On the Remote Drivers of Rainfall Variability in Australia

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ABSTRACT

This work identifies and documents a suite of large-scale drivers of rainfall variability in the Australian region. The key driver in terms of broad influence and impact on rainfall is the El Niño–Southern Oscillation (ENSO). ENSO is related to rainfall over much of the continent at different times, particularly in the north and east, with the regions of influence shifting with the seasons. The Indian Ocean dipole (IOD) is particularly important in the June–October period, which spans much of the wet season in the southwest and southeast where IOD has an influence. ENSO interacts with the IOD in this period such that their separate regions of influence cover the entire continent. Atmospheric blocking also becomes most important during this period and has an influence on rainfall across the southern half of the continent. The Madden–Julian oscillation can influence rainfall in different parts of the continent in different seasons, but its impact is strongest on the monsoonal rains in the north. The influence of the southern annular mode is mostly confined to the southwest and southeast of the continent. The patterns of rainfall relationship to each of the drivers exhibit substantial decadal variability, though the characteristic regions described above do not change markedly. The relationships between large-scale drivers and rainfall are robust to the selection of typical indices used to represent the drivers. In most regions the individual drivers account for less than 20% of monthly rainfall variability, though the drivers relate to a predictable component of this variability. The amount of rainfall variance explained by individual drivers is highest in eastern Australia and in spring, where it approaches 50% in association with ENSO and blocking.

1. Introduction

The variability of Australian rainfall has been well documented and is noteworthy for its strength compared to places with seemingly similar climates elsewhere in the world (Nicholls et al. 1997). Intraseasonal-to-interannual Australian rainfall variability has been linked to a variety of processes, mostly tropical in origin. The principal tropical influence is thought to be the El Niño–Southern Oscillation (ENSO) in the Pacific Ocean (Allan 1988; Nicholls et al. 1997; Wang and Hendon 2007), though it has been recognized that the Indian Ocean also plays a role (Nicholls 1989). Recent work has highlighted the contributions of both the Indian Ocean dipole (IOD) (Ashok et al. 2003) and Madden–Julian oscillation (MJO) (Wheeler and Hendon 2004; Wheeler et al. 2009) to rainfall variability in Australia. The focus on extratropical sources of variability has been on the southern annular mode (SAM) (Hendon et al. 2007a; Meneghini et al. 2007), variations in storm tracks (Simmonds and Keay 2000; Frederiksen and Frederiksen 2007), the subtropical ridge (Pittock 1975), and atmospheric blocking (Pook and Gibson 1999).

Most of these studies consider the role of only a single process or “driver” of rainfall variability at a time. There are some exceptions to this, such as the work of Nicholls (1989) and Meyers et al. (2007) on interactions between both ENSO and IOD and patterns of Australian rainfall, and Murphy and Timbal (2008) and Nicholls (2009) on processes contributing to the recent drought in southeastern Australia. The point is that there has been much less effort on the construction of a broader picture of contributions to rainfall variability. From the perspective
of the broader picture one would like to know answers to questions such as

(i) What are the relative contributions of the different processes to rainfall variability?
(ii) How do these contributions vary by location across the country?
(iii) How do these contributions vary by time of year?
(iv) To what extent are the different driving processes independent of one another?

The goal of this work is to begin to address these questions by considering a variety of drivers of rainfall variability and their interactions. In the first instance, answers to these questions would help those in industries affected by rainfall variability to focus on the right processes at the right times of year. From some users’ perspectives there is a bewildering array of processes to monitor to derive indications of rainfall variations, and it may be helpful to know which processes are most relevant. In the longer run, one would also like to be able to forecast changes in these processes and their impacts on rainfall variability. A first step to improving forecasts is to identify the processes of relevance and to direct model evaluation and development efforts to improving them.

As an organizing framework in which to view a variety of drivers of rainfall variability in Australia, we developed a schematic representation of influences on Australian rainfall. This schematic is shown in Fig. 1. It features some of the salient synoptic (higher frequency) processes associated with rainfall in Australia as well as large-scale (lower frequency) oceanic and atmospheric phenomena. Rainfall from synoptic-scale events is usually associated with a low pressure system, which may be frontal in nature or cutoff from the westerlies (Pook et al. 2006). The cutoff low is in turn associated with a blocking high and a jet stream orientation favorable for development (Risbey et al. 2009). These low pressure systems are part of the storm tracks that bring rainfall to the southern half of the continent in particular. The systems can be thought of as “steered” in part through the longwave pattern, which in turn is thought to be sensitive to phenomena such as ENSO in low latitudes (Hoerling and Ting 1994) and SAM in high latitudes (Carleton 2003; Hendon et al. 2007a). Atmospheric flow patterns and rainfall across Australia are influenced by ENSO and IOD modes as well as by the phase of the MJO in stimulating convection or anomalous circulations. In
the north of Australia, rainfall derives from tropical cyclones, troughs, monsoon depressions, and onshore circulations, which are also influenced by ENSO, IOD, and the MJO (Leroy and Wheeler 2008).

In the sections that follow we discuss each of these drivers of variability. In each case we try to show how the rainfall associated with the driver varies by season across the Australian continent, whether the patterns of rainfall associated with the driver are robust to the definition of the driver, whether the patterns are robust through time, and whether there appear to be significant interactions between drivers.

Note that the drivers of variability considered here are largely remote from the Australian continent, pertaining to coherent large-scale processes in the oceans and atmosphere. ENSO and IOD span ocean basins, the MJO is a traveling tropical phenomenon, and SAM is a hemispheric circulation feature. Blocking is linked to the hemispheric longwave pattern, though we consider its manifestation in one location of prominence in the Australian region. Blocking is thus used as a proxy here for the influence of the longwave pattern. Variability in rainfall in Australia is also driven by local processes such as land–ocean temperature gradients and mesoscale convection and may also be related to vegetation characteristics and soil moisture. The focus of this work is on the remote drivers of variability. The remote drivers generally offer better prospects for predicting rainfall because they vary at low frequencies and can modulate rainfall at these frequencies via their links to processes affecting rainfall. Our temporal focus is on intraseasonal-to-interannual variability and we use mostly monthly data.

2. Methods and data

For each of the climate drivers considered here we relate the driver to rainfall over the Australian continent. The primary rainfall data used for this analysis are the 0.05° gridded data described by Jeffrey et al. (2001). These data are interpolated to the 0.05° grid from Bureau of Meteorology station data (Lavery et al. 1997) and are least accurate in the middle of the continent and in the mountains of southeast Australia where stations are sparse. Sea surface temperature data are used to calculate time series for a number of the climate drivers. The sea surface temperature dataset used is Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST) (Rayner et al. 2003), which provides data on a 1° × 1° grid from 1870 to the present. The shortcomings of the sea surface temperature data as they relate to each driver index are discussed in the relevant sections.

The manner in which each of the drivers is related to rainfall over Australia follows the standard methods used in the literature for each driver. It is not possible to use the same technique for each driver. The influence of ENSO is determined by standard correlation methods in the four standard seasons. The IOD is only observed to occur from May to November, and we choose to explore the peak IOD period June–October, also using linear correlation. Because ENSO and the IOD also appear to exhibit some phase dependence (to El Niño/La Niña; IOD+/IOD− state) in their rainfall response, we also utilize composites of ENSO and IOD in different phases to assess rainfall relationships. The comparison of this method with the correlation method helps emphasize phase dependence and interactions between these two drivers. The MJO is not amenable to correlation techniques because it is measured by two indices rather than one (Wheeler and Hendon 2004). The compositing method and results of Wheeler et al. (2009) are used to show the MJO’s relationship with rainfall. The relationship of SAM to rainfall is analyzed using the compositing techniques of Hendon et al. (2007a) and via standard correlations. This provides an opportunity to highlight differences between composite methods and correlation methods. The former tend to highlight amplitude agreement, while the latter highlight temporal consistency.

With the exception of the MJO, we use a single index of each driver at a time to compare with rainfall. It is difficult to characterize complex physical phenomena like ENSO and IOD with a single index. A single index may not be sufficient to determine the maximum correlations between these features and rainfall. Our approach here is to test multiple, but separate, indices of the same driver and to highlight differences where they occur. This is a limitation in that it may not capture all the features of each driver that are most relevant for rainfall.

The set of drivers are not independent. In particular, ENSO appears to exert influence on, or mutually interact with, some of the other drivers. ENSO is more highly correlated with IOD, SAM, and blocking than any of the other drivers are with one another. To account for this influence we use partial correlation techniques (Johnston 1980; Nicholls 1989) to explore the effect of removing a given driver (usually ENSO) in correlating rainfall with another driver. The partial correlation technique attempts to isolate the part of the rainfall explained by a given driver that is not correlated with a second driver. This does not necessarily remove the influence of the second driver if, for example, there are phase lags from the signal in the second driver. Conversely, the method may unduly penalize the original
driver, since the part of the original driver that is correlated with the second driver might still reflect the operation of the original driver.

In each case below we show results for only simultaneous relationships between each driver and rainfall. There are significant lag relationships between the drivers and rainfall also (McBride and Nicholls 1983; McIntosh et al. 2008). However, these are generally not as strong as the simultaneous relationships. The sections that follow provide the definitions and analyses for each of the drivers considered.

3. ENSO

The canonical driver of Australian rainfall variability is ENSO. There are a variety of different indices used to characterize ENSO. These include the Southern Oscillation index (SOI), which relates to the atmospheric signature, and the sea surface temperature–based indices Niño-3 (5°S−5°N, 150°E−90°W), Niño-3.4 (5°S−5°N, 170°E−120°W), and Niño-4 (5°S−5°N, 160°E−150°W). There is also an index of Modoki-type ENSO events, denoted the ENSO Modoki index (EMI) (Ashok et al. 2007), which captures the distinction between El Niño events that have maximum warming in the central Pacific and the traditional events that have maximum warming in the far east Pacific. We use each of these indices to characterize ENSO. The SOI index is a measure of the anomalous pressure difference between Tahiti and Darwin and is provided by the Australian Bureau of Meteorology. The Niño indices are calculated from HadISST data in the regions given. The EMI is also calculated from areal-averaged HadISST data according to the definition EMI = SST_A − 0.5SST_B − 0.5SST_C, where A denotes the region 10°S−10°N, 165°E−140°W; B is 15°S−5°N, 110°−70°W; and C is 10°S−20°N, 125°−145°E (Ashok et al. 2007).

In general, the highest (simultaneous) correlation of the various ENSO indices with Australian rainfall is obtained by using the SOI, perhaps because this index is more closely related to the rainfall process through its relation to large-scale surface pressure. The ocean-based indices are one physical step removed from rainfall, though they may be more directly linked to the predictable component of the variability. Indeed, ocean-based ENSO indices are more skillful as predictors of Australian rainfall than the SOI at longer lead times (Lo et al. 2007). Another reason for using the SOI is that there is more confidence in data early in the period of record than in early SST-based indices. The SOI is based on consistent pressure observations from two stations. Ocean-based indices are based on interpolation of observations that are increasingly sparse as one goes further back in time.

There are a number of ways of relating the SOI to rainfall. The SOI phase system of Stone et al. (1996) is widely used for seasonal forecasts. However, to keep the analysis simple, we use simultaneous correlation between the SOI and rainfall to document this relationship. Figure 2 shows this correlation for the four standard seasons over the long-term period from 1889 to 2006. It is clear that ENSO affects the eastern and northeastern regions of Australia most strongly, particularly in winter and spring. However, most regions of Australia have a significant correlation with ENSO in at least one season. While at first sight it might seem strange that in winter the SOI is more strongly related to rainfall in the southern half of the country, it must be remembered that this is the dry season in the tropics. Note also that ENSO does not seem to have a significant effect on rainfall along the New South Wales (NSW) coast in winter. The results for seasonal and geographical variations in rainfall response to ENSO shown here are qualitatively consistent with those of McBride and Nicholls (1983), who used shorter-length datasets covering an early period of the record.

There is considerable multidecadal variability in the relationship between ENSO and Australian rainfall patterns (Nicholls et al. 1997; Power et al. 1999, 2006). There is also variability from event to event such that “every ENSO is different” (Wang and Hendon 2007). These factors mean that the spatial patterns displayed in Fig. 2 are not fixed in time. Furthermore, rainfall at any given location has a stochastic “weather” contribution from individual storms that is largely unrelated to ENSO or other remote drivers (i.e., ENSO could be expected to influence some, but not all, rainfall from storms). An isolated storm can skew the rainfall record for a location over even long periods. As such, the patterns displayed in Fig. 2 are not robust at small spatial scales. Features of these patterns on spatial scales of less than a few hundred kilometers are not robust unless they are specifically “anchored” by flow over topography, as in the southeast coast and western Tasmania. On larger spatial scales the weather noise contribution tends to average out in longer time records and we can be more confident that the results do not simply reflect this source of variation. Results at larger spatial scales may still be confounded by variations introduced by other processes or drivers, since not all such variation will average out in any given period. This is most important in regions where the influence of multiple drivers overlaps and in cases where the length of record to discern the role of a given driver is short. In the case of ENSO, these concerns are partially alleviated by its dominance on rainfall compared to other drivers and by the longer records available to study its influence.
To illustrate the long period variability of ENSO and rainfall, we show the correlation of SOI with Australian rainfall in spring for four 29-yr periods in the dataset in Fig. 3. While one might question the reliability of the rainfall records in the earlier part of the dataset (Figs. 3a,b; pre-1948), these have been quality checked (Lavery et al. 1997). In any case, the differences between periods are also evident in the latter periods (Figs. 3c,d) when the data are most reliable. Thus, it seems reasonable to assume that at least part of the difference reflects substantial decadal variability in the relationship of rainfall patterns to ENSO.

The rainfall–SOI correlations in Fig. 3 show the smallest area of significant correlation in Fig. 3b for the period 1919–47 and the largest area of significant correlation in Fig. 3c for the period 1948–76. These results are consistent with those of Power et al. (1999), who find that the relationship between ENSO and Australian rainfall is (weakly) modulated by the phase of the Inter-decadal Pacific Oscillation (IPO). When the IPO is positive, as in the period 1919–47, the correlation with interannual Australian rainfall variations is weaker, and when the IPO is negative, as in the period 1948–76, the correlation with Australian rainfall is stronger. The negative IPO phase favors La Niña conditions over El Niño conditions, and La Niña is more highly correlated with Australian rainfall than El Niño (Power et al. 2006). Thus, the correlations are stronger during the negative IPO phase. The merit of the IPO as an independent process has been questioned by Newman et al. (2003) and others who note that it may be viewed as a low-frequency response to high-frequency atmospheric forcing and ENSO. The notion that there is decadal variability in ENSO is not questioned as much as the source of that variability, which may have implications for longer-term predictability of ENSO.

The different indices for characterizing ENSO that we tested display similar relationships with Australian rainfall. Figure 4 shows the correlation between spring rainfall and Niño-3, Niño-3.4, Niño-4, and the EMI. Note
the opposite sign correlation to that of the SOI. It is encouraging to see that the sea surface temperature indices accord so well with the SOI in their relationships with Australian rainfall. The similarity of the ENSO Modoki index correlations with the correlations of the other indices is somewhat unexpected, however, as the EMI is associated with a different Pacific warming pattern and different rainfall signatures (Weng et al. 2007). The EMI characterizes a warm central Pacific region and differentiates warm events that occur there as opposed to the eastern Pacific. Rainfall in eastern Australia is most strongly correlated with central Pacific SST (Wang and Hendon 2007) and thus should reflect a strong EMI association. However, the region of correlation extends well into the eastern Pacific and thus Australian rainfall shows a similarly strong relationship with conventional ENSO. The four ENSO indices tested here do show some differences in their relationship to Australian rainfall in the other seasons (not shown), though these differences are not marked.

4. IOD

The Indian Ocean dipole is an ENSO-like coupled ocean–atmosphere phenomenon in the equatorial Indian Ocean (Saji et al. 1999). It typically peaks in spring, but can be seen from May to November. The IOD and ENSO can occur together in such a way as to reinforce each other, but this need not happen (Meyers et al. 2007). A measure of the IOD is the dipole mode index (DMI), which is defined by Saji et al. (1999) as the difference in SST anomaly between the tropical western Indian Ocean (10°S–10°N, 50°–70°E) and the tropical southeastern Indian Ocean (10°S–equator, 90°–110°E). We calculate the DMI from the HadISST dataset. There is some debate over the extent to which the IOD is independent of ENSO (Saji et al. 1999; Ashok et al. 2003; Meyers et al. 2007). Meyers et al. (2007) developed an index of IOD using a lagged EOF approach that takes into account variation in ENSO in defining the IOD. We denote this index the Meyers IOD.
The correlation between the DMI and Australian rainfall for the peak IOD period of June–October is shown in Fig. 5a. We use the same years 1889–2006 as for the ENSO correlations above. The IOD is broadly correlated with rainfall across central and southern Australia. If the effect of ENSO, as measured by Niño-3, is “removed” using partial correlation, then the significant correlations in the regions where ENSO might be considered to be dominant disappear (contrast Fig. 5b with Fig. 5a). This leaves a broad southern portion of Australia where the IOD most directly affects rainfall. The methods and results described here are very similar to those of Ashok et al. (2003). Note that Niño-3 is used as a measure of ENSO here rather than the SOI, although the two are highly correlated. We were concerned that, because the SOI contains Darwin pressure, it may contain some direct signal from the IOD because of Darwin’s proximity to the Indian Ocean region defining the eastern pole of the DMI.

By way of contrast, we also present the ENSO–rainfall correlation with the effect of the IOD “removed.” Figure 6a shows the ENSO correlation with rainfall for the June–October period (using Niño-3 as a measure of ENSO). Figure 6b shows the same correlation with the effect of the IOD removed. We can see that removing the effect of either ENSO or the IOD has a significant effect on the correlation pattern for the other driver. We also see that when the partial correlation with the other driver is removed, the regions of influence separate out quite well, with ENSO affecting the northeast half of Australia, and the IOD affecting the southwest half. For the June–October period, both drivers are important in different regions. Note also that the two drivers are correlated because of the effect on the correlations of removing one or the other. Over the 1889–2006 period the time series of Niño-3 and DMI are correlated at $r \sim 0.6$ without removing trends. If a first difference is applied to both time series as a crude high-pass filter to remove the trend, the correlation increases to 0.7. Restricting this last calculation to the more recent period 1970–2006 increases the correlation further to 0.8.
Another technique for diagnosing the effect of ENSO and the IOD on Australian rainfall involves classifying years as El Niño, La Niña, positive IOD, negative IOD, and neutral ENSO or IOD, and then forming composite rainfall maps in similarly categorized years. This approach can account for nonlinearities in the relationship between ENSO and rainfall. For example, La Niña is generally more highly correlated with Australian rainfall than El Niño (Power et al. 2006). This asymmetry is obscured by the standard correlation method, which combines all years and hence both phases of ENSO.

Meyers et al. (2007) have classified years from 1877 to 1998 into three ENSO categories and, independently, three IOD categories, giving nine possibilities overall. Two of these combinations seldom occur, leaving seven combinations. For each combination they produced maps for June to November rainfall based on the percentage of years above or below the all-years median. We have produced similar maps showing the mean rainfall anomaly in June–October in the different year types (Fig. 7). This map is produced using the years 1889–1998 because Meyers et al. (2007) have not classified recent years. An informal classification of recent years, extending the period to 1889–2006 does not change the results significantly. These maps show that the IOD can have an effect on Australian rainfall of similar magnitude to the effect of ENSO.

The spatial rainfall signatures for ENSO and IOD in Fig. 7 are broadly consistent with the results obtained using the correlation method (Figs. 5 and 6). However, asymmetries in response stand out also. The asymmetric El Niño/La Niña response cited above shows up as stronger positive rainfall anomalies for La Niña (bottom middle) than the negative anomalies for El Niño (top middle).

![Fig. 5. (a) Correlation between DMI and Australian rainfall for June–October. (b) As in (a), but with the effect of ENSO removed. Only correlations significant at the 95% level are shown.](image1)

![Fig. 6. (a) Correlation between Niño-3 and Australian rainfall for June–October. (b) As in (a), but with the effect of the IOD removed. Only correlations significant at the 95% level are shown.](image2)
middle), though the spatial patterns are similar. By contrast with ENSO, there is a spatial asymmetry in the IOD response. The negative IOD phase in neutral ENSO years (middle left) is not simply of opposite sign to the positive IOD phase (middle right) and has regions of negative rainfall anomaly in eastern Australia where a positive (or no) anomaly is implied by Fig. 5.

The results in Fig. 7 also illustrate the interactive effects of ENSO and IOD. For example, the combined effect of ENSO and the IOD is generally more extreme than either on its own. As such, combined La Niña/IOD− years (bottom left) are particularly wet across eastern Australia, and combined El Niño/IOD+ years (top right) are particularly dry.

As was the case for ENSO, the relationship between the IOD and Australian rainfall may also vary on interdecadal time scales. Figure 8 shows the correlation of the DMI with Australian rainfall in June–October for four 29-yr periods in the dataset. The effect of ENSO has been “removed” in each period to isolate the IOD–rainfall signal. The areal extent of significant correlation varies in the figures across the region of IOD–rainfall influence. It is unclear in this case how much of the variation is due to limitations of the data. The DMI is defined from western and eastern Indian Ocean surface temperatures, which were not nearly as well observed in the first two periods shown (Figs. 8a,b; pre-1948). Thus one can discount these two patterns as evidence of interdecadal variability. The latter two periods (Figs. 8c,d) have many more observations and also show stark differences. The differences in the latter two periods are suggestive, but not definitive, in isolating interdecadal variability in this relationship.

As a final test of IOD relationships with Australian rainfall we compared the Meyers IOD index with the DMI index. Figure 9 shows correlations of the Meyers

Fig. 7. Mean rainfall anomaly (mm) in June–October for ENSO/IOD year types spanning 1889–1998. The year types are defined in Meyers et al. (2007).
IOD index with rainfall for the June–October period, both without (Fig. 9a) and with (Fig. 9b) the effect of ENSO removed. The results are very similar to those for the DMI (Fig. 5), suggesting that the relationships are robust to the definition of IOD. This is also encouraging in that the more simply defined DMI is largely consistent with the more complex Meyers index. The correlation between the two IOD indices is very high (~0.9) over the June–October period.

5. MJO

The MJO is a large-scale eastward-propagating wave-like disturbance in equatorial latitudes. The MJO produces periods of enhanced and diminished convection, particularly in its transits of the Indian and Pacific Oceans. The MJO may be classified into eight phases based on the leading patterns of variability of convection and zonal wind in near-equatorial latitudes (Wheeler and Hendon 2004). These phases usefully describe the position of the MJO and are used in both analysis and forecasting of the MJO (Waliser et al. 2006; Jiang et al. 2008).

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 thought to interact with ENSO (Hendon et al. 2007b). In the Australian region, wet MJO-related monsoon bursts have similar characteristics in El Niño and La Niña years, but the MJO-forced dry breaks are drier in El Niño years than during La Niña years. This mechanism is thus associated with the reduction in rainfall in Northern Australia during El Niño years and illustrates the manner in which the relationship between rainfall and one driver (in this case ENSO) can depend on the actions of another driver (MJO).

The impacts of the MJO on Australian rainfall have been well summarized by Wheeler et al. (2009). They show strongest rainfall signals in a broad band across northern Australia during the monsoon season (particularly
associated with phases 5 and 6 of the MJO), with responses in the north in the monsoon shoulder seasons as well. The monsoon season (December–February) maps of composite weekly rainfall probabilities for each MJO phase are shown in Fig. 10. For maps of the response in other seasons, see Wheeler et al. (2009). The wintertime rainfall response to the MJO in the north of Australia is mostly evident along the Queensland coast, where it relates to a modulation of the trade winds by the MJO.

Rainfall responses to the MJO in the extratropics (southern Australia) are generally more localized and less consistent than those that occur in the north, though significant responses occur in all seasons. These responses are related to changes in continental circulation induced by the MJO. Though such circulation responses are not fully understood at present, the work of Wheeler et al. (2009) suggests that blocking may be involved in transmitting the extratropical response. Their composite maps show circulation features indicative of blocking for MJO phase 4 in summer and winter. In summer there is a blocking feature in the Tasman Sea at 160°E, which would enhance rainfall in parts of southeastern Australia, consistent with the rainfall response pattern for phase 4. In winter the blocking feature is centered farther upstream over Tasmania, which would tend to reduce rainfall in parts of southeastern Australia and increase it over Queensland, consistent with the winter phase 4 rainfall response.

While the spatial extent of patterns of MJO association with rainfall is not as great as for ENSO and IOD, the MJO operates on a much shorter time scale, with shifts between phases occurring over days to weeks rather than seasons or years as for ENSO and IOD. Furthermore, the MJO phases are predictable out to 15 days or so (Maharaj and Wheeler 2005; Waliser et al. 2006). This offers an opportunity to utilize MJO predictions for rainfall guidance over two-week time scales in those areas where significant responses occur.

6. SAM

The SAM is the dominant mode of atmospheric variability in the mid- and high latitudes of the Southern Hemisphere (Thompson and Solomon 2002). The SAM reflects north–south shifts in mass between the pole and midlatitudes and zonal wind anomalies between about 30° and 60° latitude. The positive (high index) SAM phase is defined where pressures are lower than normal in the polar region with enhanced westerly winds along 55°–60° latitude (Thompson 2007). A simple index of the SAM was defined by Gong and Wang (1999) as the difference between normalized monthly zonal mean sea level pressure at 40° and 65°S. This index has been calculated from station pressures by Marshall (2003) for the period from 1957 to the present, and it is used here.

Variations in the SAM are thought to relate to rainfall variability in each of the Southern Hemisphere landmasses (Hendon et al. 2007a). Hendon et al. (2007a) have carried out an analysis of SAM contributions to rainfall variability in Australia. They use a daily SAM index that was constructed by projecting daily 700-hPa height anomalies onto the leading EOF of monthly mean 700-hPa height. They found that the SAM explains up to about 15% of weekly rainfall variance in parts of southwestern and southeastern Australia. They noted that this is similar to the amount of rainfall variance related to ENSO for these regions, though ENSO also has significant rainfall relationships for broader sections of the continent.

A number of studies have related the positive phase of SAM to reduced rainfall in southern Australia in association with the contraction of the westerly wind belt.
FIG. 10. Composites of weekly rainfall probabilities, expressed as a ratio with the climatological probability (contours and shading), and 850-hPa wind (vectors) for each of the eight MJO phases for the summer (DJF) season. Probability ratios greater (less) than 1 indicate an increased (decreased) chance of weekly rainfall exceeding the upper tercile. The probability ratios are shaded only where they are determined to be significant at the 95% level. Adapted from Wheeler et al. (2009).
toward the poles. Indeed, Hendon et al. find that there are statistically significant reductions in winter rainfall in the southwestern tip of Western Australia and the southeastern tip of eastern Australia (southern Victoria and Tasmania) in association with the positive SAM phase (see Fig. 11c). Hendon et al. also find statistically significant increases in rainfall in association with the SAM in spring and summer (Figs. 11d,a). The region of increased rainfall is mostly confined to the southeast coast, particularly in NSW. The positive phase of SAM is associated with an onshore circulation in this region and period, which enhances rainfall there.

Hendon et al. (2007a) used a technique of compositing differences of extreme values of daily SAM indices to produce the plots shown in Fig. 11. Other studies have used monthly or seasonal values of the SAM to correlate with Australian rainfall. This includes studies by Meneghini et al. (2007), Rakich et al. (2008), and this work. These studies show similar results to one another. The results are largely unaffected by removal of a linear trend from the data before correlating and by removal of common ENSO variation from the datasets. We therefore show results for the straight correlation of SAM with rainfall in Fig. 12 for each of the four seasons using data spanning 1979–2005 (to match the period used by Hendon et al. 2007a). The results are also broadly consistent with those of Hendon et al. shown in Fig. 11, with one major exception. The exception occurs in the summer season (December–February). In summer there is an increase in significant rainfall associated with the positive SAM phase in southeast Australia (accentuated along the coast) in the Hendon et al. plot (Fig. 11a), which is not significant in Fig. 12a. Part of this difference could be because compositing procedures highlight areas of higher rainfall, and thus the coastal area is favored in the Hendon et al. analysis.

An important difference between the studies is that Hendon et al. used daily data and the other studies use
monthly or seasonal data. Some of the shorter-period fluctuations in the SAM and rainfall are not picked up in the monthly and seasonal average data. In addition, Hendon et al. only use extreme values of the SAM (plus or minus one and a half standard deviations) for their compositing. Rainfall events along the coast of NSW in summer may be particularly sensitive to instantaneous and/or extreme values of the SAM.

There is a fair amount of consistency across studies of the influence of SAM on Australian rainfall. However, some differences relating to the temporal resolution of the data and the method of relating SAM indices to rainfall variations remain. This means that it is difficult to produce a single definitive plot of the relationship between SAM and Australian rainfall. The more robust features of this relationship include

(i) a reduction in winter rainfall in the southwest and southeast tips of the continent associated with the positive phase of the SAM;

(ii) a reduction in rainfall in all seasons along the west coast of Tasmania associated with the positive phase of the SAM. This rainfall is orographic in association with the zonal westerlies, and the reduction indicates a weakening of the westerly stream over Tasmania during the positive SAM phase;

(iii) an increase in spring rainfall in New South Wales and southwest Western Australia in association with the positive phase of the SAM.

7. Blocking

The significance of atmospheric blocking as an important climate driver for southern Australia is now more broadly recognized (McIntosh et al. 2008). Individual occurrences of blocking are influenced by the configuration of the atmospheric longwaves around the Southern Hemisphere at any time, but their onset and maintenance in the Australasian region is not fully understood.

FIG. 12. Correlation between the SAM and Australian rainfall for each season (a) DJF, (b) MAM, (c) JJA, and (d) SON. Only correlations significant at the 95% level are shown. The data span the period 1979–2005.
and is poorly simulated in climate models (Palmer et al. 2008; McIntosh et al. 2008). Blocking is partly predictable in numerical weather prediction models (Tibaldi and Molteni 1990) but less so in extending to intraseasonal time scales (Watson and Colucci 2002). The Tasman Sea and southwest Pacific sector is the dominant region for blocking to occur in the Southern Hemisphere, and there is a maximum frequency of occurrence near southeastern Australia in winter (Coughlan 1983; Pook and Gibson 1999).

Atmospheric blocking is associated with a splitting of the upper-tropospheric westerly airstream into two distinct branches, and the degree of this splitting of the westerlies can be represented by a simple blocking index. The index developed by the Bureau of Meteorology for use in the Australian region is defined as follows: blocking = 0.5(50 - 50 - 50 - 50 - 50 + 50 + 50 + 50) where 50 represents the zonal component of the mean 500-hPa wind at latitude y (Pook and Gibson 1999). We use this expression to calculate a monthly blocking index at 140°E, which is a typical longitude for blocking in the Australian region to influence synoptic systems over much of Australia. The wind data used to calculate the index are taken from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996).

When blocks form there is a tendency for cold fronts approaching the blocking region from the west to weaken and distort before being steered southeastwards. Hence, periods of blocking are often associated with extended dry spells in southern Australia (Pook and Gibson 1999). However, blocking presents something of a paradox in that significant rainfall events are also known to occur over southern and inland Australia when high pressure systems dominate to the south or southeast of the continent (Hopkins and Holland 1997; Qi et al. 1999; Pook et al. 2006). This apparent paradox is explained in terms of the symbiotic relationship between the extensive high-latitude anticyclonic component of blocking on the one hand and the cutting off or breaking away of a relatively small cyclonic component equatorward of the high. The resulting cutoff lows are known to be major contributors to rainfall in southeastern Australia (Pook et al. 2006).

The response of rainfall across Australia to blocking depends on the precise location of the block. Blocking in the Great Australian Bight region favors rainfall in western Australia, whereas blocking farther to the east around 140°E favors rainfall in southeastern Australia. As an illustrative example, we consider the case of blocking at 140°E, which is a typical location for blocking in the Australian region. The correlation between the blocking index at 140°E and Australian rainfall is shown for each of the four seasons in Fig. 13. For all of the seasons except summer, there is a broadscale region of significant correlation across southeastern Australia. This reflects rainfall from cutoff systems in this area in conjunction with blocking at 140°E. In these seasons there is also a negative correlation to rainfall in southwestern Tasmania. That is because the rainfall in this region is frequently due to orographic uplift in westerly and southwesterly streams, and these streams do not occur in blocking situations.

Blocking in the Southern Hemisphere undergoes variation in position and intensity from year to year and decade to decade (Trenberth and Mo 1985). From the perspective of a single longitude such as 140°E we expect to see some variation in blocking index across decades. Such variation is evident in Fig. 14, which suggests a stronger and more broadscale association with blocking in the recent three decades relative to the three decades before that. This trend needs further work to corroborate, however, as the 500-hPa wind data in the Australian region are less reliable in the former decades.

Blocking in the Australian region is moderately correlated with ENSO indices. The blocking index at 140°E in winter is correlated with the SOI at r = 0.5 and with Niño-3 at r = −0.3. A positive correlation between the blocking index and SOI suggests that blocking in the southeastern Australian region is more probable during the La Niña state in the Pacific than it is in the El Niño phase. This observation may provide insight into the physical mechanisms that operate to link the tropics with the midlatitude atmospheric circulation and help to explain how ENSO interacts with southern Australia. When the effect of ENSO is removed by excluding the contribution from Niño-3 and calculating the partial correlation between the blocking index and SOI it suggests that blocking in the southeastern Australian region is more probable during the La Niña state in the Pacific than it is in the El Niño phase. This observation may provide insight into the physical mechanisms that operate to link the tropics with the midlatitude atmospheric circulation and help to explain how ENSO interacts with southern Australia. When the effect of ENSO is removed by excluding the contribution from Niño-3 and calculating the partial correlation between the blocking index and SOI it suggests that blocking in the southeastern Australian region is more probable during the La Niña state in the Pacific than it is in the El Niño phase. This observation may provide insight into the physical mechanisms that operate to link the tropics with the midlatitude atmospheric circulation and help to explain how ENSO interacts with southern Australia. When the effect of ENSO is removed by excluding the contribution from Niño-3 and calculating the partial correlation between the blocking index and SOI it suggests that blocking in the southeastern Australian region is more probable during the La Niña state in the Pacific than it is in the El Niño phase. This observation may provide insight into the physical mechanisms that operate to link the tropics with the midlatitude atmospheric circulation and help to explain how ENSO interacts with southern Australia. When the effect of ENSO is removed by excluding the contribution from Niño-3 and calculating the partial correlation between the blocking index and SOI it suggests that blocking in the southeastern Australian region is more probable during the La Niña state in the Pacific than it is in the El Niño phase. This observation may provide insight into the physical mechanisms that operate to link the tropics with the midlatitude atmospheric circulation and help to explain how ENSO interacts with southern Australia.

8. Combined drivers

Until we have a better understanding of the ways in which the different climate drivers interact, it is difficult to know how to assess their effects on rainfall relative to one another or in combination. Nonetheless, it would be useful to have at least a crude indication of their relative influences in different places and seasons. On the basis that the “first cut” at this problem should be fairly simple, we compare the drivers according to the magnitude of their correlations with rainfall. In Fig. 15 we assess the
correlation of each driver with rainfall at every grid point on the continent and show only the driver with the highest correlation at each grid point. We excluded the MJO from this comparison as we use monthly rainfall here and the influence of the MJO is strongest at shorter time scales. This provides a crude indication of the dominant driver in each location and season.

In some cases, two or more drivers may have a similar influence as measured by their correlations with rainfall at a particular point. Figure 15 may partially obscure such outcomes by showing only the driver with the largest correlation. To discriminate more quantitatively among the drivers one would need to develop a model of the way in which the drivers interact, since this will change the quantitative details about just how dominant a particular driver is in a particular region. Lacking such a model, it does not seem appropriate to make too fine a distinction among them at this stage, and the figure should be interpreted as giving only a qualitative overview of where and when each driver is active compared to the others.

The first result of interest in Fig. 15 is that the results are reasonably spatially coherent. There are large contiguous regions over which one or another of the drivers is consistently dominant, implying that the results are not simply random. ENSO stands out as the leading driver in terms of overall spatial coverage and consistency through the seasons. Blocking is important in southeastern Australia (including Tasmania) in all seasons. In the nonsummer seasons there is very little correlation of ENSO with rainfall along the strip of land on the coastal side of the Great Dividing Range in southeastern Australia. Accordingly, blocking and SAM are the leading correlated drivers in this region. Rainfall in this region is particularly sensitive to the prevalence of onshore flow, which is influenced by both blocking and SAM.

SAM is perhaps the leading driver in the far southwest of the continent, though all the drivers usually have some signature here. SAM is also important through all the seasons in western Tasmania. Rainfall in western Tasmania is also acutely sensitive to prevailing (westerly) flow, which is modified by blocking events and SAM phases.
The pattern of IOD influence across southern Australia evident in Fig. 5b is still evident in Fig. 15, though it is partially masked by blocking in the southeast. Indeed, southeastern Australian rainfall is significantly correlated to all the drivers in most seasons, and they each dominate rainfall variability in different parts of the southeast. As such, this region could be expected to be particularly sensitive to any interactions among drivers.

To gain a measure of the importance of the leading drivers in each region and season, we have plotted the amount of rainfall variance explained by the climate driver with the highest correlation at each point. This result is shown in Fig. 16. The season with the strongest relationship to the drivers is spring, where larger areas show a higher percentage of rainfall variance explained. Eastern Australia also typically has more variance explained than other parts of Australia. The amount of variance explained ranges from about 10% to 50%, but with most of the continent at the lower end of that range. The higher levels of explained variance are mostly associated with ENSO and blocking. Areas of higher explained variance include northeastern Australia in spring in association with ENSO; southeastern Australia in spring in association with blocking, IOD, and ENSO; and western Tasmania in spring in association with SAM. While the amount of variance explained in Fig. 16 is less than 50% in each case, these are due to a single driver only and do not take into account potential higher explanatory power by considering multiple drivers and their interactions.

9. Conclusions

The remote drivers of rainfall variability considered here have their influence on Australian rainfall in preferred, but different, geographic locations and seasons. ENSO influences rainfall in eastern and northern Australia, with strongest influence in winter and spring in the east and nonwinter seasons in the north. IOD is important through the months of June–October and influences rainfall in the south and west of the continent. The MJO has an influence on rainfall in different parts of the continent in different seasons, though the strongest and most coherent relationship is with the monsoonal rains in the north. The SAM can be important in all seasons, though the influence of SAM is weakest in autumn and confined mostly to the southwest and southeast parts of the continent. Blocking can affect rainfall in the southern part of the continent, with the precise area depending on the location of the block. For blocking at 140°E considered here, the influence is mostly in the southeast. This influence is strongest in winter and spring and weakest in summer.

Knowledge of where and when the different drivers have an influence could be helpful in directing the attention of users of seasonal forecasts to the drivers of most importance for their region. For most regions there are one or two drivers that seem important at any given time of year. An interesting exception is the southeast region, which is subject to the influence of multiple drivers. Autumn, winter, and spring rainfall in the southeast are influenced by ENSO, IOD, SAM, and blocking.

The results described above apply at the level of spatial detail given above (gross regional categorizations). The areas of influence for each of the drivers do exhibit considerable decadal variability. The broad regions of influence are roughly the same from decade to decade, but the patterns of correlation within those broad regions do shift quite a bit. From the perspective of any given location, there could be large decadal
variability in the association of rainfall with any given driver. Interdecadal variability is difficult to characterize in the first half of last century when data coverage was sparse, but the level of interdecadal variability exhibited then is consistent with that in the last half century when the data are more reliable.

On the other hand, the above results are not particularly sensitive to the choice of index used to represent the driver. A variety of ENSO indices all yield similar results, including the ENSO Modoki index. The EMI has a different rainfall signature to the conventional ENSO indices in other parts of the Pacific basin but not clearly so in Australia in monthly data. As for ENSO, the two IOD indices tested, the DMI and Meyers IOD index, yield similar results.

Both correlation and compositing methods were used here to determine relationships between remote drivers and rainfall. While the results from the two approaches are generally consistent in terms of the broad pattern of rainfall response, there are also noticeable differences. Despite asymmetries in the magnitude of rainfall responses between El Niño and La Niña, the geographical pattern of response is broadly similar in each phase and to the overall ENSO pattern determined from correlation methods. By contrast, the IOD rainfall response exhibits spatial asymmetries between the positive and negative phases of IOD.

The drivers are not independent of one another. The strongest relationships are between ENSO and the other drivers and in particular between ENSO and IOD. The other drivers are more weakly correlated with one another. The interaction between ENSO and the IOD makes it difficult to characterize their impact on rainfall independently of one another. One can develop one-to-one relationships between each driver and rainfall by removing the covariance with the most strongly dependent

![Fig. 15. Each map shows the climate driver with the highest correlation to monthly rainfall at each grid cell across the continent for each season (a) DJF, (b) MAM, (c) JJA, and (d) SON. The drivers included are blocking (BLK), SAM (SAM), IOD (DMI), and ENSO (SOI). Only correlations significant at the 95% level were included in selecting the driver with the highest correlation. In the blank areas none of the drivers has a significant correlation with rainfall. The data span the period 1957–2006.](image-url)
codriver (as we have done here), but such relationships should be viewed with caution. When this is done there is a more distinct separation of the regions of influence, with the IOD confined to south and west regions and ENSO confined to north and east regions.

From the perspective of monthly Australian rainfall variability the dominant driver is probably ENSO because it typically accounts for the largest amount of rainfall variance, the statistically significant rainfall response to ENSO covers a larger portion of the continent, the relationship extends through each of the seasons, and it is most strongly correlated with the other drivers. ENSO accounts for up to 25%–50% of rainfall variance, depending on the season and region. Blocking is also prominent in terms of variance explained, though the other (non-ENSO) drivers typically account for less variance and the statistically significant relationship is confined to smaller areas and fewer seasons. For most regions of the continent any given driver accounts for typically less than 20% of the variance. Thus, the importance of these drivers should not be overestimated. They provide a guide to rainfall variations but are only a part of the story. We rely on them because they are partly predictable and therefore provide a predictable component of rainfall variation.

This work has highlighted and quantified the effects of a set of remote drivers of rainfall. We have not explored here the processes by which each of the drivers interact with one another or the processes by which each of the drivers transmits their influence to rainfall. For example, 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 (Wheeler et al. 2009). The IOD appears to influence Australian rainfall via the warm (cold) SST anomalies that set up in the region northwest of the continent.
of Australia in association with negative (positive) IOD phases. The SST here can influence the orientation of the subtropical jet, thereby influencing the development of synoptic systems over the continent (Risbey et al. 2009). The SSTs in this region may also play a role in setting the entrainment of moisture into synoptic systems over the continent (McIntosh et al. 2007). There are a variety of pathways via which ENSO may influence Australian rainfall, including its effect on atmospheric blocking. It is important to understand the mechanisms linking these drivers and rainfall if we are to ultimately improve forecasts of rainfall at a variety of time scales.

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