COMPREHENSIVE REVIEW INTO THE CORE CLIMATE PATTERNS, DROUGHTS, RAINFALL SYSTEMS AND ASSOCIATED CAUSAL PROCESSES RELEVANT TO THE MURRAY-DARLING BASIN AT A RANGE OF ASSOCIATED TIME SCALES

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Executive Summary

An analysis of major climate mechanisms and ‘drivers’ of rainfall variability over the Murray-Darling Basin (MDB) demonstrates a range of systems as being responsible for rainfall variability in this region. The El Niño-Southern Oscillation system (ENSO) has been and remains a major driver of year-to-year rainfall variability over the MDB with strong impacts during the winter, spring and summer. Impacts in summer are especially relevant for northern regions of the MDB through affecting inflow into the MDB system via northern river systems influenced by tropical and extra-tropical systems. Additionally, the Indian Ocean Dipole (IOD), especially when considered in conjunction with ENSO, can influence rainfall variability over the MDB. The ‘sub-tropical ridge’ appears to have a considerable influence on rainfall variability and drought occurrence across the MBD and is notable for being a probable mechanism, through its increasing intensity over recent years, for rainfall reduction and subsequent drought through the region, especially in regards to the important autumn period in the southern MDB.

Low-frequency systems/modes, such as the Pacific Decadal Oscillation (PDO) and the Interdecadal Pacific Oscillation (IPO), are also examined and although appearing to show statistical correlation with rainfall in the region through ameliorating or enhancing rainfall associated with ENSO, it is suggested these features currently lack any predictive capability.

Aspects related to high-frequency patterns and mechanism that are responsible for transporting the rainfall and drought signal into the MDB warrant further attention. Identification of the linking mechanisms between these high-frequency patterns and the larger signals may provide further insight into many of the core causes responsible for rainfall and temperature variability over the MDB. Such systems of interest include the Madden Julian Oscillation (MJO) and atmospheric ‘blocking’ processes that can enhance or ameliorate otherwise rainfall producing systems relevant for the MDB.

Introduction

It is recognised that the Murray-Darling Basin (MDB) is one of Australia's largest river basins and has a significant role in the national economy especially as this region has been Australia's foremost agricultural region with approximately 40 per cent of Australia's agricultural production being produced in this region in the past. 90 per cent of the MDB is classified as either arid or semi-arid with the highly variable nature of Australia's climate on a year-to-year basis compounding the impacts of the Basin's aridity and the frequent severe flood and drought occurrence (Draper, 2007). Importantly, it is estimated that 86% of the MDB generates little run-off except during floods (Prasad and Khan, 2002).

The Murray-Darling Basin Commission estimated that potential evaporation from the MDB is four times the annual mean rainfall across the Basin (503.5mm) (Murray-Darling Basin Commission, 2003). Much of this evaporation occurs from seven river systems which drain internally into wetlands and into the lower reaches of the River Murray. Additionally, while the majority of the MDB is arid it also includes some relatively humid zones. The 'annual average' rainfall across the MDB varies widely and ranges from less than 200mm/year in the western plains up to 1000mm/year in the south-eastern highlands. Prasad and Khan (2002) showed that the Upper Murray, Murrumbidgee and Goulburn River catchments generate 45.4 per cent of the MDB's runoff from just 11 per cent of the MDB's area. Conversely, the catchments draining into the Darling River in the north of the MDB generate just 31.7 per cent of the MDB's discharge from 60.4 per cent of the MDB area (Draper, 2007) (Figure 1).

Additionally it has been recognised that the *El Niño-Southern Oscillation* (ENSO) has an especially strong influence on rainfall and streamflow variability on the MDB, especially in more northern regions in summer but generally overall throughout the basin as well. Maheshwari *et al*. (1995) estimated that the annual discharge from the Murray-Darling systems, between 1894 and

1993, ranged remarkably from 1,626GL to 54,168GL with the added comment that drought is a common occurrence in the MDB and 'it is not unusual for rivers in the system to cease flowing during dry periods'. Additionally, it is recognised that 'floods are also a common occurrence in the Basin, and are exacerbated by the Basin's generally low surface gradients' (Maheshwari *et al.*, 1995).

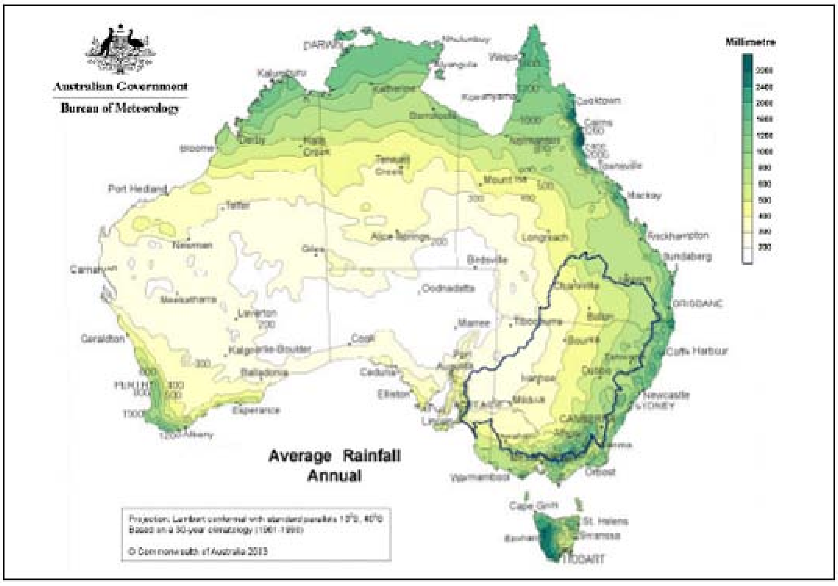

Figure 1. Annual average rainfall with the Murray-Darling Basin depicted (Draper, 2007).

Drought severity.

Aspects associated with rainfall deficits and drought for the MDB show a marked decline in rainfall in southern regions, especially those areas with proximity to the River Murray catchment and system. Figure 2 provides detail of rainfall decile ranges for the three years up until end-May 2009. Southern areas of the MDB are either in the 'lowest on record' (for the time period referred to) or in the lowest decile (lowest 10 per cent of possible values). Also noteworthy is that rainfall deciles are low in the some upper summer rainfall dominant sections of the MDB for this time period.

Figure 3 provides values for the eight year period until end-May, 2009 and provides information that shows much of the MDB, especially the mid-lower sections were the lowest on record for that time period. Additionally, rainfall in some upper sections relevant to the provision of inflows in the Condamine-Balonne and thus the Darling River system was in the lowest 10 per cent of values for this time period (8 year totals).

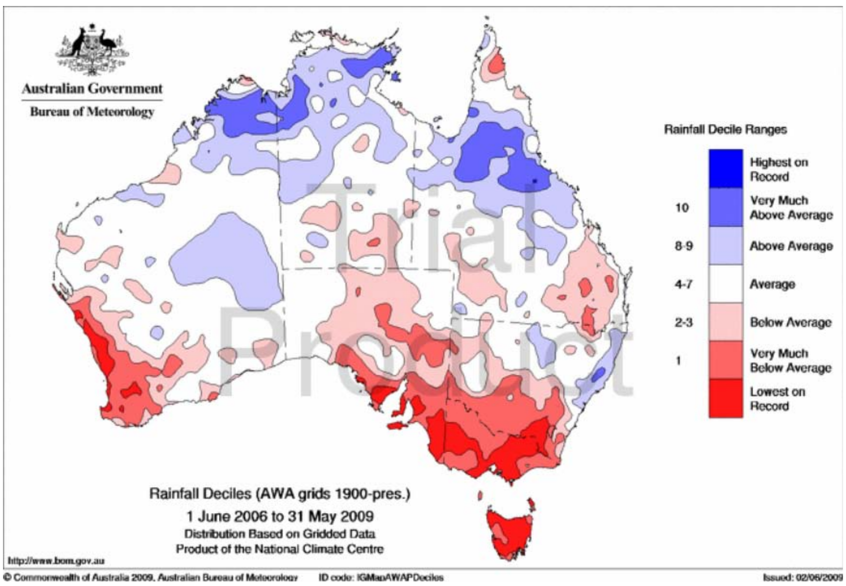

Figure 2, Rainfall deciles for the 3 year period 1 June, 2008 until 31 May, 2009 (BoM).

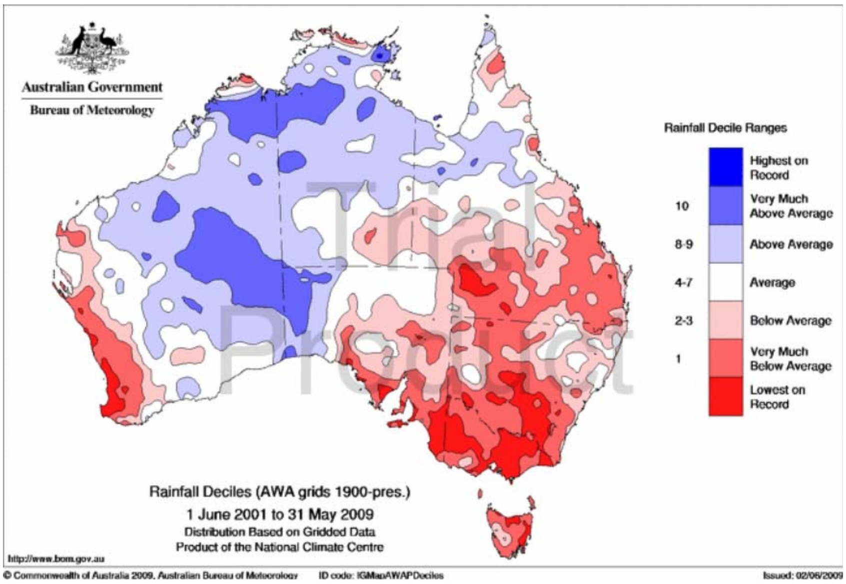

Figure 3. Rainfall deciles for the 8 year period 1 June 2001 until 31 May, 2009 (BoM).

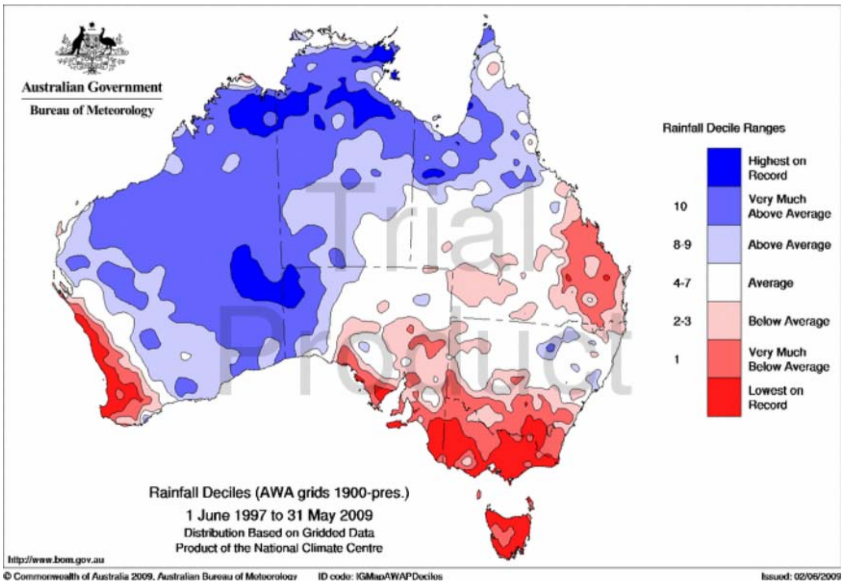

Figure 4. Rainfall deciles for the 12 year period 1 June 1997 until 31 May, 2009 (BoM).

It is instructive to consider rainfall deficits (drought) at a range of timescales in order to asses the relative impacts and severity on a range of systems. Figure 4 shows the major extent of the drought/rainfall amount (in deciles), especially across Victoria and the lowest parts of the MDB at this timescale. Sections of the upper regions of the MDB in Queensland that provide inflows into the

Condamine-Balonne-Darling River system have also recorded rainfall in just the lowest decile for this extended period.

Figure 5 provides an indication of the accumulated deficits through the per cent variation over the most recent 8-year period. At the 8-year time scale the % variation of the most recent 'drought period' is comparable (but slightly less) than the period between 1934 and 1947 for much of the MDB.

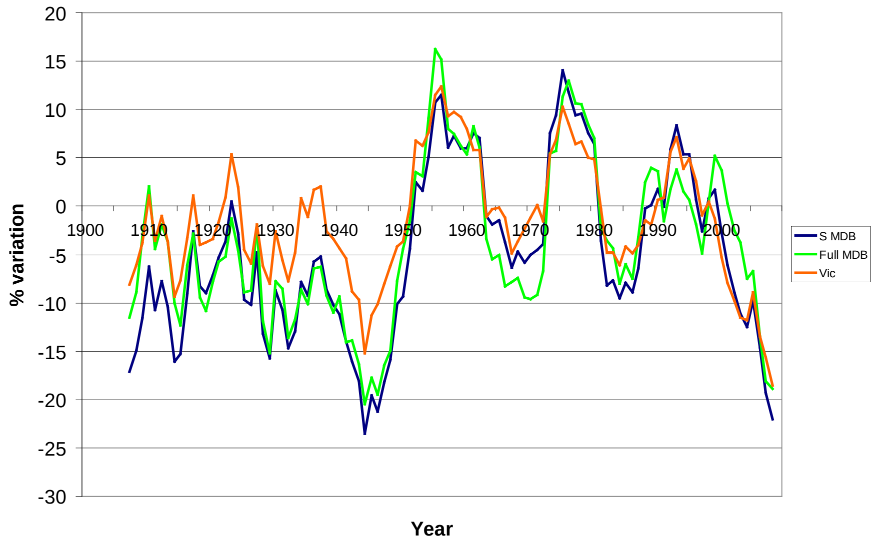

Figure 5. Per cent variation in rainfall using 8 year rainfall totals (B Trewin, BoM, 2009).

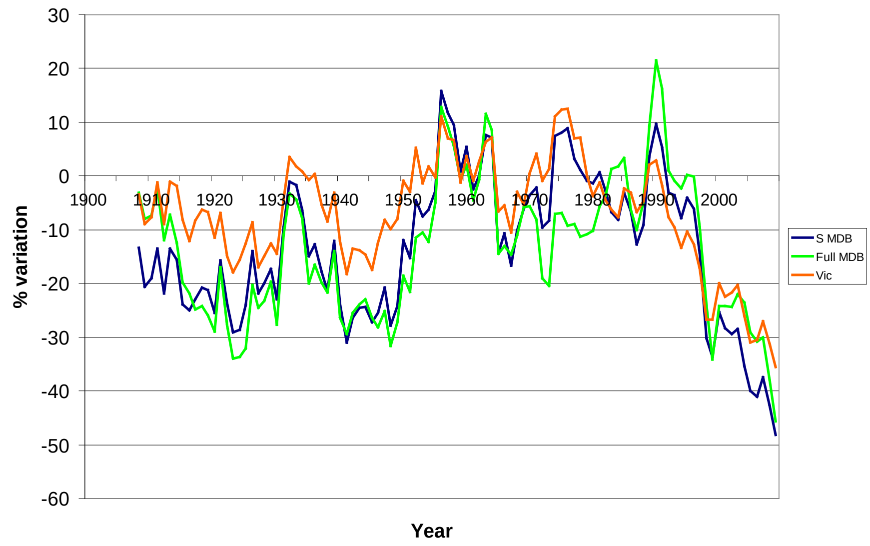

Figure 6. Per cent variation in rainfall for the autumn period using 9 year rainfall totals (B. Trewin, BoM, 2009).

Figure 6 provides information on the key autumn period (for agriculture) and associated decline in rainfall for the Southern MBD, the overall MDB and for Victoria, respectively. Figure 6 shows the autumn decline in rainfall has been the most significant since rainfall records commenced. Figure 7 provides information at a longer time scale (19 years) and depicts the more 'insidious' impacts of the long-term decline in autumn rainfall in the MDB, especially since 1990.

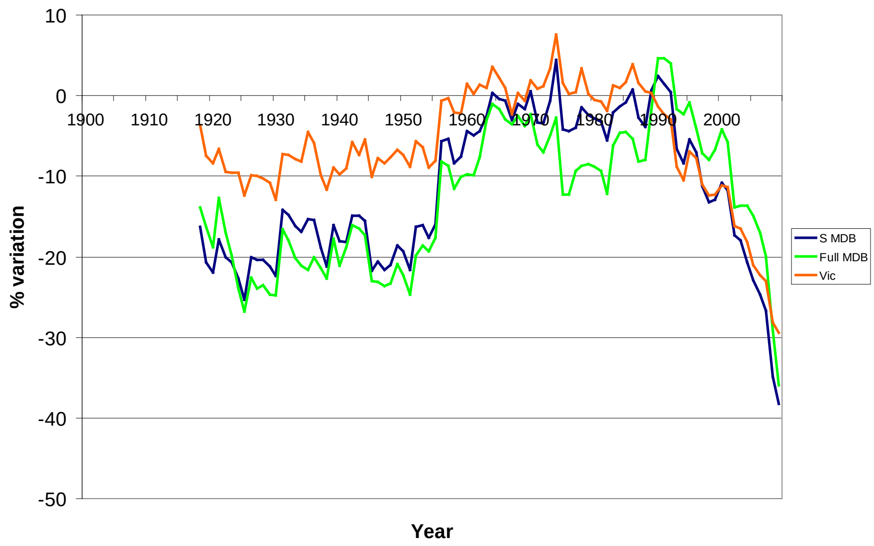

Figure 7. Per cent variation in autumn rainfall on a 19 year timescale for the MDB (B Trewin, BoM, 2009).

Long-term shifts in rainfall and streamflow are occurring in the MDB. Figure 8 provides an example of such issues and shows rainfall and streamflow variability and shifts in the Hume River with a stepped decline and drought-type conditions evident over recent decades.

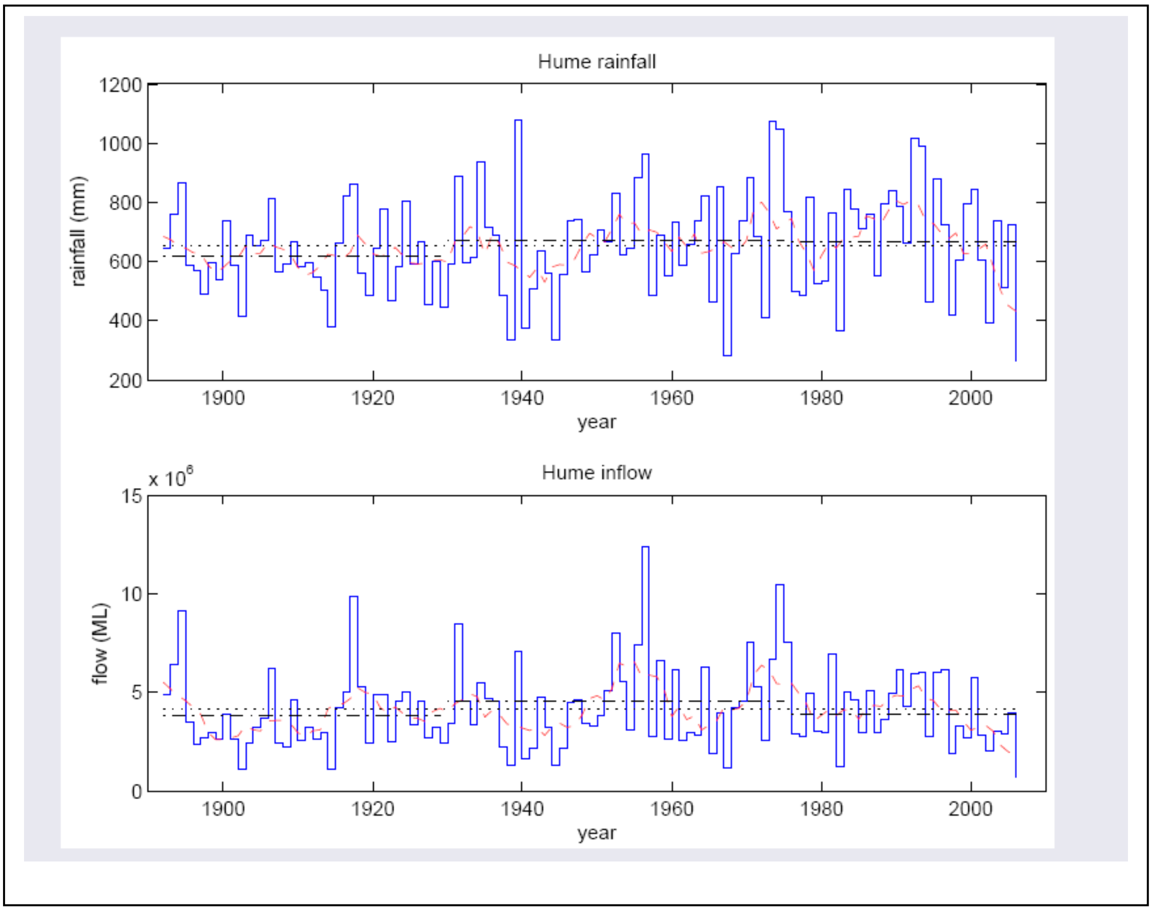

Figure 8. Rainfall and streamflow time series for Hume Reservoir (Source: Risbey, Pook, and McIntosh, CSIRO).

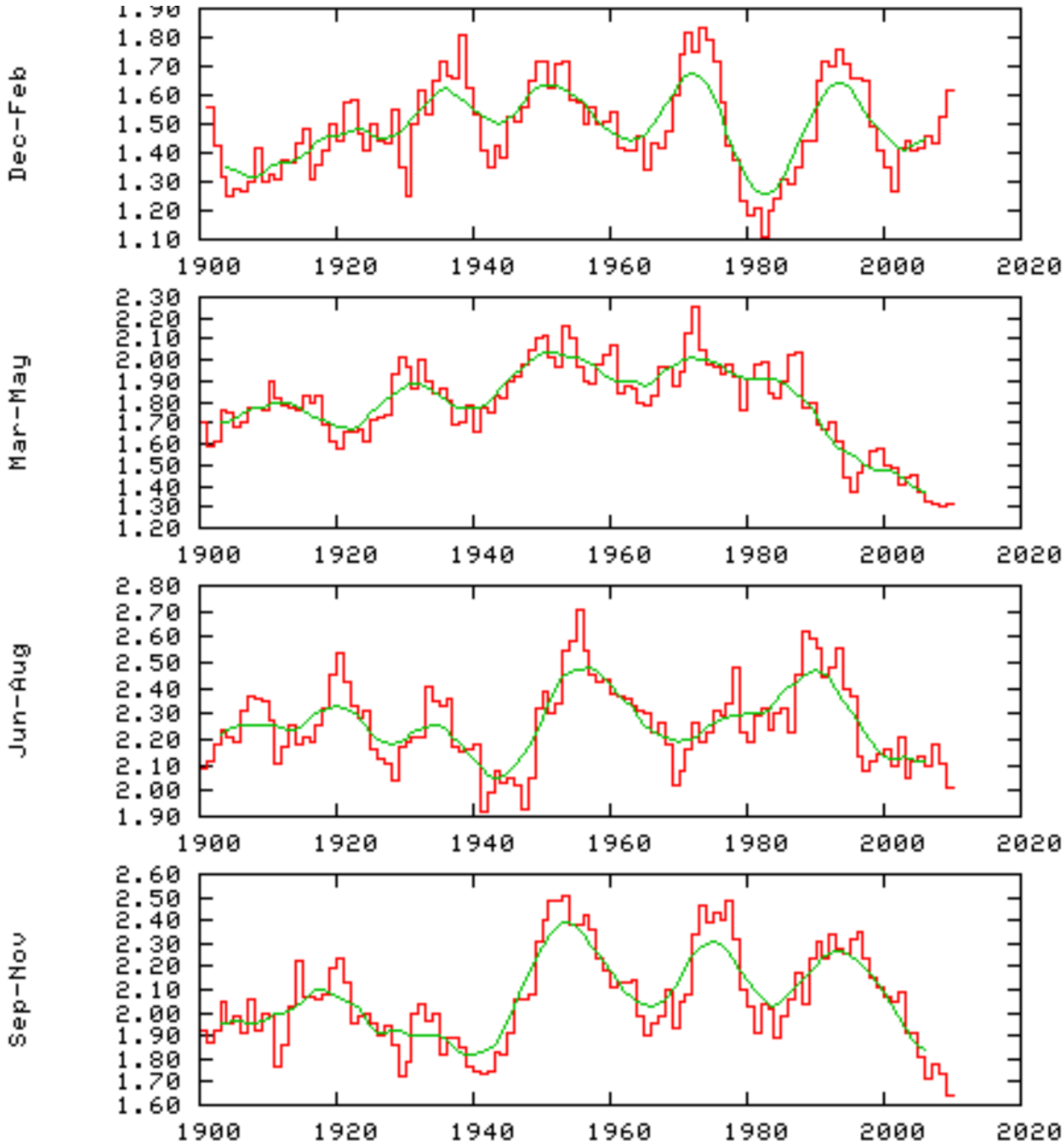

Figure 9. Time series of rainfall for seasonal periods for south-east Australia and of relevance for the southern MDB showing a marked decline in March-May rainfall and, more recently, September-November rainfall. Green line indicates 10-year running mean and red line indicates 7 year running mean).(from Timbal, 2009, courtesy, H Hendon, Bureau of Meteorology (Centre for Australian Climate and Weather Research)).

In terms of drought relevance, Timbal (2009) notes that as of March 2009, the twelve-and-a-half year rainfall average of 504*mm/year* (from October 1996) for south-east Australia is now the lowest within the instrumental period; the previous lowest being 506.4*mm/year* before and during WWII (December 1934 to May 1947).

Notably, autumn rainfall decline and drought is the most significant component of this decline: a 25% rainfall reduction from the long term mean (99.7 mm versus 132.4 mm) which accounts for ~60% of the total rainfall decline and is significant at the 95% level (Figure 9). Timbal (2009) notes the autumn signature in rainfall decline is especially dominant in southern regions of the MDB, with March, April and May recording the largest month by month (negative) anomalies in absolute values. However, 'an evolution is noticeable' compared to a similar analysis conducted in 2006 where there is now a continuum of 8 months from March to October showing a major rainfall deficiency (Timbal, 2009).

Aspects related to northern rainfall and river systems have particular importance for river systems and industry in that region and in also gaining an appreciation of impacts of climate change and variability relevant across the entire MDB through the input of flows from this region into the overall MDB. Figure 10 provides an example of (unencumbered) flow in the McIntyre River at Goondiwindi (Queensland-NSW border region) and demonstrates a long-term decline since the middle of the last century in streamflow in this river system, despite the fact that rainfall itself is not showing a similar level of decline in the Goondiwindi region. However, considerable rainfall decline is occurring further to the east in the headwater source regions of this river system. Also noteworthy is that, as well as an over rainfall decrease and obvious association of major flow reduction during El Niño/drought years, is the apparent drop in major flows during normally La Niña years (ie; lower peaks in extreme flows).

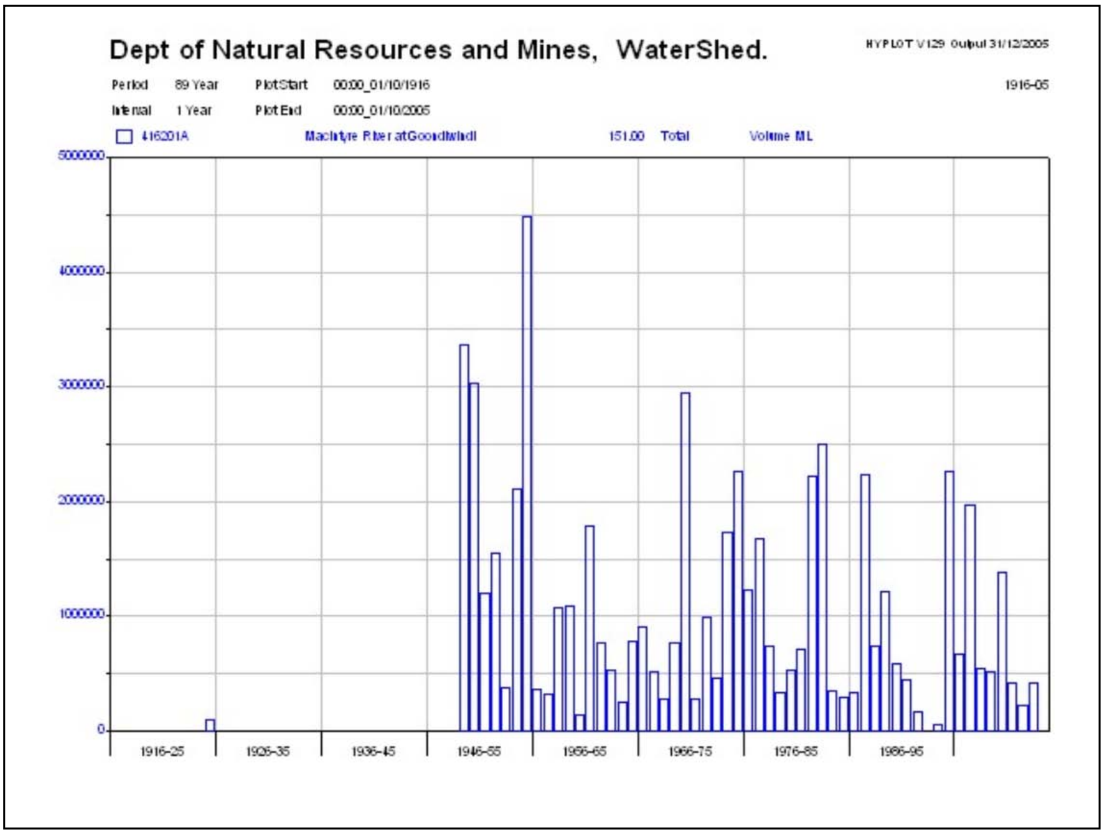

Figure 10. Time series of unencumbered flow in the McIntyre River at Goondiwindi, Queensland since 1945 (courtesy Queensland Department of Natural Resources and Mines).

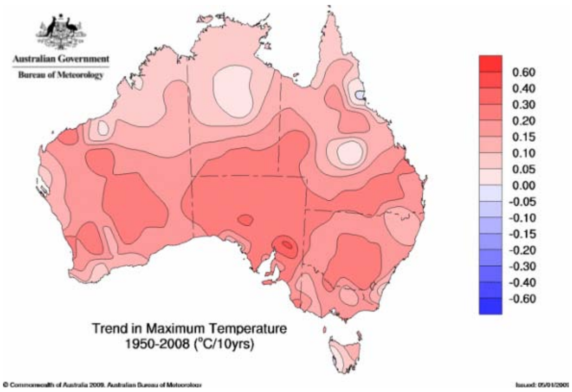

Figure 11(a) Trend in maximum temperature over Australia since 1950 in degree C per decade.

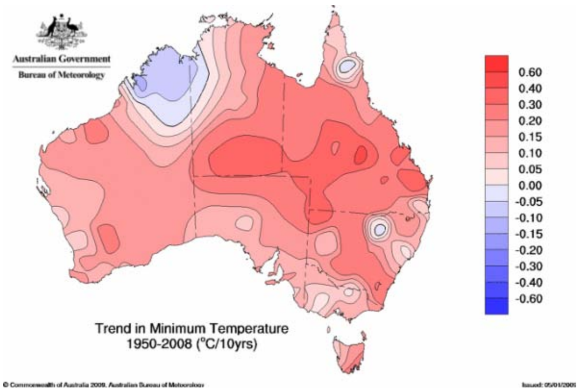

Figure 11(b) Trend in minimum temperature over Australia since 1950 in degree C per decade.

Trends in maximum and minimum temperature for Australia are shown in Figures 11(a) and 11(b), respectively. Most noticeable is the trend in minimum temperature and this also reflects in shifts in the date of first and last frost for certain stations so far examined (Stone *et al*., 1996a). Changes occurring since 1950 are considered especially important as “The 50-year trend may be particularly important as this is the period during which the global climate has moved outside the bounds of experience during the last 1,000 years, at least” ((J. Sims, Bureau of Rural Science, Personal communication, 2004). Issues relevant to increases in evaporation are especially relevant, although aspects related to evaporation trends are currently undergoing re-examination.

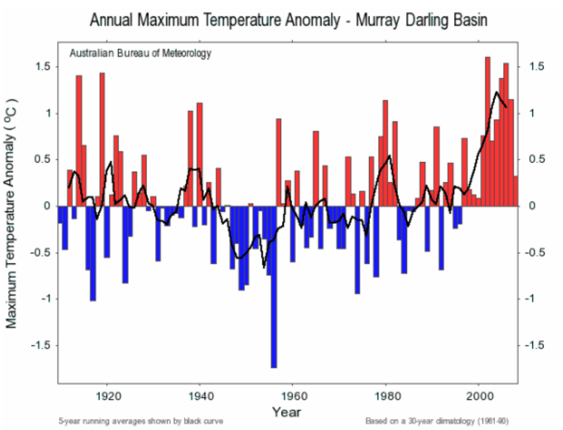

Figure 12 (a) Time series of annual maximum temperature anomaly for the Murray Darling Basin (BoM).

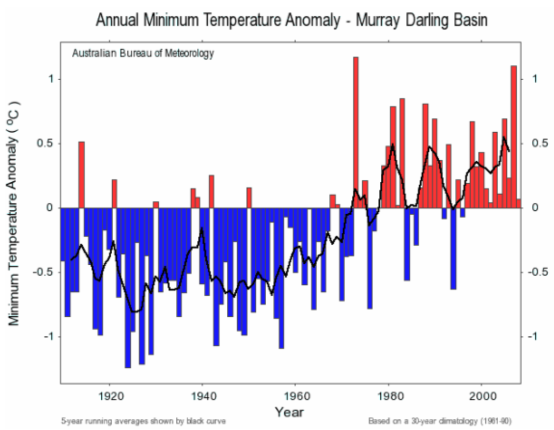

Figure 12 (b) Time series of annual minimum temperature anomaly for the Murray Darling Basin (BoM).

Aspects related to the time series of annual maximum and minimum temperature anomalies are especially important. Nicholls (2004) provided information that demonstrated that annual precipitation has been lower several times in the last half century than in a year such as 2002 (eg., 1982 and 1994) during which drought symptoms were less severe, Nicholls (2004) points to additional issues regarding the rainfall deficiencies of years such as 2002 in that the preceding years were considerably dry in southeast Australia but that, importantly, temperatures during 2002 were exceptionally high. B Trewin (personal communication, 2009) shows that the all Australia mean seasonal maximum temperatures were the highest on record in autumn, winter, and spring, “all by considerable margins” in that period. Temperatures across southeast Australia and the MDB also remained above average throughout 2003 and 2004 and included periods of intense heat waves. Furthermore, Nicholls (2004) showed that mean maximum temperatures have been especially high during recent drought periods (as was evaporation) and makes the point that each drought from the mid-twentieth century has been warmer than the previous drought. This warming trend is a continuation of a trend noted by Nicholls *et al*. (1996) that for any value of rainfall maximum temperature had tended to be higher than previously. This trend closely matches the global warming of the past century and suggests that the observed intensification of MDB droughts is likely to be the result of increased greenhouse gas concentrations (Nicholls, 2004). Nicholls (2004) make the point that Jones and Page (2001) warned that warming associated with the enhanced greenhouse effect was likely to lead to reduced inflow and mean annual storage in water storages in the MDB (Nicholls, 2004).

Earlier relevant analyses.

Many early developments made in order to better understand climate processes in eastern Australia (with relevance to the Murray Darling Basin(MDB)) identified *Darwin pressure*, now known to be a component of the Southern Oscillation Index (SOI), as being important in identifying relationships between global scale circulation systems and rainfall in this region. Quayle (1929) identified lag relationships between Darwin pressure anomalies and rainfall in eastern Australia, including value in understanding rainfall in regions such as the Murray River catchment and northern Victoria. Additionally, Priestley (1962; 1963) observed a marked persistence in east coast spring and summer rainfall and established rainfall relevant to northern inflows in the MDB was associated with prior Darwin pressure during October/November. Nicholls and Woodcock (1981) verified the stability of the relationship between Darwin pressure and subsequent rainfall over much of eastern Australia (relevant to the MDB) established by Quayle (1929) some fifty years earlier.

Nicholls (1977) examined wet and drought spells over Australia and the associated relevance of upper-air patterns over Australia to ENSO. The strength of the upper level westerlies between 30S and 45S were demonstrated to be related to ENSO strength and also wet and dry spells. Coughlan (1979) identified patterns in trends in temperatures over Australia that could be related to trends in circulation features related to either *the mean latitude of the sub-tropical high pressure belt* or the *Southern Oscillation*. Holland and Nicholls (1985) showed that cooling sea-surface temperatures around the Indonesian/Australia region may precede the first appearance of warmer than normal water in the eastern equatorial Pacific Ocean (El Niño) by several months. Furthermore, considerable large-scale circulation anomalies occurred in the northern Australian region up to a year before the peak in El Niño warming. Holland (1986) further established the high degree of correlation between the Southern Oscillation Index (SOI) with the intensity and degree of convergence in the low-level monsoonal shear zone over northern Australia.

One of the more important studies in assessing the various circulation indices, especially that relating to the SOI was provided by McBride and Nicholls (1983) where both lag and simultaneous relationships between mean values of the SOI and Australian rainfall were demonstrated. The degree of variability of rainfall with SOI was indicated through use of correlation maps and it was demonstrated the SOI was most effective in accounting for rainfall variability in this region during the southern hemisphere winter and spring. However, only seasonal mean values were used in the McBride and Nicholls (1983) analyses which may have hidden aspects related to important changes in atmospheric response to the Southern Oscillation over eastern Australia. Williams (1987) suggested that smoothing of SOI values and discounting 'where the SOI was coming from and going to' (c/f Quinn *et al.*, 1978) may mean additional features associated with SOI/rainfall relationships may be missed.

The importance of circulation, atmospheric responses and drought in Australia during major ENSO events was recognised by Allan (1985; 1988). Realisation of the general importance of the SOI as a predictor of rainfall in eastern Australia and relevant to the MDB was already recognised by Nicholls (1977; 1983) so that by 1982/83 statistical relationships between the SOI and rainfall were used to predict the 1982/83 drought which had devastating impacts on the MDB and eastern and southern Australia. Relevance to summer inflows into the Darling River catchment was implied through the work of Nicholls (1982; 1984) and the compilation of a drought index using the SOI (Nicholls, 1985; 1988).

Aspects related to identifying additional aspects related to use of the SOI for predicting rainfall and streamflow variability in which patterns or 'phases' of the SOI that accounted for both variability and important medium-term shifts in the SOI (as per the relevance of the work of Williams (1987) and Quinn *et al*. (1978), described above) were provided by Stone and Auliciems (1992) and Stone *et al*. (1996). This work used principal components analysis and cluster analysis to objectively identify patterns or *phases in the SOI* and related these patterns (rather than three month average values of the SOI) to rainfall in eastern Australia and globally. Notably, this approach has since found application in the prediction of crop yields over eastern Australia and the MDB (e.g., Hammer *et al*., 1996; Stone and Meinke, 1999; Carberry *et al.,* 2000; Hill *et al.,* 2001; Potgieter *et al*., 2003; Meinke and Stone, 2005) and in application in streamflow forecasting for this region (Clewett *et al*., 1994; Abawi *et al*., 2001)

Pittock (1975) demonstrated that the dominant pattern of year-to-year variability in Australian rainfall, especially over regions such as the Murray Darling Basin, is 'not unlike the pattern of secular change observed on a time-scale of decades' (Pittock, 1975). Furthermore, Pittock (1975) pointed out that this pattern of variation has amplitude correlated with the *Southern Oscillation Index (SOI)* which suggests that climatic variations in this region at least on the time-scale of decades are associated with variations in the amplitude of the standing wave pattern of the general circulation of the atmosphere. It was further pointed out that there is persistence over periods up to a year in the

SOI, with a tendency for this to break down during the Southern Hemisphere autumn (Troup, 1965). The existence of spatially coherent patterns of variability is related to the spatial scale of variations induced by changes in the general circulation of the atmosphere.

Pittock (1975) also emphasised the value of the (then) new application of principal components analysis (PCA) as a more objective method of providing a description of the basic patterns which underlie year-to-year variations in rainfall in a region such as the Murray Darling Basin. This approach provides a set of patterns (called eigenvectors of the covariance matrix) which, importantly, are mutually uncorrelated in space and the amplitudes of the different patterns vary but in mutually uncorrelated time. *Applying this approach demonstrated that the first pattern, for Australia (and with relevance to the Murray Darling Basin) accounts for thirty-six per cent of the total variance and its amplitude is correlated with the SOI at R=-0.53). The second pattern so devised accounts for an important additional 18% of the total variance and its particular amplitude correlates with the latitude of the sub-tropical ridge (STR)(as defined by Pittock as being measured using aspects of eastern ridging) with its amplitude having a correlation with the STR at R=+0.83) (Pittock, 1975*).

El Niño-ENSO-the 'MEI' and similar systems.

Use of harmonic analysis on ENSO-streamflow relationships and teleconnections by Chiew and McMahon (2002) suggested strong relationships between *El Niño* and streamflow in southern and eastern Australia. These authors used both the SOI and another indicator of ENSO, 'the *Multivariate ENSO Index – MEI'* (a method also employed by Kiem and Franks (2001) in an attempt to find more robust indicators of ENSO that use 'multiple climate parameters' for this type of analysis). Simpson *et al*. (1993) showed that forecasting annual discharge of the River Murray can be achieved using a geophysical model of ENSO due to the strong (inverse) relationship between discharge in the River Murray and sea-surface temperature anomalies in the eastern equatorial Pacific Ocean. In this, Simpson *et al*. (1993) applied a geophysical model that used observed wind fields and sea-surface temperatures that permitted forecasting of ocean temperatures with significant skill up to at least on year in advance. *They make the point that the important features of interannual variability in natural discharge in the MDB are strongly related to occurrence of the El Niño phase.*

Aspects related to the sub-tropical ridge.

The substantial the rise of Mean Sea Level Pressure (MSLP) across southern Australia (Timbal and Hope, 2008) and in particular the *intensification of the Sub-Tropical Ridge (STR)* (as defined by Drosdowsky, 2005) was found to be associated with a very sizeable part - ~ 70% of the rainfall decline in eastern and southern Australia and of relevance to the MDB (Timbal *et al*., 2007). Williams and Stone (2008) have recently further discussed the value of the inclusion of aspects of the STR in diagnosing rainfall variability in southern and eastern Australia.

It is therefore noticeable that the area with the largest rainfall deficit and drought in the MDB coincides closely with the area showing the biggest negative influence of the STR intensity on rainfall, thus strongly suggesting a role for the STR intensification on the on-going drought across eastern Australia and the MDB (Figure 13).

Interestingly, Kidson (1925) also pointed to STR intensity (and a periodic north-south movement in the STR) as being highly relevant in an understanding of rainfall variability and drought for this region of Australia.

Timbal (2009) noted that recent studies show major global scale changes in the extent of the tropics, and, notably, in the extent and intensity of the Hadley circulation. In this respect, the tropics appear to be getting wetter over time *and they appear to be expanding. Importantly for aspects related to the STR, the Hadley Circulation also appears to be expanding (Lu et al., 2008). This suggests that variations or long-term changes in the STR over the MDB may be part of a much larger scale change in the global scale circulation, particularly as it provides a physical link between the decline in rainfall in south-west Western Australia and that now seen in southern Australian and, by implication, the MDB* (Hope *et al.*, 2009; Timbal, 2009). Timbal (2009) showed that between April 2006 and March 2009 both positive and negative phases of ENSO occurred but without any bias towards either phase. Timbal (2009) also suggests that it is unlikely that ENSO variability, while important in general terms for rainfall variability in the MDB, has contributed to the overall worsening of the drought and drying trend in southern Australian and the southern component of the Murray Darling Basin (although it may have contributed to the drying in more northern areas of the Basin).

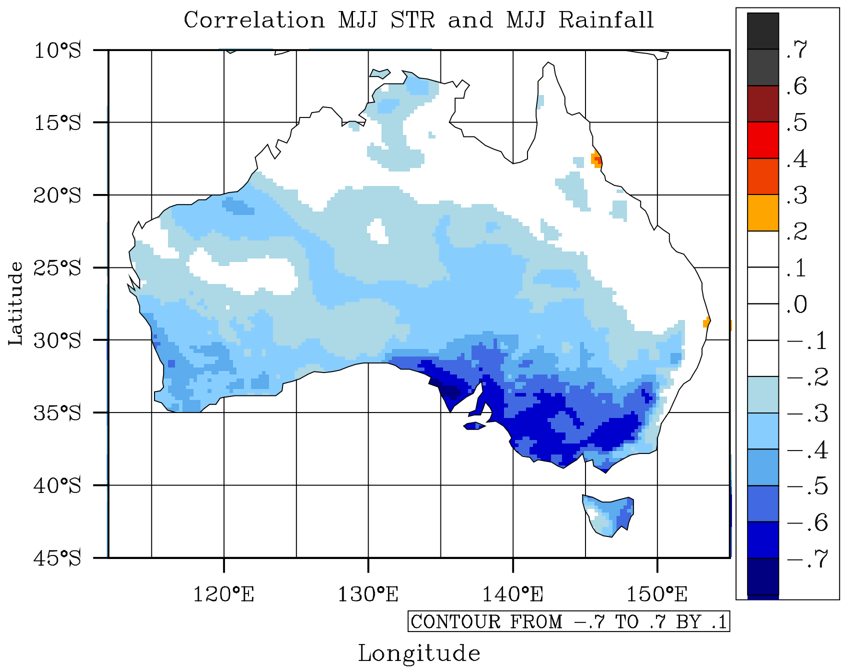

Figure 13. Correlation between the Sub-Tropical Ridge intensity and rainfall across Australia in May-June-July, correlations significant at the 95% level and above are colour shaded (Maps courtesy of Clinton Rakich, BoM NSW regional office).

Aspects related to ENSO and the Indian Ocean Dipole (IOD).

Timbal (2009) evaluated the role of key modes of variability associated with the on-going drought in southern Australia, especially across the Murray Darling Basin. In particular, those aspects associated with the tropical oceans were evaluated: the El Niño Southern Oscillation (ENSO) in the Pacific and, additionally, aspects associated with the Indian Ocean Dipole (IOD). Although, these systems are known to be important drivers of the Australian climate (McBride and Nicholls, 1983; Nicholls, 1989), it was noted that their impact is very weak in autumn where nearly two thirds of the rainfall decline has occurred over the past decade (Timbal and Murphy, 2007). *Therefore combination of both the ENSO and IOD drivers, while important in general terms for year-to-year rainfall and temperature variability, are unlikely to have contributed significantly to the rainfall decline up to 2006.*

Thus, ENSO is not the only important source of climate variability in eastern Australia and relevant to the MDB that may be potentially predictable (Hendon *et al*., 2007). In this respect, low frequency variations of SST in the tropical Indian Ocean are regarded as a source of climate anomalies in eastern Australia (Nicholls 1989; Drosdowsky, 1993; Drosdowsky and Chambers, 2001). Saji *et al*. (1999) describe the Indian Ocean Dipole (IOD) is as a coupled ocean-atmosphere mode (pattern) of variability in the tropical Indian Ocean characterized by sea-surface temperature (SST) anomalies of opposite sign in the east and west of the Indian Ocean, coincident with anomalous large-scale circulation patterns (see Saji *et al*., 1999; Allan *et al.,* 2001).

It is believed the IOD has effects on rainfall in countries surrounding the tropical Indian Ocean (Saji and Yamagata, 2003a, b). Allan *et al.* (2001) suggest the IOD should be carefully scrutinized before use in detailed rainfall studies as different types of IOD have been described (Nicholls, 1989). Figure 14 provides some detail of relationships between August and October rainfall and the association of that rainfall with eleven positive IOD events. However, it should be noted that 7 out of the past 11 ‘positive IOD’ years have also been El Niño years (B. Trewin, Bureau of Meteorology, personal communication, 2009).

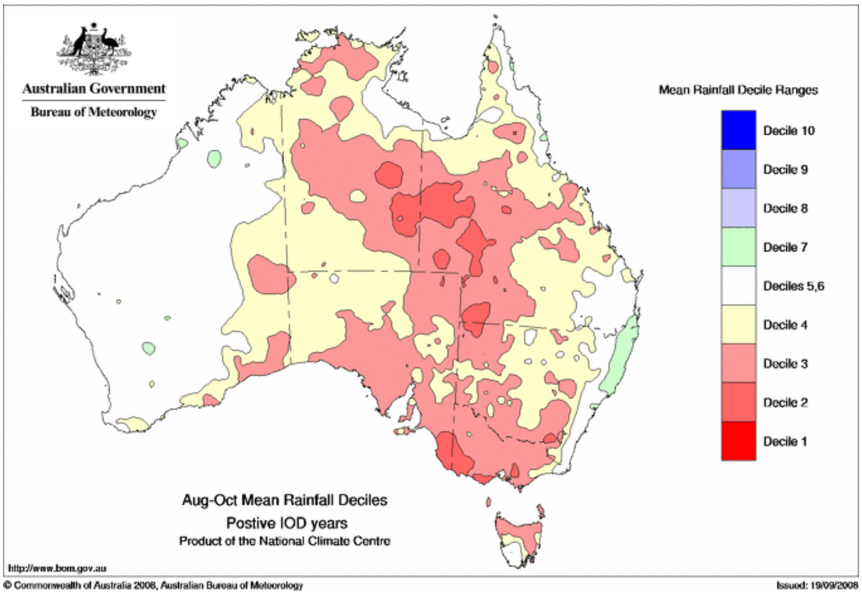

Figure 14. Australian August to October mean rainfall deciles for eleven positive IOD events (1961, 1963, 1967, 1972, 1977, 1982, 1983, 1994, 1997, 2006 and 2007). Deciles are expressed using the long-term climatology from 1900 to 2007. The box used for SEA average is shown in black (Maps courtesy of Robyn Duell, National Climate Centre) (from Timbal, 2009).

Furthermore, Timbal (2009) demonstrates that in the case of the tropical Indian Ocean, the period from April 2006 to March 2009 was notable for a positive phase bias of the IOD. Three positive IOD events were recorded in that period, a first from the instrumental record (Cai *et al.*, 2009). In addition, the 3 years rainfall decile map has some similarities in particular across Eastern Australia including the southern MDB, with the known impact of IOD on Australian climate which peaks in late winter early spring. *This suggests that Indian Ocean variability has likely contributed to the worsening of the rainfall decline and drought during the last three years but largely providing the additional shortfall in spring on top of the continuing autumn decline.*

However, Timbal (2009) notes the importance of the IOD on the observed southern Basin rainfall decline since 1997 should not be overestimated since the effect of the IOD is limited to the latter part of the wet season (i.e. the spring contribution of the rainfall decline since1997 is 10%). However this aspect is worth noting and monitoring since climate model future projected rainfall decline in the southern Basin has a strong spring signature (Timbal, 2009). Hendon *et al*. (2007) showed that forecast skill for the IOD appears to be limited by the ability to predict SST variations in its eastern pole of the equatorial Indian Ocean. However, forecast skill in the western pole of the tropical Indian Ocean is comparable to forecast skill of ENSO in the Pacific (i.e., skill in the western pole extends beyond 9 month lead time for forecasts initiated in the June-January period).

Aspects related to the southern annular mode (SAM).

Hendon *et al*. (2007) point out that SST variations in the tropical Indian Ocean are sources of important climate anomalies in eastern Australia but also draw attention to aspects associated with the Southern Annual Mode (SAM) and the intraseasonal Madden Julian Oscillation. Timbal (2009) points out that, besides tropical influences, the role of the Southern Annual Mode (SAM)(the largest pattern of variability in the southern hemisphere atmosphere overall) can be especially important in enhancing understanding of rainfall variability in the MDB and, especially, associated regions to the east (H. Hendon, personal communication, 2009) (Figure 15).

SAM is a global atmospheric system characterized by deep, symmetric or “annular” structures, with geopotential height perturbations in the upper atmosphere of opposing signs in the polar cap region and in a surrounding zonal ring centered near 45° latitude. The structure and dynamics of the Southern Hemisphere Annular Mode have been extensively documented. The *influence* of a positive phase of SAM on southern MDB rainfall is highly seasonal, being positive in summer, negative in winter but with little or no influence in autumn (Timbal *et al.*, 2007). The lack of influence in autumn was pointed out as a reason why SAM is unlikely to be an important contributor to the overall MDB rainfall decline and drought but can be important in year-to-year variability, especially in spring (Timbal and Murphy, 2007) (Figure 15). The interaction of SAM with rainfall mechanisms and systems over the MDB requires further analyses and studies to be undertaken.

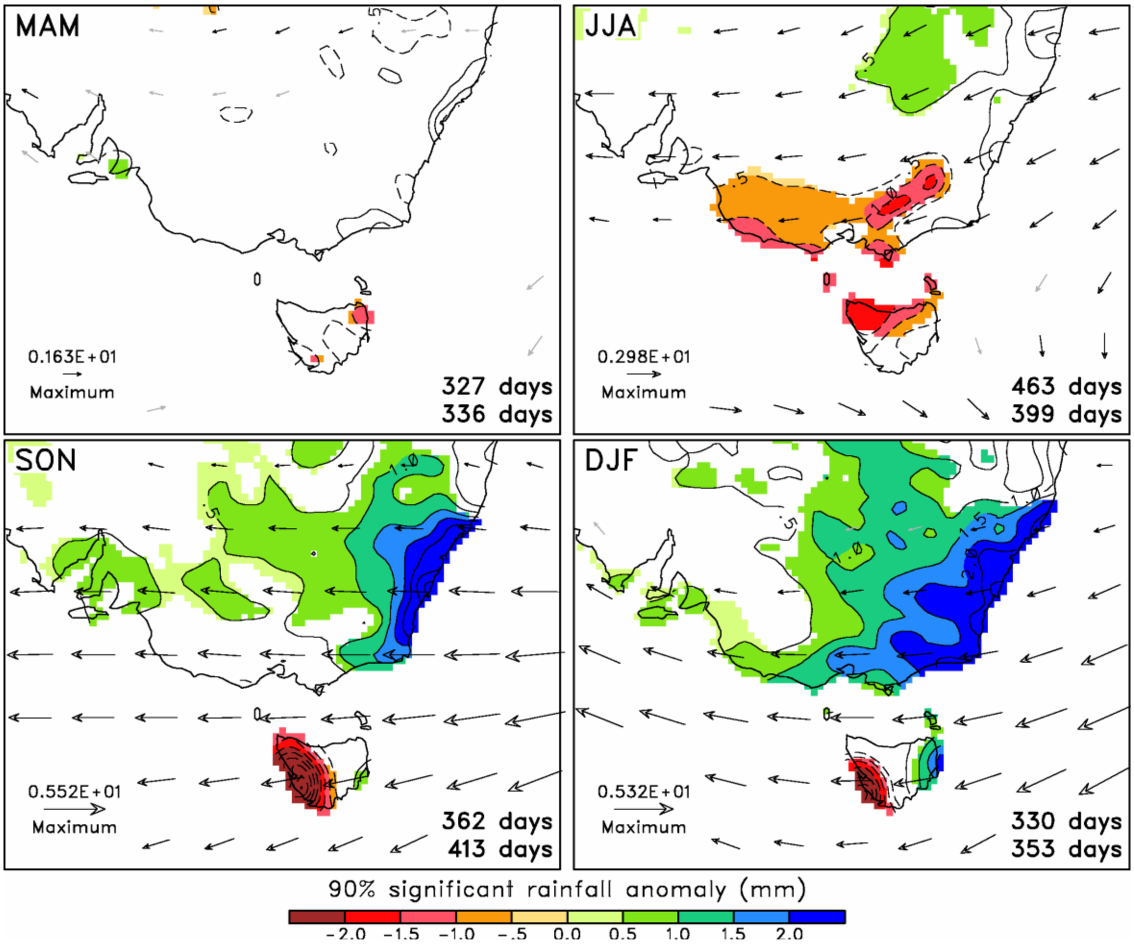

Figure 15. Southern Annular Mode (SAM) rainfall composite maps indicating relationships between SAM and rainfall anomalies. Note the influence in the December-February period (courtesy, H Hendon, Bureau of Meteorology, Centre for Australian Climate and Weather Research, 2009).

Composite analyses, including aspects associated with the Madden-Julian Oscillation (MJO).

Risbey *et al*. (2009) make the key point that the eastern Australian region, including the MDB, is influenced by both tropical and midlatitude systems, as well as by local circulations and processes. Key tropical influences on eastern Australia include ENSO (Allan, 1988; Nicholls *et al.,* 1997; the Madden Julian Oscillation (MJO) (Wheeler and Hendon, 2004, Wheeler *et al.,* 2009), and the Indian Ocean Dipole (IOD) (Ashok *et al*., 2003). The ENSO association with eastern Australian rainfall is one of the strongest on the continent. Risbey *et al.* (2009) provide a useful diagram that provides an indication of the dominant mechanisms responsible for climate variability over Australia and of relevance to the MDB (Figure 16).

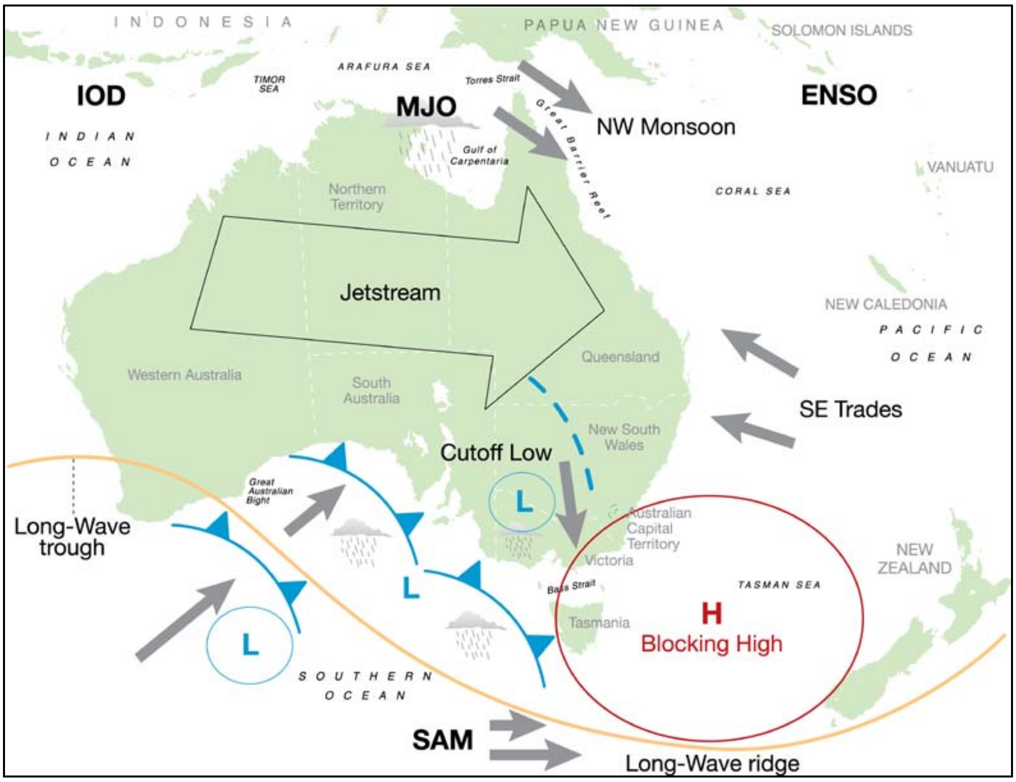

Fig 16 {Schematic representation of the main drivers of rainfall variability in the Australian region.}(Risbey *et al*., 2009)

Risbey *et al*. (2009) suggest ENSO and IOD are the major sources of seasonal to interannual variability of rainfall in eastern Australia, although ENSO tends to be much stronger in the MDB than the IOD. By using correlation analysis, Risbey *et al*. (2009) suggest the correlations of ENSO with eastern Australian rainfall are strongest in winter and spring.

However, while correlation analyses show broad regions of ENSO influence, they do not depict asymmetries in the relationship between ENSO and rainfall. Stone *et al*. (1996b) suggest there are 'non-linearities' in rainfall-ENSO relationships in Australia (and globally) so that correlation analyses may not always be optimal in identifying detailed rainfall-ENSO relationships.

Risbey and co-workers have also produced a series of figures that provide insights into some major systems responsible for rainfall variability across Australia (Figure 17). Figure 17 shows some relative contributions from major climate systems for core seasonal time periods (December-February; March-May; June-August; September-November). Interestingly, for the MDB region, this approach indicates the SOI (average values) dominated in terms of impacts for the March-May period throughout the MBD and in central and northern regions of the MDB through winter (June-August). 'Blocking patterns' which may be related to aspects of the sub-tropical ridge) (delineated 'BLK' in the figure) are shown to dominate during September-November in southern parts of the MDB. Note, that diagram shows the major contributors and not all components of rainfall variability existing at one time.

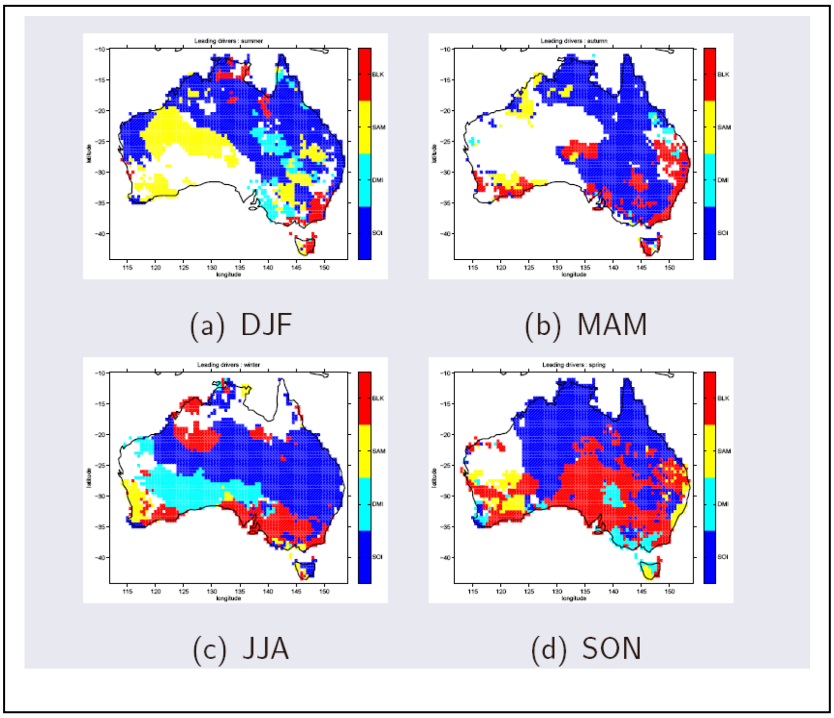

Figure 17. Key contributors to rainfall variability over Australia and of relevance to the Murray-Darling Basin as identified by McIntosh, Pook, and Risbey, CSIRO (2009.) 'BLK' refers to 'atmospheric blocking'; 'SOI' to the Southern Oscillation Index mean value for the period; 'DMI' and index of the Indian Ocean Dipole, and 'SAM' to the Southern Annular Mode. (Courtesy, McIntosh, Pook, and Risbey, CSIRO, 2009).

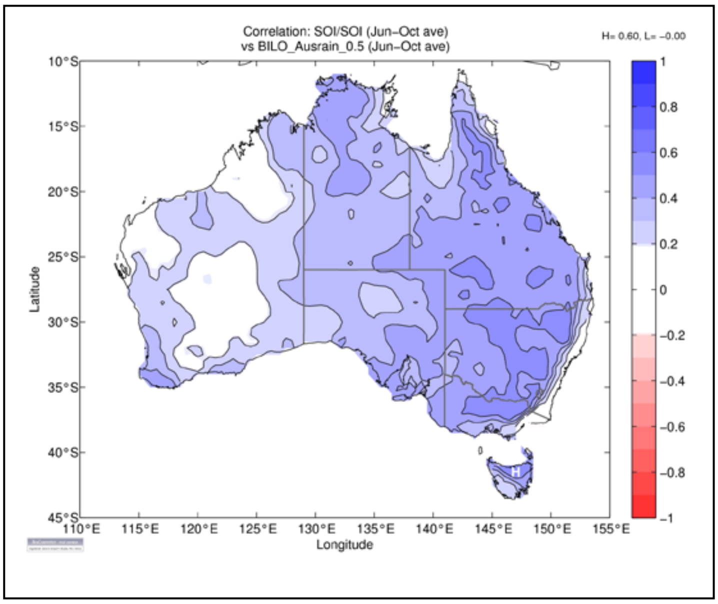

Fig 18 Correlation between ENSO (SOI) and Australian rainfall through the June-October period. Only correlations significant at the 95% level are shown.

Figure 18 provides a useful re-appraisal of the dominance of ENSO/SOI on rainfall in Australia and it shows particular relevance to the MDB. Note, that the values shown are correlation values and these may mask other important relationships in regard to certain extreme events that are also associated with ENSO and the SOI.

While ENSO influences rainfall over the MDB on seasonal to interannual scales, there is also considerable long-period variability in the relationship between ENSO and rainfall (Nicholls *et al.,* 1997; Murphy and Ribbe, 2004; Power *et al*., 2006) and from event to event (Wang and Hendon, 2007). Power *et al*. (2006) note that the relationship between ENSO and Australian rainfall is weakly modulated by the phase of the Interdecadal Pacific Oscillation (IPO). Power *et al*. (2006) suggest that when the IPO is in a positive mode (when the low frequency variation of sea surface temperature anomalies is positive) the correlation with interannual Australian rainfall variations tends to be somewhat weaker. Power *et al.* (2006), also suggest the converse situation applies. The relatively strong association between ENSO and rainfall in the *eastern* Australian region means that there is potentially more seasonal predictability here than in other parts of Australia (further analyses and aspects related to the IPO in itself as a low-frequency system are also discussed in a later section below).

The Madden Julian Oscillation (MJO).

The Madden Julian Oscillation (MJO) is a large scale eastward propagating wave in equatorial latitudes that produces periods of enhanced and diminished cloud/convection across tropical regions (enhanced cloud mass developments and shifts in near-surface winds) and occasionally impacts rainfall variability at the 30-50 day time scale over higher latitudes in Australia. Wheeler and Hendon (2004) classified the MJO into eight phases based on the leading patterns of variability of the convective systems and masses and on the zonal wind in near-equatorial latitude. Risbey *et al*. (2009) point out that the MJO modulates rainfall in the Australian region, both directly via stimulation of convection in the Australian monsoon, and indirectly via tropical-subtropical circulation interactions. The MJO is also believed to interact with ENSO (Hendon *et al*., 2007). The impacts of the MJO on Australian rainfall as well as relationships with ENSO phase have been summarized by Wheeler and Hendon, (2008).

High-frequency components: weather systems relevant to longer-term rainfall variability in the MDB

Risbey *et al*. (2009) show that weather systems (fronts, cutoffs, blocking) are particularly important in the eastern Australian and MDB region outside of the summer season. They point out at while frontal systems provide some of the winter rainfall in eastern Australia, their contribution is likely to be greatly exceeded by 'cutoff low systems' (Figure 19).

Risbey *et al*. (2009) provide an analysis of heavy rainfall events in eastern Australia in autumn and winter shows that most of these are associated with cutoff low. Figure 20 provides an example of the type of rainfall decline (also showing the decline in numbers of cut-off lows) in the region with an example of rainfall trends for northwest Victoria.

These events are particularly useful in contributing water to catchments when evaporative losses are much lower. Cutoff lows in eastern Australia and relevant to the MDB are usually associated with a blocking high in the Tasman Sea and an upper level trough over Queensland. Since blocking is such an important factor in setting the climatology of cutoff events in eastern Australia Risbey *et al*. (2009) show blocking is moderately correlated with ENSO indices such as the SOI (McIntosh *et al*., 2008) (Figure 21). They also suggest that blocking over the MDB is more probable during a La Niña in the El Niño phase. Stone (1993) also showed that higher tropopause heights and enhanced mixing-ratio moisture levels are more likely over the MDB during ‘consistently positive SOI phases’, common during La Niña phases.

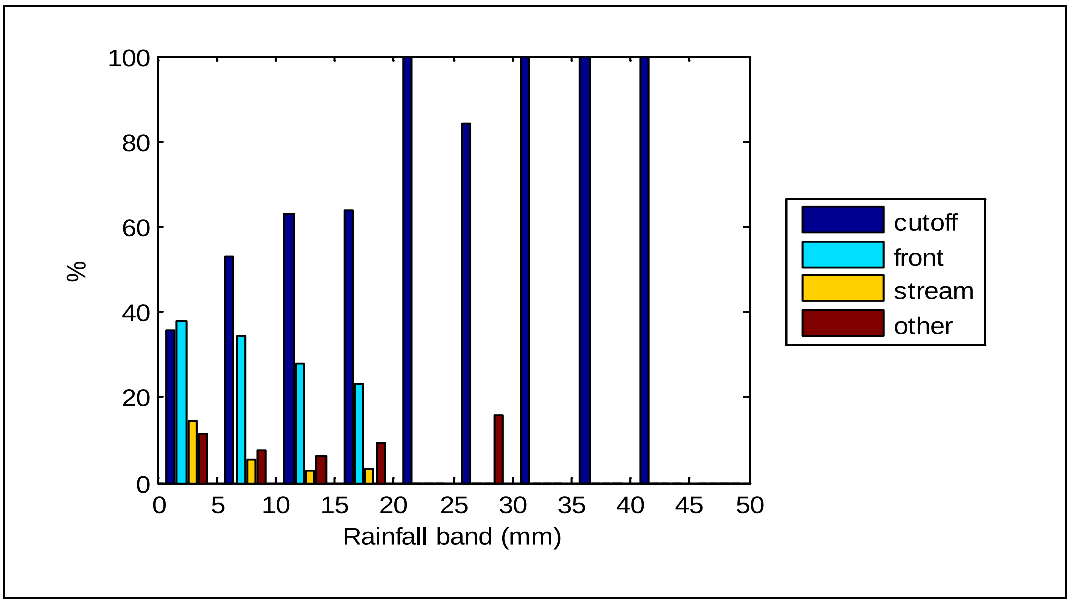

Figure 19. High rainfall in the MDB and southern Australia due to ‘cut-off lows’ (Courtesy McIntosh, Pook, and Risbey, CSIRO, 2009.)

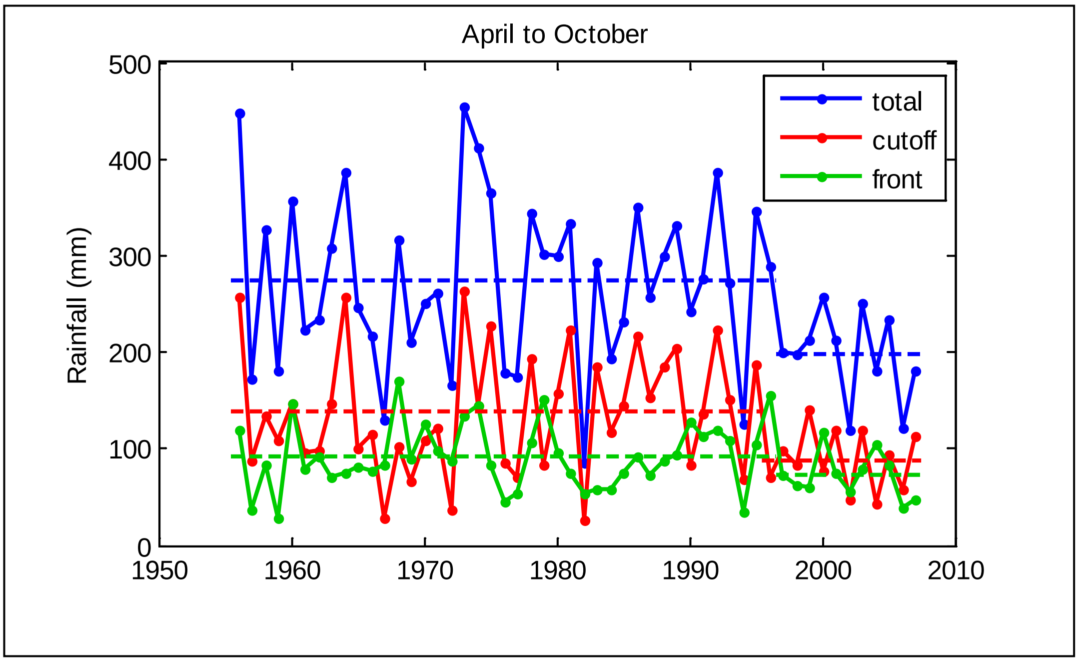

Figure 20. Example of rainfall decrease in the MDB region for the April-October period – example for northwest Victoria and showing the associated decline of ‘cut-off lows’ (Courtesy, McIntosh, Pook, and Risbey, CSIRO, 2009).

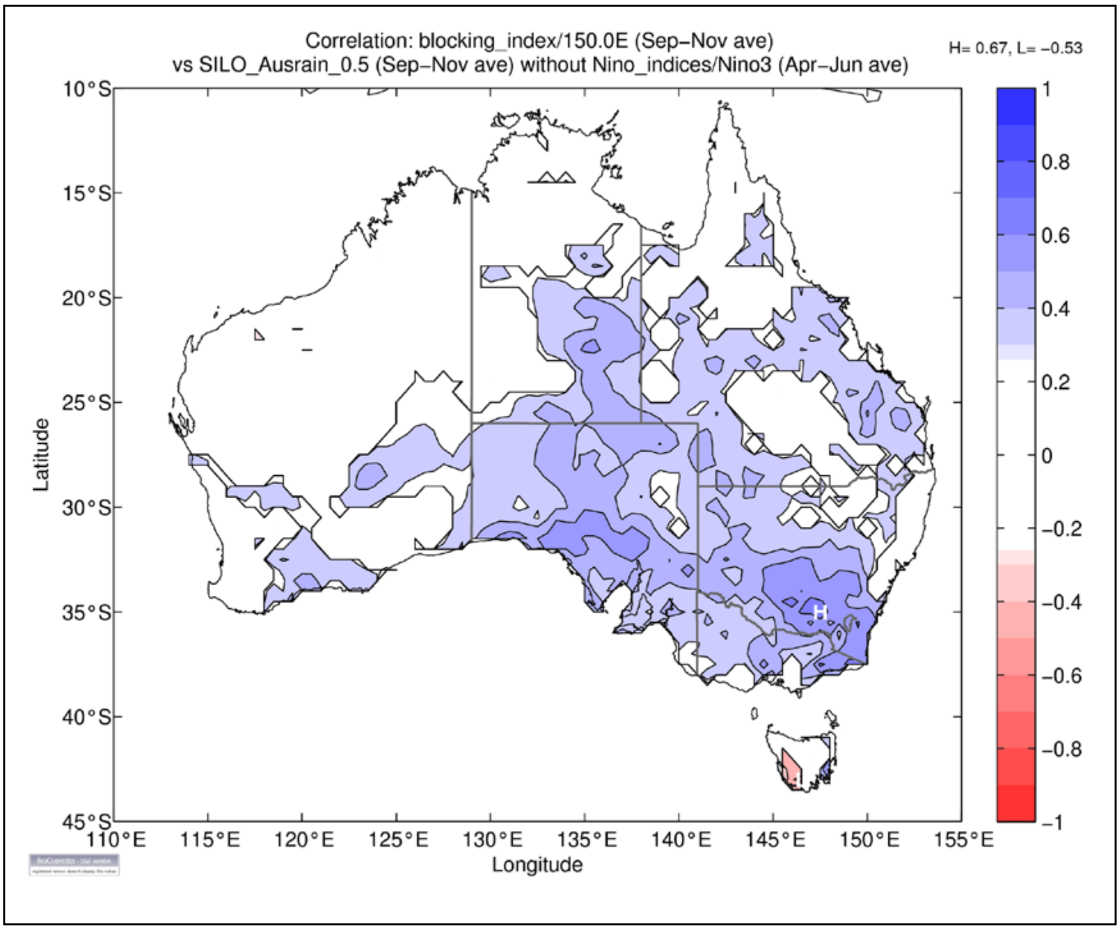

Figure 21 Correlation of blocking index at 150E with rainfall for September-November averages (Risbey *et al*., 2009).

Risbey *et al.* (2009) demonstrate that cutoff low systems in the MDB region are often the result of the more mature phase of upper troughs in the Queensland region with aspects of interaction described above relevant upper troughs and their impacts as well. They show that there has been a marked decrease in the incidence of upper troughs in eastern Australia over the past three decades and a corresponding decrease in rainfall.

Example of application to streamflow forecasting.

Development and use of a seasonal streamflow forecast model based on an optimal linear combination of forecasts derived from climatology, persistence, the Southern Oscillation index (SOI), and equatorial Pacific sea surface temperatures (SST) has proven useful in further understanding rainfall and drought variability in eastern Australia and the MDB. Piechota *et al*. (1998)

built models based on work of the Australian Bureau of Meteorology and others who investigated variability in flow of southeast Australian rivers. They tested the model using 66 years of unimpaired streamflow data from 10 eastern Australian catchments.

Piechota *et al.* (1998) suggested the results from testing the model further supported the strong ENSO-hydroclimate link, supporting the aspect that eastern Australia *generally receives below normal streamflow* during El Niño conditions and above normal streamflow during La Niña conditions. They showed that in southeast Australia the SOI is a better predictor for July–September and October–December streamflow and the SST a better predictor of January–March and April–June streamflow.

Piechota *et al*. (2001) further developed an understanding of streamflow variability for southern and eastern Australia and provide a methodology for forecasting seasonal streamflow using an extension of previously developed categorical streamflow forecast models that used persistence (i.e., the previous season's streamflow) as well as El Niño-Southern Oscillation (ENSO) indicators. They also used mathematical/statistical clustering process variations such as linear discriminant analysis to produce forecasts expressed as probability of exceedance of continuous streamflow amounts. They suggest sea surface temperatures (SSTs) and the SOI, may be more useful for forecasts with longer lead times when the degree of persistence in streamflow for the MDB is less noticeable.

Low-frequency climate modes/patterns.

Table 1 provides an example of the large range of temporal scales on which climate systems can vary and having relevance for the MDB. In the right hand column, low frequency modes of climate variability are represented by the components that show 'decadal, inter-decadal and multi-decadal frequencies. For interest, various decision-making types are also provided in the left-hand column (Meinke and Stone, 2005).

Table 1. *Agricultural decisions at a range of temporal and spatial scales that could benefit from targeted climate forecasts (Meinke & Stone, 2005).*

Farming Decision Type	***Climate system frequency (years)***
Logistics (eg. scheduling of planting / harvest operations)	Intraseasonal (> 0.2)
Tactical crop management (eg. fertiliser / pesticide use)	Intraseasonal (0.2 – 0.5)
Crop type (eg. wheat or chickpeas) or herd management	Seasonal (0.5 – 1.0)
Crop sequence (eg. long or short fallows) or stocking rates	Interannual (0.5 – 2.0)
Crop rotations (eg. Winter or summer crops)	Annual/bi-annual (1 – 2)
Crop industry (eg. grain or cotton; native or improved pastures)	Decadal (~ 10)
Agricultural industry (eg. crops or pastures)	Interdecadal (10 – 20)
Landuse (eg. agriculture or natural systems)	Multi-decadal (20 +)
Landuse and adaptation of current systems	Climate change

Aspects associated with climate variability at decadal and interdecadal time scales, including the possible capability to predict such low-frequency patterns in order to improve water resource planning and flood mitigation, seems to have (understandably) quickly captured the imagination and interest of many in the water resource (and farming systems) community (eg Kiem *et al*., 2002; Franks, 2002; Kiem and Franks, 2004; Meinke *et al*., 2005).

Yet, Power *et al*. (2006) make the point that decadal variability can arise for a number of reasons that include the fact that instabilities in the atmosphere can drive internal atmospheric variability on time-scales up to and beyond a decade and this aspect can drive the surface flux variability that alters surface climate (James and James, 1989; Power *et al*., 1995). Additionally, these modes can have subtropical or extra-tropical origins (Kleeman *et al*., 1999; Liu *et al*., 2002).

Power *et al*. (2006) add that some of the decadal variability associated with ENSO may be generated within the tropical Pacific Ocean itself without the need for decadal boundary forcing through nonlinear mechanisms. Indeed, they suggest that instabilities such as eddies and tropical instability waves already present in the ocean might help drive some of this variability at decadal time scales.

Power *et al*. (1999) previously related interdecadal variability in the association between the SOI and year-to-year changes in rainfall, maximum surface temperature, and wheat crop yields, all averaged over Australia as well as, importantly, water volume transport in the Murray River. Power *et al*. (1999) suggested that the variance in year-to-year changes in the SOI and the association between the SOI and these Australian climate-related variables (note: this was achieved using correlation analysis in 13-year running blocks) 'waxed and waned' during the 20th Century in conjunction with the Interdecadal Pacific Oscillation (IPO). (The IPO has previously been described as observed 'ENSO-like' or 'El Niño-like' sea-surface temperature patterns that have been identified through interpretation of near-global interdecadal sea-surface temperature variability (Folland *et al.,* 1999).

Power *et al.* (1999) showed that the index for the IPO is very similar to the interdecadal component of an index for the Pacific Decadal Oscillation (PDO) derived by Mantua *et al.* (1997). Folland *et al*. (2002) provided additional evidence supporting the view that the IPO can be regarded as the Pacific-wide manifestation of the PDO. This work involving the IPO has, somewhat understandably, been seized upon in the climate applications community as a means of further improving work that attempts to provide improved predictability of major climate and associated hazards (such as drought and flood return periods and similar). Indeed, Power *et al*. (1999) established that the modulation of ENSO teleconnections by the IPO was statistically significant at the 95 per cent level. Power *et al*. (1999) also showed that interdecadal changes in the skill of an ENSO-based forecast scheme were coherent with the IPO.

However, Power *et al*. (2006) then provided information on whether these interdecadal changes were in any way predictable using a series of experiments using general circulation models (GCMs). Remarkably, it was found that the level of predictability of interdecadal variability is very low. This important result means that any evidence of a statistical relationship between IPO/PDO indices and interdecadal variability in ENSO's impact on such as river flow, rainfall, and crop yield (in the MDB, for instance) is "not necessarily underpinned by any interdecadal predictability. Instead, the statistical association could largely reflect unpredictable changes in the impact that ENSO has on the variable of interest." (Power *et al*., 2006).

Based on the output of Power *et al*. (2006) it is strongly suggested more work needs to be done on developing GCM-based outputs/forecasts of decadal or interdecadal variability to establish whether patterns, apparently existing at these scales, can be better understood and also predicted before related inputs are provided into decision-systems that are relevant for the Murray-Darling Basin. (eg; some of the outputs of van Loon *et al.* (2004) may be of interest in this developing area in regards to decadal and inter-decadal variability).

Conclusions and recommendations.

An analysis of major climate mechanisms and ‘drivers’ of rainfall variability over the Murray-Darling Basin (MDB) has been made with the following results:

- The El Niño-Southern Oscillation system (ENSO) is a major driver of year-to-year rainfall variability over the MDB with strong impact during the (southern hemisphere) winter, spring and summer. Impacts in summer are more noticeable for more northern regions of the MDB and in providing inflow into the MDB system through northern river systems influenced by tropical systems.

- The Indian Ocean Dipole (IOD), especially when considered within an overall systems approach to climate mechanisms with ENSO, can influence rainfall variability over the MDB but not to the same extent as in other more western regions in Australia.

- The ‘sub-tropical ridge’ (a systems somewhat neglected in media systems and in agricultural extension activities) appears to have a considerable influence on rainfall variability across the MBD and is notable for being a probable mechanism, through its increasing intensity over recent years, for rainfall reduction in the key autumn period in the southern MDB.

- Low-frequency systems/modes, such as the Pacific Decadal Oscillation (PDO) and the Interdecadal Pacific Oscillation (IPO), while appearing to provide statistical relationships with rainfall in the region through ameliorating or enhancing rainfall associated with ENSO, do not seem to extend to provision of any predictive capability of value and may, in fact, be a manifestation of 'noise' associated with the stronger ENSO signal and variability (cf: Power *et al*., 2006). It is suggested more research be conducted into this system and its interaction with other core climate drivers.

- Aspects related to high-frequency patterns and mechanism that are responsible for transporting the rainfall and drought signal into the MDB warrant further attention and identification of the linking mechanisms between these high-frequency patterns and the larger signals may provide further insight into the core causes responsible for rainfall and temperature variability over the MDB. Systems of interest include the Madden Julian Oscillation (MJO) that can trigger high latitude responses in rainfall producing systems as it traverses regions to the north of Australia and 'blocking' processes that can enhance or ameliorate otherwise rainfall producing systems relevant for the MDB.

- Aspects related to the Southern Annular Mode (SAM) have certain relevance at certain times of the year (eg; spring) and have relevance in regards to interaction with other systems.

Recommendations.

- It is recommended that a more comprehensive output of climate indices and information relating to the systems identified in this report be available to agricultural extension, media, and managers responsible for water and agricultural systems in the Murray Darling Basin. It is believed this approach is needed in order to provide ownership of this information to managers and others so they may become acquainted with the terms applied and are then better able to discriminate among occasional misleading media reports and start to equip themselves with necessary information that may needed to assist long-term planning for the region.

- Aspects associated with long-term climate change have not been specifically addressed in this report. However, the intersection of the systems responsible for climate variability with climate change processes will provide the necessary mechanism for climate change to produce impacts on the MDB. These relationships need to be researched and suitable outputs for management systems produced as a result.
- In practical terms, it is believe enhanced research into aspects off the sub-tropical ridge, long neglected in core climate studies in Australia but of relevance to this region, is needed.
- There is a need to improve climate model capabilities in simulating atmospheric blocking relevant for southern Australia.
- There is a need to improve the representation of mid-latitude weather systems in order to have confidence in low frequency (long-term) model forecasts at the seasonal, decadal, century scales.

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