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Rainfall variations in south-eastern Australia part 1: consolidating evidence from pre-instrumental documentary sources, 1788–1860

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ABSTRACT: This study fills an important gap in south-eastern Australia's climate record by compiling qualitative historical data from the time of first European settlement of Australia in 1788 until widespread meteorological observations become available in 1860. In this study, we consolidate twelve documentary-based rainfall chronologies for five sub-regions of south-eastern Australia (SEA) over the 1788–1860 period using a range of secondary historical sources. Our analysis identified 27 drought years in SEA between 1788 and 1860, and 14 years of high rainfall in New South Wales (NSW) between 1788 and 1840. Given that our current understanding of Australian drought is still largely confined to the post-1900 period covered by instrumental records, we provide an outline of the drought and wet periods to provide a consolidated reference of historical accounts of lesser known pre-instrumental rainfall variations for researchers working in the field. This index is also intended to serve as an independent inter-annual verification source for palaeoclimate reconstructions being developed in the Australian region. This study confirms that SEA has experienced considerable rainfall variability that has influenced past Australian societies since the first European settlement in 1788. Of the droughts identified in this study, 1837–1841 was the longest and most widespread event influencing all subregions. The 1793–1809 period was particularly wet, with periods of heavy rainfall often resulting in devastating floods on the Hawkesbury River region of Sydney. Despite the geographical biases present in the documentary material, it is clear that historical records provide important information on rainfall variations in SEA and their societal impacts over the 1788–1860 pre-instrumental period. The results presented here provide an important basis for developing an extended rainfall index for eastern NSW from 1788–2008, and is the subject of part 2 of this study (Gergis J, Ashcroft L. 2012. Rainfall variations in south-eastern Australia part 2: a comparison of documentary, early instrumental and palaeoclimate records, 1788–2008. *International Journal of Climatology*).

KEY WORDS south-eastern Australia; climate variability; rainfall; historical data; documentary records; ENSO

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1. Introduction

The 1997–2009 'Big Dry' in south-eastern Australia (SEA) had extreme impacts on the agricultural sector and on water availability, promoting major research efforts to determine if the drought fell within the observed range of natural climate variability, or was symptomatic of the projected drying of the mid-latitudes associated with anthropogenic climate change (Karoly and Braganza, 2005; Hennessy *et al*., 2007; Timbal *et al*., 2010; Keenan and Cleugh, 2011). Despite recent advances in understanding rainfall variations in the Australian region (Murphy and Timbal, 2008; Risbey *et al*., 2009; Verdon-Kidd and Kiem, 2009; Timbal *et al*., 2010; Gallant and Gergis, 2011; Gergis *et al*., 2011; Ummenhofer *et al*., 2011), there is still a pressing need to establish the natural range of rainfall variability prior to the 20th century. Extended rainfall records are needed to assess the stability of regional teleconnection patterns associated with global circulation features such as El Niño–Southern Oscillation (ENSO) that influence rainfall variability in the region (Nicholls *et al*., 1996; Nicholls, 2009; Risbey *et al*., 2009).

Rainfall in SEA, and Australia more broadly, is very variable. In fact, rainfall variability in Australia has been described as among the highest in the world, while Australian climate is generally characterised by drought and wet periods, sometimes exhibiting sharp transitions or sudden shifts between the two extremes (Pittock *et al*., 2006). ENSO is the dominant influence on these wet and dry periods and the impact of ENSO on Australia is particularly severe in a global context (Allan, 1988; Nicholls, 1992; Allan *et al*., 1996). In Part 2 of this paper, Gergis and Ashcroft analyse the relationship between dry and wet years in eastern New South Wales (NSW) and ENSO from 1788–2008. To

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do so, Gergis and Ashcroft (2012) use the index of dry and wet years developed in this paper, a five-station composite of historical instrumental rainfall observations from the Sydney region from 1832–1859, a nine-station network of rainfall stations covering eastern NSW for the 1860–2008 period and a 45-station network available from a broader SEA region over the 1860–2008 period.

In the absence of widespread instrumental meteorological records in Australia before 1860, it is helpful to consider historical material to reconstruct past climate variations (Nicholls, 1988). Documentary material provides a societal record of the impact of past climate in areas of Australia where observational or annually resolved palaeoclimate data such as tree rings are limited. Surprisingly, unlike Europe and the Americas, Australian historical records remain virtually untapped for use in mainstream climate analysis (Gergis *et al*., 2009, 2010). As such, immense opportunity exists to use historical archives to develop our understanding of Australian climate history and its impact on past societies.

Astonishingly, aside from the pioneering work of the 19th century (Jevons, 1859; Russell, 1877), there have only been a handful of recent attempts to reconstruct Australian pre-20th century drought using documentary archives (Foley, 1957; Nicholls, 1988; Grove, 2005). Currently, our knowledge of Australian drought is largely confined to the post-1900 period when an extensive network of meteorological observations becomes available (Jones *et al*., 2009). Colonial archive reports, personal diaries and newspaper accounts provide detailed information about past drought, wet years and other significant weather events since the time of first European settlement in 1788 (Gergis *et al*., 2009, 2010).

In part 1 of this analysis, we consolidate information from 12 documentary-based rainfall chronologies for SEA over the 1788–1860 period using a range of secondary historical sources that comprise primary qualitative data. This study fills a gap in SEA's climate record by compiling qualitative historical data from the time of first European settlement of Australia in 1788 until the year 1860 when a number of long-term meteorological records from the region become available (McAfee, 1981; Williams, 1984; Trewin and Fawcett, 2009). By 1860, weather observatories were established in each Australian colony (Day, 2007), marking the beginning of a continuous numerical record of climate in all regions in SEA (NSW, Tasmania, Queensland, Victoria and South Australia). Once a chronology of rainfall variations from SEA has been tabulated, we outline the significant drought and wet events over the 1788–1860 pre-instrumental period. To verify our results, we use independent historical accounts of fluctuations in the water level of Lake George within in SEA study region shown in Figure 1.

In part 2 of this study (Gergis and Ashcroft, 2012) compare the newly developed documentary rainfall record presented in this paper to a five-station network of historical instrumental rainfall observations from the Sydney region from 1832–1859 and a 45-station network available from a broader range of SEA locations over the 1860–2008 period. After assessing the influence of geographical biases in the documentary and meteorological record due to population settlement, we develop a long-term rainfall index for the eastern NSW subregion of SEA. This rainfall index is then compared to palaeoclimate reconstructions of SEA rainfall (Gergis *et al*., 2011) and ENSO (Braganza *et al*., 2009; Gergis and Fowler, 2009; McGregor *et al*., 2010) for the 1788–1988 period of overlap. We then investigate the relationship between drought and wet years in eastern NSW and ENSO since 1788, noting the coastal NSW rainfall–ENSO relationship is not as pronounced as in inland areas of Eastern Australia (McBride and Nicholls, 1983; Allan *et al*., 1996; Risbey *et al*., 2009). Finally we assess apparent changes in broad scale drought and wet periods in SEA over the full 1788–2008 period highlighting important caveats and biases in our conclusions.

2. Data

2.1. Historical Sources

To develop an understanding of SEA rainfall variations over 1788–1860, we use the 12 historical sources listed in Table I. European settlers developed a folk-knowledge of climate and weather from their experience of living in the Australian landscape. As settlement spread and agricultural and pastoral pursuits expanded, the need to understand climate variations grew. Although individuals and newspapers recorded qualitative weather and climate information, this information was not collated systematically until William Stanley Jevons, a government economist and amateur meteorologist, published *Some Data Concerning the Climate of Australia and New Zealand* in 1859. Jevons (1859) used qualitative primary source data collected from newspapers like the *Sydney Gazette and New South Wales Advertiser*, contemporary publications, explorer's diaries and personal diaries to create a detailed list of climate events like drought, flood and bushfires from the population centres of SEA.

In 1877, Henry Chamberlain Russell, government astronomer for NSW, published *Climate of New South Wales: Descriptive, Historical and Tabular*, adding substantially to contemporary understanding of 19th century Australian climate. Russell wanted to create a reference book of climate in NSW and felt that this publication would help answer 'the important question of periodicity in our climatic changes' (Russell, 1877, 1). Russell (1887b) also published *Notes Upon the History of Floods in the River Darling*, which added new primary source material to the history of drought and wet periods in western NSW drawn from settler accounts of weather and climate. Both Jevons (1859) and Russell (1877) are limited in that they focus mainly on NSW and occasionally use similar sources. Although a number of subsequent

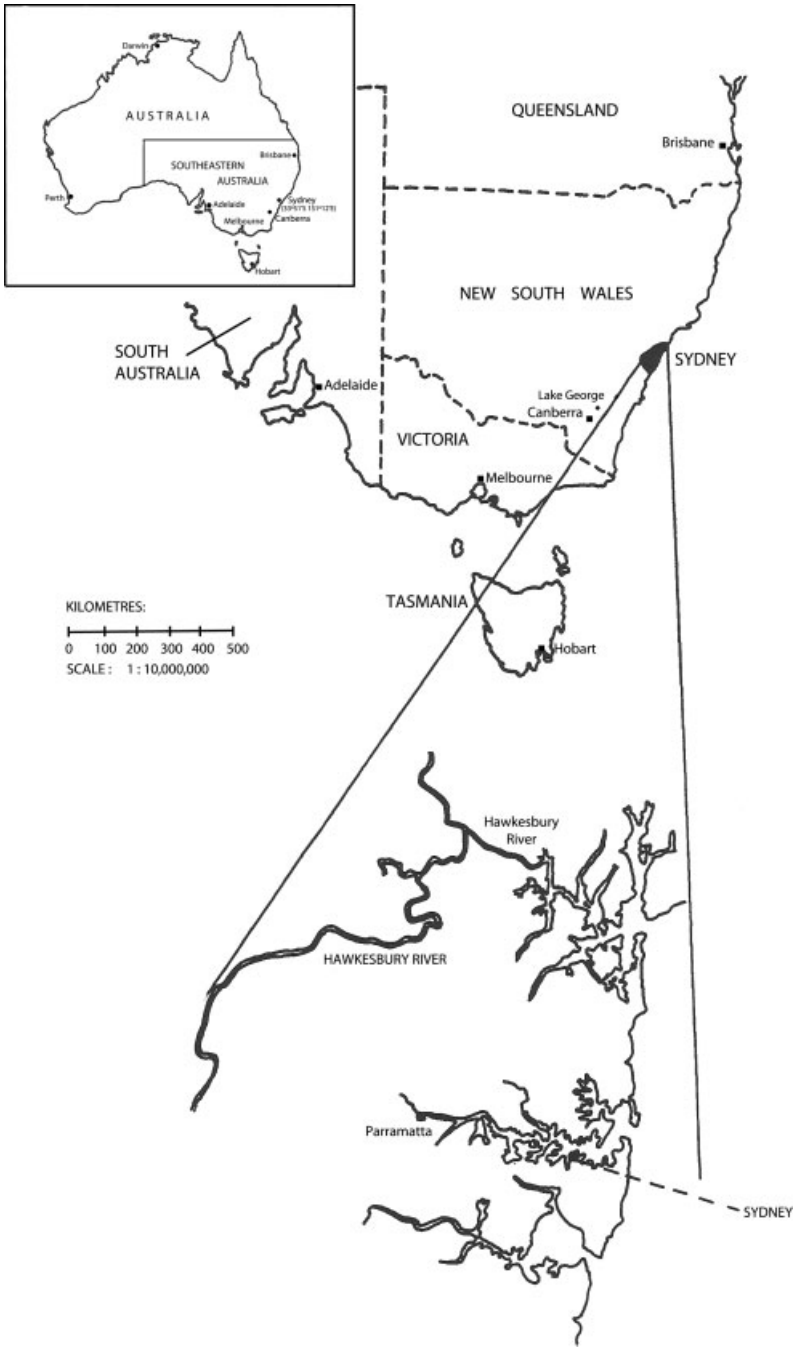

Figure 1. Map of SEA showing state/colony divisions, capital cities, Lake George and the Hawkesbury River region. Figure adapted from McAfee (1981).

drought, flood and storm chronologies have been compiled in more recent years (Table I), there has been no comprehensive attempt to consolidate a diverse range of historical sources to specifically analyse rainfall variations in SEA prior to 1900 when the national rainfall network becomes available (Jones *et al*., 2009).

Although the Australian Bureau of Meteorology's *Results of Rainfall Observations* series (Hunt, 1911, 1914, 1918; Watt, 1936; Warren, 1948) compiles qualitative and quantitative climate data for each subregion of SEA, they simply describe past weather extremes and/or provide tables of historical weather observations. The qualitative data used in this series are based on newspapers, observatory records, government records, almanacs, local histories and the personal recollections of individuals. Notable meteorological events are well described for NSW (Warren, 1948) and Victoria (Hunt, 1911), while conditions from Tasmania (Watt, 1936), South Australia (Hunt, 1918) and Queensland (Hunt, 1914) are not as comprehensively covered. For example, Watt (1936) only compiles information on floods and above-average rainfall, and despite Queensland being settled from 1824, Hunt (1914) only reports flooding from 1841 and drought from 1858. While South Australia's

Table I. List of sources used to construct rainfall variation chronologies (Tables II and III) for SEA.

Source	Geographical region	Time period
Jevons (1859)	Australia	1788–1858
Russell (1877)	NSW	1788–1860
Russell (1887b)	Western NSW	1818–1886
Hunt (1911)	Victoria	1839–1910
Hunt (1914)	Queensland	1841–1913
Hunt (1918)	South Australia	1837–1917
Watt (1936)	Tasmania	1809–1934
Warren (1948)	NSW	1788–1945
Foley (1957)	Australia	1788–1955
McAfee (1981)	SEA	1788–1860
Keating (1992)	Victoria	1834–1983
Callaghan and Helman (2008)	East Coast Australia	1770–2008

record appears comprehensive (Hunt, 1918), the drought record does not provide adequate information on event location and duration, making it difficult to establish dry periods in this region.

The climate almanacs published by the Australian Bureau of Meteorology were supplemented using an in-depth, single-region analysis (Keating, 1992). Keating (1992, xi) presents a drought chronology for Victoria, remarking that 'there has been surprisingly little analysis of [drought's] historical impact on the nation or its states,' apart from a large-scale analysis of drought provided by Foley (1957).

Foley's (1957) *Droughts in Australia: Reviews of Records from First Settlement to 1955* contains qualitative and quantitative data relating to drought in each Australian state; it is one of four sources used in this study that focus on *multiple* regions in SEA. All droughts for which historical records are available have been studied in terms of their duration, intensity and effect on primary production (Foley, 1957). Other multi-regional sources used in this study include McAfee's (1981) unpublished seasonal drought chronology for SEA from 1788–1859, and a chronology of severe storms on the east coast of Australia since 1770 (Callaghan and Helman, 2008). While the latter is predominantly a chronology of storm activity and coastline change, Callaghan and Helman (2008) also include information about coastal droughts and floods.

Although this study uses data from secondary sources, these sources consolidate weather and climate event chronologies compiled from a vast range of primary source material. Chronologies of drought and wet periods were published in these sources, initially identified in commentary from newspapers, unpublished diaries and letters, almanacs, observatory reports, 19th century Australian publications and official government reports. The 19th century sources compiled by W. S. Jevons and H. C. Russell alone contain 79 unique primary sources, which include 40 accounts from personal diaries, letters and direct communications with the authors. Russell even used his 1877 publication to correct an error published in *Ford's Almanac* and repeated by Jevons, indicating Russell's critical understanding of the primary source material. While the rich collection of primary weather and climate information available in the secondary source data set used in this study warrant further investigation, as analysis of this kind has not been undertaken for the Australian region before.

The material available in many of the extensive primary source compilations used in this study represent the first attempts to trace rainfall variations in Australia (Table I). It is worth noting that these records were not drawn together by amateurs – all secondary source authors are/were scientists, aside from Jenny Keating who is an historian. For example, the *Results of Rainfall in Australia* series (Hunt, 1911, 1914, 1918; Watt, 1936; Warren, 1948) was published by the Australian Bureau of Meteorology, Australia's federal provider of weather forecasts and observations, established in 1908. The 19th century chronologies were compiled by two of the leading scholars in Australia at the time, William Stanley Jevons and Henry Chamberlain Russell. Jevons was a polymath who moved to Australia and took up a job as an assayer at the Sydney Mint in 1854. Although employed by the Mint, he applied his scientific training from University College London to Australian meteorology. H. C. Russell later declared that Jevons' meteorological research was 'the most valuable contribution to the meteorology of Australia that had been made up to the time of its publication [1859].' (La Nauze, 1972).

Russell was Australia's first Government Astronomer whose duties also included meteorological research. He is described as 'one of the most eminent men of science in Australia in the nineteenth century' (Walsh, 1976). Russell stated that a scientist should be 'patient in investigation, accurate in measurement, cautious in accepting results, content to stand one in a long series who, for the good of humanity, are striving to interpret the laws of Nature' (Walsh, 1976).

The primary data contained in the secondary sources considered here have the potential to identify rainfall variations in SEA and also offered an opportunity for climate researchers to better understand the gaps and limitations evident in Australian qualitative climate data. Since the works of the late 19th century scholars used in this study were published, very little research using historical qualitative data has been undertaken in the Australian region. This study represents the most comprehensive attempt to consolidate existing documentary compilations to better understand weather and climate in the region.

When using historical documents to develop a chronology of rainfall variations there is the potential for primary reports of an event to be duplicated in more than one source, which increases the risk that an event may be perceived as widespread or extreme. Where replication is easily identifiable, these sources are not included in the final collation of data. For example, Helman (2009) draws predominantly upon Russell's (1887b) study of the River Darling to compile *Droughts in the Murray–Darling*

Basin Since European Settlement, so excluded from this analysis.

The historical data sources used in this analysis have some limitations. The dataset has a geographical bias caused by patterns of European settlement in SEA that is impossible to overcome. The region of NSW was first settled by Europeans in 1788, while the colonies of Victoria and South Australia did not have permanent European settlements until the mid-1830s. Cultural biases are also evident in the documentary records. For example, droughts in Tasmania were less-likely to be recorded than wet periods compared to regions like NSW, possibly due to the persistent myth that drought was not a prominent feature of the Tasmanian climate. Despite these limitations, it is important to examine this archive of qualitative weather and climate information. This study is one of the first of its kind in the Australasian region and provides a consolidated starting point for future research. We not only identify drought and wet years in SEA prior to the establishment of a weather station network, but also identify limitations in the data that will affect further research in this field.

To independently verify the drought and wet periods for SEA from 1788–1860 (Tables II and III), finally we compare our results to a historical record of water level fluctuation of Lake George, NSW, available from 1816 derived from land and lake surveys, documentary accounts and personal recollections (Russell, 1887a). Lake George is a precipitation-sensitive basin in NSW with no known outlet and strong correlations to SEA rainfall (Gergis *et al*., 2011). It has long been recognised as having highly variable lake levels due to its location west of the Great Dividing Range, a mountain chain that provides an orographic barrier to easterly rain-bearing systems reaching inland Australia (Russell, 1877). As such, fluctuations in its water level reflect regional rainfall variability over time, providing us with an extremely useful independent rainfall proxy located directly within our study region of SEA (Figure 1).

3. Methods

3.1. Defining drought conditions

Using the sources listed in Table I, months classified as 'dry' or 'wet' were compiled into Table II (drought periods) and III (wet periods) over a May–April year. SEA was analysed using the following subregions: New South Wales (NSW), southern Queensland (QLD), Victoria (VIC), South Australia (SA) and Tasmania (TAS). Note that these subregions are named using current Australian state divisions, not the British colonial divisions that existed during the 1788–1860 study period (e.g. Van Diemen's Land for Tasmania).

Aside from quantitative rainfall deficiencies, drought can be broadly defined as a prolonged period of very dry conditions when there is not enough water available to meet communities' needs. Acknowledging that drought does not have a universal definition, the Australian Bureau of Meteorology (2010b) provides the following drought classifications:

- *Meteorological drought*: defined by rainfall deficiencies
- *Agricultural drought*: determined by the impact of water shortage on primary industries
- *Hydrological drought*: quantified using ground water levels, and
- *Sociological drought*: assessed by social expectations and perceptions of rainfall.

Quantitatively, drought is defined by the Australian Bureau of Meteorology as three consecutive months of low rainfall that has interrupted normal water usage (Bureau of Meteorology, 2010a). To avoid artefacts associated with hyperbolic accounts of dry conditions and localised drought conditions, a year is classified a 'drought year' in Table II when at least 40% of historical sources in Table I indicate drought for at least 6 months using a May–April 'ENSO' year, the period with strongest association between SEA rainfall variations and ENSO (Risbey *et al*., 2009). By using a more stringent drought definition of at least 6 months, we are less likely to classify seasonal summer dryness as drought.

Historical sources often refer to the impact of water shortage on agriculture, ground water, flora and fauna and social responses. For example, explorer Charles Sturt detailed the devastating effects of the 1826–1829 drought in NSW, stating: 'Culinary herbs were raised with difficulty, and crops failed even in the most favourable situations. The settlers drove their flocks and herds to distant tracts for pasture and water, neither remaining for them in the located districts . . . Men at length began to despond under so alarming a visitation.' (Jevons, 1859, 67). Sturt's account describes meteorological, agricultural, hydrological and sociological drought and is an example of the climate information that historical accounts can provide.

The severity of a drought is difficult to determine using qualitative data sourced from disparate regions. In this study, a drought is considered severe if at least 6 months are characterised by rainfall deficiencies that negatively impacted agriculture, ground water and was perceived by society as severe. An indication of the number of sources and regions in agreement is also given in Table II. This is represented as a fraction of the total number of sources available for that region (or regions, if drought occurs in more than one area).

As it is difficult to identify the beginning and end of a drought from qualitative historical accounts, assessing the exact duration of a drought from documentary records is problematic. In this study, when one source states that very dry conditions were felt during an entire year, and another claims that only the months of May through to December were very dry, the shorter, more conservative duration estimate period is plotted. Because of disagreement between sources, and the difficulty associated with judging the onset of drought without the use of quantitative meteorological data, it is likely that

Table II. Drought chronology for SEA, 1788–1860.

Drought in South-Eastern Australia															
Year	Month												S.F.	R.	M.
	M	J	J	A	S	O	N	D	J	F	M	A			
1787–1788														0	0
1788–1789														0	0
1789–1790														1/1	3
1790–1791														1/1	10
1791–1792														1/1	8
1792–1793														1/1	12
1793–1794														1/1	12
1794–1795														1/1	9
1795–1796														0/1	0
1796–1797														0/1	0
1797–1798														1/1	N/A
1798–1799														1/1	6
1799–1800														0/1	0
1800–1801														0/1	0
1801–1802														0/1	0
1802–1803														1/1	11
1803–1804														1/2	8
1804–1805														0/2	0
1805–1806														0/2	0
1806–1807														1/2	1
1807–1808														0/2	0
1808–1809														1/2	4
1809–1810														1/2	12
1810–1811														1/2	12
1811–1812														1/2	8
1812–1813														1/2	4
1813–1814														1/2	12
1814–1815														1/2	12
1815–1816														1/2	8
1816–1817														0/2	0
1817–1818														0/2	0
1818–1819														0/2	0
1819–1820														1/2	3
1820–1821														0/2	0
1821–1822														1/2	5
1822–1823														0/2	0
1823–1824														1/3	4
1824–1825														1/3	6
1825–1826														1/3	4
1826–1827														2/3	11+
1827–1828														2/3	12
1828–1829														2/3	12
1829–1830														2/3	8
1830–1831														1/3	12
1831–1832														0/3	0
1832–1833														1/3	N/A
1833–1834														1/3	8
1834–1835														1/4	4
1835–1836														1/5	8
1836–1837														2/5	4
1837–1838														3/5	12

Table II. Continued

Drought in South-Eastern Australia															
Year	Month												S.F.	R.	M.
	M	J	J	A	S	O	N	D	J	F	M	A			
1838–1839														3/5	8+
1839–1840														2/5	6+
1840–1841														1/5	4
1841–1842														1/5	8
1842–1843														1/5	6
1843–1844														0/5	0
1844–1845														1/5	4
1845–1846														1/5	11
1846–1847														1/5	4
1847–1848														2/5	4
1848–1849														0/5	0
1849–1850														1/5	8
1850–1851														1/5	3
1851–1852														1/5	1
1852–1853														0/5	0
1853–1854														0/5	0
1854–1855														1/5	4
1855–1856														0/5	0
1856–1857														0/5	0
1857–1858														2/5	4–6
1858–1859														2/5	8
1859–1860														1/5	7
1860–1861														0/5	0

Regional Distribution of Drought		Number of Sources	
	New South Wales		< 3
	Victoria		3–5
	Queensland		6–9
	Tasmania	**R.**	Region
	South Australia	**M.**	Months

Drought has been plotted for all subregions in SEA between 1788 and 1860 using qualitative data derived from 12 sources (Table I). Column S.F. shows the number of sources that report drought for each year. A drought year was not declared if less then three sources agreed. Column R. shows the number of regions affected by drought as a fraction of the number of regions settled by Europeans. Column M. shows the number of months in a year that drought was reported.

the onset and end of the drought periods are only an approximation. Nevertheless, Table II is likely to give a good indication of dry periods in SEA.

3.2. Defining high rainfall conditions

Note that the index of wet years presented in Table III is compiled differently to Table II. Unlike the drought chronology presented in Table II, only Russell (1877) was used to identify months of good rainfall. The reason for this is that many of the secondary sources listed in Table I only contain information about floods and a few severe storm events. Because Australian rainfall has high spatial variability and the fact that flood events are often localised episodic events, it was difficult to discern any coherent rainfall variations over a broad region from the secondary historical sources analysed here. While flood reports provide important local information they cannot provide information about widespread rainfall variations unless enough local reports are available for compilation from a number of subregions. Unfortunately there were too few reports of severe rain events from the other secondary sources listed in Table I to discern coherent rainfall patterns from the secondary source material for the broad region of SEA. Since the information presented in Table III relates to the single region of NSW from 1788–1840, it is not possible to compare wet conditions across colonies like the drought conditions listed in Table II.

Table III. Wet years in NSW, 1788–1840.

Wet Years in Coastal New South Wales																
Year	Month												F	C	P	I
	M	J	J	A	S	O	N	D	J	F	M	A				
1787–1788									■	■	■	■				
1788–1789	■	■	■	■	■	■	■	■	■	■						
1789–1790										■	■					
1790–1791		■														
1791–1792		■														
1792–1793				■	■											
1793–1794	■			■		■		■	■		■					
1794–1795				■					■		■		x			
1795–1796				■				■					x			
1796–1797				■		■		■	■	■	■	■		x		
1797–1798			■		■	■	■		■	■	■			x		
1798–1799	■	■	■				■						x			x
1799–1800		■					■				■		x			x
1800–1801				■									x			
1801–1802			■										x			
1802–1803								■								
1803–1804						■						■				
1804–1805					■			■	■	■	■	■	x	x		x
1805–1806				■		■	■	■	■	■	■	■	x			
1806–1807					■	■	■		■		■		x	x		x
1807–1808		■														
1808–1809			■		■	■	■	■		■	■	■	x	x		
1809–1810	■		■		■		■						x			
1810–1811	■	■				■							x	x		x
1811–1812							■		■	■	■		x	x		x
1812–1813				■	■		■				■		x			
1813–1814						■					■	■				x
1814–1815							■		■							x
1815–1816				■	■	■	■	■			■		x			
1816–1817	■	■	■			■	■	■		■	■	■	x			
1817–1818				■							■	■	x	x		x
1818–1819					■		■	■			■	■	x			x
1819–1820		■									■		x			
1820–1821	■	■	■				■	■	■				x	x	x	
1821–1822			■		■	■			■	■			x			
1822–1823						■		■		■	■	■				x
1823–1824						■	■	■		■	■			x		
1824–1825	■		■		■			■	■		■		x			x
1825–1826			■						■	■		■	x	x		
1826–1827					■								x			
1827–1828							■					■				
1828–1829	■	■				■			■					x	x	x
1829–1830		■	■	■		■	■	■	■		■	■	x	x	x	
1830–1831	■		■	■		■	■	■	■	■	■	■	x	x	x	
1831–1832	■	■		■				■		■	■	■	x			x
1832–1833				■						■			x			x
1833–1834	■							■	■				x			
1834–1835					■		■	■					x			x
1835–1836						■			■			■				
1836–1837	■	■	■		■				■		■		x		x	
1837–1838			■			■		■		■		■	x			
1838–1839												■	x			x
1839–1840		■		■	■	■	■				■	■	x		x	x
1840–1841	■	■	■			■	■	■					x	x		

Table III shows months of good rainfall in coastal NSW, 1788–1840, derived from qualitative data published in Russell (1877). An 'x' in Column F indicates the occurrence of flood(s). Column C shows years in which an abundant harvest was reported, Column P indicates years where pasture levels were described as abundant or stock described as very healthy, and Column I denotes years when insect plagues were reported. These factors are often indicative of high rainfall in the SEA region.

Of the studies listed in Table I, Russell (1877) was the only source that contained detailed yearly reports about rainfall and weather in NSW, identifying where rain fell and whether the European settlers perceived it as adequate for their needs. Unfortunately, Russell (1877) did not continue to collate detailed records of weather beyond 1840 in this publication noting that 'it has not been thought necessary at present to carry these notes beyond 1840, as in that year meteorological observations were begun [at South Head Observatory in Sydney]' (Russell, 1877, 54). While it is regrettable in the context of the current study, his compilation represents a milestone in 19th century Australian meteorology. As a result of the spatio-temporal biases in the historical material detailed above, we confine the analysis of wet years to the population centre of coastal NSW where settlement has been continuous since 1788.

Table III shows months when good rainfall was reported in coastal NSW between 1788 and 1840. A year was classified as wet when at least 6 months of good rainfall was reported within the May–April 'ENSO year'. References to thunderstorms, lightning storms and hailstorms were included in the monthly classification process because although these events may be short lived, substantial rainfall is possible during these episodes.

An example of a report describing good rainfall is given by the following passage written by Colonel David Collins in March 1790: 'the weather had been very wet during this month; torrents of rain again laid every place under water; many little habitations which had withstood the inundations of last month now suffered considerably' (Russell 1877, 56). Identifying months of good rainfall was chosen instead of counting individual reports of rain because the number of reports increased as European settlement expanded and the population grew. Tallying each report of rain resulted in later years appearing wetter years simply because of an increase in the availability of historical sources (not shown). Since newspapers often published instances of fleeting rain during predominately dry conditions, it was necessary to exclude these reports of inadequate or poor rainfall from the analysis. Rainfall reports from western NSW were also excluded because weather updates from this region were too inconsistent between 1788 and 1840 to provide adequate information for inland NSW.

Aside from reports of good rainfall, the monthly classifications of Table III also indicate the occurrence of flood events, insect plagues, reports of 'abundant' harvests and accounts of 'abundant' or 'luxuriant' pasture, and healthy, fat stock. Table III indicates reports of flood (F), abundant crops (C), excellent pasture (P) and insect plagues (I) in the historical record from 1788 to 1840. Initially, phenological information and flood events were also used to classify wet years. However, the inclusion of this material made it difficult to identify years of high rainfall during the early years of European settlement in NSW. From 1788–1794 the population was confined to the region around Sydney Harbour, far from major waterways like the flood-prone Hawkesbury River (see inset of Figure 1), reducing the settlers' vulnerability to inundations. In addition, the Sydney region was known for its poor sandy coastal soils, a factor that would have influenced crop yields until agricultural production expanded into the richer alluvial plains of the Hawkesbury River. To add to the complexity of the data, it soon became apparent that agricultural success was not guaranteed in wet years. In fact, years of very heavy rainfall and severe flooding often caused widespread damage to crops, rather than a lack of water availability.

4. Results

4.1. Droughts in SEA, 1788–1860

Table IV summarises the droughts experienced in SEA over the 1788–1860 period. Of the droughts identified in this analysis, 1837–1841 was the longest and most widespread event. Between 1837 and 1841, NSW, Queensland, Tasmania and Victoria were all affected by severe drought. Given that our current understanding of Australian drought is still largely confined to the post-1900 period covered by instrumental records (Verdon-Kidd and Kiem, 2009; Timbal *et al*., 2010), we provide a brief outline of each event listed in Table IV below to provide a consolidated reference of historical accounts of lesser known pre-instrumental droughts for researchers working in the field. The list is also intended to serve as an independent inter-annual verification source for palaeoclimate reconstructions being developed in the Australian region (Gallant and Gergis, 2011; Gergis *et al*., 2011; Neukom and Gergis, 2012).

4.1.1. 1790–1791, NSW

According to historical sources listed in Table I, European settlers experienced drought only two years after arriving

Table IV. Years of drought in SEA, 1788–1860.

	1790s	1800s	1810s	1820s	1830s	1840s	1850s
Drought years			1810–1811	1824–1825			
	1790–1791	1802–1803	1811–1812	1826–1827	1835–1836	1841–1842	1857–1858
	1791–1792	1803–1804	1813–1814	1827–1828	1837–1838	1842–1843	1858–1859
	1798–1799	1809–1810	1814–1815	1828–1829	1838–1839	1845–1846	1859–1860
			1815–1816	1829–1830	1839–1840	1849–1850	

See Table II for subregional information.

in Australia. Settlers in NSW first reported periods of dry weather in 1789, but it was not until June 1790 that drought was declared, continuing until December 1791 (Russell, 1877). Crop failures occurred in 1790, before the onset of a hot and dry summer (Tench, 1793). On their arrival, European settlers were faced with a period of agricultural trial and error, resulting in crop failures during the early years of settlement. In addition to this, conditions onboard ships sometimes damaged plant seeds and cuttings during the long sea voyage from Great Britain to Australia, rendering them useless when planted. In October 1790, during a period of drought, Colonel David Collins remarked that some European crops had failed: 'the gardens and corn grounds were again parching for want of moisture; the grass was so dried that a spark got it on fire' (Russell, 1877, 56). This statement implies that both European and indigenous plants were affected by a period of drought, increasing the likelihood that crop failure was due to drought. By June 1791, 'the ground was so dry, hard and literally burnt up, that it was almost impossible to break it with a hoe' (Collins, 1804, 136). In a study of First Fleet meteorological journals spanning 1788–1791, Gergis *et al*. (2009) found that minimum temperatures for the summer (December–February) of 1790–1791 were 1.96 standard deviations warmer than average. A comparison of quantitative data with qualitative historical accounts suggest that reports of stifling heat are likely to be true, rather than an overstatement made by settlers unfamiliar with Australian climate (Gergis *et al*., 2009, 2010).

4.1.2. 1798–1799, NSW

A 6-month drought period is reported in NSW from September 1798 to February 1799, accompanied by reports of bushfires between December 1798 and February 1799. In a journal entry written in February 1799, David Collins remarked that 'the great drought and excessive heat had affected the water; such ponds as still retained any were reduced so very low that most of them became brackish and scarcely drinkable; and the bush from Sydney to Parramatta was completely on fire, the trees being burnt to their tops' (Russell, 1877, 63). Relief came to the settlers at Sydney with good rainfall in March 1799 (Russell, 1877). No further information is available regarding the area affected by dry weather or its social impact. It is particularly difficult to find further information regarding the spatial spread of drought, because settlement on mainland Australia was limited to Sydney Harbour and its surrounds at this time.

4.1.3. 1802–1803, NSW

NSW settlers experienced a longer drought from July 1802–May 1803. Despite the reported water scarcity, this dry period does not seem to be as severe as those in 1790–1791 and 1798–1799. On 5 March 1803, the *Sydney Gazette* stated that 'the long drought has deprived many of the settlers of their late crop of maize,' but went on to report the success of other crops on 19 March 1803, and even reported that granaries were full (Russell, 1877, 66). Reports show that the 1802–1803 drought did not have a severe impact on agriculture, pastoral pursuits or indigenous vegetation (Russell, 1877).

4.1.4. 1809–1815, NSW

Dry weather was reported in NSW from 1809, culminating in serious drought in 1811. Foley (1957) describes crops failures (maize in particular) and that by March 1811 there were notable water shortages. The water storage basins of the Tank Stream in Sydney were empty for the first time since they were constructed during the 1790–1791 drought (Russell, 1877). Good weather was reported in 1812, but drought set in again in 1813. By October 1813, approximately 5000 cattle and 3000 sheep had died because of pasture and water scarcity caused by a lack of rain (Foley, 1957). Gregory Blaxland, William Lawson and William Wentworth, the explorers who first crossed the Blue Mountains in NSW in 1813, observed that signs of the drought that afflicted the coastal regions were also visible on the western side of the mountain range 'because of the dead and brown appearance of the grass' (Russell, 1877).

4.1.5. 1824–1830, NSW and Queensland

Jevons (1859) identified a drought of 'great intensity' in NSW in 1824. Russell (1877) verified this, adding that the turnip crop failed because of low rainfall. There was a reprieve from dry weather in 1825 before reports of drought occur again in 1826. Sir William Macarthur, a landowner at Camden and Taralga in southwestern Sydney, remarked that the winter of 1826 was very dry, only broken by substantial rainfall in July and September, and then followed again by dry, hot weather from the end of spring and throughout summer (Russell, 1877). Callaghan and Helman (2008) note that except for early 1825 and late 1826, prolonged drought affected the east coast of Australia during the 1824–1830 period. Russell (1877) reported that the drought in 1828 was so severe that stock was removed from 30 000 acres at Camden south of Sydney, due to water shortages.

In 1829, Russell (1877) quotes inland Australian explorer Charles Sturt to support the presence of drought, who 'saw rivers cease to flow and sheets of water disappear' in his expedition north of Sydney (Russell, 1877, 104). The Brisbane Distillery at Parramatta ceased operations because their water supply of the Black Wattle Swamp dried up. In rural areas of NSW, cattle were perishing at an alarming rate (Jevons, 1859). On November 12, 1829 a public thanksgiving mass was called to beg God for relief from the continuing drought (Jevons, 1859). Drought was reported not only along the coast of NSW but also in southern Queensland (Callaghan and Helman, 2008).

4.1.6. 1835–1843, NSW, Tasmania, Queensland, Victoria, South Australia

The 1835–1843 period is the first time drought is reported across all five regions (NSW, Tasmania, Queensland, Victoria and South Australia) of SEA. Jevons (1859) states that, with the exception of a few short periods of favourable rain, the period from 1835–1841 can be considered a drought. The water shortage caused a 'general failure of agricultural crops' and failure of pasturage in the Bathurst and Hunter districts of NSW (Russell, 1877). During his explorations of inland Australia, Major Thomas Mitchell reported that regions near the Bogan and Darling Rivers in central NSW were influenced by drought (Mitchell, 1839). He also recounted that many creeks and waterholes in Western NSW were dry and river levels were low (Mitchell, 1839). In April 1835, Mitchell remarked: 'it was now evident that no rain had fallen in these interior regions since the summer heat had parched the earth' (Mitchell, 1839, 168).

Russell (1877) collected weather reports from *The Monitor* newspaper that reported in September 1835: 'the drought has been dreadfully fatal to the stock of this country. At the Cowpastures one gentleman lost ten working bullocks in one day.' (Russell, 1877, 130). Rain fell in each month from March to December (except May) [1835], but only amounted to showers and light rain. Bourn Russell, a store owner in West Maitland, NSW, reported that 'about the end of 1835 stock about Maitland had to be driven up country for feed, owing to the extreme drought then prevailing in the Lower Hunter' (Russell, 1877, 131). According to Jevons (1859, 68), water shortages were not as severe in 1836 and 1837, with the weather in the latter half of 1836 being 'temperate and favourable'. Jevons (1859, 68) goes on to write that despite sufficient rainfall during this time 'the whole period from 1835 to 1839 was with small exception a drought' in NSW.

The widespread nature of the 1835–1841 drought is evident from a number of sources listed in Table I. On an overland journey from Southern NSW to Lake Alexandrina in South Australia, Charles Bonney observed that the River Murray was very low in January 1837, and that the River Darling was nearly dry at the junction of the two rivers (Russell, 1877). January 1838 saw the onset of drought in Victoria and Queensland, while drought continued in NSW. Very dry weather is also reported in South Australia but, as outlined in Section 2, it has been difficult to establish the duration or area affected.

Keating (1992) collected evidence of drought in Victoria between 1838 and 1840. The newly established township of Melbourne was affected as 'the water level of the Yarra River declined and was contaminated by more salt water from the Bay' (Keating, 1992, 26). At this time, the Yarra was the main source of water for Melbourne and the brackishness of the water caused problems with water supply to the town. While exploring the unsettled northern districts of Victoria in 1838, Captain Charles Sturt remarked that the ground was cracked and dry and that 'the rivers had become a series of waterholes' (Keating, 1992, 26–27). Settlers, reacting to reports of fertile land fit for farming, moved to the Colac area, south-west of Melbourne, in the late 1830s. In 1841, Alfred Taddy Thomson recalled that 'a series of dry seasons had altered the face of the country, and the fertile region which had presented itself to his delighted view had been converted into an arid waste, destitute of either grass or water' (Keating, 1992, 27).

Callaghan and Helman (2008) also classify 1838 as a severe drought in south-eastern Queensland, also noting that very low rainfall fell on the east coast of Australia between 1837 and 1839. Jevons (1859) tracked the progress of east coast drought using newspaper articles, periodicals and explorers records. Jevons (1859) includes remarks from the *Asiatic Journal* which determined that 'the present year [1839] must be looked upon as the most calamitous the Colony [New South Wales] has ever experienced, occasioned by the long-continued drought' (Jevons, 1859, 69). In NSW, the drought ended in October 1839 with the onset of heavy rains. The *Sydney Gazette* reported that 'by the end of the year vegetation was luxuriant'(Jevons, 1859, 70).

According to the analysis presented here, drought was only reported once in Tasmania between 1788 and 1860. Table II shows that dry weather influenced the island between January and September 1841. With regard to the state of the climate of NSW in 1841, Jevons (1859) wrote that 'minor vegetation had ceased, and crops nearly destroyed from drought, which was felt also as far south as Van Diemen's Land' (Jevons, 1859, 70). It is likely that the lack of dry years noted from this region of SEA reflects the availability of fewer consolidated sources of historical information for the region than true climate conditions experienced over the study period.

The Australian Bureau of Meteorology's *Results of Rainfall Observations made in Tasmania* (Watt, 1936) is the only publication that includes a chronology of climate and weather events focused solely on Tasmania. Interestingly, the Bureau of Meteorology's chronology does not include information on drought periods. The only reference to low rainfall listed in Watt (1936) is a section written by J. C. Foley, the Tasmanian divisional meteorologist, who tabulated a 6 month period of low rainfall recorded in Hobart, southern Tasmania, from April to September 1841 (Watt, 1936). The Tasmanian historical material does not go into further detail about the social, ecological or economic effects of the 1841 drought. This reinforces the notion that the absence of Tasmanian droughts is very likely to reflect a limited compilation of historical material from the population sparse region, rather than any true climatic features.

4.1.7. 1845–1850, NSW

The period 1845–1850 is characterised by a number of short dry periods in NSW. Table II shows rainfall deficiencies in NSW from January–December 1845, February–August 1846 and from August 1849–March

1850. The 1845 drought was reported in NSW in both the eastern and western districts. Louis Piesse, a member of Captain Sturt's expedition to the central districts of Australia, remarked that the Darling River in western NSW was quite low and had less water in 1845 than in 1844 (Russell, 1887b). Russell (1877) describes the year 1845 has having 'droughty weather' but does not go into any more detail, while Foley (1957) remarked that during this period the Hunter River at Singleton on the east coast of NSW was reduced to a chain of ponds.

From August 1849–March 1850, drought appeared again in NSW. A settler, referred to as E. Morley, remarked that during the early part of 1850 he and two others 'went up the Darling looking for new country . . . The whole course of the river for 60 miles above Menindie [western NSW] was only a chain of water holes, in some places miles apart, and good feed in the river bed' (Russell, 1887b, 5). Another settler referred to as B. Dickinson, reported that in 1850 there was 'drought all the year, no grass, no saltbush. Cattle bogged in waterholes' (Russell, 1887b, 5).

4.1.8. 1857–1858, NSW and Queensland

The year 1858 is classified as a drought in south-east Queensland and NSW by 40% of the sources (Table II). Reports of drought from the Barcoo River region, the Richmond region and Rockhampton (Russell, 1877; Hunt, 1914; Foley, 1957) indicate drought in Queensland but these areas are slightly north of our study area. News reports indicate that farm stock was severely suffering as the drought desiccated pasture in southern Queensland (*Sydney Morning Herald*, 13 May 1858, 5). A correspondent from Moreton Bay (now known as Brisbane) noted that the drought had been 'almost ruinous to the settlers' (*Empire*, 12 April 1858, 4). During 1858, Robert Copeland Lethbridge inspected a station near Coonamble in northwest NSW. Writing in 1910, Lethbridge recalled: 'In May 1858, I went from Sydney out to the Castlereagh River to inspect a station near where Coonamble now stands. A little rain had fallen by the time I reached there, but before that there had been a terrible drought. I rode for two days over the run, which I went to inspect, and saw no grass at all, and only about 50 head of cattle. The stock had all been taken out to the Warrumbungle Mountains [western tablelands of northern NSW] to save their lives. My horse had nothing to eat during the three days I was there, except sprouts of saltbush; and evidently it was a drought of unusual severity, and covered a large area of country. I experienced none like it again until 1902' (Hunt, 1914, 50). This drought could be quite localised, given that the references located so far only refer to the impact of dry weather in northern NSW and Queensland.

4.1.9. 1859–1860, South Australia

Hunt (1918) and Foley (1957) both report drought in South Australia from September 1859 to March 1860. The drought was described as 'general' (widespread) and the weather described as 'very dry' (Hunt, 1918, 145). It is difficult to pinpoint the exact duration of this drought and it may be a continuation of dry weather reported in South Australia in 1858 (Hunt, 1918). In April 1858 rain was 'badly wanted; hardly a blade of grass was to be seen, and horses, sheep, and cattle almost starved' (Hunt, 1918, 145), but no further information is available regarding the length of this drought.

In January and February 1859 severe bushfires in South Australia heralded a very dry summer in the region (Hunt, 1918). Along with two deaths, it was estimated that '10,000 bushels of wheat were destroyed' during the blazes, with damage to houses, fences, crops and property also reported (Hunt, 1918, 145). Recovery from these bushfires may have been hampered by the onset of dry weather and drought later in 1859. Wheat yield statistics were first recorded in SA in 1859, 'when the average yield was 9.6 bushels per acres as against 11 to 14 bushels for the four following years' (Foley, 1957, 159). A lower wheat yield may indicate crop failure caused by low rainfall and/or the damage inflicted by widespread bushfires.

4.2. Wet years in NSW, 1788–1840

Table V lists the wet years experienced in NSW between 1788 and 1840. The 1793–1809 period was particularly wet, with periods of heavy rainfall often resulting in devastating flooding. Notably severe floods occurred on the Hawkesbury River in 1806 and 1809. Once again, we provide a brief outline of each event listed in Table V below to improve our understanding of pre-instrumental wet periods indicated by the historical record often not considered by climate researchers. Given that wet conditions are not as well described as drought conditions, only a decadal overview is provided in the descriptions below. This is provided in an attempt to balance the historical bias of drought research in Australia (Nicholls, 1988).

4.2.1. 1780s and 1790s: Sydney Cove

The Europeans' arrival in NSW in 1788 was characterised by high rainfall that sometimes hampered efforts to establish infrastructure in the new penal colony (Gergis *et al*., 2010). Colonel David Collins remarked in August 1788 that 'such heavy rain fell this month that it prevented outdoor labour, destroyed a great number of bricks, and the brick-kiln fell in more than once, much damage was done to the settlement and the roads made impassable' (Russell 1877, 55). The colony's surgeon George Worgan noted that in 1788 'the vicissitudes from serenity to squalls of wind, rain, accompanied with terrible thunder & lightning are sudden' (Gergis *et al*., 2009, 93).

Damage to infrastructure also accompanied the wet weather that coincided with the 1793–1794 La Niña event (Gergis and Fowler, 2009), particularly during summer (Russell 1877). In December 1793 a violent storm caused a boat to run aground on the wharf, endangering

Table V. Wet years in coastal NSW, 1788–1840.

	1780s	1790s	1800s	1810s	1820s	1830s	1840s
Wet years	1788–1789	1793–1794 1796–1797 1797–1798	1804–1805 1805–1806 1808–1809	1816–1817	1829–1830	1830–1831 1831–1832 1836–1837 1839–1840	1840–1841

its cargo of corn. In January 1794, heavy summer rains at Government House in Parramatta levelled fences and caused substantial crop damage (Russell 1877).

Wet years in the late 18th century were not always accompanied by crop losses and the destruction of roads, buildings and fences. Heavy rain resulted in an abundant harvest in January 1799, but unfortunately the accompanying thunder and lightning ignited large bushfires around Sydney (Russell 1877). Thankfully, heavy summer rain at the beginning and end of February helped to dampen the blazes. The settlers were lucky to be spared crop losses by fire or excessive wet weather, and by April 1799 the colony's three public granaries were reportedly full (Russell 1877).

4.2.2. The early 1800s: high rainfall and severe flooding of the Hawkesbury River, NSW

The wet years in the early 1800s were often accompanied by severe flooding on the Hawkesbury River (see Figure 1), causing widespread distress among the farmers who had settled on the river's floodplains (Russell 1877). Months of heavy rainfall in 1804 caused an enormous surplus of grain. Wealthy landowner, William Wentworth, noted that 'the harvest of the year 1804 was so abundant, and the surplus grain so extensive that on sale could be had for more than half the crop.' (Russell 1877, 67–68). The continuation of heavy rainfall into 1805, however, posed considerable risk for floodplain settlements. In March 1805, the rain was described as 'incessant' and the settlers at the Hawkesbury had narrowly escaped flood the month before (Russell 1877). By April 1805 'deluges' of rain submerging low-lying farms (Russell 1877).

While heavy rainfall ensured the agricultural success of the young colony, it also had the potential to be highly destructive. The year 1806 is iconic in New South Wales' history, owing to the 'Great Flood' on the Hawkesbury River in March 1806 (Russell 1877). It was the most destructive flood the Europeans had experienced since their arrival in NSW in 1788. The extensive inundation resulted in the loss of lives, crops and stock, and caused damage to houses, farming equipment and other infrastructure (Russell 1877). In their assessment of the flood damage, the government estimated that the 'Great Flood' had swept away £35 000 worth of goods, and caused crop losses in the colony's 'food bowl' that brought them to the brink of famine (Russell 1877). In 1809 and 1816 further flood events of a comparable magnitude occurred on the Hawkesbury River, with similar societal impacts (Russell 1877).

By 1816, Hawkesbury settlers could read the signs of flood and were acutely aware of the widespread damage that flooding could reap on low-lying farms. As the river rose on 2 June 1816, following days of heavy rain, 'the settlers, with their families, had from necessity abandoned such of the houses and farms as were likely to be inundated' (Russell 1877, 80). The wet weather continued into the summer of 1816–1817, with 'incessant rains' damaging wheat before farmers had a chance to store it in their barns. Despite the sometimes-destructive nature of high rainfall, the *Sydney Gazette* noted in December 1817 that 'with infinite satisfaction we congratulate the public on the abundant and luxuriant harvest, with which, under Providence, we are likely to be favoured' (Russell 1877, 81).

4.2.3. The 1829–1841: drought-breaking rains

The periods of high rainfall that occurred between 1829 and 1841 can be classified as 'drought-breaking rains' as they mark the termination of prolonged periods of dry conditions. For example, the years 1829 and 1839 are identified as years of high rainfall (Table III) but are also defined as drought years in Table II. While this may appear contradictory, these results represent years that contained a dry spell followed by enough rainfall to relieve drought conditions. Such conditions are still noted in contemporary Australian climate, particularly during ENSO phase transitions, as recently observed during the breaking of the 1997–2009 'Big Dry' (Gergis *et al*., 2011). The documentary evidence reveals some overlap between periods of drought and high rainfall, suggesting that it took longer for the drought to break in some areas, or reflect geographical biases in the availability historical sources. In May 1829, settlers despaired that good rain at Sydney had not extended to the southerly Cowpastures district, and that some regions were still exhibiting signs of drought (Russell 1877). However, ten days later *The Sydney Gazette* announced that steady rain had fallen in all districts, easing the settlers' worries.

Good rainfall returned to NSW following the 1835 drought. In October 1836, farmers described the most recent harvest as 'one of the most plentiful seasons ever remembered in the Colony' (Russell 1877, 133). The summer of 1836–1837 was wet, with heavy rain in January 1837 having a 'beneficial effect' throughout the settled districts of NSW, a far cry from the brown pastures of a hot Australian summer (Russell 1877). By March 1837 there was 'plenty of pasturage for the sheep and cattle' and settlers looked forward to a good harvest (Russell 1877, 134).

In June 1839, newspaper reports described as beautiful the land along the River Murray, the district of Mannus (120 km southwest of Canberra) and Camden Forest (50 km southwest of Sydney) (Russell, 1877). A report stated that 'although the quantity of rain fallen lately is limited, the grass is good. About Kyamba [Kyeamba, near Wagga Wagga, NSW] and Billy Bong Ranges the rains have been very heavy, and the creeks and flats are flooded. On the Murrumbidgee River, from the lowest down stations to Yass [60 km northwest of Canberra], the country is in a most deplorable condition – not a blade of grass to be seen – and in passing along the road you may travel 20 miles before you can get a drink of water for either horse or bullock, or even as much as would make a quart of tea' (Russell, 1877, 141). By July 1839 the situation had changed – rivers were running and water was plentiful (Russell, 1877). This passage shows the spatial variation of rainfall throughout NSW – drought conditions could persist in some regions while others experienced plentiful rain and flooding.

4.3. Verification of NSW drought and wet periods with Lake George water levels

To independently verify our rainfall chronology, next we compare drought (Table II) and wet calendar years (Table III) for NSW with estimates of historical Lake George water levels between 1816 and 1860 (Russell, 1887a; Jacobson *et al*., 1991). Fluctuations in the level of Lake George are known to occur in response to seasonal and long-term variations in rainfall, evaporation and stream inflows (Singh and Geissler, 1985). Because Lake George has no subterranean discharge, water fluctuations are caused primarily by evaporation and rainfall (Singh and Geissler, 1985). Figure 2 shows the strong association between low water levels in Lake George and the occurrence of drought in NSW, but does not show a similar result for wet years. Unfortunately, droughts in NSW cannot be compared to the Lake George record during 1788–1815 as the record only begins in 1816. Nonetheless, those droughts that do occur in the period of overlap between the two records (1816–1860) all coincide with drops in lake levels.

Figure 2 shows that all 12 calendar-year droughts in NSW coincide with a decrease in the level of Lake George. In two years of drought the lake maintained a steady level (1839 and 1846) and in both these years the lake was completely empty. These results indicate that in all calendar years identified as drought in the documentary record, in-flow of water to the lake was low and evaporation was high.

Interestingly Figure 2 shows that of the six wet calendar years in the 1816–1860 period of overlap, only one year coincides with an increase in the amount of water in the lake (1840). The lack of association between the chronology of wet years and high Lake George levels may reflect lags in surface water level increases due to issues associated with our high-rainfall chronology for NSW, groundwater recharging or temperature changes resulting in increased evaporation (Jones *et al*., 2001). Two wet years coincide with years of drought years (1829 and 1839), but this indicates the arrival of drought-breaking rains. The three remaining wet years correspond with a decrease in the level of the lake (1830, 1831 and 1836). Although small decreases in the lake level are evident, we can see that the fall of Lake George water levels that started in 1823 was arrested by good rainfall in 1830 and 1831. Rainfall in 1836 appears to have slowed the evaporation of water in Lake George, following drought in 1835 and before the long 1837–1839 drought.

Note that in this study, we only provide a simple qualitative comparison of our results with Lake George to avoid detracting from the main focus of the study, which is to present a new dataset of historical drought and wet years in SEA using documentary sources. A thorough statistical analysis between the newly developed rainfall chronology and instrumental and palaeoclimate records, including a comparison of the NSW rainfall chronology and Lake George water levels over the full 1819–1989 period, is presented in part 2 (Gergis and Ashcroft, 2012).

5. Discussion

There are a number of issues that influence the rainfall results presented in Tables II and III. Australia's documentary record contains geographical biases associated with the short span of European settlement in some parts of SEA. NSW was Australia's only colony until 1803, when settlement expanded to Tasmania. Queensland was settled in 1824, Victoria in 1835 and South Australia in 1836. As such, our understanding of historical climate in SEA is limited because settlement was confined to small geographical areas in the Sydney region of NSW and there were long periods between settlement expansions. This results in fewer documentary records for some colonies (Queensland, Victoria and South Australia) compared to others (NSW and Tasmania). Like all documentary research, problems such as report duplication and a local geographic focus in the source material creates geographical biases in the results.

There are some biases associated with historical patterns of population settlement that will never be overcome. From first settlement in 1788 until as late as the 1830s, explorers report drought and flooding in regions without permanent European settlement making it virtually impossible to extend our knowledge of these events from documentary sources. For example, in January 1798, explorers George Bass and Matthew Flinders arrived at Western Port in Victoria and noted 'unmistakeable signs of drought' (Jevons, 1859, 61–62). Waterholes were dry and the streams they came across were brackish. Flinders wrote that '[N]o more than four natives were seen, and their shyness prevented communication; the borders of the port, however, bore marks of having been much frequented, but the want of water seemed to have occasioned a migration to the higher lands' (Flinders,

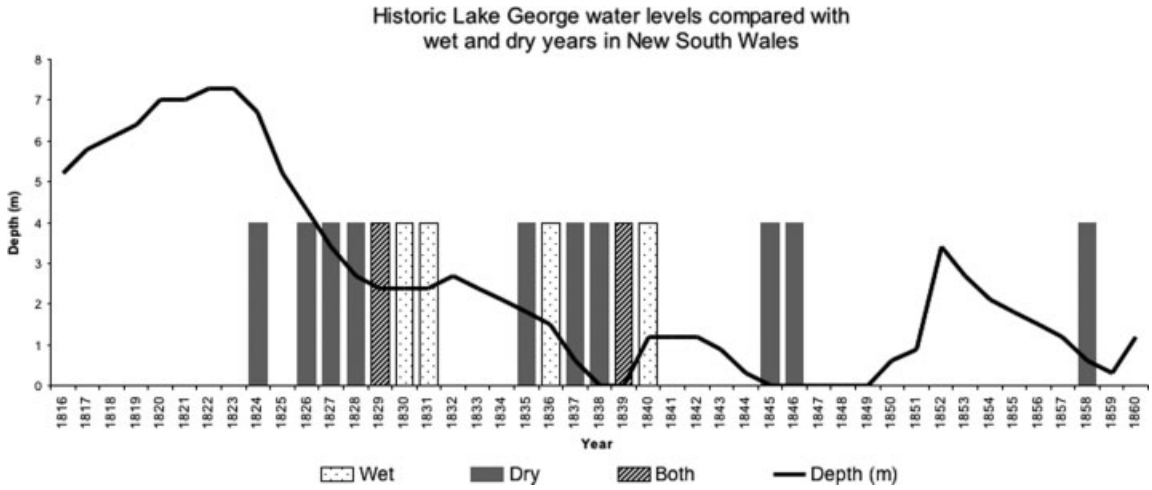

Figure 2. A comparison between the levels of Lake George (Russell, 1887a; Jacobson *et al*., 1991) and calendar years of drought and high rainfall in NSW identified in this study (see Tables II and III). Note that this comparison is restricted to the 1816–1860 period of overlap, noting that wet years are only provided for the 1788–1840 period (see Section 4.2.). Lake level depths are approximated in metres using historical estimates provided by original and secondary sources (Russell, 1887a; Jacobson *et al*., 1991).

1814). Because Bass and Flinders were only in Western Port from 4–14 January 1798 it is impossible to tell whether the drought they report was merely summer dryness or the result of long-term rainfall deficiency.

Some early explorers recorded comments on rainfall variations as they moved throughout SEA. For example, periods of South Australian drought are reported for 1839, 1845 and 1846 in the exploration records of Charles Sturt, Edward John Eyre and John Tennant (Hunt, 1918). In these cases, it is difficult to get a clear picture of drought duration as explorers moved from one area to another. Their qualitative accounts of the climate cannot be compared to previous seasons making it difficult to establish whether rainfall in the area was unusually wet or dry using documentary records. As such, we recommend that historical accounts be analysed in conjunction with instrumental meteorological records wherever possible for mutual verification (Gergis *et al*., 2009).

The previous example also highlights a problem with solely relying on documentary records to reconstruct drought. Since droughts in South Australia have not been well reported by Jevons (1859), Foley (1957), Hunt (1918) or McAfee (1981), this has hampered our ability to discern rainfall variations from this region. Although Hunt (1918) provides some information on drought occurrence, the beginning and end of a drought conditions are often not mentioned. Instead, reference is made to when the drought reached its peak and some of the social impacts.

Gaps in the Tasmanian source material are also noted in this analysis. Apart from Jevons (1859), whose chronology only rarely mentions Tasmanian climate conditions, the only other significant source of secondary historical material for the region is provided by the Bureau of Meteorology's *Results of Rainfall Observations in Tasmania* (Watt, 1936), which only focuses on flood events and storms. Even then, an exact date of the flood event is not always recorded. This means that this qualitative data cannot be solely used in Tasmania, suggesting the need for further research using primary source material to establish the full extent of pre-instrumental drought and wet periods in Tasmania.

One of the shortcomings apparent in the chronology of wet years presented in Table III is the limited availability of data from inland areas. While detailed rainfall information is readily available for coastal NSW, information from regions west of the Great Dividing Range are too limited to determine rainfall conditions from these areas over time. A compilation of flood information available for each colony of SEA during the study period was attempted (not shown) but the episodic nature of flood and inconsistencies in the reports provided in the secondary source material meant that it was not possible to identify any coherency in the results. We conclude that primary source material is needed to compile detailed indices of wet years for each subregion of SEA, and is recommended as a focus of future research.

It is also possible that source duplication may affect the results shown in the drought chronology presented in Table II. This is particularly a problem with Jevons (1859) and Russell (1877) as they use similar news sources and both focus on NSW. Duplication may also be a problem when using data from the Australian Bureau of Meteorology *Results of Rainfall* almanacs listed in Table I as the original source material is rarely referenced, making it difficult to identify whether or not a record has been duplicated. This issue would mainly be a problem for NSW as it is likely that Warren (1948) has drawn upon both Jevons (1859) and Russell (1877). Duplication will be less of a problem for other regions in SEA as they are less comprehensively documented. As such the Australian Bureau of Meteorology publications for areas outside of NSW are probably the most thorough compilation of historical material compiled for these regions (Hunt, 1911, 1914, 1918; Watt, 1936).

6. Conclusion

The purpose of this study was to develop a consolidated record of historical rainfall variations over as much of SEA as possible over the 1788–1860 pre-instrumental period using documentary records. Given that our understanding of Australian rainfall variations in the pre-1860 period is still very limited (Gergis *et al*., 2011), it is necessary to revisit historical sources to recover both early instrumental observations and documentary accounts of past climate conditions. Although documentary climate research is still in its infancy in Australia, this analysis represents a significant attempt to consolidate more readily available secondary historical sources into a single reference detailing Australian drought conditions that can now be compared to other documentary compilations from other ENSO-effected regions of the Southern Hemisphere (Quinn and Neal, 1992; Ortlieb, 2000; Garcia-Herrera *et al*., 2008; Nash and Endfield, 2008; Neukom *et al*., 2009; Nash and Grab, 2010).

Our analysis of 12 secondary sources identified 27 drought years in SEA between 1788 and 1860, and 14 years of high rainfall in NSW between 1788 and 1840. While our research is an important advance in understanding pre-instrumental rainfall in SEA, we also acknowledge that substantial biases and gaps still remain in the region's documentary records. Further research using additional primary source material such as newspapers, personal diaries, letters and government reports is needed to augment the historical climate record in many regions in SEA. Nonetheless, the documentary rainfall chronology presented here provides an important basis for verifying early instrumental meteorological observation records and palaeoclimate reconstructions, and is the subject of part 2 of this analysis (Gergis and Ashcroft, 2012).

This study highlights that further research is needed to improve our record of droughts and wet years for all regions in SEA. Even for the well-described region of NSW, further work can still be done to improve our knowledge of the duration and severity of pre-1860 droughts. For example, Russell (1877) noted that material had grown so voluminous after the 1840s he had not been able to continue compiling weather reports (Russell, 1877). Subsequently, he turned to instrumental meteorological observations kept at Sydney's South Head Observatory to understand variations in historical climate.

This study confirms that SEA has experienced considerable rainfall variability that has influenced past Australian societies since first European settlement in 1788. Despite the geographical biases encountered in this study, it is clear that historical records provide important information on rainfall variations in SEA and their societal impacts over the 1788–1860 pre-instrumental period. The documentary rainfall chronology presented here provides the foundation for developing an extended rainfall index along with early instrumental meteorological observations from 1788–2008. The development of an extended rainfall index for NSW and its verification with palaeoclimate reconstructions of SEA rainfall and ENSO is the subject of part 2 of this study (Gergis and Ashcroft, 2012).

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