



Understanding hydroclimate processes in the Murray-Darling Basin for natural resources management

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Abstract. Isolating the causes of extreme variations or changes in the hydroclimate is difficult due to the complexities of the driving mechanisms, but it is crucial for effective natural resource management. In Australia's Murray-Darling Basin (MDB), ocean-atmosphere processes causing hydroclimatic variations occur on time scales from days to centuries, all are important, and none are likely to act in isolation. Instead, interactions between all hydroclimatic drivers, on multiple time scales, are likely to have caused the variations observed in MDB instrumental records. A simplified framework is presented to assist natural resource managers in identifying the potential causes of hydroclimatic anomalies. The framework condenses an event into its fundamental elements, including its spatial and temporal signal and small-scale evolution. The climatic processes that are potentially responsible are then examined to determine possible causes. The framework was applied to a period of prolonged and severe dry conditions occurring in the southern MDB from 1997–2010, providing insights into possible causal mechanisms that are consistent with recent studies. The framework also assists in identifying uncertainties and gaps in our understanding that need to be addressed.

which standard management practices are based, making socioeconomic and some natural systems vulnerable. The unprecedented impacts of these extremes can sometimes necessarily force a somewhat ad hoc management response, which may be successful but may also lead to undesirable outcomes (i.e., maladaptation). Recent periods of prolonged wet and dry conditions have provided further cause for thought as NRM debate the causes of these extreme conditions, whether they are linked to anthropogenic climate change, whether similar dry and wet conditions may become more prevalent in the future, and even whether such periods should be considered the new norm.

Several prolonged extreme climatic periods have recently occurred in the Murray-Darling Basin (MDB), which contributes a significant proportion of Australia's agricultural yield. Much of the region experienced ongoing drought from around late-1996 to mid-2010 (Murphy and Timbal, 2008), which was followed by a rapid transition to extremely wet conditions across the MDB, the northern half in particular, from late 2010 to the time of publication of this article. Here, the northern and southern MDB are defined as the halves of the Basin north and south of 33° S. Management practices were tested throughout the sometimes-unprecedented nature of both periods and there were several instances when water resource managers, agriculturalists and biodiversity managers (hereafter collectively referred to as NRM) increasingly questioned whether the conditions in parts of the MDB contained an anthropogenic component.

To understand the causes of the recent changes to the MDB climate and potential future changes that include the

1 Introduction

Periods of prolonged, severe drought and moisture surplus are challenging for natural resources management/managers (NRM). These periods that are at the very edge of past experience are of particular concern as they push the limits upon

effects of anthropogenic climate change, several national research initiatives were established. These initiatives included the Murray-Darling Basin Sustainable Yields Project (MDBSY; <http://www.csiro.au/en/Organisation-Structure/Flagships/Water-for-a-Healthy-Country-Flagship/Sustainable-Yields-Projects/MDBSY.aspx>); the South Eastern Australian Climate Initiative (SEACI; www.mdbc.gov.au/subs/seaci); the Indian Ocean Climate Initiative (IOCI; www.ioci.org.au); and the CSIRO-BoM Climate Change in Australia project (www.climatechangeinaustralia.gov.au). The collective research from these, and other, initiatives has provided invaluable information that is highly relevant to the NRM community.

However, increasing the body of knowledge has the potential to be confusing for NRM. For example, the climate science community has identified a number of physical processes that influence variations in the MDB hydroclimate, which are often relayed to the NRM community as climate indices (i.e., simplified metrics of these atmosphere-ocean processes). Unavoidably, the number of these indices, and opinions as to what is important and what is not, increases as more research is conducted, adding uncertainty and complicating the information for those relying on it for risk assessment.

Given the difficulties NRM might have utilising the large amount of climate information available, this paper has two primary objectives. The first is to synthesise knowledge about the processes governing climatic variations across the MDB. This synthesis will distil up-to-date information in a concise form so that it may be interpreted more easily than compiling information from self-guided literature surveys. Murphy and Timbal (2008) have previously presented a synthesis of the major processes driving inter-annual and shorter time scale climatic variations in southeast Australia. While useful for the southern MDB, Murphy and Timbal's (2008) paper did not describe the importance of these and other climate processes for the northern MDB. Furthermore, information on decadal and longer-scale climate processes, interactions between climate drivers and interactions between climate and hydrological processes were not included in their review, but are highly relevant for NRM in the MDB.

The second objective is to identify a broad framework that allows NRM to scrutinise existing climate knowledge in order to better isolate the potential cause/causes of extreme climatic periods. This might make information relating to hydroclimatic processes more useful in risk management applications. Such a framework simplifies a complex problem and so inherently includes a large degree of uncertainty as it is derived from a mostly chaotic system. So, while the framework does not provide absolute answers, we argue that it establishes a more focused set of considerations for NRM. Furthermore, the framework highlights areas where the knowledge base is lacking (i.e., areas with large uncertainty or actual knowledge gaps), thus, identifying areas of

future research that, if undertaken, will also prove useful for NRM.

To fulfil these objectives, the paper is presented as follows: first, a hydroclimatology of the MDB provides context. The review of climate processes is then presented. This includes describing processes acting on inter-annual and shorter scales as an update to Murphy and Timbal (2008) and an explanation on the drivers of decadal and longer-scale variability, which has not previously been presented. We then show analysis for an emerging area of the science that, we argue, is critical to understanding and predicting wet and dry cycles in the MDB, namely interactions between climate processes. Finally, the framework for highlighting the potential cause/causes of specific climatic anomalies for NRM is presented and applied to the case of the prolonged drought that affected the southern MDB for over 13 yr from the mid 1990s.

2 Hydroclimatology of the Murray-Darling Basin: 1900–2010

The range of hydroclimatic variability on which NRM practices are based has traditionally been defined using historical data. By global standards the climate records in the MDB are long, spanning 111 yr from 1900–2010 with some individual stations going back to the mid-1800s. Here, we give an up-to-date overview of the hydroclimatology of the MDB based on these instrumental observations.

Spanning from the subtropics (24° S) to the middle latitudes (38° S), approximately 90 % of the MDB is classified as either arid or semi-arid (Maheshwari et al., 1995). The topography of the Basin consists mostly of extensive plains and low undulating areas, with much of the Basin less than 200 m above sea level. The landscape varies throughout the catchment from the sub-tropical rainforests of the eastern uplands, to the temperate, sub-alpine regions of the south-east and the hot, dry semi-arid plains in the west (Barros and Bowden, 2008).

Annual rainfall averaged across the MDB is approximately 470 mm per year (calculated over the period 1900–2010). However, the spatial variations in annual mean rainfall across the MDB are large (Fig. 1). Rainfall is highest in mountainous areas in the southeast where the mean annual totals can exceed 1500 mm, and lowest in the west of the Basin where they are typically less than 300 mm yr⁻¹. Averaged across the Basin, evaporation (estimated using pan evaporation) is approximately four times the annual mean rainfall. Geographically, evaporation ranges from approximately 1200 mm yr⁻¹ in the southeast of the Basin to around 2400 mm yr⁻¹ in the west (BoM, 2010).

Over the 111 yr from 1900–2010, MDB rainfall has exhibited large inter-annual to multi-decadal fluctuations (Fig. 2). Averaged across the MDB, conditions were broadly drier during the first half of the 20th Century with Basin-averaged

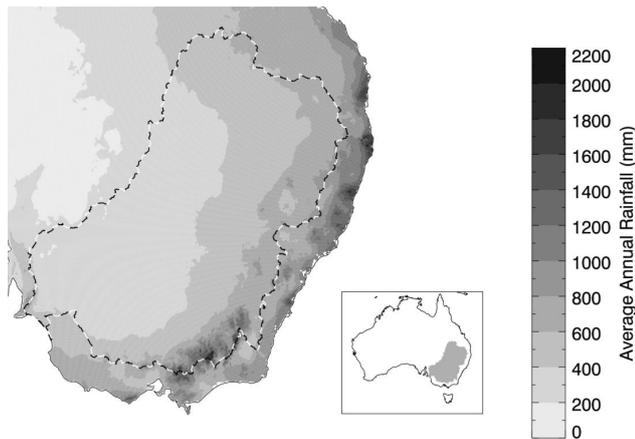


Fig. 1. The Murray-Darling Basin (dashed outline) overlaid on mean annual January–December (1900–2010) observed rainfall (mm), from the Australian Bureau of Meteorology Australian Water Availability Project rainfall grids (Jones et al., 2009a). Adapted from Draper and Mills (2008).

rainfall deficits frequently exceeding 100 mm yr^{-1} , equivalent to rainfall being at least 20% below average (Fig. 2). Several periods of multi-year rainfall deficits occurred, including the “Federation Drought” (ca. 1895–1902) and the “World War II Drought” (ca. 1937–1945) (Ummenhofer et al., 2009b; Verdon-Kidd and Kiem, 2009b). Though 19 yr in the instrumental record had above average rainfall during the first half of the 20th century (Fig. 2), there was only one multi-year wet period prior to 1950 (i.e., 1916 to 1917 when MDB rainfall was at least 20% above average).

The period from 1950 to 2010 was dominated by large decadal-scale variations in rainfall. Two distinct periods during the 1950s and the 1970s had several years with rainfall considerably greater than average and major floods occurred during 1952, 1956 and 1974. Multi-year periods with below average annual rainfall marked the 1960s, early 1980s and mid-1990s to early 2010. However, there were also some notable floods during these dry epochs, for example, 1990 across much of eastern Australia and more recently 2008 and 2009 in the northern MDB.

The dry conditions from the mid-1990s to early 2010 were dubbed the “Big Dry” or the “Millennium Drought” (hereafter referred to as “The Big Dry” only) (Ummenhofer et al., 2009b; Verdon-Kidd and Kiem, 2009b) (Fig. 3). This drought was mainly confined to the southern MDB and was dominated by autumn and early winter rainfall deficits stemming from both a decrease in the number of rain days and a reduction in the intensity of daily rainfall events (Verdon-Kidd and Kiem, 2009b). The drought was broken in spectacular fashion in 2010, which was the wettest year on record averaged across the MDB. Much of this stemmed from late winter and spring rainfall, which led to annual rainfall being 70% above average (Fig. 2).

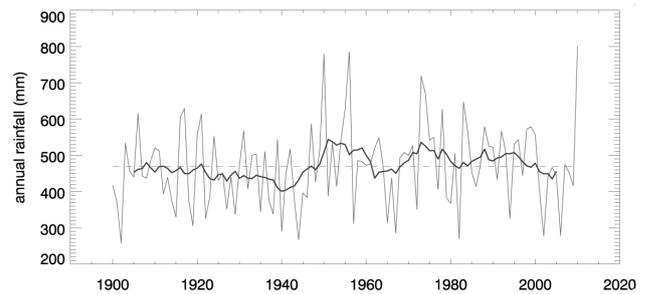


Fig. 2. Area-average annual (January–December) rainfall (thin grey line) and decadal mean rainfall (thick black line) for the Murray-Darling Basin from 1900 to 2010, generated from the Australian Water Availability Project rainfall grids (Jones et al., 2009a). The dashed line indicates the mean annual rainfall total over the 1900–2010 mean (471 mm).

3 Hydroclimate processes of the Murray-Darling Basin

We direct readers to the review paper by Murphy and Timbal (2008) for a broad overview of the key processes relevant to climate variations in the southern MDB on inter-annual and shorter time scales, including the mechanisms by which they occur and their climatological characteristics (e.g., frequency, persistence, etc.). Here, we expand on these topics and include information relevant to the northern MDB and interactions between hydroclimate driving mechanisms that are relevant to the whole MDB. To date, less focus has been given to understanding climate processes in the northern MDB by the climate science community and a synthesis has not previously been presented. An explicit discussion of relevant daily-scale processes, a synthesis of the most recent findings on inter and intra-annual processes since Murphy and Timbal (2008) was published and a discussion on the inter-decadal processes, which has not previously been presented for the MDB, are provided.

3.1 Daily to intra-annual processes

The types of weather systems that produce and inhibit rainfall in the MDB are summarised in Fig. 4. The origins of these systems vary regionally with the most distinct differences occurring from north to south. The importance of a particular type of weather system to seasonal rainfall totals is heavily dependent on the location. There can be substantial differences in the relative contributions from particular weather systems to seasonal accumulations over distances of several hundred kilometres only (Verdon-Kidd and Kiem, 2009a).

The rainfall accumulations associated with different occurrences of the same type of weather system also vary, and there are differences in the relative amount of rainfall each type of system tends to produce (Pook et al., 2006). For example, tropical cyclones are more likely to produce higher rainfall totals in the northern MDB compared to frontal

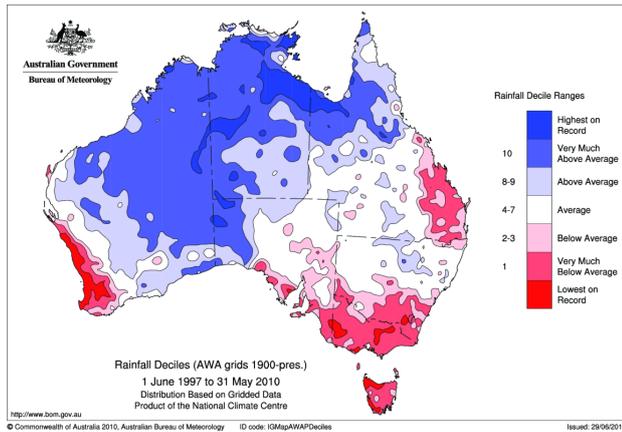


Fig. 3. The 13-yr June 1997 to May 2009 rainfall totals shown as deciles compared to all other 13-yr June to May periods from June 1900 to January 2009. Figure provided by the Australian Bureau of Meteorology.

systems in the southern MDB. The typical amount of rainfall produced depends on the intensity and duration of each system. Their contribution to the climate depends on those factors and also on the frequency at which those systems impact on an area.

The make up of the daily-scale rainfall distribution is particularly important for water resources management. For example, the impact of a one-month rainfall total of 100 mm on a hydrological system would be very different depending on whether the rainfall had fallen evenly throughout the month, or in a single event (McIntosh et al., 2007; Verdon-Kidd and Kiem, 2009b).

Rainfall in the southern MDB mostly stems from extra-tropical weather systems (Wright, 1989; Qi et al., 1999; Pook et al., 2006; Risbey et al., 2008). Figure 4 illustrates some of these systems, such as cold fronts, cut-off low-pressure systems and cloud bands. Cut-off low pressure systems contribute the most rainfall from a single type of system, between approximately 25 % and 50 % of rainfall to the region (Wright, 1989; Pook et al., 2006). Cut-off lows are also responsible for over 80 % of the rainfall that occurs on heavy rain days (described as days with over 25 mm or rain) during these months (Pook et al., 2006).

Frontal systems that interact with tropical air masses (e.g., cloud bands that form from a surface or middle troposphere pressure trough entraining tropical moisture, such as the Northwest cloud band in Fig. 4), those that do not (e.g., the cold fronts in Fig. 4), and post-frontal rainfall provide smaller, but significant, contributions to southern MDB rainfall totals, although the influence of each varies regionally (Wright, 1989; Verdon-Kidd and Kiem, 2009a). Post-frontal rainfall is only a significant contributor close to the mountain range spanning the southeast MDB, where orographic uplift is the primary mechanism causing rainfall. In the

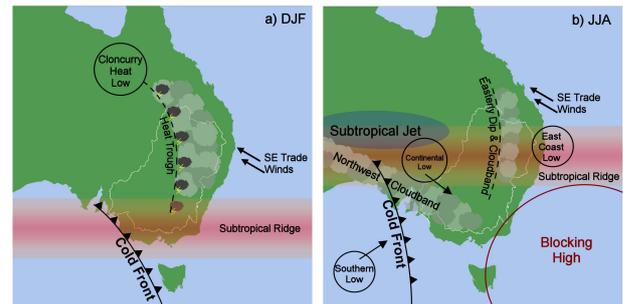


Fig. 4. The key weather systems that affect the Murray-Darling Basin during the austral (a) summer (December-January-February) and (b) winter (June-July-August). The southern half of the Basin is primarily affected by extra-tropical systems and receives the majority of its annual rainfall during the cooler months (May–October). The northern half of the Basin is primarily affected by tropical systems and interactions between tropical and extra-tropical systems and receives the majority of its annual rainfall during the warmer months (November–April). The systems that tend to suppress rainfall are shown in red.

southern MDB, frontal rain contributes between 25 % and 40 % of monthly rainfall totals, with this contribution decreasing moving further north (Pook et al., 2006). Verdon-Kidd and Kiem (2009a) attribute sizeable proportions of rainfall in the state of Victoria in the southern MDB to systems such as pre-frontal and inland troughs that produce cloud bands. However, Wright (1997) and Pook et al. (2006) state that such systems are generally responsible for less than 10 % of total rainfall in this region.

In the northern MDB, rainfall mostly stems from tropical systems, or from interactions between tropical and extra-tropical systems (Wright, 1997; Sturman and Tapper, 2005). Meridional troughs that extend through the subtropics of eastern Australia, sometimes called “easterly-dips” (Fig. 4), can be associated with widespread rain via cloud bands, particularly from April to October. Cloud bands that are initiated from convergence caused by the trough alone account for some 25–40 % of rainfall in the northern half of the MDB (Wright, 1997). There is a similar contribution from the interaction between these tropical cloud bands with extra-tropical features such as cold fronts (Wright, 1997).

Strong cold fronts can penetrate as far north as the Australian tropics. When they occur during the onset and breakdown of the northern wet season (approximately November–March), they may trigger thunderstorms along their leading edge, bringing very localised, heavy rain to areas in the northern MDB (Sturman and Tapper, 2005). From December–April, tropical cyclones that have moved inland from the east Australian coast can occasionally contribute large rainfall totals to the northern MDB.

High-pressure systems are the features that primarily inhibit rainfall (Sturman and Tapper, 2005). Over the MDB, these may constitute part of the climatological belt of

high-pressure, known as the sub-tropical ridge (STR), or be independent of it. Persistent and stationary high-pressure systems that are removed from the STR are responsible for the phenomenon of atmospheric blocking, where rain bearing weather systems are diverted around the immobile blocking high-pressure system (e.g., Fig. 4). In the southern MDB, atmospheric blocking and the STR that are situated directly over the region are the primary systems responsible for rainfall suppression (Pook et al., 2006; Risbey et al., 2008; Verdon-Kidd and Kiem, 2009a). In addition to high-pressure systems that inhibit rainfall, some mechanisms that usually trigger rainfall (e.g., a cold front) will fail if atmospheric moisture is not available (Drost and England, 2008).

Intra-seasonal climate variations across the MDB have been linked to the Madden-Julian Oscillation (MJO), which describes an eastward propagating region of enhanced tropical convection (Hendon and Liebmann, 1990). Typically, the impacts of the MJO on intra-seasonal MDB rainfall vary sub-regionally, seasonally and with the phase of the MJO (Wheeler et al., 2009). However, across the MDB, the strongest impacts are during the winter and spring months. See Murphy and Timbal (2008) and Wheeler et al. (2009) for a description of the impacts of the MJO on the southern MDB and regional Australian circulation respectively.

Intra-annual wet and dry periods in the MDB are primarily linked to shifts in the atmospheric circulation inherent to the seasonal cycle. In the northern MDB (at subtropical latitudes), rain bearing systems are more prevalent during the warmer months (approximately November–April), due to the greater influence of tropical weather systems, such as those shown in Fig. 4a. The opposite is true for the southern MDB, where extra-tropical weather systems dominate (Fig. 4b) and rainfall mostly occurs during the cooler months (approximately May–October).

3.2 Inter-annual processes: an update

The El Niño – Southern Oscillation (ENSO) can be responsible for over 20 % of local annual rainfall variations in the MDB (Pittock, 1975; McBride and Nicholls, 1983; Ropelewski and Halpert, 1987; Nicholls, 1988; Power et al., 1998; Risbey et al., 2009).

Seasonally, winter, spring and summer MDB rainfall variations are most strongly associated with ENSO events (McBride and Nicholls, 1983; Risbey et al., 2009), although the winter relationships may also be due to Indian Ocean influences and their coincidence with ENSO (discussed further below). The effects of ENSO in the MDB also include magnified fluctuations in streamflow volumes compared to rainfall (Chiew et al., 1998; Wooldridge et al., 2001; Verdon et al., 2004b), elevated flood risk during La Niña events (Kiem et al., 2003), and increased risk of drought (Kiem and Franks, 2004; Barros and Bowden, 2008) and bushfire (Verdon et al., 2004a) during El Niño events.

The intensity of wet and dry periods in the MDB is not directly proportional to the strength of ENSO events, where the strength of an ENSO event is determined based on the size of the departure from normal sea-surface temperature (SST) or sea-level pressure (SLP) conditions. In fact, the rate at which the state of the Pacific changes from one phase of ENSO to another appears to be just as important as the strength of the ENSO event (Quinn et al., 1978; Stone and Auliciems, 1992; Stone et al., 1996; Kiem and Franks, 2001). This is demonstrated by the fact that some of the strongest El Niños have not been associated with severe, widespread drought (e.g., 1997/1998), while other weaker El Niño events have coincided with particularly intense drought (e.g., 2002/2003) (Wang and Hendon, 2007; Brown et al., 2009). The nonlinear relationship between Australian rainfall variations and the magnitude of ENSO has been attributed to interactions with random atmospheric noise (Wang and Hendon, 2007), interactions with other climate drivers (Meyers et al., 2007; Verdon-Kidd and Kiem, 2009a; Kiem and Verdon-Kidd, 2010), and the location of the SST anomalies associated with ENSO (Wang and Hendon, 2007).

Larkin and Harrison (2005) and Wang and Hendon (2007) showed that Australian rainfall is particularly sensitive to ENSO-like behaviour in the central Pacific. A pattern of central equatorial Pacific SST variations has recently been identified by Ashok et al. (2007) and defined as an “ENSO Modoki” (“Modoki” is a Japanese word meaning “a similar but different thing”). An El Niño Modoki is characterised by warm central Pacific waters flanked by anomalously cool SSTs to the west and east, separating the Walker Circulation into two distinct circulations. Conversely, a La Niña Modoki is characterised as having cool central Pacific waters that are flanked by warmer than normal SSTs.

The location, seasonality and magnitude of the regional Australian climate response induced by an ENSO Modoki event can be stronger than for a traditional ENSO event (Ashok et al., 2009; Cai and Cowan, 2009; Taschetto and England, 2009; Taschetto et al., 2009) and Cai and Cowan (2009) also associated La Niña Modoki events with elevated autumn rainfall in the MDB (i.e., a season not typically influenced by traditional ENSO events). However, the work on ENSO Modoki is in its infancy and there have been conflicting conclusions in the literature as to the impacts of El Niño Modoki on the Australian climate. For example, Taschetto and England (2009) reported strong associations between El Niño Modoki events and reduced rainfall over parts of Australia during autumn, but Cai and Cowan (2009) detected no significant correlations during such events. Lee and McPhaden (2010) also recently identified a significant increase in the intensity of central Pacific El Niño events since 1982. Given the potential links to the MDB climate, the role of Central Pacific ENSO events must be investigated further.

Inter-annual variations in southern MDB winter, June–July–August (JJA), and spring, September–October–November (SON), rainfall have been linked to Indian Ocean SST anomalies (Nicholls, 1989; Simmonds, 1990; Drosowsky, 1993; Ashok et al., 2000; Drosowsky and Chambers, 2001; Verdon and Franks, 2005) and the Indian Ocean Dipole (IOD) (Saji et al., 1999; Ashok et al., 2003). Verdon and Franks (2005) also showed strong relationships between east Indian Ocean SST anomalies and the northern MDB hydroclimate (in some cases stronger than the Indian Ocean–southern MDB relationships). This is contrary to the commonly accepted understanding that the influence of the Indian Ocean on the northern MDB is weaker than in the southern MDB. Either way the influence of the Indian Ocean on MDB hydroclimate needs further investigation, particularly with respect to the northern MDB.

The IOD is characterised by SST anomalies of opposite sign in the east and west of the Indian Ocean Basin, which are coincident with large-scale anomalous circulation patterns. During the phase of the IOD associated with cool east and warm west Indian Ocean SST anomalies, low winter rainfall over the southern MDB is likely, and vice versa for the opposite phase of the IOD (Saji et al., 1999; Ashok et al., 2003; Meyers et al., 2007). However, several studies show a similar modulation of rainfall with eastern Indian Ocean SSTs only (Verdon and Franks, 2005; Cai and Cowan, 2008; Nicholls, 2009), suggesting that the influence of the SST gradient (combined western/central and east Indian Ocean SSTs) on southeast Australian rainfall is perhaps not as important as the state of eastern Indian Ocean SSTs alone (Nicholls, 1989; Verdon and Franks, 2005).

Several recent studies have also supplied convincing evidence for the non-existence of an equatorial IOD as an independent mode of climate variability and have argued that it is the result of random variations in the east and west of the Indian Ocean Basin. The two nodes of the IOD are sometimes in phase (i.e., not always negatively correlated), indicating the lack of a consistent dipole structure (Dommenget and Latif, 2001). Moreover, Dommenget (2007) and Dommenget and Jansen (2009) have shown that the dipole structure can be reconstructed by applying the same statistical technique used to decompose the mode to random noise, suggesting the IOD is simply an artefact of this technique and not a physical structure. Several studies have also suggested that the appearance of an IOD is simply a combination of a byproduct of ENSO and random variations (Nicholls, 1984; Cadet, 1985; Chambers et al., 1999; Allan et al., 2001). This interaction is discussed further in Sect. 4.

Along with the weight of evidence suggesting the existence of the IOD as unproven, its links to Australian rainfall have recently been debated. Ummenhofer et al. (2009a) used a climate model to demonstrate that the eastern pole of the IOD does not regulate Australian precipitation on its own and that a slightly stronger response occurs when there is a forced SST differential between the southern and eastern

Indian Ocean. Other studies have shown a stronger response between Australian rainfall and eastern Indian Ocean SSTs (Verdon and Franks, 2005; Cai and Cowan, 2008; Nicholls, 2009) and SSTs to the north of Australia (Smith and Timbal, 2010). In light of these recent findings it seems that though the Indian Ocean likely has an effect on the MDB climate, the existence of a dipole mechanism as an atmosphere/ocean interaction is questionable. Indeed the strongest evidence suggests southern MDB rainfall variations are more likely associated with SST variability in the eastern Indian Ocean. We stress that, on the balance of current evidence, the Indian Ocean does play a role in regulating the MDB hydroclimate, but it is likely that this role is as an intermediary driver only. What is in question is the modulation via an east–west dipole (i.e., IOD) mechanism and its dependence on or independence of the Indian Ocean teleconnections from ENSO.

Variations in the Southern Annular Mode (SAM) effectively describe variations in the position of the Southern Hemisphere mid-latitude storm track (Karoly, 1990; Thompson and Wallace, 2000; Thompson and Solomon, 2002). The SAM has links to MDB rainfall that vary regionally and seasonally (Gillett et al., 2006; Hendon et al., 2007; Meneghini et al., 2007). With a poleward contraction of the mid-latitude storm track, far southern sections of the MDB are more likely to experience lower rainfall during winter (Hendon et al., 2007) due to southward displacement of rain-bearing cold fronts and cyclones. However, during the spring and summer months, anomalously poleward SAM induces changes to the local circulation that draw moist easterly winds inland and increase the likelihood of rainfall across much of the MDB, particularly in the eastern half of the Basin (Meneghini et al., 2007).

The weather systems described in Sect. 3.1 regulate inter-annual variations in MDB rainfall as their frequency, persistence and intensity changes from year-to-year. For example, the STR changes in average strength and location from year-to-year. A stronger STR has been linked to rainfall suppression in southern Australian rainfall during autumn and early winter, while the position of the STR further north or south than normal is associated with summer rainfall variations (Larsen and Nicholls, 2009).

Atmospheric blocking was also previously described as a regional synoptic process affecting daily rainfall, and its importance as an inter-annual driver of the southern Australia climate has recently been recognised (Risbey et al., 2009). The position and intensity of Southern Hemisphere blocking undergoes variations from year-to-year and decade-to-decade (Trenberth and Mo, 1985). Specifically, the prevalence of blocking systems in key regions has been linked to fluctuations in the frequency of cut-off low pressure systems (Risbey et al., 2008), which are responsible for a significant portion of rainfall in the southern MDB (Pook et al., 2006). The frequent occurrence of blocking highs centred near 140° E (longitude close to the southwest MDB) favours rainfall in the southern MDB (Risbey et al., 2008, 2009).

3.3 Inter-decadal processes

In the Pacific Ocean, a coherent pattern of SST and SLP variability operating on multi-decadal timescales has been identified (Zhang et al., 1997). In the North Pacific, this variability is commonly termed the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997; Mantua and Hare, 2002). Power et al. (1999b) refer to a similar Pacific Basin-wide mode of variability as the Interdecadal Pacific Oscillation (IPO). Importantly, the PDO and IPO time series are highly correlated and represent variable epochs of warming (i.e., positive phase) and cooling (i.e., negative phase) in both hemispheres of the Pacific Ocean (Mantua et al., 1997; Folland et al., 2002; Franks, 2002). In fact, Folland et al. (1999) suggested that the IPO can be regarded as the Pacific wide manifestation of the PDO.

The IPO and PDO have been described as a sustained ENSO-like pattern of Pacific climate variability (Zhang et al., 1997). However, as noted by Mantua and Hare (2002), two characteristics distinguish the PDO (and IPO) from ENSO: the persistence of PDO/IPO epochs (15–30 yr) and the fact that the climatic fingerprint of the PDO is most dominant in the north Pacific sector with a secondary signature in the tropics (whereas the opposite is true for ENSO).

Links between the IPO/PDO phenomena and climate variability in Australia include decadal and annual-scale fluctuations in rainfall, maximum temperature, water volume transport and wheat crop yield (Power et al., 1999a; Kiem et al., 2003; Kiem and Franks, 2004; Verdon et al., 2004b). The IPO/PDO primarily influences the eastern Australian climate, which includes the MDB, during the austral spring, summer and autumn by inducing variations in the South Pacific Convergence Zone, which tends to be active during these months (Folland et al., 2002).

The IPO/PDO regulates the eastern Australian climate indirectly by modulating both the magnitude and frequency of ENSO impacts (Power et al., 1999b; Kiem et al., 2003; Verdon et al., 2004b; Cai and Cowan, 2009). When the IPO/PDO is in a warm phase, the relationship between ENSO and Australian rainfall is weakened, while it is strengthened during the cool phase (Power et al., 1999a). The greatest effect of this modulation is a magnified response of rainfall and streamflow to La Niña events during a cool IPO/PDO phase. During the cool (i.e., negative) IPO/PDO phase, wet events are likely to be wetter and more frequent than during a neutral or warm IPO/PDO phase, elevating flood risk in the MDB (Kiem et al., 2003; Verdon et al., 2004b). Conversely, during the warm (i.e., positive) IPO/PDO phase wet events are less frequent and not as wet as they are during the IPO/PDO cool phase which results in an increased risk of drought across the MDB and other parts of eastern Australian (Kiem and Franks, 2004; Verdon-Kidd and Kiem, 2009a). Verdon and Franks (2006) confirmed that the relationships between IPO/PDO phase and the frequency of ENSO events is consistent over the past 450 yr by examining paleoclimate

reconstructions of the two climate modes. Lough (2007) showed that the relationship between ENSO, IPO and rainfall/streamflow in northeast Queensland is consistent for at least the last 400 yr.

Also important to note is the strong and statistically significant relationships between decadal rainfall in the MDB and SSTs in the Tasman Sea north of New Zealand and south of 15° S – wetter decades are associated with warmer SSTs in the Tasman Sea (Power et al., 1999a). This Tasman SST-MDB rainfall relationship is also evident on inter-annual time scales. The effect of this association on regional circulation patterns is not yet understood. However, it is reasonable to suppose that larger rainfall totals would be caused by warmer, moist air being transported to, and converging over, the Australian mainland (White et al., 2003).

Decadal and multi-decadal scale variations in SSTs and surface pressures around Australia that are reminiscent of an ENSO pattern have been linked to multi-year summertime droughts in eastern Australia (White et al., 2003, 2004). Such droughts may be due to random fluctuations of ENSO (Kestin et al., 1998) or they may be due to some other as yet unknown process(es). The established statistical relationships suggest a connection between decadal-scale SST variability and fluctuations in MDB rainfall. However, the physical mechanisms which cause the decadal-scale SST variability and the links between changes in SST and regional-scale variability in synoptic patterns (and rainfall) are currently unknown and require further investigation.

In addition to the natural variability described above, anthropogenic influences will very likely also be responsible for future multi-decadal scale climate variations in the MDB (CSIRO and BoM, 2007; IPCC, 2007). Anthropogenically-induced changes in some aspects of the regional Australian climate have already been detected (Karoly and Braganza, 2005). There are a wide range of projected impacts for the MDB climate (i.e., “wetter and warmer” or “drier and warmer”) and unfortunately, there is no clear signal in the direction of these changes across the MDB.

The uncertainties primarily stem from large differences between future rainfall changes in the MDB projected by global climate models in response to future greenhouse gas emission scenarios. While these projections consistently show increasing temperatures across the MDB over the 21st century, they do not show consistent changes in rainfall (Sun et al., 2011). One regional exception is the southern MDB, for which many climate models consistently project drying. However, the magnitude of this drying varies considerably between models (Chiew et al., 2008) and the dynamical mechanisms behind this drying have not yet been identified. Given the potential for anthropogenic warming to be associated with significant negative impacts across the MDB (Alexander and Arblaster, 2009; BoM, 2010), the uncertainty associated with climate model projections must be addressed so that the contribution of anthropogenic forcing to inter-annual, multi-decadal and longer changes in MDB can be

properly assessed. The numerous sources of uncertainty associated with global climate model projections for the MDB are discussed further in Sect. 5.

4 Interactions between hydroclimatic processes: a missing link in our understanding?

4.1 Interactions between climate processes

As single processes alone account for less than 20 % of monthly rainfall variability (Risbey et al., 2009), it is unlikely that the climate drivers influential on the MDB are independent of each other or act to drive the MDB climate in isolation (Risbey et al., 2008; Verdon-Kidd and Kiem, 2009b; Kiem and Verdon-Kidd, 2010). Deducing the interactions between climate drivers and their subsequent impact on the Australian hydroclimate is only an emerging area of research, but one that is crucial to better capturing the causes of variations in the MDB climate.

There is increasing evidence that the mean state of the atmosphere/ocean system, which is partially modulated by the inter-annual and inter-decadal processes previously described, plays a part in regulating the occurrence of daily weather events. For example, the large-scale climate processes described in Sect. 3 have been linked to variations in the positions of the jet streams, regulation of moisture availability and other aspects of the atmosphere/ocean system, as well as variations in weather systems (Risbey et al., 2008; Verdon-Kidd and Kiem, 2009a).

The characteristics of weather systems, including their location, frequency of occurrence and intensity, show dependence on intra-seasonal, inter-annual and decadal drivers of climate such as the MJO, ENSO and the IPO/PDO (Nicholls and Kariko, 1993; Pezza et al., 2008). The intensity of cyclones and anticyclones in the mid-latitudes increases and their frequency decreases when there is a strong warm phase of the PDO (Pezza et al., 2007). Verdon-Kidd and Kiem (2009a) also found that warm phases of the IPO decrease the likelihood of wet weather events in parts of the MDB, while cool phases increase this likelihood, and vice versa for dry weather events.

Variations in the prevalence of atmospheric blocking have been linked to the state of ENSO, with blocking frequency and associated rainfall becoming more prominent during La Niñas and less prominent during El Niños (Risbey et al., 2008). Weather features such as pre-frontal troughs and “easterly-dip”-type patterns are more prominent during La Niñas, and broad high pressure systems across southeastern Australia and a northward retraction and weakening of easterly troughs are more prominent during El Niños (Verdon-Kidd and Kiem, 2009a). The wetter and drier phases of SAM and Indian Ocean SSTs are similarly linked to weather systems that are more or less likely to enhance or suppress

rainfall in the MDB (Hendon et al., 2007; Verdon-Kidd and Kiem, 2009a; Kiem and Verdon-Kidd, 2010).

We present analysis in Fig. 5 demonstrating the connections between climate processes operating on inter-annual and daily time scales. Pook et al. (2006) found that at least 80 % of April–October heavy rain days (defined as days with accumulations above 25 mm) were associated with cut-off low-pressure systems in a domain covering the far southwest MDB. They also showed that cut-off low-pressure systems strongly modulate inter-annual rainfall there. Given that Sect. 3.2 outlined the modulation of inter-annual rainfall in the MDB by ENSO, SAM and the Indian Ocean, a logical hypothesis is that these remote drivers partially act by modulating the number of cut-off low-pressure systems that influence the region. This influence was examined here by using heavy rain days as a proxy for cut-off lows.

The number of heavy rain days was calculated at seven stations for every April–October period from 1970–2002, the same period used by Pook et al. (2006) for their analysis. All stations fall within the Pook et al. (2006) domain and come from the Lavery et al. (1992) high-quality daily rainfall network. The average number of heavy rain days during years in a particular extreme state of the SAM, ENSO and eastern Indian Ocean SSTs were compared to neutral years for each index. The SAM, ENSO and eastern Indian Ocean SSTs were represented by the SAM index of Marshall (2003), the Southern Oscillation Index (SOI) of Troup (1965) and the eastern pole of the Dipole Mode Index (DMI_{east}) of Saji et al. (1999), generated from the global HadISST sea-surface temperature data set (Rayner et al., 2003). A positive (negative) phase of each driver was defined if the standardised index was above (below) 0.5 (−0.5) standard deviations, giving about 30 % of years in each of the positive or negative phases. All indices were standardised over the 1970–2002 period. To determine if the mean frequency of heavy rain days during a particular phase of a driver was statistically significantly different from neutral years, a 95 % confidence interval was generated from neutral years. The mean number of rain days from 1000 bootstrap replicates of n neutral years were used, where n was the number of years when the inter-annual driver was in its positive or negative phase.

Every station in the domain had a statistically significant link between April–September heavy rain days and ENSO, with a higher than average number of heavy rainfall days during La Niña years and a lower than average number during El Niño years (Fig. 5). This result was the same whether SOI or SSTs from the Niño3.4 region were used to represent ENSO and is consistent with the links described between ENSO and cut-off lows in the region by Pook et al. (2006). All but one station had a lower than average number of heavy rain days during negative SAM events, with three stations showing a statistically significant difference. These results may reflect the influence of the SAM during the austral spring, where negative SAM is associated with decreased rainfall in the region (Hendon et al., 2007). The majority of stations also

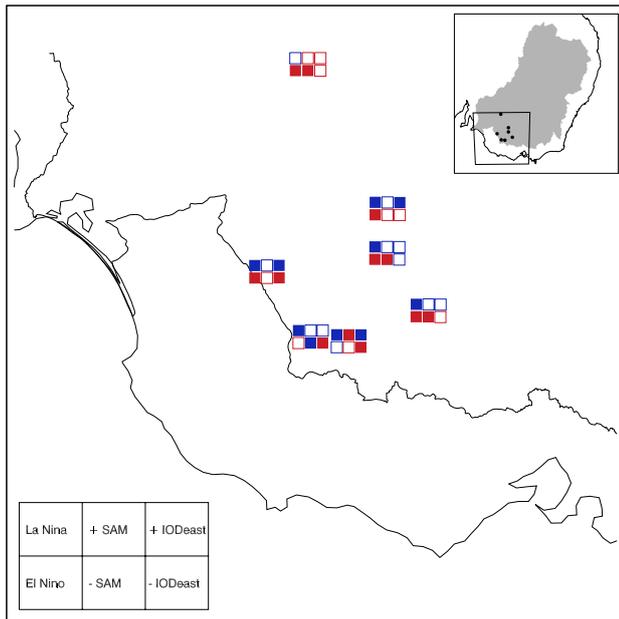


Fig. 5. The squares represent the difference in the 6-monthly (April–September) mean number of heavy rain days (defined as days with over 25 mm of rainfall) between years experiencing neutral and extreme phases of ENSO, SAM and Indian Ocean SST variations. The mean number of rain days during years in the positive (top row) and negative (bottom row) phases of ENSO (left column), SAM (centre column) and eastern Indian Ocean SSTs (right column) are shown. Blue indicates that a station has more, and red indicates that a station has less heavy rain days than in neutral years. A solid square indicates this difference is significant at the 95% level based on a confidence interval generated from 1000 bootstrap replicates of neutral years.

had significantly more heavy rain events during years with warmer than normal eastern Indian Ocean SSTs and fewer heavy rain events when these SSTs were cooler than normal. The results here suggest that all three major drivers of inter-annual climate variations in the region partially regulate rainfall by changing the frequency of heavy daily rainfall events, which in turn are likely to be via modulation of the frequency of cut-off low pressure systems.

The above analysis showed that large-scale climate drivers play a role in regulating daily weather events. However, the large-scale drivers themselves also undergo decadal and multi-decadal scale variations. These variations may be largely independent or they may co-occur, indicating relationships between processes that, in turn, affect regional climates.

Figure 6 shows fluctuations in the relationships between indices representing ENSO, SAM, Indian Ocean SST variability and STR location and intensity for running 30-yr periods from 1905–2004. The indices were chosen so the longest period possible could be analysed. The SOI represents ENSO variations and an extended reconstruction of the

Marshall (2003) SAM index by Jones et al. (2009b) was used as the Marshall (2003) index is available from 1958 only. The eastern pole of the DMI (Saji et al., 1999) represents eastern Indian Ocean SSTs. Despite the fact that we are reluctant to accept the IOD as a physical atmosphere/ocean processes for the reasons outlined in Sect. 3, we also include the DMI (representing the IOD) in our analysis for a later discussion surrounding evidence that any large-scale climate variations in the Indian Ocean may be partially linked to ENSO. The latitude and intensity of the STR (Drosowsky, 2005) is also assessed as an inter-annual driver of MDB rainfall variations. All indices were detrended by removing the line-of-best-fit over the 1905–2004 period, computed using linear regression, to highlight relationships on inter-annual time scales only.

The fluctuations in the relationships between inter-annual drivers of the MDB climate vary between pairs of drivers and season. For example, summer (December–February) STR intensity has a statistically significant relationship with SAM that has remained fairly consistent from 1905–2004. Conversely, the relationship between the inter-annual variations in ENSO and the eastern Indian Ocean SSTs were barely statistically significant in the 1930s (correlations around -0.35), while the 30 yr centred on 1970 had a correlation of almost -0.9 . These indicate large changes in the relationship between ENSO and the eastern Indian Ocean during the 20th Century. There are consistent statistically significant relationships between SAM and STR intensity from winter through to summer (June–February) and between SAM and STR latitude during winter and spring (June–November), perhaps highlighting broader scale fluctuations in the Hadley circulation. Interestingly, there has been a consistent strengthening of the relationship between the SAM and STR latitude during the austral autumn (March–May) where correlations in the early 1900s were insignificant and negative and were statistically significant and positive from around 1960 (Fig. 6). As the indices were detrended prior to computation of the correlations, the strengthening of this relationship over time is probably not associated with the trends that have occurred in both process since around this time (Marshall, 2003; Larsen and Nicholls, 2009). The trend may reflect poor data coverage for calculation of the SAM prior to the 1960s. However, if this were the case, a step-function, rather than a monotonic trend might be expected.

Previous authors have shown how interactions between various large-scale climate drivers impact on the MDB climate (Risbey et al., 2009; Silvestri and Vera, 2009; Verdon-Kidd and Kiem, 2009a). Many studies provide evidence that the IOD is a combination of a byproduct of ENSO and stochastic variations (Nicholls, 1984; Cadet, 1985; Chambers et al., 1999; Allan et al., 2001). The extreme phases of ENSO and IOD are also often “phase locked” meaning that there is a high probability that a La Niña will occur with warm, and an El Niño with cool, eastern Indian Ocean SSTs (Meyers et al., 2007). As these coinciding phases are indicative of wet

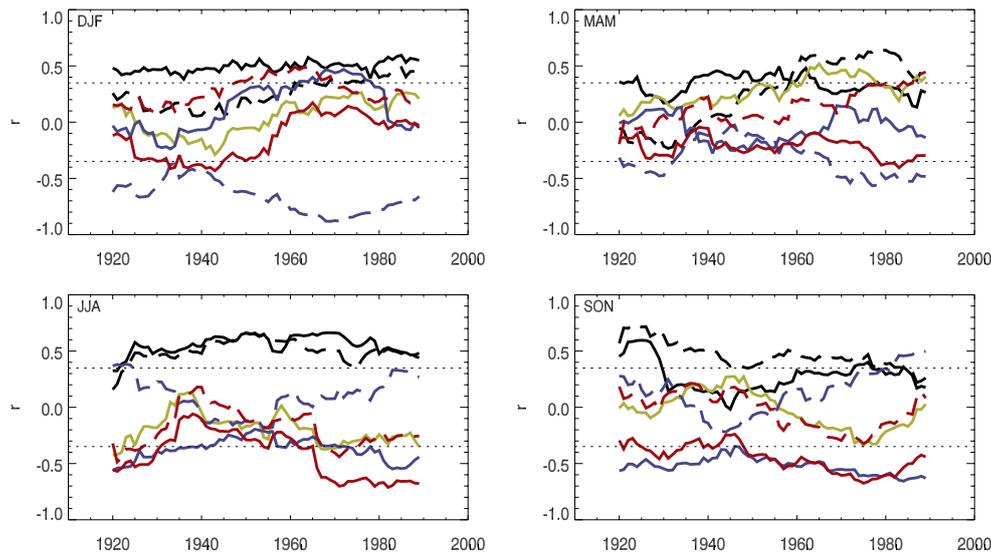


Fig. 6. Running 30-yr correlations between pairs of seasonal indices representing the drivers of inter-annual climate variability in the MDB. SAM and STR intensity (solid black line), SAM and STR latitude (dashed black line), SAM and ENSO (solid yellow line), ENSO and IOD (solid blue line), ENSO and the eastern pole of the IOD (dashed blue line), ENSO and STR intensity (solid red line), and ENSO and STR latitude (dashed red line) are shown. A t -distribution with a sample size of 30 yr was used to estimate the bounds of statistical significance and is indicated by the thin dashed lines ($t = \pm 0.35$).

or dry conditions for both ENSO and the IOD, the result is often an amplification of the rainfall signature (Meyers et al., 2007). The synchronicity between extreme ENSO and IOD variations suggests dependence between the two and Allan et al. (2001) reported significant lag correlations in ENSO and IOD indices.

Using the IOD and ENSO indices previously described from 1905–2004, we found statistically significant correlations of -0.57 between spring indices, and -0.59 when a lag correlation was calculated between the winter (June–August) SOI and the DMI in the subsequent spring (September–November). Both correlations are strongly indicative of dependence between the two during the time when the Indian Ocean has its greatest influence on MDB rainfall. Furthermore, temporal variations in correlations between September–November SOI and DMI for running 30-yr periods from 1905–2004 show consistent statistical significance from at least 1960, when data is most reliable (Fig. 6). Moreover, when the SOI was correlated against the eastern pole of the DMI only (i.e., eastern Indian Ocean SSTs) there were statistically significant relationships during winter, spring and summer.

However, others have presented evidence that Indian Ocean SST anomalies can occur irrespective of the state of the tropical Pacific Ocean (Nicholls, 1989; Saji et al., 1999; Webster et al., 1999). Saji et al. (1999) report that the IOD is the most active during the austral winter (June–August) and that there is a lack of statistically significant correlations between winter IOD and ENSO indices, potentially indicating independence. Webster et al. (1999) demonstrated that the

Indian Ocean can exhibit strong ocean-atmosphere-land interactions that are self-maintaining and capable of producing large perturbations that are independent of ENSO. Fischer et al. (2005) used a GCM to study the triggers of the IOD and showed that two types of IOD may actually exist, one entirely independent of ENSO and the other a consequence of tropical Pacific conditions (i.e., ENSO). This is supported by the fact that the IOD is not always phase locked with ENSO and that there are few incidences where a La Niña coincides with a positive IOD and vice versa (i.e., when El Niño coincides with negative IOD).

While none of the above studies provide a physical mechanism for the IOD as a climate process that is independent of ENSO, the Indian Ocean still has an important influence on MDB hydroclimate. However, that influence is more likely to be driven by eastern Indian Ocean SSTs rather than the east-west dipole (i.e., IOD). This is demonstrated by Verdon and Franks (2005) who found that the relationship between eastern Indian Ocean SSTs and eastern Australian hydroclimate still holds when ENSO events are removed.

The interaction between SAM and ENSO and their combined impact on Australian rainfall has received little attention in the literature. From correlation analysis performed here, the relationship between SAM and ENSO is not significant during any season, except perhaps in more recent years during the austral autumn (March–May) (Fig. 6). Correlations between ENSO and SAM using data from 1905–2004 at lags of one to three months were generally not statistically significant. Again, a potential exception is during the austral autumn when the correlation between SAM and

ENSO lagged by one and two months was marginally significant at the 95 % level ($r = 0.21$ and $r = 0.22$, respectively, $n = 100$). However, neither driver shows a statistically significant relationship with rainfall in the MDB during this season (Hendon et al., 2007; Meneghini et al., 2007; Risbey et al., 2009). In general, the evidence presented here suggests that SAM and ENSO are largely independent modes of variability. However, Karoly (1989) described covariations between the Southern Hemisphere middle latitude circulation and ENSO events, which perhaps indicates a relationship between SAM and ENSO in summer.

Despite the fact that ENSO and SAM appear to act in an independent manner, there are competing effects between the two that influence MDB seasonal rainfall. Kiem and Verdon-Kidd (2009, 2010) reported that dry conditions during autumn are more likely if an El Niño event occurs in combination with a positive SAM. Previous La Niña events have not necessarily been associated with above-average rainfall in the southern MDB (Gallant and Karoly, 2009), which may be due to interactions with coinciding SAM events that place the storm track further south than normal (Kiem and Verdon-Kidd, 2009, 2010).

An example of the impacts of competing SAM and ENSO phases on MDB rainfall are illustrated in Fig. 7. The rainfall anomalies were generated using the operational Australian Bureau of Meteorology AWAP rainfall grids (Jones et al., 2009a) from 1905–2004. The Jones et al. (2009b) SAM index, described previously as an extension of the Marshall (2003) index, was used to maximise the number of years available for analysis. As previously, the SOI represents ENSO variability. A positive SAM or ENSO event was defined when the standardised indices (relative to the 1905–2004 period) exceeded 0.5 standard deviations. However, the results were similar when thresholds of between 0.5 and 1 standard deviation were applied and when SSTs from the Niño3.4 region were used to represent ENSO.

In all seasons, when combinations of the extreme phases of each driver co-occurred the SAM typically enhanced or tempered the impact of ENSO, depending on the phase of the SAM. However, the extent of this influence depended on the season. Specifically, the strength of the relationship between MDB rainfall and each process tended to dictate the influence each had on seasonal rainfall. For example, neither the SAM nor ENSO, when considered in isolation, have a strong relationship with autumn (March–May) rainfall in the MDB but when SAM-ENSO interactions are analysed some autumn rainfall variability is explained (e.g., Kiem and Verdon-Kidd, 2009, 2010). In comparison, winter (June–August) rainfall has a stronger relationship with both SAM and ENSO (Risbey et al., 2009), making competing influences more noticeable (Fig. 7). During the austral winter the southern MDB was typically drier, while the northern MDB was wetter, for a co-occurring La Niña and positive SAM event, compared to a La Niña event occurring in isolation. Conversely, the drier conditions in the southern MDB during past El Niño events

have been enhanced by positive SAM and tempered by negative SAM.

Note that the frequencies at which combined events occurred were small in several cases. So, producing composites from n randomised years tested the statistical significance, where n was equal to the number of years used to produce each composite (see Fig. 7). Statistical significance was defined if the value of the composite being tested was larger/smaller than 97.5 % of the randomised composites.

During combined positive SAM and El Niño, and negative SAM and La Niña, the rainfall anomalies in Fig. 7 were statistically significant across most of the MDB (not shown). Interestingly, during winter, the extreme phases of ENSO during neutral SAM had few statistically significant rainfall anomalies in the southern MDB. Thus, across the MDB, particularly the southern half, there is significantly enhanced drying and wetting, respectively, when positive SAM/El Niño or negative SAM/La Niña phases co-occur.

For combined positive SAM/La Niña events, the rainfall anomalies were not statistically significantly different in the southern MDB. However, when La Niña combined with negative or neutral SAM conditions it was statistically significantly wetter in this region, indicating that positive SAM may have some tempering effect. Similarly, for combined negative SAM/El Niño years, significant drying was limited to the far northeast of the Basin. However, for neutral SAM/El Niño, significant drying extended across the northern and eastern two-thirds of the Basin and across most of the MDB for a positive SAM/El Niño combination.

Interactions between climate processes have also been demonstrated between drivers operating on decadal and inter-annual time scales. The IPO/PDO regulates the eastern Australian climate indirectly by modulating both the magnitude and frequency of ENSO impacts (Power et al., 1999b; Kiem et al., 2003; Verdon et al., 2004b; Cai and Cowan, 2009). When the IPO/PDO is in a warm phase, the relationship between ENSO and Australian rainfall is weakened, while it is strengthened during the cool phase (Power et al., 1999a). The greatest effect of this modulation is a magnified response of rainfall and streamflow to La Niña events during a cool IPO/PDO phase. During the cool (i.e., negative) IPO/PDO phase, wet events are likely to be wetter and more frequent than during a neutral or warm IPO/PDO phase, elevating flood risk in the MDB (Kiem et al., 2003; Verdon et al., 2004b). Conversely, during the warm (i.e., positive) IPO/PDO phase wet events are less frequent and not as wet as they are during the IPO/PDO cool phase which results in an increased risk of drought across the MDB and other parts of eastern Australian (Kiem and Franks, 2004; Verdon-Kidd and Kiem, 2009a).

Given the temporal fluctuations in the relationships between the major climate drivers, further work is needed to understand the mechanisms that cause these fluctuations and how they impact on regional climates, such as the MDB. The long-term variations could stem from random variations

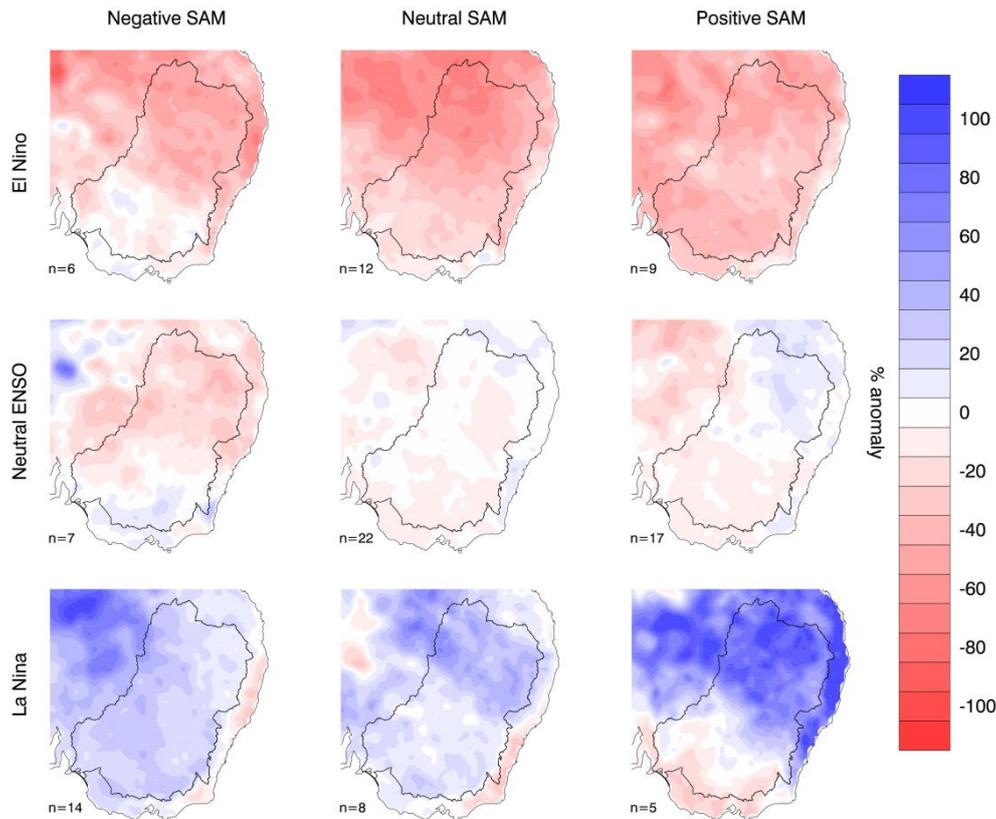


Fig. 7. Composite mean percentage winter (June–August) rainfall anomalies in the MDB during co-occurring phases of the SAM and ENSO from 1905–2004. A positive or negative phase of SAM and ENSO was defined when the standardised anomalies (relative to 1905–2004) of each index exceeded ± 0.5 standard deviations. Red colours indicate rainfall deficits and blue, rainfall surplus. The number, n , in each panel indicates the number of years from which the composite was computed, this is, the number of years in which the particular phases of ENSO and SAM co-occurred. Rainfall data is from the AWAP high-quality Australian rainfall grids (Jones et al., 2009a).

(Kestin et al., 1998), interactions with unknown climate processes on numerous time scales (Power et al., 1999a), other external forcings (Meehl et al., 2006), or a combination of all or some of these. Also unclear at this stage is how large-scale climate processes such as ENSO, Indian Ocean SSTs, SAM, STR and IPO/PDO might be affected by anthropogenic climate change.

4.2 Hydrological drivers and their interactions with climate processes

Interactions influencing the MDB hydroclimate (e.g., rainfall, temperature, runoff, streamflow, etc.) are not limited to those between climate processes. Hydrological and land surface processes also play an important role in regulating hydroclimatic variability in the MDB. Rainfall and surface temperature persistence are related to soil moisture, which can retain some memory of the recent climate (Timbal et al., 2002). Antecedent land surface conditions play an important role in runoff and streamflow variability (Chiew et al., 1998; Kiem and Verdon-Kidd, 2009). CSIRO (2008) also suggests that it is likely that after a prolonged dry period,

there is less connectivity between the subsurface storage and the river system and, therefore, significant amounts of rainfall and recharge are required to fill the subsurface storage before runoff can occur.

It is likely that vegetation feedbacks also play a role in regulating regional climate and that extensive land clearance across the Australian continent has contributed to some long-term climatic trends (Murphy and Timbal, 2008). Rainfall recycling feedbacks (and the memory the system has of previous rainfall) is poorly understood because the soil moisture-vegetation-rainfall feedbacks are complex. However, it is believed to be important in determining downwind rainfall in continental areas (Koster et al., 2004). This is an area of ongoing research that also has, as an added complexity, the difficulties and computational limitations associated with integrating land surface models with climate models.

5 A framework for focussing climate information for natural resource management

Knowledge of the MDB hydroclimate, and its driving mechanisms, assists NRM in developing appropriate management strategies. As this environment changes management strategies must be adapted. Given that the MDB has large natural climate cycles and more recently the possibility of anthropogenic influences, it is critical that NRM is better able to isolate the potential causes of extremes or changes in the climate.

There are numerous, complex processes modulating the MDB hydroclimate (see Sects. 3 and 4) and sifting through this vast amount of knowledge can be an arduous task. So, we present a broad framework that summarises the relevant climatic information and assists in isolating the possible causes of a climatic event. It is important to note that this is a simplified framework for a complex problem and will not provide definitive answers. This is because the processes previously presented do not equal the sum of knowledge required for complete understanding of a climate system that is substantially chaotic and involves complex nonlinear and non-stationary interactions – as well as several significant knowledge gaps. However, the framework does allow the user to qualitatively estimate the likelihood of a cause of a climatic event. We stress that this framework is not intended to be a decision-making tool – only to better focus understanding.

The framework breaks down a climatic event into its fundamental components, isolating (i) spatial signatures, (ii) temporal signatures and (iii) small-scale evolution. Spatial information identifies the regional coverage of the event, including where it occurred and over what size area. Temporal signals identify the persistence of the event, including any seasonality or recurrence. For example, a single season might experience an extreme climatic event, but this may re-occur for multiple years. Small-scale evolution deconstructs the event to isolate the small-scale features. For example, the make-up of the daily rainfall distribution causing a seasonal anomaly – is the deficit due to a lack of rain days, or a decrease in rainfall intensity or magnitudes? Small-scale evolution also includes assessing changes in weather systems.

Following the characterisation of an event using the above framework, the event's features can be compared to those typical of the known climatic drivers described in Sects. 3 and 4. This comparison allows the user to rank the possible mechanisms, where the ranks are based on the consistency between a feature and the known impacts of a climatic process. Allowances must be made where the consistency between the fundamental elements of the event and the climatic driver are unknown or the uncertainty is large. The consideration that there are likely to be processes (or interactions and feedbacks) of which we are currently unaware that are affecting the event must also be made. These caveats are discussed in the case study presented below.

5.1 Case study: identifying potential causes of the Big Dry (ca. 1997–2010)

The framework presented above is now applied to a case study, namely, the Big Dry (ca. 1997–2010). Here, we focus solely on the rainfall deficits to simplify the framework for presentation. However, formal event attribution for NRM should be applied to multiple variables (i.e., incorporate knowledge of other changes such as soil moisture, temperatures, etc.). The major characterising features of the Big Dry are identified below and each feature is tagged with the superscripts 1–7 for later comparison with climate processes.

5.1.1 Spatial signatures

The rainfall deficits were mainly confined to the southern MDB¹. The largest deficits were in the far southeast and southwest of the region (Fig. 3). Note that drought was also experienced in the northern MDB from 1997–2006, however, for this exercise the northern MDB drought is considered to be a different event to the Big Dry, which is characterised by rainfall deficits in the southern MDB from 1997–2010.

5.1.2 Temporal signatures

The 13-yr rainfall deficit was primarily driven by consistently lower than normal rainfall during autumn². However, several individual years also experienced deficits during winter and spring³ (Verdon-Kidd and Kiem, 2009b). While deficits generally did not last more than a few consecutive seasons, there was a distinct lack of periods with very high rainfall⁴ (Gallant and Karoly, 2010).

5.1.3 Small-scale evolution

There was a lack of high one-day rainfall totals⁴ (Murphy and Timbal, 2008; Verdon-Kidd and Kiem, 2009b), which is consistent with a reduction in the amount of rainfall associated with cut-off low pressure systems over this period⁵ (Pook et al., 2006; McIntosh et al., 2007) and an absence of persistent pre-frontal troughs that aid the penetration of rain producing cold fronts into the southern MDB⁶ (Verdon-Kidd and Kiem, 2009a; Alexander et al., 2010). The recent drying has also coincided with an increase in regional surface pressure⁷ (Drosowsky, 2005; Timbal and Murphy, 2007; Larsen and Nicholls, 2009; Williams and Stone, 2009; Alexander et al., 2010). The Big Dry has also been associated with abnormally high temperatures (Nicholls, 2004; Gallant and Karoly, 2009). However, the causal mechanisms behind the relationship between elevated temperatures and the hydroclimate (e.g., evaporation and streamflow) are largely unknown when compared with changes in other atmospheric conditions such as radiation, humidity and wind (Donohue et al., 2010). This is another area in need of further study.

As the drought primarily occurred on inter-annual and longer time scales with symptomatic small-scale changes

(i.e., weather systems), Table 1 present simplified summaries of climate processes (from Sect. 3) relevant to these time scales. Table 2 then compares the seven main features of the Big Dry to this information, thus, focusing causal candidates. Note that while the simplified comparison in Table 2 identifies where links between drought features and climate processes are unknown, it does not incorporate the uncertainties described in Sects. 3 and 4, which are very important (see later discussion). Further, longer term trends in some inter-annual processes have recently been identified including an increase in the intensity of the STR (Drosowsky, 2005; Timbal and Murphy, 2007; Larsen and Nicholls, 2009; Williams and Stone, 2009) and a poleward retraction of the mid-latitude storm belt (Frederiksen et al., 2011) which is consistent with trends towards a more positive SAM (Marshall, 2003). As such, these trends have also been included and assessed in Table 2 as potential causal mechanisms of the Big Dry.

Based on the number of consistencies, unknowns and inconsistencies between each drought feature and climate process indicated in Table 2 it is then possible to rank the most likely causal mechanism(s) of the Big Dry with the highest ranks given to those processes with the most consistencies and fewest inconsistencies. Note this method is biased towards those processes that are most well understood and as such processes that included many unknowns should not necessarily be ruled out as possible causes.

Using the above approach, the most likely causal mechanisms behind the Big Dry were (in order); a southerly shift in the storm track; ENSO/SAM interactions, increases in STR intensity; anthropogenic climate change; more positive SAM; and the IPO/PDO. Less likely was Indian Ocean variability and ENSO, when considered as isolated processes, mainly due to the inconsistencies in the seasonality of the most persistent rainfall deficits. While it is likely that these processes contributed to a worsening of the drought, on their own they were probably not responsible for the majority of the rainfall deficits (Verdon-Kidd and Kiem, 2009b). Also worth noting, although there is no evidence of this in existing literature, is the possibility that the Big Dry was caused by interactions between IPO, ENSO and SAM. This inference is based on the following reasoning: IPO modulates the magnitude and frequency of ENSO impacts, the impacts of ENSO are also modulated by SAM and vice versa, therefore, it is possible that IPO also influences SAM impacts (either directly or via IPOs modulation of ENSO impacts). This hypothesis is currently under investigation.

The high ranking of ENSO/SAM interactions supports the point made previously (see Sect. 4, Figs. 5, 6 and 7), that all climate processes have some degree of interaction and should not be taken as isolated causes. For example, the three La Niña events occurring during the Big Dry were been associated with unusually low rainfall in the context of historical events (Gallant and Karoly, 2009). Kiem and Verdon-Kidd (2009) attribute this to a compounding influence from

a positive SAM and this is consistent with Fig. 7. The lack of La Niña events during the 1990s (i.e., the initiation of the Big Dry) is also consistent with the IPO being in a positive phase (Kiem et al., 2003).

The rankings from Table 2 are also in agreement with Nicholls (2009) and Verdon-Kidd and Kiem (2009b) who suggested that a consistently positive SAM since the 1990s, associated with a poleward retraction of the mid-latitude storm track (Frederiksen et al., 2011), may be responsible for the recent trends in southeast Australian rainfall. However, there are some conflicts between these results and other studies that show there are no significant associations between southeast Australian autumn rainfall and the SAM (Hendon et al., 2007; Timbal and Murphy, 2007; Risbey et al., 2009). However, the critical difference is that the studies finding no significant associations have only examined the SAM in isolation as opposed to considering interactions with other processes (e.g., Figs. 6 and 7), which potentially enhance/suppress typical impacts (Kiem and Verdon-Kidd, 2010).

The association between the intensity of the STR and rainfall variations has also previously been suggested as a potential cause (Timbal and Murphy, 2007; Timbal et al., 2007; Murphy and Timbal, 2008; Larsen and Nicholls, 2009). Though plausible, it is unclear whether an increase in STR intensity is the ultimate cause. Indeed, Fig. 6 shows positive relationships between STR intensity and SAM during autumn and winter that indicate that the SAM is associated with up to 44 % of the variance in STR intensity (the largest rainfall declines have been reported during late autumn and early winter; Murphy and Timbal, 2008; Verdon-Kidd and Kiem, 2009b).

All hypotheses of the cause of the Big Dry have a common similarity. That is, all involve decadal scale variations in the major climate drivers and how they influence southern MDB rainfall, and that the causes are possibly linked, either via interactions with each other or via some ultimate cause, which may include anthropogenic climate change (Thompson and Solomon, 2002; Arblaster and Meehl, 2006). Indeed, the possible climate processes responsible for the drought identified in Table 2 are probably a combination of both natural and anthropogenic sources. However, although anthropogenic climate change was identified as a possible or partial cause of the drought there are very large uncertainties stemming from many sources that surround this statement.

The most obvious source of uncertainty is that there are numerous aspects of the climate system that are still not well understood and probably many more that are yet to be identified. This is particularly true of decadal and longer-scale processes for which knowledge is fundamentally limited by a lack of observations (e.g., the MDB only has 110 yr, or 11 independent decades, of climate records). This makes it particularly difficult to gauge the true extent of decadal-scale variations in MDB hydroclimate (i.e., to put the Big Dry into context) and to differentiate between the impacts of natural

Table 1. The seasonality of the inter-annual and longer hydroclimate processes for the Murray-Darling Basin is identified. The “x” indicates the months in which previous studies (see Sect. 3) have reported an influence of the process stated in the left-half column on the Murray-Darling Basin’s climate. The months in bold (March, April, May, June) are those that experienced large and persistent rainfall deficits during the Big Dry (ca. 1997–2010).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Inter-annual processes												
El Niño – Southern Oscillation	x	x	x			x	x	x	x	x	x	x
Indian Ocean SSTs						x	x	x	x	x	x	
Southern Annular Mode	x	x				x	x	x	x	x	x	x
Sub-Tropical Ridge Intensity				x	x	x	x					
Sub-Tropical Ridge Position	x	x										x
Tropical North Australia SSTs									x	x	x	
ENSO/SAM interactions	x	x	x	x	x	x	x	x	x	x	x	x
Inter-decadal – centennial												
Inter-decadal Pacific Oscillation	x	x				x	x	x	x	x	x	x
Anthropogenic climate change	x	x	x	x	x	x	x	x	x	x	x	x

Table 2. Identifies the characteristics of the Big Dry that are consistent with the typical influences of known climate processes. These include similarities in spatial and temporal features and associated small-scale influences e.g., the influence of an inter-annual process on weather systems. The seven major defining characteristics of the drought identified in Sect. 5 are stated below the table. A tick indicates that a characteristic feature of the drought is consistent with current understanding of how the processes in the far-left column influence the regional climate, a cross indicates an inconsistency and a dash indicates that the link between that characteristic and the climate process is unknown.

Characteristic drought feature	a	b	c	d	e	f	g
<i>Inter-annual processes</i>							
El Niño – Southern Oscillation	✓	x	✓	–	–	–	x
Indian Ocean SSTs	✓	x	✓	–	–	–	–
Southern Annular Mode	✓	x	✓	–	–	✓	–
Sub-Tropical Ridge Intensity	✓	✓	✓	–	–	–	✓
Sub-Tropical Ridge Position	✓	x	x	–	–	–	✓
Tropical North Australia SSTs	✓	x	✓	–	–	–	–
ENSO/SAM interactions	✓	✓	✓	✓	–	✓	–
<i>Inter-decadal – centennial</i>							
Inter-decadal Pacific Oscillation	✓	x	✓	✓	–	–	–
Anthropogenic climate change	✓	✓	✓	–	–	–	✓
<i>Trends</i>							
Trend in STR intensity	✓	✓	✓	–	–	–	✓
Southerly shift in storm track	✓	✓	✓	–	–	✓	✓
Warmer Indian Ocean SSTs	✓	x	✓	–	–	–	–

Major defining characteristics of the Big Dry.

- ^a Impacts the southern Murray-Darling Basin (south of approximately 33° S).
- ^b Persistent late autumn and early winter (March–April–May–June) rainfall deficits.
- ^c Occasional winter/spring rainfall deficits.
- ^d Lack of high rainfall periods and high one-day rainfall totals.
- ^e Reduction in rainfall stemming from cut-off low pressure systems.
- ^f Absence of rain-bearing troughs.
- ^g Increases in surface pressure.

inter-decadal to centennial variability and anthropogenic climate change. This can be overcome by continuing two major research streams.

The first involves complementing the limited instrumental record (approximately 100 yr) by extending the historical record using various sources of palaeoclimate information (Verdon and Franks, 2006; Lough, 2007; Gallant and Gergis, 2011). Verdon and Franks (2006) estimated variations in east Australian rainfall using reconstructions of the PDO for the past 400 yr. More recently, Gallant and Gergis (2011) and Gergis et al. (2012) developed an experimental reconstruction of River Murray streamflow and southeast Australian rainfall, respectively, and showed that the streamflow deficits associated with the Big Dry were very rare, but not necessarily unprecedented during the period 1783–1988. In both studies, palaeo records indicate there have been large decadal-scale variations in the east Australian hydroclimate prior to the instrumental record. Palaeoclimate reconstructions are useful for estimating the bounds of past climate variability. However, interpreting the physical processes behind the pre-instrumental variations is difficult. This is something that can only be properly studied via complementary modelling studies.

To date, much of our understanding of the processes driving the MDB climate has been established through the identification of consistent patterns and modes of variation in the atmosphere/ocean system. As such, the second approach to understanding decadal-scale hydroclimate variations, which as mentioned is difficult with limited instrumental data, is via studies utilising climate models that represent the fundamental physics of the atmosphere/ocean system. However, this presents a further problem, as climate models can still not sufficiently model all these processes that are known to drive regional hydroclimatic variability. A subsequent issue is that their teleconnections with regional climates are not well captured. Thus, while climate models may suggest a particular

future change that is consistent with a present-day trend, it is difficult to ascertain whether the mechanisms behind these trends in model-space are consistent with reality. This is a knowledge gap that requires immediate attention.

Given the lack of understanding about the physics behind both anthropogenic and natural processes, we suggest that if a framework similar to that presented here is utilised by NRM, that a weighting should be applied to each process that is inversely proportional to the uncertainty (i.e., the higher the uncertainty the less weight given to that causal process). This weighting factor may be arbitrary or based on some quantitative measure of uncertainty associated with each process. Developing such weighting factors is a complex process and is outside the scope of this paper. So at present, the best we can do given the current state of knowledge is to propose how the processes we understand, and the interplay between them, fit in the context of this event (Table 2). However, it is important to remember that the certainty of our attribution is proportional to our understanding and hence, is limited by it.

6 Concluding remarks

This paper demonstrates advances in our understanding of the climate processes influencing the MDB, however, it also highlights that there is much that is not well understood. The framework presented in Sect. 5 is designed to improve understanding to better focus NRM. So, in conclusion we summarise the key areas of research that we believe will assist in improving the reliability of hydroclimatic insights and forecasts for the MDB (on seasonal to decadal scales) and better quantification of climate related risk for NRM.

6.1 Expanding data records – instrumental and palaeoclimate-proxies

A maximum of 60 to 110 yr of instrumental data are available in the MDB and other regions that regulate its climate (e.g., the Southern Ocean). As such, reliable estimates of climate variations on multi-decadal and longer time scales are not possible due to limited degrees of freedom. This is a problem for NRM, which often assumes that the instrumental hydroclimate records are representative of current and future climatic conditions. Given the lack of long-term instrumental data, research investment into expansion of the instrumental record and the use of palaeo records is recommended.

6.2 Improving understanding of interactions between climate drivers

In Sect. 4.1, we performed some simple analysis to highlight interactions between the processes driving the MDB climate on multiple time-scales. From this analysis, it is clear that a better understanding of climate driver interactions on all time scales is required. Until such knowledge is gained it is difficult to: (i) know how to assess their impacts relative to one

another; (ii) determine the extent of their independence and how their contributions vary spatially and temporally; (iii) discriminate between impacts associated with natural and anthropogenic climate variations; (iv) develop (and/or improve) climate models to have greater confidence in future climate projections – it is unclear how climate models (either statistical or dynamical) can simulate climate processes that we do not yet properly understand.

6.3 Improving understanding of interactions between climatic and hydrological processes

Section 4.2 described the limited body of work examining interactions between ocean-atmosphere circulation patterns and hydrological/land-surface processes. Given its potential importance, further examination of (i) connections between antecedent hydrological conditions and/or land cover change and regional climates; (ii) the mechanisms driving the apparent relationship between increased temperature and decreased streamflow; (iii) the possibility of a rainfall recycling phenomena (Koster et al., 2004) in the MDB, is required.

6.4 Improving the representation of climate processes in climate models

Climate models provide a complementary way of examining variations in MDB hydroclimate. However, improving how climate models simulate the processes that drive the MDB hydroclimatic variability is crucial, as is the need for regionally specific information. Improved modelling capabilities will assist with the previous three research aims and vice-versa.

The research areas outlined above focus on improving understanding of natural climatic variations, the processes behind these and possible future changes. These research areas require urgent investigation as it is clear that there is still a lot we do not understand with respect to historical climate patterns and causal processes in the MDB – and even less is known about the future.

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