknown	NSW	Parramatta	April	1823	March	1824	Monthly	0	0	1	0	0
12	Sydney Monitor	Unknown	NSW	Sydney	July	1826	December	1841	Daily	0	1	0	1	0
13	Sydney Herald	Unknown	NSW	Sydney	April	1831	July	1838	Daily	0	1	0	1	0
14	Dunlop, James*	Astronomer	NSW	Parramatta	January	1832	December	1844	Monthly	0	0	1	0	1
15	Milligan, Joseph	Doctor	TAS	Hampshire Hills	January	1835	December	1839	Monthly	0	0	1	0	1
16	Fawkner, John Pascoe	Explorer	VIC	Melbourne	November	1835	July	1836	Daily	0	1	0	1	2
17	Robinson, George Augustus	Chief Protector of Aboriginals	TAS	Flinders Island	January	1836	December	1839	Daily	0	1	0	0	1
18	Lempriere, Thomas	Public official	TAS	Port Arthur	May	1837	December	1842	Daily	1	1	1	1	2
19	Wyatt, William*	Doctor	SA	Adelaide	January	1838	December	1847	Monthly	1	1	0	1	1
20	Kingston, George Strickland	Surveyor, politician	SA	Adelaide	January	1839	December	1879	Daily	0	0	1	1	2
21	Chronicle	Unknown	NSW	Sydney	December	1839	May	1848	Daily	0	1	0	1	0
22	Wickham, John	Naval officer	QLD	Brisbane	January	1840	December	1850	Monthly	0	0	1	0	3
23	Edward Peacock, Port Jackson Government Gazette*	Trained convict	NSW	Sydney	April	1840	December	1855	Monthly	1	1	1	1	3
24	Port Phillip Government Gazette	Trained convict	VIC	Melbourne	July	1840	June	1851	Monthly	1	1	1	1	1

(continued)

Table 1. (continued).

No	Source name	Observer occupation	State	City	Start date	End date	Frequency	Variable T	P	R	RD	Metadata availability
25	Port Macquarie Government Gazette	Trained convict	NSW	Port Macquarie	August 1840	November 1851	Monthly	1	1	1	1	1
26	Hobarton Observatory	Astronomers	TAS	Hobart	January 1841	December 1848	Daily	1	0	0	0	2
27	Abbott, Francis	Watchmaker, amateur meteorologist	TAS	Hobart	January 1841	December 1870	Monthly	1	1	1	0	3
1841–1860												
28	Stevens, Charles	Schoolmaster	NSW	Dooral	November 1841	December 1846	Daily	0	1	1	1	1
29	Purser, Edward	Soldier	NSW	Castle Hill	February 1842	September 1844	Daily	0	1	1	1	1
30	King, Phillip Parker	Naval officer, hydrographer	NSW	Port Stephens	January 1843	December 1847	Monthly	1	1	1	0	1
31	Adelaide Survey Office*	Unknown	SA	Adelaide	April 1843	December 1851	Monthly	1	1	0	0	0
32	Waugh, James	Farmer	NSW	Jamberoo	June 1843	June 1847	Daily	0	1	0	1	1
33	Watson, David	Schoolmaster and clerk	NSW	Campbelltown	November 1845	November 1847	Daily	0	1	1	1	1
34	Pugh, William Russ	Doctor	TAS	Launceston	August 1846	December 1849	Daily	1	1	1	1	1
35	Portland Guardian	Unknown	VIC	Portland	March 1849	August 1851	Daily	0	1	0	1	0
36	Cape Otway Government Gazette	Unknown	VIC	Cape Otway	January 1851	December 1851	Monthly	1	1	1	0	0
37	Slade, Edgar	Policeman, horticulturalist	VIC	Alberton	July 1853	January 1857	Daily	1	1	1	1	1
38	Sydney Morning Herald	Trained convict	NSW	Sydney	January 1855	November 1856	Daily	1	1	1	1	3
39	Jevons, William Stanley	Gold assayer, amateur meteorologist	NSW	Sydney	August 1856	4 1858	Daily	1	1	1	1	2

Sources marked with an asterisk were obtained in digital form only. In the ‘Frequency’ column, ‘Daily’ indicates that at least one observation was taken each day. ‘Monthly’ means that only monthly summaries or totals are available. In the ‘Variable’ column, P represents atmospheric pressure, T represents temperature, *R* represents numerical rainfall values and RD represents rainday counts. A number 1 means the variable is available from a source, while a 0 means it is not. In the ‘Metadata availability’ column, a 0 indicates no metadata, a 1 indicates either the observer, instrument location or instrument type is known. A 2 or 3 indicate that two or three of these pieces of information have been determined. Additional metadata are given with the dataset.

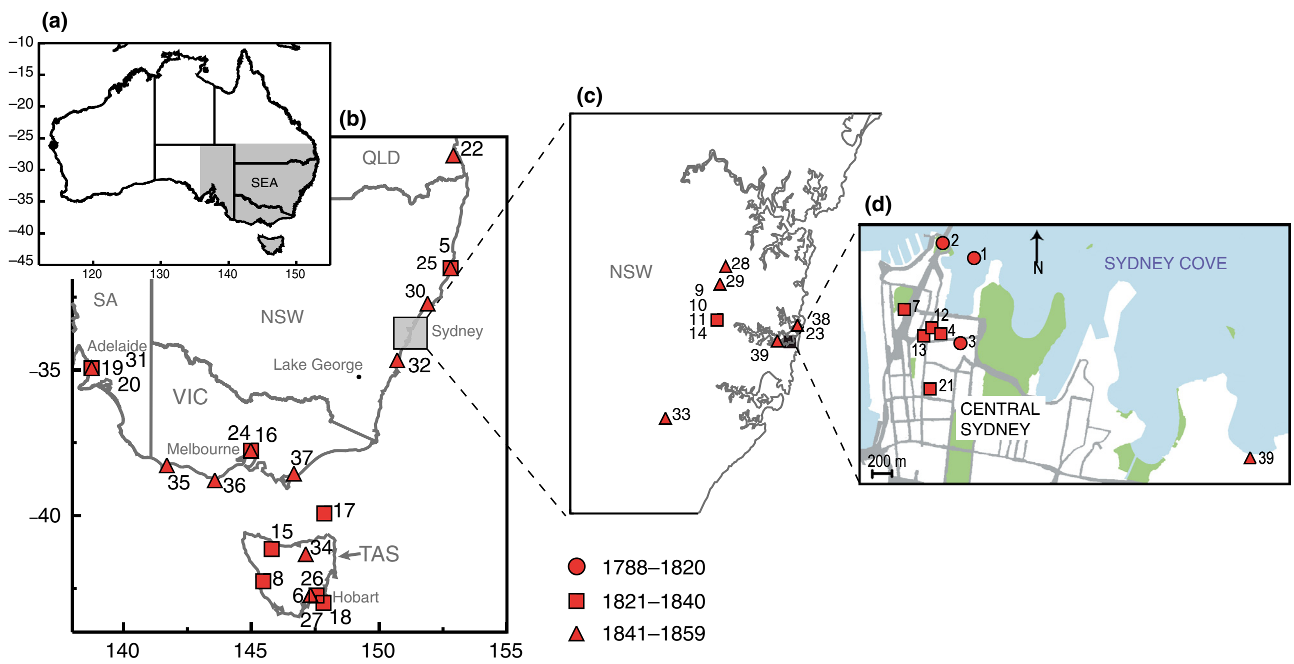

Figure 1. Location of the 39 historical southeastern Australian (SEA) climate data sources: (a) SEA as defined in this study; (b) historical climate stations used in this study in SEA; (c) the Sydney region; (d) and central Sydney. Symbols indicate the period in which observations began: between 1788 and 1820 (circle), between 1821 and 1840 (square) and between 1841 and 1859 (triangle). The states and state capital cities within SEA are marked in (b): South Australia (SA), Victoria (VIC), Tasmania (TAS), New South Wales (NSW) and Queensland (QLD). Lake George, an inland lake in NSW with historical lake level data, is also marked.

at different times during the day (if available) and an examination of the observations in original units.

For the temperature observations, visual comparisons were made to ensure that maximum temperatures (T_{max}) were greater than minimum temperatures (T_{min}), and that morning and evening observations were generally cooler than observations taken during the middle of the day. If this was not the case then the original observations were consulted to confirm that the discrepancy matched the accompanying weather description e.g., the comments reported a hot north wind in the morning followed by a cool change.

2.2. Observer bias

Histograms of the original temperature, pressure and rainfall observations were plotted for all sources of daily and subdaily data to identify the presence of any observer bias. For temperature, which was recorded to the nearest whole degree Fahrenheit, the last digit of each original observation was counted to see if the observer was rounding their observations (Trewin, 2010). To examine any observer bias in pressure observations, the numbers to the right of the decimal point of each observation (in inches of mercury) were examined and a frequency distribution plotted for every source with daily and fixed hourly pressure values. If there was no observer bias, then these plots would show a random distribution.

Observer biases in rainfall observations were determined by grouping the observations into 0.05-inch bins and examining the distribution curve, following the methods of Lavery *et al.* (1992) and Daly *et al.* (2007). The 0.01–0.05 inch range was also examined in 0.001-inch bins, to check for higher-resolution biases associated with an undercount of low rainfall events (e.g., Burnette and Stahle, 2013). If there was no observer bias then both the 0.05-inch and 0.01-inch frequency curves would resemble gamma distributions, with high counts in the low rainfall bins tapering to small counts of high rainfall totals.

Almost all of the temperature observations displayed a rounding bias of some kind, mainly towards even values or values ending in five. Figure 3(a,b) show examples of this for the temperature observations from farmer James Waugh in Jamberoo, NSW (source number 32 in Table 1). Waugh's fixed hourly observations show a clear bias towards even values, while the maximum temperatures he recorded display an additional rounding bias towards values ending in five. Similar biases were also observed in many subdaily pressure observations, with observers tending to record pressure observations to the nearest 10^{th} of an inch of mercury. The biases in colonial secretary Frederick Goulburn's pressure observations (source 4 in Table 1, shown in Figure 3(c)) are representative of several subdaily pressure sources.

2.2.1 Observer bias analysis

For the most part, the historical rainfall observations fit a gamma distribution, with highest rainfall count occurring in the 0.01–0.05-inch bin for the 0.05-inch

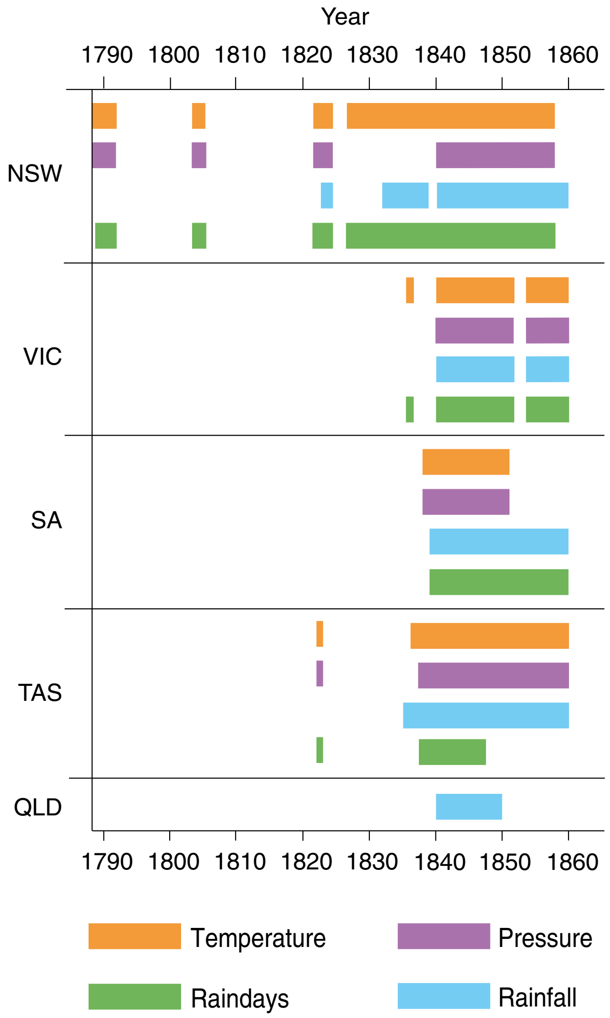

Figure 2. A schematic diagram of the temporal coverage of southeastern Australian historical data for each state, 1788–1859. Orange lines represent temperature records, purple represents atmospheric pressure, blue represents numerical rainfall and green represents rainday counts. Note that some historical sources provide data after 1859 (see Table 1), but are not represented in this figure.

analysis and the smallest 0.00–0.001 inch bin for the high resolution 0.001-inch analysis. Dr William Pugh's rainfall observations from Launceston in TAS for example (source 34, Figure 3(d)) display no bias, indicating his reliability as an observer. However, it must be noted that only half of the sources with rainfall data provided daily observations, and several of them (e.g., sources 28, 29 and 33) gave rainfall observations to the nearest tenth of an inch only. Biases and undercount issues may still be present in the sources of monthly rainfall totals.

Rounding biases in the temperature and pressure observations could be due to observer diligence, or to the scales on early meteorological instruments, which were often graded at two degrees or 10ths of an inch (McGuffie and Henderson-Sellers, 2012). Similar biases are common in modern temperature and rainfall observations (e.g., Daly *et al.*, 2007; Trewin, 2013). While such biases do impact threshold analysis and the study of high-resolution daily data (Zhang *et al.*, 2009), they do not have a great effect on monthly or annual mean values, because the rounding up or down tends to cancel out over time (Trewin, 2010). No effort was made to correct the observer biases identified, but they were recorded in the metadata for each source (see metadata accompanying dataset) for consideration in future analysis of the data.

2.3. Maximum and minimum temperature estimation method

To compare the 1788–1859 temperature data to each other as well as modern SEA observations, it was necessary to convert fixed hourly temperature records into estimates of daily T_{max} and T_{min}. This was achieved by calculating a regression between modern T_{max}, T_{min} and fixed hourly observations taken at the same time of the day as the corresponding historical observations. This method is similar to that used by Bergström and Moberg, (2002) and Andrighetti *et al.* (2009) in their examination of historical European temperature data. While there are other methods to transform fixed-hourly temperatures (e.g., Burnette *et al.*, 2010), this approach was chosen because it was easily adaptable for the different historical SEA data sources, which provide temperature for a range of times throughout the day.

T_{max} and T_{min} were estimated from the historical SEA temperature data using Equations (1) and (2):

$$T_{max} \approx \left(\sum_{i=1}^{n} a_i \times T_i \right) + c \qquad (1)$$

$$T_{min} \approx \left(\sum_{i=1}^{n} a_i \times T_i \right) + c \qquad (2)$$

where a_i is the regression coefficient derived from modern data, T_i is the historical temperature value at time i, c is constant derived from modern data, and n is number of historical observation times (minimum = 2).

Each month was examined separately to account for the different relationships between fixed hourly data and T_{max} and T_{min} throughout the year. At least two observations were required for a T_{max} and T_{min} estimation to be made, and data were required to be available for at least 60% of the days in a month for a monthly average to be calculated. This threshold was set to maximize the availability of monthly means for analysis, while ensuring that the monthly average values were an accurate reflection of weather experienced.

The regressions were determined using monthly T_{max}, T_{min}, and fixed-hourly temperature data from nearby Australian Bureau of Meteorology (BoM) stations. The modern BoM stations, listed in Table 2, were selected based on the availability of fixed hourly

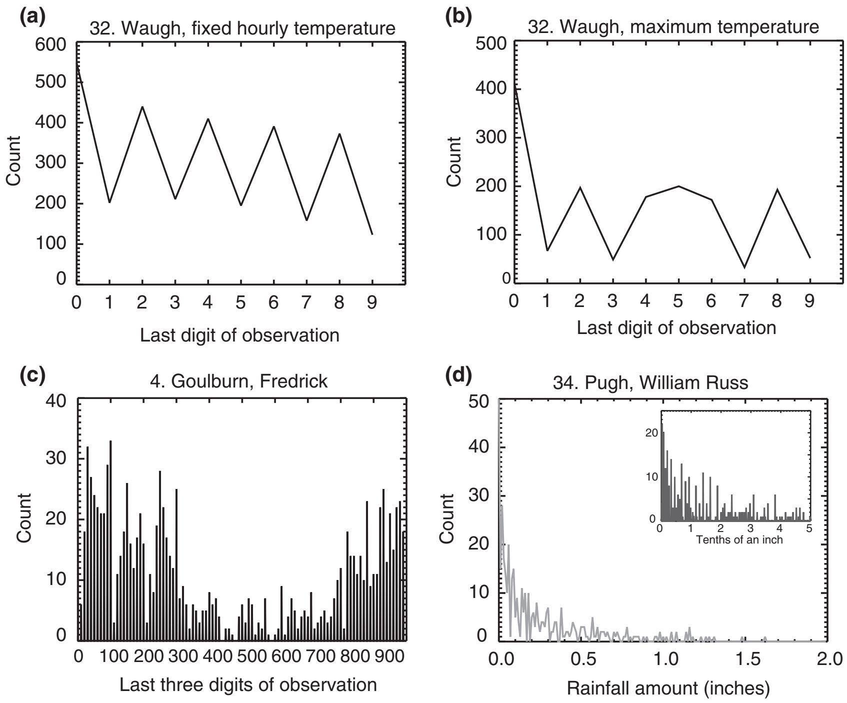

Figure 3. Frequency distributions of the last digit of fixed-hourly observations: (a and b) subdaily temperature and maximum temperature observations (in °F) taken by James Waugh at Jamberoo, NSW, 1843–1847 (source 32 in Table 1); (c) the last three digits of all fixed hourly pressure observations (in inches of mercury) taken by Fredrick Goulburn in Sydney, 1821–1822 (source 4 in Table 1); (d) rainfall observations (in inches, 0.05-inch bins) taken by William Russ Pugh in Launceston, TAS, 1846–1849 (source 34 in Table 1). The inset of Figure 3(d) shows the frequency distribution of low rainfall observations (0–0.5 inches) in 0.001-inch bins.

temperature data, and on their proximity and similarity to the historical sources. Table 2 also provides the Pearson's correlation coefficient (r), and the root mean square error (RMSE) of each regression derived for the historical data sources, comparing the actual T_{max} and T_{min} data with estimates derived from the modern fixed hourly observations. Further information is provided with the dataset.

Half-hourly and hourly observations were available for some nearby BoM stations, making it straightforward to determine how the observations at specific times related to T_{max} and T_{min}. Since many of the historical observations were taken three or four times a day, the resulting regressions made using modern half-hourly data were able to estimate T_{max} and T_{min} with high accuracy (e.g., source 13 in Tables 1 and 2). For other sources, such as the Port Macquarie *Government Gazette* abstracts and observations recorded by Edward Purser and David Watson in Castle Hill and Campbelltown (sources 25, 29 and 33 in Tables 1 and 2), nearby modern fixed hourly observations were only available at 9 am and 3 pm (0900+10:00 and 1500+10:00 UTC respectively). This made the resulting T_{max} and T_{min} estimates somewhat less reliable, as seen by the lower correlations in Table 2. Some sources additionally provided observed T_{max} and T_{min} data, while others, such as the Port Jackson *Government Gazette* abstracts (source 23 in Table 1) and data from Dr William Wyatt (source 19), recorded T_{max} and T_{min} for only a part of their observing period.

To improve the accuracy of the estimated temperature values, a range of T_{max} and T_{min} estimates were calculated for each source, moving the historical observation times forward and backwards by half an hour and recalculating the regression. This method was used to account for the fact that standardized time in Australia did not commence until 1895 (Davison, 1992; Holland, 2004), and that the times given with each historical observations are unlikely to exactly correspond to the modern day equivalents. The mean of the T_{max} and T_{min} estimates was then taken as the 'true' T_{max} and T_{min} estimate for each source.

For some sources, it was not possible to calculate a regression to estimate T_{max} and T_{min} at all, due to a lack of suitable modern fixed-hourly data (e.g., sources 8 and 32 in Table 1). In these cases, the highest and lowest observed temperatures of each day were determined from the historical temperature data, and the monthly mean of these values used to represent T_{max} and T_{min}. Fortunately, the majority of sources in this category had temperature observations from several times during the day, including early morning and mid-afternoon. Temperature observations at these times are likely to be close to the daily T_{max} and T_{min} values (Australian Bureau of Meteorology, 2011).

Comparing the regressions to the morning and afternoon fixed hourly temperature using modern data (taken as 6 am and 3 pm local time, respectively) revealed high correlations ($r > 0.95$ for all T_{max},

Table 2. Details of the regressions used to estimate maximum and minimum temperature (T_{max} and T_{min}) from historical subdaily temperature observations.

Station no	Station name	Frequency of modern observations	Start year	End year	Historical sources from Table 1	Historical observation times (local time)	r value		RMSE	
							T_{max}	T_{min}	T_{max}	T_{min}
23090	Adelaide (Kent Town)	Half-hourly	1993	2012	19	9 am, 3 pm, 9 pm	0.92	0.90	0.29	0.15
					31	10 am, noon, 2 pm, 4 pm	0.92	0.81	0.27	0.10
60026	Port Macquarie (Bellevue Gardens)	9 am and 3 pm	1957	2003	5	Sunrise, 6 am, 9 am, noon, 3 pm, 6 pm, sunset	0.91	0.74	1.84	1.94
					25	8:30 am, 2:30 pm, sunset, 9 pm	0.91	0.74	1.84	1.94
66037	Sydney Airport	Half-hourly	1972	2010	23	8:30 am, 2:30 pm, sunset, 9 pm	0.96	0.92	0.55	1.33
66062	Sydney (Observatory Hill)	Half-hourly	1993	2010	2	Various times (taken as 6 am, 9 am, noon, 4 pm, 10 pm)	0.98	0.98	0.34	0.03
					3	8 am, noon, 4 pm, 8 pm	0.97	0.95	0.34	0.03
					4	6 am, noon, 8 pm	0.97	0.98	0.34	0.03
					7	7 am, 1 pm, 7 pm	0.98	0.97	0.36	0.03
					12	9 am, noon, 6 pm	0.97	0.92	0.33	0.03
					13	6 am, noon, 6 pm	0.97	0.98	0.33	0.03
					21	6 am, noon, 6 pm	0.97	0.98	0.33	0.03
66124	Parramatta North	9 am and 3 pm	1967	2012	29	Sunrise, 8:30 am, noon, 2:30 pm, sunset, 9 pm	0.94	0.66	0.64	0.35
68081	Campbelltown Swimming Centre	9 am and 3 pm	1962	1984	33	8:30 am, 11 am, 2:30 pm, 3:30 pm, sunset, 9 pm	0.95	0.38	0.68	2.26
86071	Melbourne Regional Office	Half-hourly	1997	2012	16	Various times (taken as 6 am, noon, 6 pm)	0.91	0.87	0.25	0.40
					24	8:30 am, 2:30 pm, sunset, 9 pm	0.90	0.87	0.15	0.36
90015	Cape Otway Lighthouse	Half-hourly	1994	2012	35	8 am, noon, sunset	0.91	0.86	1.31	1.47
					36	8:30 am, 2:30 pm, sunset, 9 pm	0.91	0.85	1.63	1.94
99005	Flinders Island Airport	Hourly	1993	2012	17	6 am, 10 am, 2 pm, 6 pm	0.96	0.93	0.08	0.08

The numbers and names of the modern Australian Bureau of Meteorology (BoM) stations used are given, as well as the frequency and temporal coverage of the modern fixed-hourly temperature observations available. The numbers of the historical sources (as listed in Table 1) used with each BoM station are also provided, along with the Pearson's correlation coefficient (r), and root mean square error (RMSE) of the monthly T_{max} and T_{min} estimates compared to the actual T_{max} and T_{min} values over the period of modern fixed-hourly temperature data. The r and RMSE values were calculated between monthly anomalies relative to the period encompassed by the start and end year of the fixed hourly data. All r values are statistically significant ($P < 0.01$).

$r > 0.90$ for all T_{min}), suggesting this simple approach was also valid for estimating T_{max} and T_{min}. In fact, for some historical sources, taking the highest and lowest daily temperature would be more likely to capture the true T_{max} and T_{min} than using a regression model, due to poor availability of modern fixed hour data (e.g., source 33, see r and RMSE values for the regression method in Table 2). For consistency, monthly means of highest and lowest values were calculated for all historical sources with daily temperature data, even if a modern regression could also be calculated, to provide an additional estimate of T_{max} and T_{min}.

2.3.1. Estimated maximum and minimum temperature seasonal cycle analysis

The estimated T_{max} and T_{min} values were then compared to modern observations to determine whether they were accurately capturing the local seasonal cycle. The 1788–1859 T_{max} and T_{min} estimates generally displayed a seasonal cycle within the range of temperature variability in that region for the modern period. There was a tendency for the historical SEA temperature estimates to present a slightly elongated seasonal cycle, overestimating T_{max} and T_{min} during the warmer months, and underestimating the temperature during the cooler months.

The seasonal temperature biases identified in the pre-1860 SEA temperature data are largely consistent with other temperature records of the 19th century (Parker, 1994; Nicholls *et al.*, 1996; Bergström and Moberg, 2002). During this time, thermometers were generally housed in shelters or locations that did not accurately reflect the surrounding air temperature (Parker, 1994), receiving direct sunlight in summer or poor ventilation in winter leading to biases in the temperature record. For example, the austral winter temperature estimates from *The Sydney Monitor* (source 12 in Table 1), shown in Figure 4(a), are outside the range of modern data, being around 2 °C lower than the 1971–2000 mean for Sydney.

Lower austral winter values such as these could be indicative of genuinely colder 19th century winters compared to the modern period, although comparing the historical seasonal cycles to modern data from a much longer period (not shown) produced very similar results. It is more likely that the thermometer used by *The Sydney Monitor* had sub-standard exposure, possibly in a poorly ventilated yard or screen. Unfortunately, no metadata regarding thermometer exposure have yet been found for these observations. In fact, details of instrument exposure have only been found for six of the 24 sources of pre-1860 SEA temperature data, and the details are limited to descriptions of the thermometer being placed 'in the shade' (see metadata accompanying dataset).

On the other hand, good agreement between the modern seasonal cycles and the historical T_{max} and T_{min} estimates was found for other sources. The seasonal cycles of the temperature estimates from Dr William Wyatt's observations in Adelaide (source 19 in Table 1) are shown in Figure 4(b) as an example. The T_{max} values are slightly higher for October–December and the T_{min} estimates are around 1°C higher throughout the year, but the shape of the seasonal cycle is equivalent to that of the modern record. Wyatt's observed T_{min} values for 1841–1844 (shown by the dashed blue curve), however, are much warmer than the estimated values, while the T_{max} values (the dashed red curve) are very similar. This is presumably because Wyatt determined his T_{max} and T_{min} values from his subdaily observations, which were taken at 9 am, 3 pm and 9 pm. The maximum daily temperature often occurs at around 3 pm while the minimum temperature generally occurs during the night or around sunrise (Australian Bureau of Meteorology, 2011). Wyatt's observations would therefore not have been likely to capture the full diurnal cycle (Camuffo, 2002).

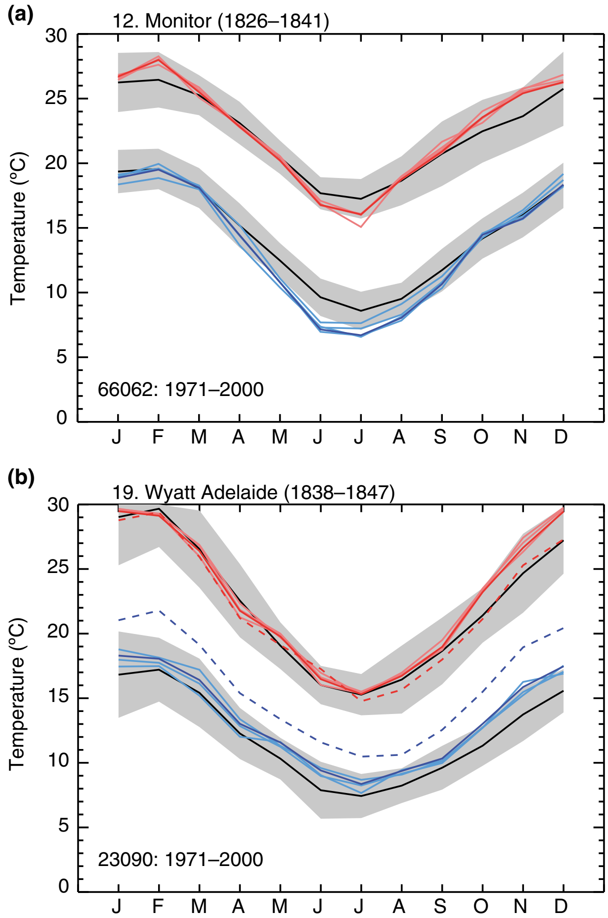

Figure 4. Seasonal cycles of T_{max} and T_{min} estimates from a) *The Sydney Monitor* newspaper (source 12 in Table 1) and b) Dr William Wyatt (source 19 in Table 1). The seasonal cycle of the mean T_{max} and T_{min} estimates (dark red and blue lines) are compared to seasonal cycles of individual estimates (light red and blue lines), recorded T_{max} and T_{min} values (dashed red and blue lines) and nearby BoM station data over 1971–2000 (black line, grey shading shows two standard deviations above and below the mean). The numbers of the BoM stations used are provided in the bottom left corner.

2.4. Statistical data homogenization

Once the 1788–1859 T_{max} and T_{min} values had been estimated and other variables had been converted to modern units, the monthly 1788–1859 temperature, MSLP and rainfall data were examined for inhomogeneities. Temperature, MSLP and rainfall data from the same source and neighbouring sources were compared to verify that the expected inter-variable relationships were present i.e., a wet month was associated with generally cool temperatures and low MSLP values (Nicholls *et al.*, 1997; Power *et al.*, 1998). Rainday counts were also examined to confirm these relationships. In general there was good agreement between neighbouring data sources and between related data from the same source. In particular, MSLP data from all historical sources were in very good agreement with each other, making it easy to identify problematic records.

If the historical data source had more than 3 years of data, it was then subjected to statistical inhomogeneity testing. Series with less than 3 years of data were deemed too short for inhomogeneities to be successfully identified (Wang and Feng, 2010). Most of the sources of pre-1825 data provide only one or 2 years of observations, making any potential inhomogeneities difficult to identify.

Statistical inhomogeneity analysis was conducted using the RHtestV3 package (Wang *et al.*, 2007; Wang, 2008; Wang and Feng, 2010). The RHtestV3 package from the Expert Team on Climate Change Detection Indices (ETCCDI, 2013) combines the penalised maximal *t* and *F* tests derived by Wang *et al.* (2007) and Wang (2008) to identify statistically significant inhomogeneities in a climate series. The penalised maximal *F* test allows for the identification of absolute inhomogeneities without the use of a reference series, while the penalised maximal *t*-test identifies relative inhomogeneities by comparing data of interest to a neighbouring or correlated dataset. Both statistical tests have been used in a range of studies to homogenize modern and historical climate data (Alexander *et al.*, 2010; Cornes *et al.*, 2012; Jovanovic *et al.*, 2012), and perform well in studies comparing different homogenization procedures (Reeves *et al.*, 2007). Further details about the tests and the RHtestV3 software package can be found in Wang *et al.* (2007), Wang (2008) and Ashcroft *et al.* (2012).

Monthly T_{max}, T_{min}, MSLP and rainfall data were examined for absolute inhomogeneities using the penalised maximal *F* test. Rainday counts were not statistically examined for inhomogeneities but were visually inspected to identify any clear changes that may be due to variations in observer or observation method. Visual examinations were also conducted on the temperature and MSLP data by examining the difference between morning, afternoon and evening observations wherever possible. MSLP sources were additionally tested for relative inhomogeneities using the penalised maximal *t*-test and neighbouring source data as a reference series. Identified inhomogeneities were then cross-referenced against the available metadata for each source and visually compared to data from neighbouring stations.

A number of the statistical inhomogeneities classified by the RHtestsV3 package were subsequently identified as real climatic variations when compared with data from neighbouring stations. For example, statistical inhomogeneities were identified in several sources of TAS and VIC data in the second half of the 1840s due to an anomalous drop in temperature and MSLP (e.g., sources 19, 24 and 27 in Table 1). Comparing these data to rainfall observations from similar areas revealed that this period was also quite wet, making the colder conditions and lower pressure values more realistic. Only statistical inhomogeneities that were clear from a visual inspection of the data or in agreement with source metadata were adjusted to improve the reliability of the historical data.

Table 3 lists the inhomogeneities found in the historical SEA source data. Inhomogeneities were identified in the data of three temperature sources and six MSLP sources, largely associated with changes in instrumentation. No inhomogeneities were identified in the instrumental rainfall observations. Adjustments calculated using the RHtestV3 package were then applied to the monthly data to minimize the influence of the inhomogeneities. One additional adjustment of +17.7 hPa was applied to the final 6 months of MSLP data from First Fleet astronomer William Dawes (source 2 in Table 1), to account for a change in barometer (Gergis *et al.*, 2009).

It is important to remember that only inhomogeneities that were clearly identifiable and supported by metadata were adjusted in this process. The short length of many of the historical records (most of them less than 10 years) makes it difficult to identify and remove statistical inhomogeneities without potentially removing signals of real climatic variability. There are likely to be more inhomogeneities in the records that could not be determined due to a lack of detailed metadata and neighbouring station data.

3. SEA climate variability, 1826–1859

The recovery and homogenization of the SEA historical data offers many new directions for future research into SEA and Southern Hemisphere climate variability. As an example of the applications that can be applied to this new dataset, interannual SEA climate variability for 1826–1859 is now examined, as it is the period that has continuous data coverage.

The relative variability of the historical SEA climate prior to 1860 is the focus here, rather than the absolute temperature, pressure and rainfall values across SEA. Although precise values cannot be ascribed due to remaining quality issues, examining relative interannual variability still provides significant new insight into

Table 3. Details of the inhomogeneities identified in the 1788–1859 historical southeastern Australian temperature (T_{max} and T_{min}) and mean sea level pressure (MSLP) data.

Variable	Date of inhomogeneity	Metadata
12. The Sydney Monitor		
T_{max}	July 1829	A change in the printed observation times from 7 am, noon and 5 pm to 9 am, noon and 6 pm
T_{min}	July 1829	A change in the printed observation times from 7 am, noon and 5 pm to 9 am, noon and 6 pm
18. Lempriere, Thomas		
MSLP	February 1841	A change in barometer
19. Wyatt, William		
MSLP	July 1844	Clear from visual inspection
22. Abbott, Francis		
T_{max}	January 1855	Movement of instruments from the Hobart Observatory to Abbott's home, and a change in observation times from 7 am, 1 pm and sunset to 10 am and 1 pm
T_{min}	January 1855	Movement of instruments from the Hobart Observatory to Abbott's home, and a change in observation times from 7 am, 1 pm and sunset to 10 am and 1 pm
	January 1856	A return to observations at 7 am, 1 pm and sunset.
MSLP	January 1857	Clear from visual inspection
24. Port Jackson Government Gazette abstracts		
MSLP	August 1843	A change from regular barometer to mountain barometer
26. Port Macquarie Government Gazette abstracts		
MSLP	April 1842	Observation times change in January 1842
32. Waugh, James		
T_{max}	January 1846	The thermometer is broken around this time, and most likely replaced with a new one

19th century climate variability in SEA, and facilitates comparison with modern climatic features.

3.1. Anomaly calculation method

Monthly anomalies for each variable were calculated relative to the 1910–1950 mean, to remove the seasonal cycle and examine relative variations in the 1826–1859 SEA climate data. The short length of some historical sources made it difficult to remove the seasonal cycle using contemporary values. The 1910–1950 base period was instead chosen because it is a period of sufficient data coverage in SEA that did not experience an anthropogenic warming signal (Fawcett *et al.*, 2012). The lack of a positive temperature trend during 1910–1950 also makes it more closely related to the 1788–1859 period than the modern 1960–2012 climate record.

The historical temperature and rainfall anomalies over 1788–1859 were calculated relative to data from the closest gridpoint of the BoM's 0.05° × 0.05° gridded Australian Water Availability Project (AWAP, Jones *et al.*, 2009) dataset, noting that the AWAP temperature dataset does not begin until 1911. The AWAP gridded data were interpolated using surface observations from 3000 rainfall stations and over 300 temperature stations across Australia (Jones *et al.*, 2009).

For MSLP data, anomalies were calculated relative to data from the nearest gridpoint from version 2 of the 20th Century Reanalysis (20CR) (Compo *et al.*, 2011). The 20CR is a global 2° × 2° gridded product, using surface pressure observations, specified sea surface temperature data and sea ice conditions to provide a 6-hourly multi-ensemble reanalysis (Compo *et al.*, 2011). The 20CR has been shown to successfully capture SEA MSLP variability during the 20th century (Ashcroft *et al.*, 2014), largely due to good data availability in the region. AWAP and 20CR data were used to determine anomalies rather than modern observational data, as it was difficult to identify appropriate BoM stations close to the historical sources with data available during 1910–1950.

Rainday anomalies, however, were calculated using 1910–1950 rainday observations from BoM stations close to each historical source with rainday counts, as no gridded rainday data were available. The chosen BoM stations were required to be close to the station of interest and have data available for the 1910–1950 reference period. The BoM rainfall stations were also used to calculate rainfall anomalies as a verification of the AWAP-derived anomalies, with very similar results.

To assess the agreement between data sources and determine if it was appropriate to combine them into a regional average, correlation matrices were calculated for each observed variable. The historical SEA data anomalies relative to 1910–1950 showed high inter-station agreement in terms of monthly and inter-annual variability. Correlations between monthly temperature anomalies from the SEA historical sources were almost entirely positive for both T_{max} and T_{min}. Neighbouring NSW observations in particular displayed high correlations on a monthly scale ($r > 0.52$ for T_{max}, $r > 0.40$ for T_{min}). Only temperature observations from exposed coastal sites, such as Flinders Island (source 17 in Table 1) and Port Arthur (source 18) were poorly correlated with neighbouring stations. This may be due to remaining quality issues, but could also reflect localized conditions at exposed stations (Power *et al.*, 1998).

The historical MSLP anomalies displayed very high correlations across SEA (Pearson's correlation coefficient r generally above 0.7), indicating remarkably high quality of the historical pressure records. The only source of MSLP data that did not show high positive correlations with the other historical data sources was the observations from Port Macquarie for 1840–1851. These observations have previously been identified as suspect (Russell, 1877; Todd, 1893), and were removed from subsequent analysis.

Correlations between monthly rainfall and rainday anomalies separated the historical SEA data into two distinct climate regions. Sources on the eastern coast of NSW and QLD were highly correlated with each other, while observations from the southern states of SA, VIC and TAS displayed positive correlations. A comparison between eastern and southern SEA rainfall data revealed weak and negative correlations. This is likely to be indicative of the different synoptic patterns that affect the two regions (Risbey *et al.*, 2009a).

Monthly temperature, rainfall, rainday and MSLP anomalies were then recalibrated to have a mean of zero for the period 1826–1859, and combined into annual eastern and southern SEA regional averages using a simple arithmetic mean. Eastern SEA sources were defined as observations from NSW and QLD, while southern SEA sources were taken as those from VIC, TAS and SA. These subsets were combined into two regional averages rather than a SEA-wide average to reflect the opposing rainfall patterns identified in the interstation comparison. The historical data are also mainly located in coastal southern and eastern SEA regions, so are unlikely to adequately capture inland SEA variability.

3.2. Interannual SEA climate variability, 1826–1859

Figure 5(a) shows the annual mean temperature, atmospheric pressure, rainfall and rainday anomalies for eastern SEA from 1825 to 1859, along with data from each individual source. Temperature and rainday records were first published in the Sydney newspapers from June 1826, providing the start of an almost continuous Sydney climate record that extends to present day. Unfortunately there are limited metadata detailing how or where the Sydney newspaper temperature observations were taken, and so the conclusions drawn from the data must be considered tentative.

The 1826–1829 period was dominated by above-average temperatures, and a generally average number of raindays. The year 1829 stands out as particularly warm. Although the temperature observations are to be treated with caution, the warm anomalies support the severe drought identified in the documentary rainfall record for the Sydney region during this period (Nicholls, 1988; Fenby and Gergis, 2013), as dry conditions are generally associated with above-average temperatures in Australia (Power *et al.*, 1998). The rainday count for Sydney during 1826–1829 indicates an average number of rainfall days in the colonial capital, although the drought may have been more persistent further inland (Fenby and Gergis, 2013).

The 1826–1829 drought broke in spectacular fashion, with a high number of raindays recorded in 1830. The years 1829, 1830 and 1831 were also identified as wet in the documentary record, with heavy rain, flooding and a dramatic increase in crop yields reported (Fenby and Gergis, 2013). The water levels of Lake George, an inland lake located in eastern NSW (see Figure 1(a)), also reportedly increased around this time (Russell, 1887; Gergis and Ashcroft, 2013), supporting the documentary and instrumental rainfall data. Average T_{max} values were recorded throughout 1830, while T_{min} values dropped dramatically from the previous year.

The instrumental temperature record for 1832–1834 in eastern SEA shows largely average conditions, with warm temperature anomalies identified during austral summer and spring, and cool anomalies during autumn and winter (seasonal analysis not shown). This signal could be genuine, or may be due to sub-standard thermometer exposure producing an elongated seasonal cycle. Rainfall observations from Parramatta in western Sydney (source 9 in Table 1) began in 1832, showing average rainfall during 1832–1834. The average rainfall totals are supported by predominantly normal rainfall conditions identified in the documentary record (Fenby and Gergis, 2013).

Instrumental observations began in southern SEA in 1835, with rainfall records from Dr James Milligan in northwestern TAS (source 15 in Table 1). Additional records from Melbourne (source 16) and Flinders Island (source 17) begin in 1836. Figure 5(b) shows the annual climate variations of southern SEA from 1835 to 1859, while Table 4 provides a summary of the annual conditions of both SEA subregions from 1835 to 1859. Warm years are classified as years with a T_{max} or T_{min} anomaly half a standard deviation above the 1835–1859 mean, while cool years are classified as years with a T_{max} or T_{min} anomaly half a standard deviation below the 1835–1859 mean. Years with above or below average rainfall, raindays and MSLP are defined in a corresponding way. Standard deviations were calculated from the data available over the

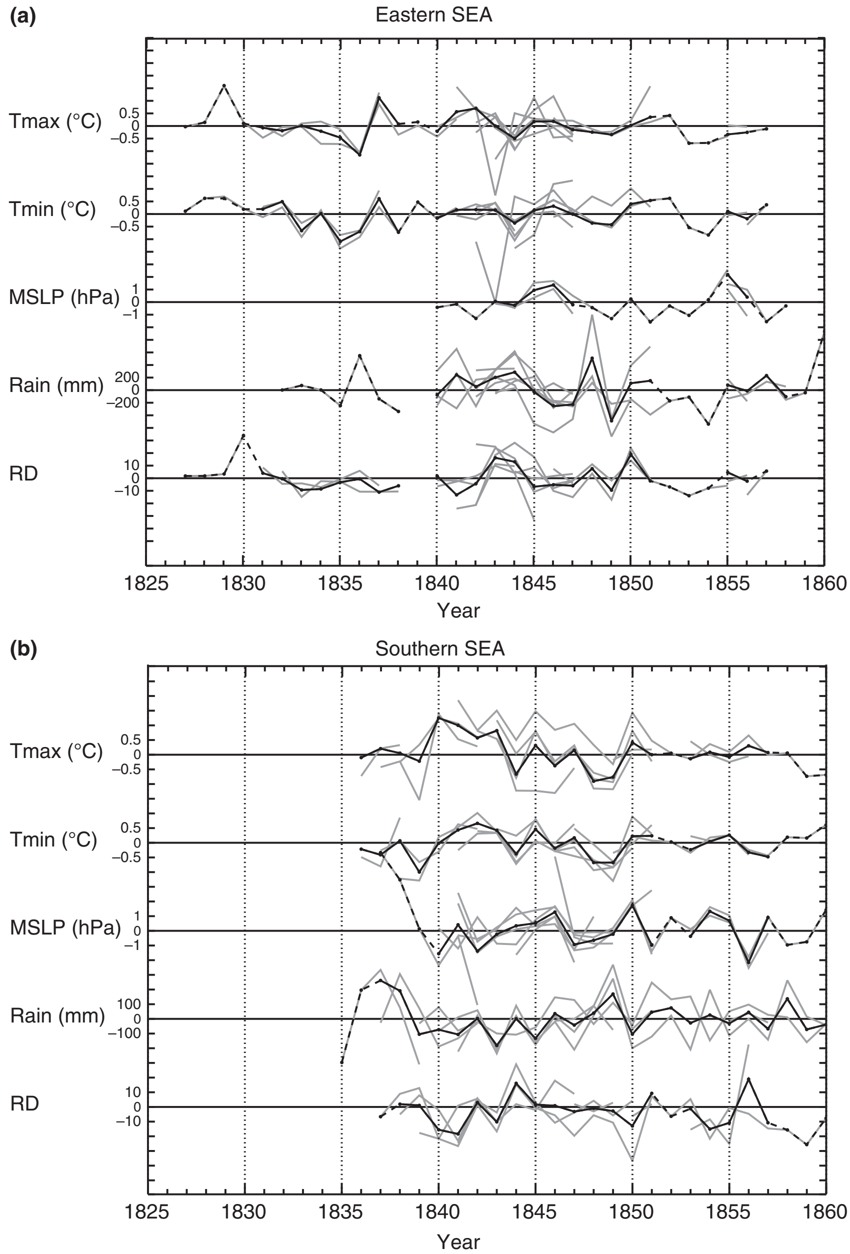

Figure 5. Annual variations of maximum temperature (T_{max}, °C), minimum temperature (T_{min}, °C), mean sea level pressure (MSLP, hPa), rainfall (Rain, mm) and rainday counts (RD) in (a) eastern SEA and (b) southern SEA, 1825–1860. A dashed line marks years with only one data source for each variable. A solid black line denotes years with more than one data source. The annual values from each source are also plotted in grey. Anomalies have been calculated relative to 1910–1950 and reset to a zero mean.

1835–1859 period. The half a standard deviation threshold was chosen to roughly divide the climate conditions of each subregion into terciles and classify the overall climate signal for each year (31% of years above and below 0.5 standard deviations, and 38% within the range defined as normal).

A large drop in eastern SEA temperature dominated the record in 1835. Similar conditions persisted in 1836 and the austral winter of 1836 was so cold that snow was recorded in Sydney on 28 June ('Meteorological Table', *The Sydney Herald*, 30 June 1836, page 2, available at http://trove.nla.gov.au/ndp/del/article/12854649). Sydney newspapers claimed that it was the first time snow had fallen in Sydney since European settlement in 1788. The year of 1836 was also associated with above-average rainfall conditions in eastern SEA.

Similar climate variations were reported in north-western TAS during 1835–1836, where dry conditions were observed in 1835 and wet conditions were prevalent for much of 1836. The southern SEA temperature observations for 1836 indicate cool conditions, including extremely cold T_{min} values during JJA. However, the instrumental temperature observations

Table 4. Summary of T_{max}, T_{min}, MSLP, rainfall and rainday conditions in eastern SEA and southern SEA for 1835–1859.

	Eastern SEA					**Southern SEA**				
Year	T_{max}	T_{min}	**MSLP**	**RAIN**	**RD**	T_{max}	T_{min}	**MSLP**	**RAIN**	**RD**
1835	**Cool**	**Cool**	–	*DRY*	N	–	–	–	*DRY*	–
1836	**Cool**	**Cool**	–	**Wet**	N	N	**Cool**	–	**Wet**	–
1837	*Warm*	*Warm*	–	*DRY*	*DRY*	N	**Cool**	*AA*	**Wet**	*DRY*
1838	N	**Cool**	–	*DRY*	*DRY*	N	N	*AA*	**Wet**	N
1839	N	*Warm*	–	–	–	N	**Cool**	N	*DRY*	N
1840	N	N	N	N	N	*Warm*	N	**BA**	*DRY*	*DRY*
1841	*Warm*	N	N	**Wet**	*DRY*	*Warm*	*Warm*	N	*DRY*	*DRY*
1842	*Warm*	N	*AA*	N	N	*Warm*	*Warm*	**BA**	N	N
1843	N	N	N	**Wet**	**Wet**	*Warm*	*Warm*	N	*DRY*	*DRY*
1844	**Cool**	**Cool**	N	**Wet**	**Wet**	**Cool**	**Cool**	N	N	**Wet**
1845	N	N	*AA*	N	*DRY*	*Warm*	*Warm*	N	*DRY*	N
1846	N	*Warm*	*AA*	*DRY*	*DRY*	**Cool**	N	*AA*	N	N
1847	N	N	N	*DRY*	*DRY*	N	N	**BA**	N	N
1848	N	**Cool**	**BA**	**Wet**	**Wet**	**Cool**	**Cool**	N	N	N
1849	**Cool**	**Cool**	N	*DRY*	*DRY*	**Cool**	**Cool**	N	**Wet**	N
1850	N	*Warm*	N	N	**Wet**	*Warm*	*Warm*	*AA*	*DRY*	*DRY*
1851	*Warm*	*Warm*	**BA**	**Wet**	N	N	*Warm*	**BA**	N	**Wet**
1852	*Warm*	*Warm*	N	*DRY*	*DRY*	N	N	*AA*	**Wet**	*DRY*
1853	**Cool**	**Cool**	**BA**	N	*DRY*	N	**Cool**	N	N	N
1854	**Cool**	**Cool**	N	*DRY*	*DRY*	N	N	*AA*	N	*DRY*
1855	**Cool**	N	*AA*	N	**Wet**	N	*Warm*	N	N	*DRY*
1856	**Cool**	N	*AA*	N	N	*Warm*	**Cool**	**BA**	N	**Wet**
1857	N	*Warm*	**BA**	**Wet**	**Wet**	N	**Cool**	*AA*	*DRY*	*DRY*
1858	–	–	–	N	–	N	N	**BA**	**Wet**	*DRY*
1859	–	–	–	N	–	**Cool**	N	N	*DRY*	*DRY*

Warm and cool years are classified as years with a T_{max} or T_{min} anomaly half a standard deviation above or below the 1835–1859 mean. Years with MSLP above or below average (AA and BA, respectively) are defined as years with an MSLP anomaly half a standard deviation above or below the 1835–1859 mean. Wet and dry years are defined as years with a rainfall (RAIN) or rainday (RD) anomaly half a standard deviation above or below the 1835–1859 mean. Years with normal condition are marked with an N. Years with no data are denoted by a dash. Standard deviations are calculated over the common 1835–1859 period. Bold is used to indicate cool and wet conditions with below-average MSLP, while italics indicate warm and dry conditions with above-average MSLP.

available for southern SEA during 1835–1837 came from exposed sites and are not considered to be a reliable representation of subregional temperature variability (see section 3.1).

Interestingly, this period corresponds with the peak Little Ice Age response in the Australasian region identified for 1830–1860 from palaeoclimate datasets (e.g., PAGES 2K Consortium, 2013). The cold and wet climatological conditions experienced in eastern SEA in 1835–1836 are also consistent with the impact of a large volcanic eruption in low latitudes (Lamb, 1970; Grab and Nash, 2010) and may be due to an eruption that occurred in Nicaragua, Central America, in January 1835 (Grab and Nash, 2010). The 1835 Nicaraguan eruption has been previously linked to cool conditions in the tropical palaeoclimatology record (D'Arrigo *et al.*, 2009) and a drop in temperatures across the Northern Hemisphere (Lamb, 1970, 1972). However, more analysis is required to determine the extent of the instrumental and palaeoclimate agreement and assess the attribution of the cold temperatures to the Nicaraguan eruption.

In 1837, the eastern SEA temperature record rebounded to warmer and drier conditions, while the western TAS rainfall records in Figure 5(b) indicate high rainfall. Anticorrelated rainfall conditions continued across SEA in 1838, with below-average rainfall and cool T_{min} values recorded in eastern SEA, and above-average rainfall and warm T_{min} conditions in northwestern TAS. This rainfall pattern may be related to large-scale circulation features such as El Niño–Southern Oscillation or the Southern Annular Mode, which are known to influence rainfall over SEA (Risbey *et al.*, 2009b). The role of large-scale circulation features on historical SEA climate variability is beyond the scope of the current study, but will be examined in future work.

No instrumental rainfall data have been found for eastern SEA in 1839, but temperature values for the subregion suggest that the year experienced average conditions. Warm temperatures were experienced during austral summer and spring, with cool T_{max} values recorded in austral winter (seasonal analysis not shown). Documentary evidence suggests that NSW was wet from August 1839, breaking a prolonged drought (Fenby and Gergis, 2013). The instrumental record for southern SEA indicates that cool conditions dominated that subregion during 1839, in association with a drop in MSLP. Interestingly, low rainfall was recorded in SA and TAS, despite the low MSLP readings. Southern SEA MSLP observations from 1839 come from Port Arthur (source number 18 in Table 1), and appear to have been taken by several untrained observers who frequently moved the barometer (see metadata accompanying dataset). This reduces the reliability of the southern SEA pressure observations for 1837–1840.

In 1840, the number of stations increased in eastern and southern SEA, improving confidence in the instrumental climate record. Importantly for southern SEA, observations began in the modern states of VIC, SA and TAS. Eastern SEA recorded a year of average temperature and rainfall in 1840, while 1841 was predominantly warm across both regions. Rainfall records indicate dry conditions in southern SEA, but wet conditions in eastern SEA. This spatial pattern is also in agreement with the SEA documentary record (Fenby and Gergis, 2013).

Average rainfall was recorded in both regions of SEA in 1842, although warm temperatures persisted. In 1843 there was an increase in rainfall across eastern SEA, corresponding with a drop in T_{max} and T_{min}. In particular, extremely cold T_{max} and T_{min} conditions were recorded at Port Macquarie (see Figure 5(a)), although the T_{max} and T_{min} estimates from this source are not considered to be overly reliable due to poor modern half-hourly data availability. On the other hand, warm and dry conditions continued in southern SEA. While documentary compilations suggest that the SEA drought broke in 1843 (Fenby and Gergis, 2013), the instrumental rainfall records indicate that much of southern SEA was still dry during this year. The discrepancy between instrumental and documentary data may reflect some unavoidable biases in the documentary record, which is based on subjective descriptions of rainfall (Fenby and Gergis, 2013). Differences in the instrumental and documentary record may also indicate issues in the monthly instrumental rainfall data, which could not be examined for observer biases.

The year 1844 was cool and wet across both regions of SEA, bringing relief to southern SEA. However, dry weather once again set in across southern SEA in 1845, accompanied by an increase in T_{max} and T_{min}. In eastern SEA, rainfall was generally average during 1845, although a drying pattern emerged in austral winter and spring (seasonal analysis not shown), and was also identified in the documentary record (Fenby and Gergis, 2013). The eastern SEA drought continued in 1846 and 1847, with dry and warm conditions dominating most seasons. Conversely, the southern SEA records show average rainfall and rainday counts recorded for both 1846 and 1847, indicating that the dry conditions were localized to the eastern SEA region.

The temperature dropped markedly in both subregions in 1848, but particularly in southern SEA. Grab and Nash (2010) determined that the austral winters of 1847–1850 were also very cold in Lesotho, southern Africa, and attributed it to a volcanic eruption on the Tongan Island of Fonualei (also known as Amargura) in June of 1846 (Spennemann, 2004). They identified a similar cold period in a Patagonian temperature reconstruction based on tree-ring records (Masiokas and Villalba, 2004), suggesting a hemisphere-wide drop in temperature. The extended SEA temperature records presented here appear to support the hypothesis that the late 1840s were unusually cold across the Southern Hemisphere (Neukom *et al.*, 2014), although more analysis is needed to confirm this agreement.

The cold temperatures in SEA continued in 1849, including a snowfall event in Melbourne, VIC, on 31 August. According to Melbourne's *Argus* newspaper, it was the first snowfall that had ever occurred in Melbourne since its formation in 1835 ('The Weather', *The Argus*, 1 September 1849, page 2, available at http://trove.nla.gov.au/ndp/del/article/4765007). Southern SEA experienced above-average rainfall, while eastern SEA was drier than average in 1849, both in terms of rainfall and number of raindays. The contrasting rainfall patterns but coherent temperature signal provides further evidence that an external factor was responsible for modulating SEA temperatures during this period, rather than regional rainfall variability alone.

Eastern SEA recorded a wet year in 1848, while average rainfall was recorded in southern SEA. The opposite occurred in 1849, with wet conditions in southern SEA and below-average rainfall in eastern SEA. After a wet year in 1849, southern SEA became much warmer and drier in 1850. In eastern SEA, temperatures returned to average and instrumental rainfall and rainday counts increased. Warm T_{max} and T_{min} values were recorded in 1851, along with a drop in MSLP across both regions.

The 1852–1854 period was dominated by below-average rainfall in eastern SEA. The rainfall observations available for this period were only taken at Port Jackson on Sydney's coast however, and may not be indicative of the wider eastern SEA region. The documentary record does not indicate any extended drought in eastern NSW during the early 1850s, suggesting that the rainfall deficit did not have a large societal impact. However, Lake George water levels also displayed a drop during 1853–1854, verifying the instrumental rainfall data (Russell, 1887). Temperature observations indicate that this period was also quite cool in eastern SEA, particularly during 1853 and 1854.

Average temperature conditions were recorded during 1852–1854 in southern SEA, with no unusual rainfall variations. The rainfall record suggests that 1852 and 1854 were moderately wet in the south, while the rainday count indicates a drop in the number of rainfall days for both years. Several flooding events in Hobart in the early 1850s support the instrumental observations of high rainfall (Evans, 2010) and the average climatic conditions in southern SEA during the 1850s are supported by documentary evidence from mainland SEA (Fenby and Gergis, 2013).

Rainfall returned to normal in eastern SEA in 1855, accompanied by a moderate increase in annual T_{max} and T_{min}. The amount of rainfall recorded in southern SEA also remained around average. Similar rainfall conditions persisted in both regions in 1856, accompanied by generally average or slightly cool temperatures. Low MSLP values dominated the southern SEA MSLP record, along with a high rainday count. Interestingly the temperatures in southern SEA during 1856 show an increase in T_{max} and a decrease in T_{min}, a pattern generally associated with decreased rainfall and high MSLP rather than the observed increased rainfall and low MSLP. This discrepancy may be due to remaining inhomogeneities in the temperature data from Francis Abbott in Hobart, TAS (source 27 in Table 1), as the recording instruments were moved in January 1856 (Table 3).

From 1857 to 1859, the rainday count in southern SEA indicates dry conditions were experienced in the region, although the instrumental rainfall totals show high rainfall variability, with below-average rainfall in 1857 and 1859, and above-average rainfall in 1858. These rainfall conditions were associated with cool T_{max} and warm T_{min} across southern SEA, particularly during 1858–1859. The southern SEA rainfall record during this time is averaged from observations in Adelaide, SA and Hobart, TAS (sources 17 and 27), while the rainday count is only from Adelaide. This may explain the disagreement between rainfall anomalies and rainday counts in southern SEA during 1857–1859. The year 1857 was wetter than average in eastern SEA, while 1858 and 1859 were slightly drier than normal, in line with the documentary record (Fenby and Gergis, 2013). The eastern SEA temperature and MSLP record ceases in 1858, and generally average temperature and MSLP conditions dominate the region until this time.

4. Discussion and conclusion

This study describes the first instrumental climate record for southeastern Australia to extend from European settlement in 1788 to the beginning of more widespread meteorological observations in 1860. Detailed quality control and homogenization of the data has shown that the historical records are of good quality, and are capable of providing information on relative climate variability in SEA. The historical observations can now be used for long-term analysis of climate variability in Australian and the wider Southern Hemisphere (Allan *et al.*, 2011).

Continuous meteorological observations are available in SEA in one form or another from June 1826. From that month, *The Sydney Monitor* newspaper began publishing subdaily temperature observations and daily weather descriptions for Sydney, NSW, providing information on relative temperature variability and rainfall fluctuations through the number of raindays reported. As European settlement expanded beyond Sydney, an instrumental climate record began in the current state of TAS in 1835, South Australia in 1839, and in VIC and QLD in 1840.

Isolated observations exist for Sydney during 1788–1791 and 1803–1805, and during 1822–1823 at three locations along the east coast of mainland SEA and two locations in TAS. These small subsets of data provide glimpses into climate variability in the early years of European settlement in Australia. In particular, the 1788–1791 data are an important resource for historical studies of the first 3 years of European settlement (Gergis *et al.*, 2009, 2010b).

The 1788–1859 SEA climate data were found to be of remarkable quality, particularly considering their diverse format and the lack of a coherent observation technique employed across SEA during 1788–1859. Neighbouring sources displayed good agreement for each of the meteorological variables, indicating that they accurately capture coherent regional climate variability in SEA. In particular, MSLP observations agreed extremely well. The T_{max} and T_{min} estimates also exhibited seasonal cycles that were generally similar the modern seasonal cycles of nearby BoM stations, although biases associated with substandard instrument exposure are apparent. Additionally, the 1826–1859 data were in good agreement with documentary accounts and lake level records representing SEA climate, further illustrating the ability of the historical instrumental data to capture interannual and interseasonal variability.

Although the development of this dataset represents a significant advance in historical climatology in the Australasian region, there are unavoidable limitations that must be considered. Observer biases and remaining inhomogeneities mean that the observations are of poorer quality than modern meteorological records, and they should be interpreted with caution. Particular care must be taken with the temperature observations, which are especially sensitive to changes in exposure (Trewin, 2010), and monthly rainfall totals, which have not been examined for undercount biases. Future homogenization work, or an alternate approach to maximum and minimum temperature derivation, may remove some of these issues.

Given the high rainfall variability in SEA (Murphy and Timbal, 2008), it is unfortunate that the first instrumental rainfall observations were not published until May 1822. Continuous numerical rainfall observations did not begin until 1832, when astronomer James Dunlop began recording rainfall in Parramatta, NSW. However, daily weather descriptions before this time have allowed for rainday counts to be estimated, providing some information on past rainfall variations in the region. The spatial limitations of the pre-1860 data also prevented the analysis of inland SEA climate variability. The majority of the historical climate records represent the coastal regions of SEA, reflecting the geographic expansion of European settlement and the importance of meteorological observations for maritime safety (Home and Livingston, 1994).

Despite these limitations, the historical SEA climate data still offer new insights into the climate experienced by colonial Australians since European settlement in 1788. An examination of the annual data for 1826–1859 reveals periods of dry conditions across SEA during 1837–1842, and a second drought period in eastern SEA from 1845 to 1852. Wet conditions were experienced in southern SEA from 1836 to 1838, and in eastern SEA from 1843 to 1844. Anomalously cool conditions were identified in SEA during 1836 and 1847–1849, and may be linked to tropical volcanic eruptions.

The extended SEA climate record now enables an instrumental examination of climate variability in SEA over the past 225 years. Future work will explore the long-term variability of the relationship between SEA rainfall and the El Niño–Southern Oscillation phenomenon, a fundamental influence on SEA climate variability (McBride and Nicholls, 1983; Murphy and Timbal, 2008; Risbey *et al.*, 2009b). The historical records will also allow a comparison between recent SEA drought periods and previously unexamined droughts in the 19th century.

The new dataset for SEA provides a large amount of information for future climate and historical research in the Australasian region, as well as for hemisphere-wide analysis of past climate variability. Comparisons between these records and documentary-derived studies of 19th century climate in African and South American countries would certainly lead to improved understanding of the spatial extent of temperature and rainfall fluctuations in the mid 19th century.

The sources of historical daily and subdaily data offer new opportunities to examine extreme rainfall and temperature events, and may be suitable for inclusion in future historical reanalysis projects (e.g., Compo *et al.*, 2012), further improving the understanding of Southern Hemisphere historical climate variability. Finally, although a large amount of historical SEA climate data has been uncovered, additional sources of pre-1860 climate information, particularly for the Tasmanian and South Australian region, remain unexplored. Ship logbooks and explorer's journals may also provide valuable information on past SEA climate (Chappel and Lorrey, 2013).

The historical SEA climate data from 1788 to 1859 presented here provide detailed information on the climate experienced in eastern and southern SEA from European settlement in 1788 until the development of larger meteorological observational networks in the 1860s. There are some unavoidable discrepancies, reliability issues and unfortunate gaps in the pre-1860 instrumental record, particularly before the 1840s. However, the examination of interannual SEA climate variability from 1826 to 1859 serves as a useful foundation to further examine historical climate variability in the Australian region.

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