Chapter

Introductory Chapter: Australia—A Land of Drought and Flooding Rain

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1. Introduction

Instrumental records of Australia's rainfall are maintained by the Australian Bureau of Meteorology (BOM) and extend back over 150 years in some locations. Annual contour maps of the continent extending back to 1900 illustrate how annual rainfall has varied across the continent [1]. The continent has a long history of droughts and floods [2], extending into recent years [3, 4]. **Figure 1** shows a map of Australia with the individual states and various locations referred to in this chapter.

Figure 1.
Map of Australia showing states and locations referred to in this chapter.

2. Drought in Australia

A book by McKernan entitled *Drought: The Red Marauder* [5] reveals a story as perceived by people who have experienced droughts in Australia throughout more than 200 years of European settlement. At any particular time, there is often a drought somewhere in continent of Australia. However, there is often a reluctance to acknowledge drought as a persistent aspect of Australian life and the arrival of drought is often greeted with surprise [5] with a tendency for each drought to be perceived as "the worst on record" [5]. Droughts are a recurrent and natural part of the Australian climate, with evidence of drought dating back thousands of years. However, deficiencies in our capability to adequately monitor, attribute, forecast and manage drought are exposed whenever a drought occurs [6].

2.1 Drought frequency and relationship to climate indices

For most Australian regions, individual climate drivers, associated with particular climate indices, generally account for less than 20% of monthly rainfall variability [7]. It is, therefore, unlikely that a single climate phenomenon is responsible for all drought events. It is probable that different periods of extended drought are driven by different and/or multiple combinations of climatic processes [8, 9].

Three periods of prolonged droughts have occurred in south-east Australia during the period of instrumental records. These are known as the 'Federation drought' (1895–1902), 'World War II drought' (1937–1945) and the 'Big Dry' (1997–2010). Verdon-Kidd and Kiem [10] showed that these major droughts were related to the combinations of four principal climate drivers extending over the Pacific Ocean (El Nino Southern Oscillation: ENSO; Pacific Decadal Oscillation: PDO), the Indian Ocean (Indian Ocean Dipole: IOD) and the Southern Ocean (Southern Annular Mode: SAM).

Hiepp et al. [11] examined the relative contributions of four climate indices (ENSO, IPO, DMI and SAM) on rainfall in New South Wales. For the period 1948–2006, the study investigated the magnitude of the influence of each climate driver and its interaction on the rainfall at 15 locations distributed over NSW. It was reported that the influence of each driver at a particular site is different although some generalised patterns were evident. The results show that the ENSO has wide influence across over the entire state of New South Wales and is the primary climate driver of influence at 10 of the 15 sites analysed. The IPO (Interdecadal Pacific Oscillation) by itself does not have evidence for an influence on rainfall at any of the considered sites, but is influential when considered in combination with ENSO. Palmer et al. showed the importance of the IPO in modulating drought across Australia over past centuries [12]. Other investigations [13] have suggested that about half of Australian interannual-to-decadal precipitation variability may originate from as far away as the Atlantic Ocean.

McGree [14] examined rainfall data for 36 BOM stations from Queensland and the Northern Territory, representing north-eastern Australia. From this data, it was found that drought frequency, duration and magnitude was greater during 1981–2010 than during 1951–1980. The IPO and ENSO were the dominant drivers of drought occurrence over the period 1951–2010. The increase was not linear and was in a large part due to low-frequency variability, namely the positive phase of the IPO from 1977 to 1998. The switch to the negative phase of the IPO from 1999 resulted in a decade from 2000 with reduced drought activity. Carvalho et al. examined rainfall variability in the Shoalhaven river catchment in southern NSW and its relation to climatic indices [15]. This study found that although drought in this region is related to El Niño years, there was only a weak positive correlation between catchment rainfall and SOI, which was moderately enhanced during negative phases of the IPO.

Kiem and Franks investigated multi-decadal variability of drought risk by examining the performance of the Grahamstown Reservoir in NSW [16], calculating the probability of the reservoir storage level falling below 30% during three different phases of the IPO. This probability was almost 20 times greater during the positive IPO phase than it was when negative.

2.2 Drought and climate change

Although some reports [17] claim links between climate change and recent droughts in Australia with a high degree of certainty, an examination of the scientific literature would suggest a more cautious approach to stating unambiguous conclusions, due to the lack of rigorous evidence. Studies by Cai et al. [18] found that although climate models generally suggest that Australia's Millennium Drought was mostly due to natural multi-decadal variability, some late-twentieth-century changes in climate that influence regional rainfall are partially attributable to anthropogenic greenhouse warming. Cook et al. [19] examined the Millennium Drought during 2003–2009 and the record-breaking rainfall and flooding in austral summer 2010–2011 in eastern Australia. They found limited evidence for a climate change contribution to these events, but such analyses are restricted by the lack of information on long-term natural variability. Analysing a reconstruction of summer (December–January–February), they reported moisture deficits during the Millennium Drought fall within the range of the last 500 years of natural variability. van Dijik et al. [20] studied the Millennium Drought in southeast Australia (2001–2009). They found that prevailing El Nino conditions explained about two-thirds of rainfall deficit in east Australia, but the results for south Australia were inconclusive with a contribution from global climate change plausible, but unproven.

2.3 Impacts of drought

The impacts of droughts have been categorised as meteorological, hydrological, agricultural and socioeconomic [21]. Many of the reported studies have emphasised the impact of drought on agriculture, and this is a topic of current focus with drought in eastern Australia affecting many farming communities. Sheng and Xu [22] estimated that Millennium drought between 2002 and 2010 reduced agricultural total factor productivity by about 18% in Australia over the period.

Studies have been directed towards evaluating the impact of climate change on agricultural production in Australia. For example, drought frequently limits Australian wheat production, and the expected future increase in temperatures and rainfall variability will further challenge the productivity [23]. Relationships between wheat yields and climatic factors including rainfall are known to be complex and the subject of ongoing investigations [24]. Studies by Hunt et al. [25] show that the reduced yields of wheat associated with lower rainfall can be offset with adaptation through early sowing of the crop.

Feng [26] examined the impacts of rainfall extremes on wheat yield in semi-arid cropping systems in eastern Australia and found that the frequent shortages of rainfall in eastern Australia created a greater threat to crop growth than excessive rainfall.

There are many impacts of droughts other than agriculture [20]. For example, droughts in Australia have had effects on wildlife populations including waterbirds [27, 28]. Studies have shown that droughts have an effect on mental health of the population, particularly in rural areas of Australia [29]. Li et al. investigated the ecological effects of extreme drought [30], including water acidification and eutrophication in the Lower Lakes (Lakes Alexandrina and Albert) in South Australia.

3. Flooding rains

Flooding rains are also recurring feature of the Australian climate. For example, prolonged rainfall over large areas of Queensland led to flooding of historic proportions in December 2010, extending into January 2011 [31, 32]. About 33 people died as a result of those floods, with more than 78% of the state (an area larger than France and Germany combined) declared a disaster zone. More than 2.5 million people were affected [31] with approximately 29,000 homes and businesses experiencing some form of inundation, with the cost of flooding estimated to be over A$5 billion [31]. In January 2011, Brisbane, the state capital of Queensland, experienced its second highest flood in over a century. Major flooding occurred throughout most of the Brisbane River catchment, with an estimated 18,000 properties inundated [32]. More recently in 2018, extreme rainfall conditions inundated the city of Townsville, located in coastal north Queensland, experiencing flooding of large parts of the urban area [3, 33].

In addition to the impacts on urban infrastructure, floods may have a substantial impact on the ecosystem. For example, runoff following extreme rainfall has been associated with detrimental impacts on coral of the Great Barrier Reef [34]. Flooding can also impact on the establishment of tree seedlings [35] and has been implicated in the dieback of mangroves in Queensland rivers, rather than the effect of herbicides as suggested previously [36].

With the devastating impacts of floods, there is interest in understanding and potentially improving predictive capabilities. Studies by McMahon suggest that floods in south-eastern Queensland do not occur randomly but are associated with a repeating 40 year cycle [37].

4. Predicting droughts and floods

In addition to general circulation models (GCMs) [38–40] that attempt to implement physical models of climatic systems, considerable research has been reported over the past decade using machine learning, particularly neural networks, to forecast rainfall [41–48]. The results suggest that the skill of the forecasts using the machine learning approach for medium-term forecast is superior to GCMs [48]. With GCMs, forecasts are usually initially generated for extended grid areas for defined geographical areas. Forecasts for more specific locations can then be generated through a process of downscaling. With the machine learning approach, forecasts are generated for specific locations for which historical data are available. If there are sufficient locations over a geographical region, contour maps representing observed and forecast rainfall can then be generated. This is illustrated for Tasmania in **Figures 2** and **3** for observed and forecast monthly rainfall, 12 months, in advance.

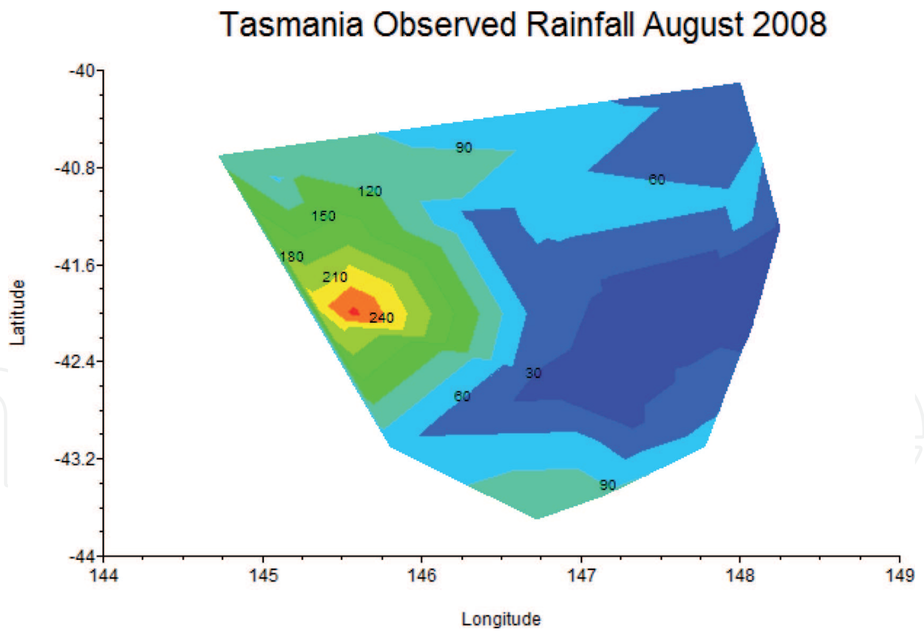

Figure 2.
Observed monthly rainfall for Tasmania August 2008.

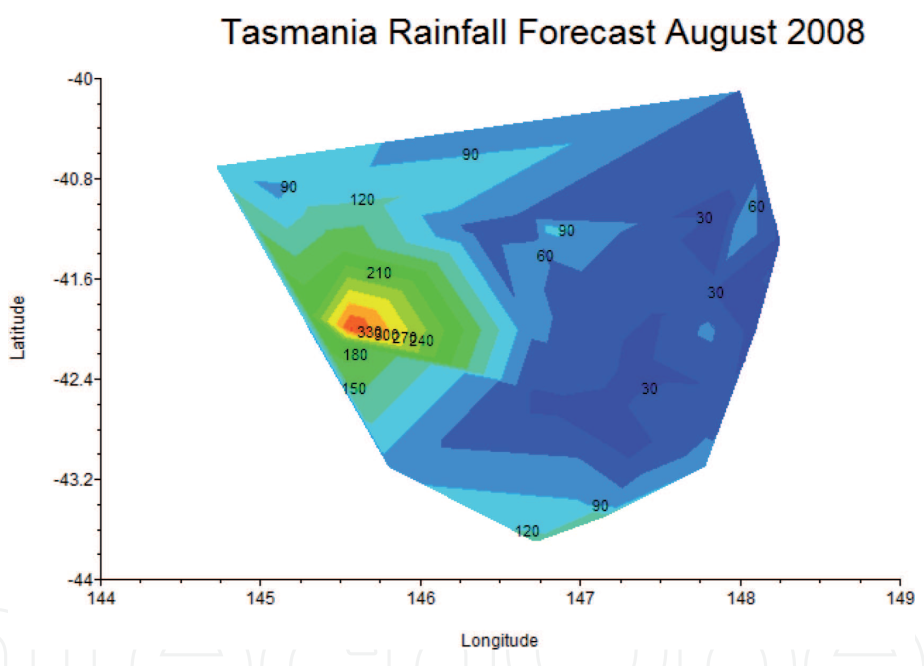

Figure 3.
Forecast monthly rainfall for Tasmania August 2008.

5. Rainfall reconstructions

Instrumental records of rainfall and temperature generally extend back only about 100 years in Australia. Reconstructions of past temperatures, extending back hundreds or thousands of years, are available for many parts of the world [49]. These are derived from palaeo data, including tree rings, corals, ice cores and stalagmites. Such reconstructions are much rarer for rainfall and, comparatively, few exist currently for Australia. However, it is important to consider the examples that exist as they enable episodes of droughts and flooding rains to be put into a wider context before asserting particular events are unprecedented, or ascribing them, with a high degree of certainty, to anthropogenic climate change.

Climate proxy data are ideally derived from sources that are located within, or in close proximity to, the region of interest. However, in cases where such proxy records are unavailable, remote proxies can be considered as a possible alternative [50]. There are relatively few in situ rainfall-sensitive palaeoclimate proxy records in Australia providing continuous records of rainfall variability [51]. An alternative is to utilise records that are from the same continent, but external to the region of direct interest. For example, Ho et al. made use of three such records [52]. The first was a study by Lough [53], who found significant correlations between coral luminescence intensity recorded in coral cores from the Great Barrier Reef and summer rainfall variability in northeast Queensland, enabling the multi-century coral record to be used to reconstruct Queensland summer rainfall back to the eighteenth century. The second study used high-resolution (approximately annual) analysis of trace elements sensitive to moisture availability present in a stalagmite from the Wombeyan Caves in south-east Australia. McDonald [54] found this to correlate with periods of above or below average rainfall from 749 BCE (before the Common Era) to 2001 CE (Common Era). The third study generated a 350 year long rainfall reconstruction at Lake Tay in Western Australia, based on tree ring widths [55].

These three Australian palaeoclimate proxies of rainfall enabled the reconstructions of rainfall in the Murray Darling Basin of south-eastern Australia [49, 50] although all three lie outside the Murray Darling Basin. The results reveal several extended periods that are likely to have been drier than indicated by the instrumental record from approximately the last century. Extended dry periods include the mid-late-1700s, 1500s, 1100s, 400s and 300 BCE. Comparisons between the reconstructed rainfalls and extreme instrumental rainfall indicated that the occurrence of extended periods wetter than the wettest decade in the instrumental record is also likely to have occurred in the mid-late-1800s and also around 1700. Multi-centennial wet epochs (or, at least, epochs without a multi-year drought) are also evident between 400–700 CE and 300 BCE–2100 CE. The reconstructions, therefore, confirm the occurrence during the last 2751 years of both wet and dry periods that have greater frequency, duration and severity than observations from the instrumental record.

O'Donnell [56] developed a 210-year tree ring-width chronology from *Callitris columellaris* from the Pilbara region of Western Australia. This was highly correlated with summer-autumn (December–May) rainfall across semi-arid northwest Australia. The reconstruction showed the periods of below average precipitation extending from one to three decades and the periods of above average precipitation which were often less than a decade. The results demonstrate that recent decades (1995–2012) have been unusually wet with average summer/autumn rainfall of 310 mm compared with the previous two centuries (average summer/autumn rainfall of 229 mm).

Freunmd et al. [57] used a diverse set of Southern Hemisphere palaeoclimate records to produce rainfall reconstructions for cool (April–September) and warm (October–March) seasons corresponding to eight regions across the Australian continent. They reported that trends towards wetter conditions in tropical northern Australia are highly unusual in the context of multi-century rainfall reconstructions. Cool season drying trends during the instrumental period in regions of southern Australia are very unusual, although not unprecedented, when compared with the past several centuries from 1600 CE.

Verdon-Kidd et al. [58] produced a 507 year reconstruction of rainfall for the monsoonal northwest of Australia, focussing on the site of Oenpelli in the Northern Territory. The study used remote proxies from Asia (tree rings), Australia (coral) and South America (tree rings) with an instrumental calibration period from 1900 to 1976. The rainfall reconstruction presented from 1470 CE suggests that the modern instrumental record on average represents a wetter climate than the pre-instrumental period. Furthermore, the reconstructions display wet and dry periods of greater duration than evident from the instrumental record. Other recent studies using tree rings to reconstruct rainfall include Allen [59] for Arnhem Land in the Northern Territory of monsoonal Australia, and O'Donnell for Western Australia [60]. Evidence is also provided from sediments from northwest Australia periods of extreme flooding and drought over past 2000 years [61].

A reconstruction of rainfall was produced by Tozer [62] for the Williams River catchment in subtropical eastern Australia (see map) extending over a period of 1013 years between 1000 and 2012 CE. Ho [50] relied on circulation teleconnections that strongly link climatic processes in one region to another. The remote proxies are calibrated with respect to an instrumental period, to develop palaeoclimate reconstructions. As no high-resolution palaeoclimate proxies were available corresponding to the Williams River catchment area, the study utilised the teleconnection between summer sea salt deposition recorded in ice cores from Law Dome in East Antarctica and rainfall variability in eastern Australia. It was found that both the dry and wet epochs persisted up to twice as long in the pre-instrumental compared with the instrumental period.

Documentary evidence can also be valuable in complementing palaeo reconstructions of rainfall. Fenby et al. [63, 64] considered 12 documentary-based rainfall chronologies for five subregions of south-eastern Australia (SEA) over the 1788–1860 period using a range of historical sources. This analysis identified 27 drought years in south-east Australia between 1788 and 1860 and 14 years of high rainfall in New South Wales (NSW) between 1788 and 1840. This study confirms that south-east Australia 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 NSW.

6. Conclusion

This chapter provides some background to the available data and understanding of rainfall patterns experienced in Australia. Compared with many counties, Australia is fortunate in having a comparatively good set of rainfall records over the continent extending back about 100 years in many cases. The continent experiences extended episodes of drought and flooding rains. It is clear that these are related to multiple climate drivers that may extend widely over the globe, and are incompletely understood. Forecasting rainfall over the medium-to-long term remains problematical, and solutions may be found in advanced data analysis techniques such as machine learning rather than physical models. There remains a scarcity of rainfall reconstructions based on palaeo evidence enabling records to be extended back multiple centuries beyond the instrumental data. These are very important as they enable more recent episodes of drought and flooding rains to be placed into context.

Without this, there is a tendency in the general community to believe that a particular event is unprecedented because something similar did not occur in recent decades. The reconstructions are also important from the perspective of assigning rainfall patterns to climate change and designating as natural or anthropogenic in origin.

Acknowledgements

This work was supported by the B. Macie Family Foundation.

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