Hydrol. Earth Syst. Sci. Discuss., 8, 7873–7918, 2011
www.hydrol-earth-syst-sci-discuss.net/8/7873/2011/
doi:10.5194/hessd-8-7873-2011

Hydrology and Earth System Sciences Discussions

Understanding climate processes in the Murray-Darling Basin: utility and limitations for natural resources management

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Received: 4 August 2011 – Accepted: 12 August 2011 – Published: 17 August 2011

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Ocean-atmosphere processes causing variations in the climate of Australia's Murray-Darling Basin (MDB) 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. The source and relative importance of each climate driver varies due to the geographic spread of the Basin from the subtropics to the middle latitudes. Such differences were highlighted during the period from 1997–2010 when the southern MDB experienced prolonged and severe dry conditions, while decadal-scale rainfall in the northern MDB remained close to normal. Although recent studies have provided insights into possible mechanisms, the cause of this recent drying is still uncertain. To this end, this paper addresses the current state of knowledge about the processes causing climate variations in the MDB and the utility and limitations of this knowledge for natural resources management.

1 Introduction

Periods of prolonged, severe drought and moisture surplus are challenging for natural resources management. The events that are at the very edge of past experience are of particular concern as they push the limits upon which standard management practices are based, making socioeconomic and some natural systems vulnerable. More recently, periods of prolonged wet and dry have provided further cause for thought as natural resource managers debate whether the conditions are linked to anthropogenic climate change, leading managers to question whether similar events may become more prevalent in the future, and even whether such periods should be considered the new norm.

Beginning around mid-1996 and notionally ending in mid-2010, much of Australia's largest food-producing region, the Murray-Darling Basin (MDB), experienced a severe drought (Murphy and Timbal, 2008). As the duration of the drought passed the 10-yr mark in the mid-late 2000s, natural resource managers increasingly questioned whether the conditions in southeast Australia were mirroring those in southwest Australia, where severe drought has not abated since the mid-1970s and has been partially attributed to anthropogenic climate change (Hope et al., 2006, 2010). As water supplies for irrigation, personal use and natural flows dwindled to record low levels in the southern part of the MDB, natural resources managers approached climatologists in the hopes of determining a cause and establishing whether it might continue.

To understand how and why Australia's climate has changed and may change in the future, several national research initiatives were established to aid government institutions and universities in performing climate research for Australia. These initiatives included the Murray Darling-Basin Sustainable Yields Project (MDBSY; www.csiro.au/partnerships/MDBSY); 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 initiatives has provided invaluable information that is highly relevant to the natural resources community. However, few syntheses of this extensive body of knowledge have been produced in a way that is directly relevant to the natural resource managers or other non-climate specialists. Specifically, the possible utility and limitations of climate information relevant to these communities has not been identified. This includes addressing what climatologists know about the processes causing wet and dry periods on a number of time scales, where knowledge is lacking and the confidence of attribution of causes of particular events given the current state of understanding.

A review paper by Murphy and Timbal (2008) described the major processes associated with climatic variations in southeast Australia on inter-annual and shorter time scales and outlined possible causes of the then, 10-yr long drought. That paper provided a useful overview, primarily for the climate science community, about the state of knowledge on the climate system at that time. While useful for the southern MDB,

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their paper did not describe climate processes important to the northern MDB. Moreover, 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. Significant scientific advances have also been made in the three years since the Murphy and Timbal (2008) review was published, which will also be critiqued here.

This paper presents discussion and analysis surrounding our understanding of the climate processes affecting the MDB, and the utility and limitations of this information for natural resource managers. Though our discussion is focussed on the MDB, the paper presents information that is useful for other regions by establishing concepts that can be applied to multiple climates. For context, we first present a hydroclimatology for the MDB. An overview of the latest information on climate processes on inter-annual and shorter time scales is then given as an update to Murphy and Timbal (2008). We include a synthesis discussion on the drivers of decadal and longer-scale variability relevant to the MDB, which has not previously been presented. We then present some preliminary 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. The paper culminates in a discussion around the utility and the limitations of climate information for natural resources management in the MDB using the example of the recent, prolonged drought in the south of the region from 1997–2010.

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

The range of hydroclimatic variability on which natural resource management practices are based has traditionally been based on 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.

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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 metres 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 southeast and the hot, dry semi-arid plains in the west.

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 year^{-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 year^{-1} in the southeast of the Basin to around 2400 mm year^{-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 rainfall deficits frequently exceeding 100 mm year^{-1}, equivalent to rainfall being at least 20 % below average (Fig. 2). Several periods of multi-year rainfall deficits occurred, including the "Federation Drought" (c. 1895–1902) and the "World War II Drought" (c. 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

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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" (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).

3 Climate 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. Here, we expand on these topics and include information relevant to the northern MDB. This includes 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.

3.1 Daily to intra-annual processes

The types of weather systems that produce and inhibit rainfall in the MDB are summarized 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 rainfall totals is heavily dependent on the season and location, and there

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can be substantial differences in the size of the relative contributions over distances of several hundred kilometres only (Verdon-Kidd and Kiem, 2009a).

The rainfall accumulations associated with individual events from the same type of weather system vary. However, 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 systems in the southern MDB. The typical amount of rainfall produced by each system has a wide distribution dependent on the intensity and duration of the event. The contribution of each type of weather system to the climate is also dependent on the frequency at which those systems impact on an area.

Establishing the make up of the daily-scale rainfall distribution for a location, and how this interacts with the climate, 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 if it had occurred in a single event (McIntosh et al., 2007).

Rainfall in the southern MDB mostly stems from weather systems with an extra-tropical origin (Wright, 1989; Qi et al., 1999; Pook et al., 2006; Risbey et al., 2008). 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. cloudbands that form from a surface or middle troposphere pressure trough entraining tropical moisture), those that do not (e.g. Southern Ocean cold fronts), and post-frontal rainfall provide smaller, but significant, contributions to southern MDB rainfall totals, though 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 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 half of the 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", 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 thunderstorm development along their leading edge, bringing very localized, 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 high-pressure system. In the southern MDB,

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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 in 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), most of the annual rainfall occurs during the warmer months (approximately November–April), due to the greater influence of tropical weather systems. The opposite is true for the southern MDB, where extra-tropical systems dominate and rainfall during the cooler months (approximately May–October).

3.2 Inter-annual processes: an update

The El Niño – Southern Oscillation (ENSO) constitutes the largest single source of inter-annual climate variability in the MDB and can be responsible for over 20 % of local annual rainfall variations (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 rainfall variations are most strongly associated with ENSO events (McBride and Nicholls, 1983; Risbey et al., 2009). 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),

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elevated flood risk during La Niña events (Kiem et al., 2003), and increased risk of drought (Kiem and Franks, 2004) and wildfire (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). For example, some of the strongest El Niños have not been associated with severe, widespread drought (e.g. 1997/1998), while other less intense events have coincided with particularly intense drought (e.g. 2002/2003) (Wang and Hendon, 2007; Brown et al., 2009). The sensitivity of Australian rainfall variations to 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 sea surface temperature 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 (La Niña) Modoki is characterised by warm (cool) central Pacific waters flanked by anomalously cool (warm) SSTs to the west and east, separating the Walker Circulation into two distinct circulations.

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). Cai and Cowan (2009) associated La Niña Modoki events to elevated autumn rainfall in the MDB. However, there have been conflicting conclusions in the

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literature as to the impacts of El Niño Modoki on the Australian climate. 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 (JJA) and spring (SON) rainfall have been linked to Indian Ocean SST anomalies (Nicholls, 1989; Simmonds, 1990; Drosdowsky, 1993; Ashok et al., 2000; Drosdowsky and Chambers, 2001) and the Indian Ocean Dipole (IOD) (Saji et al., 1999; Ashok et al., 2003). The IOD is characterized 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 erroneous, its links to Australian rainfall have recently been debated. Ummenhofer et al. (2009a) used a climate model to demonstrate that the western 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.

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 eastern sections (Meneghini et al., 2007).

Section 3.1 described the meteorological phenomena that affect the MDB. The characteristics of these phenomena, such as frequency, location and duration of these

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events show variations on inter-annual time scales that have been linked to inter-annual variations in MDB rainfall. For example, there are demonstrated links between STR intensity and southern Australian rainfall during autumn and early winter, and between summer rainfall and the position of the STR (Larsen and Nicholls, 2009).

Atmospheric blocking was also 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 multidecadal 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

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

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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 summer-time 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. 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 in the MDB. Given the potential for anthropogenic warming to be associated with significant negative impacts across

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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 multi-decadal and longer changes in MDB can be properly assessed.

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

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(cool) phases of the IPO decrease (increase) the likelihood of wet weather events and vice versa for dry weather events in parts of the MDB.

Variations in the prevalence of atmospheric blocking have been linked to the state of ENSO, with blocking frequency and associated rainfall becoming more (less) prominent during La Niña (El Niño) events (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).

Here, we present analysis demonstrating the connections between climate processes operating on inter-annual and daily time scales for the southern MDB. Using seven stations from the Lavery et al. (1992) high-quality daily rainfall data set, we calculated the number of days with rainfall accumulations above 25 mm (defined as heavy rain days) from April–October for each year from 1970–2002. Pook et al. (2006) showed that 80 % of April–October heavy rain days during this period were caused by cut-off low-pressure systems in the same domain. Hence, a threshold of 25 mm is likely to be a reasonable estimate of cut-off low frequency.

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 (DMIeast) of Saji et al. (1999), generated from the global HadISST sea-suface temperature data set (Rayner et al., 2003). A positive (negative) phase of each driver was defined if the standardized 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 standardized over the 1970–2002

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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.

Figure 5 illustrates the effects of the three main drivers of inter-annual variability in southern MDB rainfall (i.e. ENSO, SAM and eastern Indian Ocean SSTs), on daily weather events in the area. Every station in the domain had a statistically significant link between April–October heavy rain days and ENSO, with a higher (lower) than average number of heavy rainfall days during La Niña (El Niño) years. This result was the same whether SOI or SSTs from the Nino3.4 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 had significantly more (fewer) heavy rain events during years with warmer (cooler) than normal eastern Indian Ocean SSTs. The results here suggest that all three major drivers of interannual 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

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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 (Drosdowsky, 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 processes since around this time (Marshall, 2003; Larsen and Nicholls, 2009). The trend

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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). We have also previously argued that the IOD is not a physical atmosphere/ocean interaction (Sect. 3) with many studies providing evidence that it 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 (El Niño) will occur with warm (cool) eastern Indian Ocean SSTs (Meyers et al., 2007). As these coinciding phases are indicative of wet 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 the spring DMI was correlated against the winter SOI. 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 (JJA) and that there is a lack of statistically significant

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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 may actually exist, one entirely independent of ENSO and the other a consequence of tropical Pacific conditions (i.e. ENSO). However, the mechanism by which the IOD was triggered in these simulations was not clear, indicating it may simply be the result of random fluctuations in Indian Ocean SSTs. Regardless, none of these studies provide a physical mechanism for the IOD as a climate process that is independent of ENSO. As such, we continue to argue for the non-existence for an IOD and like previous studies, suggest that any apparent "IOD" is probably the result of combined ENSO influences and stochastic variations, or random variations alone. However, given the conflictions in the literature, more work needs to be undertaken to establish if this is the case.

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 (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 (March–May) 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 apparent lack of interaction between SAM and ENSO processes, 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 standardized 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 Nino3.4 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 have a strong relationship with autumn (March–May) rainfall in the MDB and as such, the influence of both was less apparent in our analysis (not shown). However, 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 (northern) part of the MDB was typically drier (wetter) for a co-occurring La Niña and positive SAM event, compared to a La Niña event

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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.

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 (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

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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 The utility and limitations of climate knowledge during "The Big Dry", 1997–2010

It is clear that the processes presented in Sects. 3 and 4 do not equal the sum of knowledge required for complete understanding of the complex climate system. However, skill in numerical weather prediction (weather forecasts) and seasonal forecasts indicates that our current level of understanding is useful for gleaning a reasonable amount of information about the potential causes of wet and dry cycles in the MDB, including "The Big Dry" (c. 1997–2010).

Given the importance of interactions between various hydroclimatic processes (see Sect. 4), identifying a single cause of a severe drought is not realistic. The interactions

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between physical processes are complex and are likely to involve a considerable chaotic component. This means that even if we could understand the physical mechanisms causing MDB climate variations perfectly, there would still be uncertainty in our attribution because of these random processes. This has considerable implications for the prediction of such events.

The limitations of our knowledge make identifying the climatic components causing The Big Dry an extremely difficult task. Furthermore, though some of the processes affecting the regional MDB circulation have been identified, there is a lack of understanding about the physics behind these processes. So, perhaps 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. However, it is important to remember that the certainty of our attribution is inversely proportional to our understanding and hence, is limited by it. Given these caveats, we now discuss how the major processes described throughout this paper have affected The Big Dry, given our current state of understanding. For natural resource managers, this provides an example of the practical application of climate knowledge to a severe hydroclimatic event and highlights the limitations of the conclusions we can draw.

At the daily time scales, The Big Dry was characterized by a lack of high one-day rainfall totals (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 period (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 MDB (Verdon-Kidd and Kiem, 2009a). The recent drying 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 an area in need of further study.

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Understanding climate processes in the Murray-Darling Basin

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Section 3 noted that ENSO, if looked at in isolation, is responsible for the largest proportion of inter-annual variability in the MDB climate compared to other drivers. There has been no significant trend in ENSO during The Big Dry (Nicholls, 2008). However, the three La Niña events occurring during this period have 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).

Nicholls (2009) and Verdon-Kidd and Kiem (2009b) suggest that a consistently positive SAM since the 1990s, associated with a poleward retraction of the mid-latitude storm track, may be responsible for 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 recent drying has coincided with changes to the local MDB circulation that have included an increase in regional surface pressure, which has been attributed to shifts in the position and intensity of the STR (Drosdowsky, 2005; Timbal and Murphy, 2007; Larsen and Nicholls, 2009; Williams and Stone, 2009). As such, the association between the intensity of the STR and rainfall variations has been suggested as a potential cause for the southeast Australian rainfall decline (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

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autumn and early winter (Murphy and Timbal, 2008; Verdon-Kidd and Kiem, 2009b)).

A lack of years experiencing an IOD phase conducive to rainfall, and a trend toward the phase of the IOD consistent with rainfall deficits, have also been put forward as a potential cause of The Big Dry (Cai et al., 2009b, a; Ummenhofer et al., 2009b). However, this influence is confined to late winter and early spring, not autumn and early winter, when the majority of the rainfall deficits have occurred. While The Big Dry has experienced some persistent rainfall deficits during winter and spring seasons (Verdon-Kidd and Kiem, 2009b), they are small, suggesting that Indian Ocean variability may have contributed to the worsening of the drought, but that it is unlikely to be responsible for the majority of the rainfall deficits. Furthermore, reduced rainfall in southeast Australia is typically associated with abnormally cool SSTs to the northwest of Australia (the eastern pole of the IOD). However, since about 1985 SSTs to the northwest of Australia have generally been warmer than normal (particularly during autumn) (Nicholls, 2009). Therefore, even if the seasonality issue mentioned above is ignored, the claim that IOD is a major cause of The Big Dry is still highly questionable. In addition, we have questioned the existence of the IOD and have formed the conclusion that the current evidence suggests that it is unlikely to be a real, physical mode of variation.

We have briefly described how our knowledge of climate processes fit within the characteristics of the rainfall decline that were observed during The Big Dry. From this knowledge, multiple theories as to its cause have emerged in the literature: (i) an increase in the intensity of the STR, (ii) the poleward movement of the mid-latitude storm-track and related mid-latitude weather systems (positive trend in SAM) (iii) a trend towards Indian Ocean conditions likely to inhibit rainfall and (iv) suppressed rainfall during La Niña events due to influences from the SAM and Indian Ocean.

Despite the lack of a definitively accepted mechanism, the theories of the cause of The Big Dry have a common similarity. That is, all causes involve decadal scale variations in the major climate drivers and how they influence 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 in some cases (Thompson and Solomon, 2002; Arblaster and Meehl, 2006). However, until the mechanistic studies, including modelling, are performed to establish the physical mechanisms behind The Big Dry, its cause remains uncertain.

The MDB has one of the longest, spatially diverse climate records in the world. However, even a century's worth of data contains only 10 independent decades on which we can assess climate variations. This is not long enough to robustly gauge the true extent of decadal-scale variations in MDB rainfall to assess events such as The Big Dry. We argue that this restriction 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) developed an experimental reconstruction of River Murray streamflow 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 climate 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. This is a knowledge gap that requires immediate attention.

6 Conclusions

This paper demonstrated advances in our understanding of the climate processes influencing the MDB, however, it also highlights that there is much that is not well understood. Several key aspects of the climate system that require more research were highlighted. We now summarise the key areas of research that we believe will assist in producing more reliable hydroclimatic forecasts for the MDB (on seasonal to decadal scales) and better quantification of climate related risk, all of which are beneficial for natural resource management in the MDB.

(i) 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 water management, 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.

(ii) Improving understanding of interactions between climate drivers

In Sect. 4.1, we performed some simple to 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 process that we do not yet properly understand.

(iii) 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.

(iv) 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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Acknowledgements. The authors would like to thank Jason Alexandra and the Murray-Darling Basin Authority for commissioning the reports that formed the basis for this paper and Stewart Allen for assistance in preparing Fig. 4. AG and DK are supported by the Australian Research Council through the Discovery Projects funding scheme (project FF0668679).

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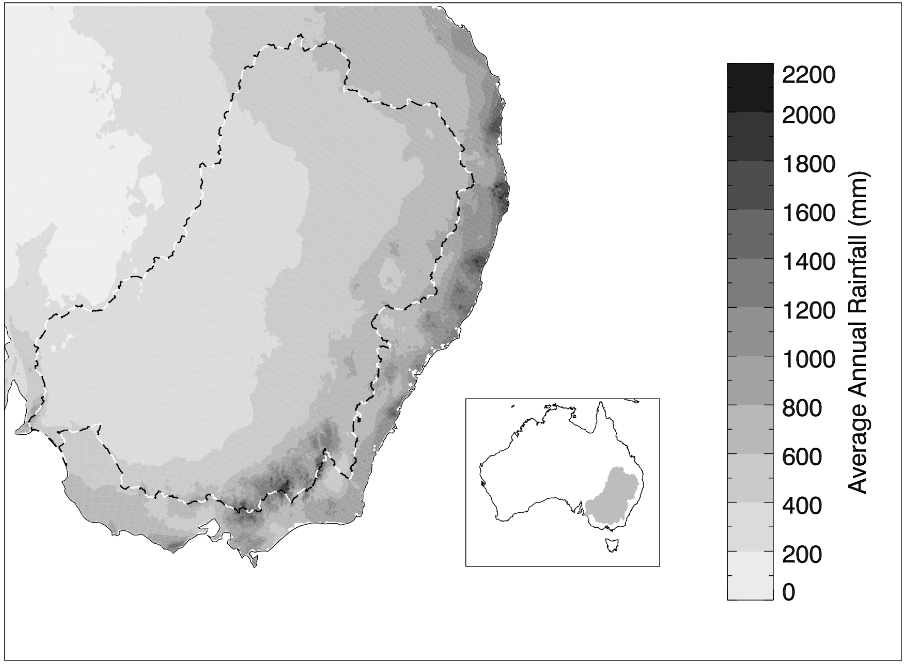

Fig. 1. The Murray-Darling Basin (dashed outline) overlaid on mean annual January–December (1900–2010) observed rainfall (mm), from the Australian Bureau of Meteorology Australian Water Availability Project rainfall grids (Jones et al., 2009a). Adapted from Draper and Mills (2008).

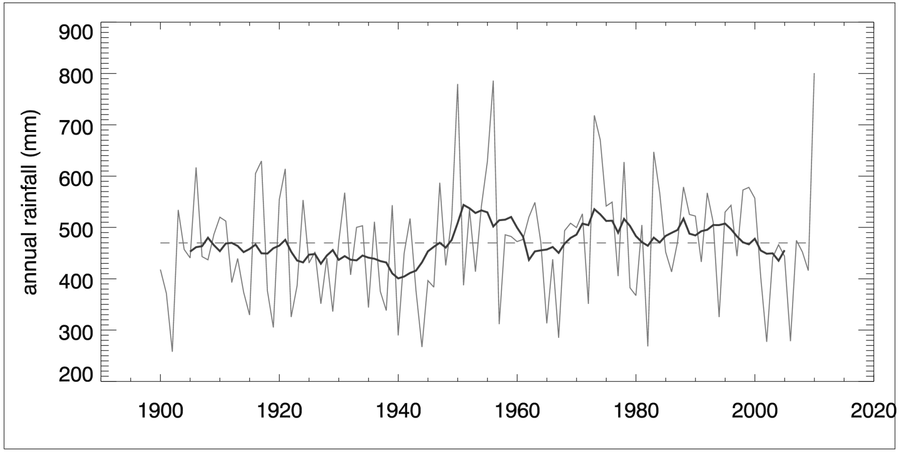

Fig. 2. Area-average annual (January–December) rainfall (thin grey line) and decadal mean rainfall (thick black line) for the Murray-Darling Basin from 1900 to 2010, generated from the Australian Water Availability Project rainfall grids (Jones et al., 2009a). The dashed line indicates the mean annual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

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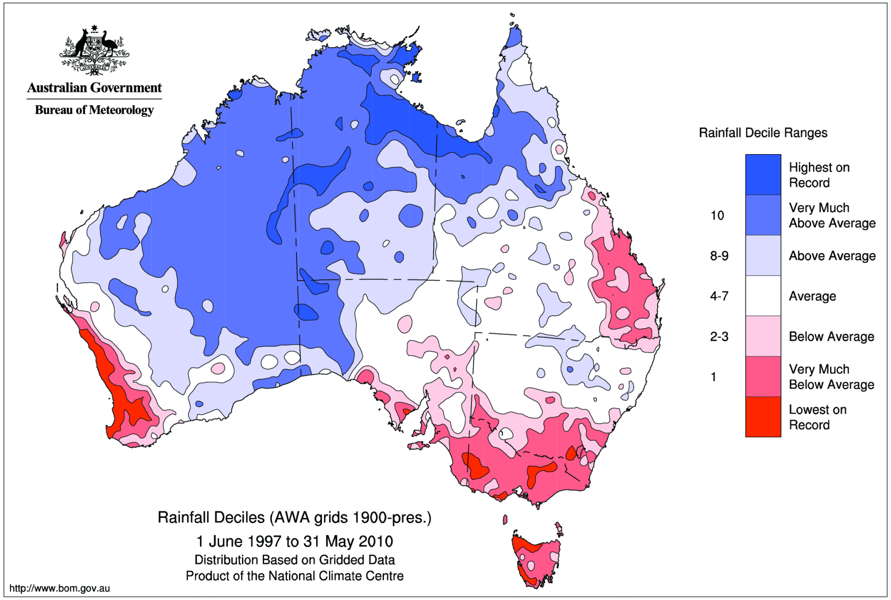

Fig. 3. The 13-yr June 1997 to May 2009 rainfall totals shown as deciles compared to all other 13-yr June to May periods from June 1900 to January 2009. Figure provided by the Australian Bureau of Meteorology.

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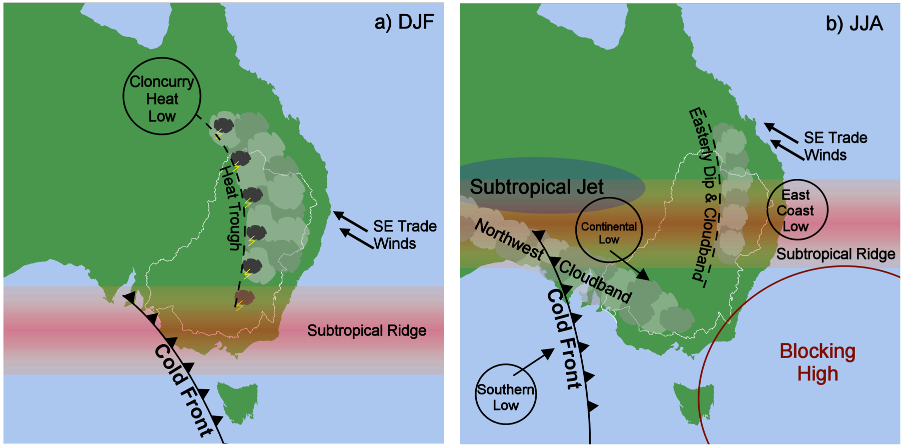

Fig. 4. Key synoptic features of the Murray-Darling Basin during the austral **(a)** summer (DJF) and **(b)** winter (JJA).

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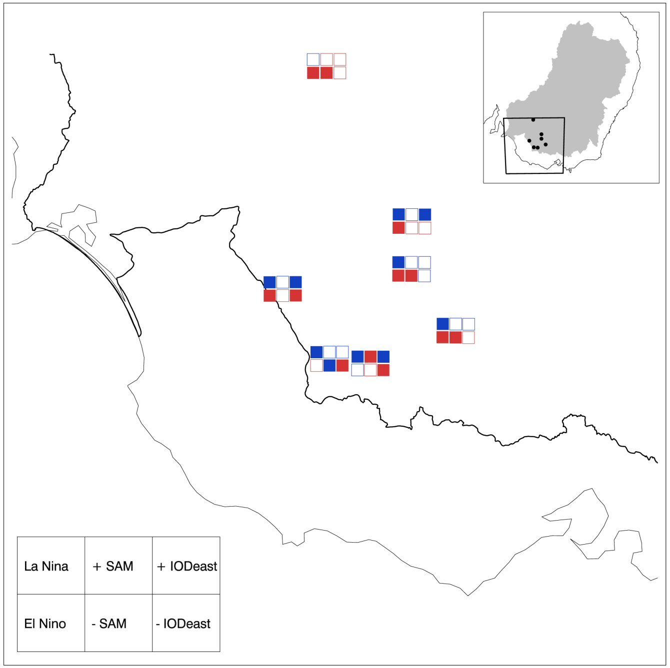

Fig. 5. The squares represent the difference in the annual (April–October) mean number of heavy rain days (defined as days with over 25 mm of rainfall) between years experiencing neutral and extreme phases of ENSO, SAM and Indian Ocean SST variations. The mean number of rain days during years in the 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 (red) indicates that a station has more (less) than 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.

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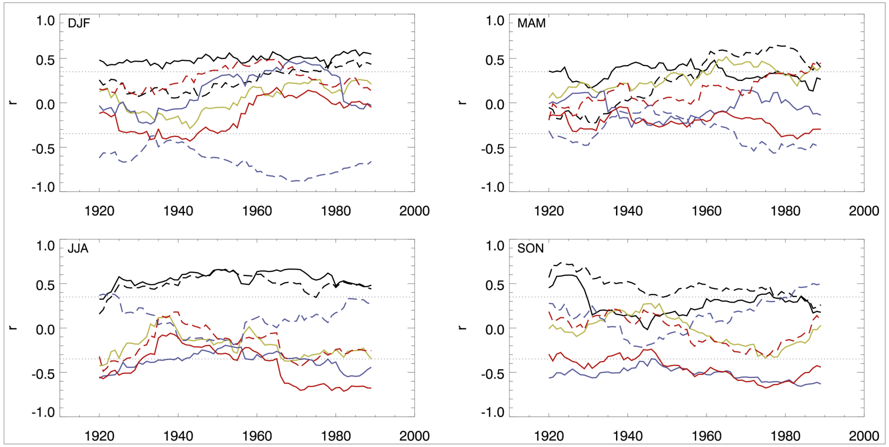

Fig. 6. Running 30-yr correlations between pairs of seasonal indices representing the drivers of inter-annual climate variability in the MDB. SAM and STR intensity (solid black line), SAM and STR latitude (dashed black line), SAM and ENSO (solid yellow line), ENSO and IOD (solid blue line), ENSO and 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 ($t = \pm 0.35$).

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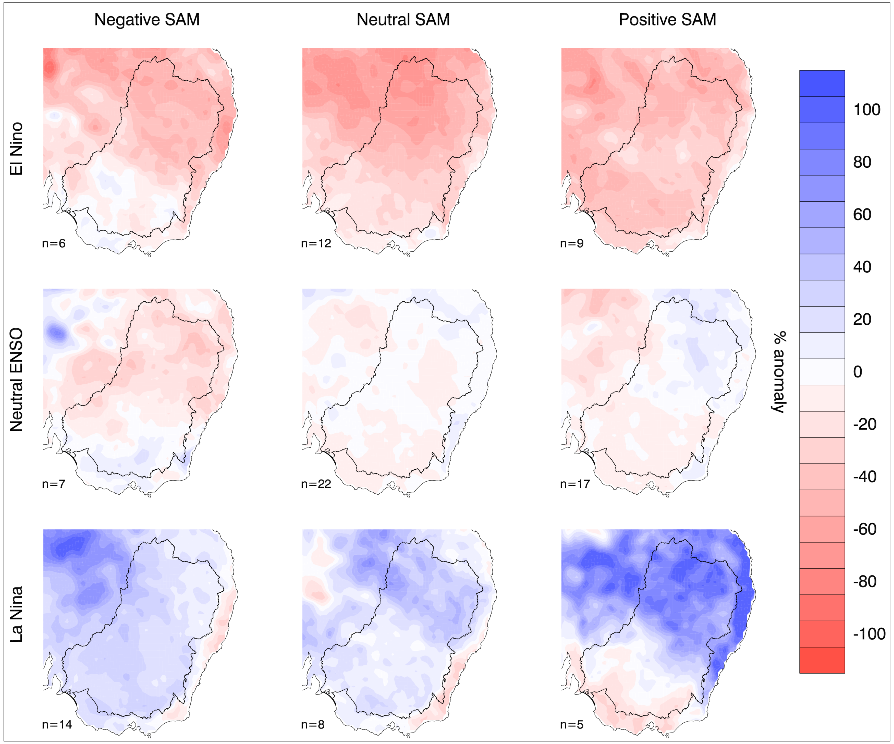

Fig. 7. Composite mean percentage winter (June–August) rainfall anomalies in the MDB during co-occurring phases of the SAM and ENSO from 1905–2004. A positive or negative phase of SAM and ENSO was defined when the standardized anomalies (relative to 1905–2004) of each index exceeded ±0.5 standard deviations.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

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