The Dynamics of Australian Monsoon Bursts

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ABSTRACT

The wet season of the Australian monsoon is characterized by subseasonal periods of excessively wet or dry conditions, commonly known as monsoon bursts and breaks. This study is concerned with the synoptic evolution prior to monsoon bursts, which are defined here by abrupt transitions of the area-averaged rainfall over the tropical parts of the Australian continent.

There is large variability in the number of monsoon bursts from year to year and in the time interval between consecutive monsoon bursts. Reanalysis data are used to construct a lag composite of the sequence of events prior to a monsoon burst. It is determined that a burst in the Australian monsoon is preceded by the development of a well-defined extratropical wave packet in the Indian Ocean, which propagates toward the Australian continent in the few days leading up to the onset of heavy rainfall in the tropics. As in previous studies on the monsoon onset, the extratropical disturbances propagate equatorward over the Australian continent. These extratropical systems are accompanied by lower-tropospheric airmass boundaries, which also propagate into low latitudes. Ahead of these boundaries, relatively warm moist air is advected from the surrounding oceans, locally increasing the convective available potential energy.

Commonly employed climate indices show that monsoon bursts are more likely to occur when the active phase of the Madden–Julian oscillation is in the vicinity of Australia. Neither El Niño–Southern Oscillation nor the southern annular mode has a significant impact on the occurrence of monsoon bursts.

1. Introduction

Like many tropical regions, the atmospheric circulation of the northern part of the Australian continent is monsoonal, leading to dry winters and wet summers. The development of the Australian monsoon is linked to inland heat lows, which themselves exist as a result of sensible heating of Earth’s surface (e.g., Suppiah 1992; Rácz and Smith 1999). In austral summer, the lower-tropospheric flow over northern Australia (equatorward of approximately 15°S) changes from a dry southeasterly trade regime to a moist northwesterly monsoon flow, and this transition is accompanied by an increase in cloudiness and rainfall. Climatologically, rainfall over northern Australia increases rapidly during December, peaks in February, and rapidly decreases during March in a similar manner to other monsoon systems (e.g., Suppiah 1992).

A rapid increase in area-averaged rainfall, termed the “monsoon onset,” has been the subject of many studies (e.g., Drosdowsky 1996). The timing of the onset is related to large-scale flow changes and can significantly affect the annual rainfall totals in northern Australia. Using station rainfall data, outgoing longwave radiation, and 8 yr of reanalysis data, Hendon and Liebmann (1990) examined the composite monsoon onset, finding that the onset coincides with the first active phase of the Madden–Julian oscillation (MJO; Madden and Julian 1971) during the monsoon. This result was corroborated by Hung and Yanai (2004), who used reanalysis data to analyze the onset, noting also that the land–sea thermal contrasts, barotropic instability, and midlatitude troughs all made contributions to the onset. More recently, Davidson et al. (2007) examined the synoptic evolution of three Australian monsoon onsets that occurred during field experiments and also generated a 15-yr composite with reanalysis data. These authors found that onsets are preceded by extratropical cyclogenesis over...
the Southern Ocean and a strong subtropical jet over the Australian continent. Rossby waves propagated from the region of cyclogenesis through the subtropical jet toward low latitudes, influencing the upper-tropospheric divergence and increasing the potential for widespread convection.

The wet period following the onset of the Australian monsoon is well known for pronounced intraseasonal variability (e.g., Wheeler and McBride 2005) with sub-seasonal periods of excessively wet or dry conditions, termed monsoon “bursts” and “breaks,” respectively. Approximately half of this variability is in the 30–60-day range (see, e.g., Hendon and Liebmann 1990) and is generally attributed to the passage of the MJO. Keenan and Brody (1988) found that on shorter (synoptic) time scales, convection in the monsoon region was modulated by the passage of upper-tropospheric subtropical troughs and ridges. They suggested that the secondary circulation associated with these upper-tropospheric features forces synoptic-scale ascent and descent in the tropics, promoting or suppressing convection. Berry et al. (2012) showed that rainfall was organized by coherent monsoon disturbances that propagate through the region and that the origin of some of these disturbances is linked to extratropical Rossby wave breaking along the eastern coast of the continent.

The aim of this study is to examine in greater detail the kinematic and thermodynamic evolution of the atmosphere leading to monsoon bursts, rather than just the onset, and to determine whether a common sequence of events exists. The results of this work will be compared with the monsoon onsets examined in previous work. It will be shown that monsoon bursts are linked to large-scale features in both the tropics and extratropics at synoptic and intraseasonal time scales. The methodology for identifying monsoon bursts is described in section 2 with the main results presented in section 3. The results are discussed along with some concluding remarks in section 4.

2. Methodology

Various methods have been used to define the monsoon onset over Australia (see, e.g., Drosdowsky 1996). Many of these methods include some measure of the atmospheric flow, such as the 850-hPa wind (e.g., Hung and Yanai 2004) as they are intended to capture the large-scale changes of the tropical circulation, although most only examine conditions at a single location. Here the focus is on synoptic, rather than seasonal, time scales including transients, as well as more long-lived changes to the monsoon system. Here, a monsoon burst is described simply as when the rainfall averaged over northern Australia rapidly changes from significantly below to significantly above average within a short period of time; the precise definition is provided below.

The rainfall records used here to define monsoon bursts come from the Australian Water Availability Project (AWAP) dataset developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO: Jones et al. 2009). These data consist of daily rainfall totals, derived from in situ station observations, which are then statistically interpolated to a 0.05° × 0.05° horizontal grid over the Australian landmass. Although these data are available from 1900 to the present day, only the period 1979–2010 are used here to permit the use of reanalysis products in producing composites.

A monsoon burst is defined by the rainfall over land in the region 10°–20°S, 120°–150°E, which is approximately the geographical extent of the summertime monsoon (e.g., Suppiah 1992). The mean AWAP rainfall in this region for the period 1979–2010 is shown in Fig. 1a. Three curves have been added to the climatology in Fig. 1a. The first is a smoothed climatology defined by the first six harmonics of the seasonal cycle, generated using all data for the period 1979–2010. The other two additional curves mark ±0.5 standard deviations from the smoothed seasonal cycle. In this study, a monsoon burst is defined as when the area-averaged rainfall transitions from at least 0.5 standard deviations below the seasonal average to at least 0.5 standard deviations above the seasonal averaged in less than a 7-day period. The standard deviations and means used in the definitions are the smoothed, seasonally varying values plotted in Fig. 1a. The sensitivity of the analysis to various standard deviation thresholds has been analyzed, but as the results are not substantially different and the overall conclusions unchanged, they are omitted for brevity. The analysis is conducted only between 1 October and 30 April, as this period encompasses the whole of the wet season. The date of each burst, on which the composites are defined, is the day on which the rainfall first reaches or exceeds the seasonally varying mean. The smoothed climatology is used to define four periods used in the analysis of synoptic composites, which are indicated by the annotations on Fig. 1a. Subjectively defined dates, based on turning points of the seasonally varying mean, are (i) the premonsoon, (ii) the monsoon onset, (iii) the peak monsoon, and (iv) monsoon retreat.

The definition used here is based wholly upon area-averaged rainfall, whereas previous studies concerned with the monsoon onset (e.g., Drosdowsky 1996) also include a dynamic metric, such as the mean layer winds at Darwin (12.5°S, 131°E) reflecting a change in the large-scale flow. Although the terminology “monsoon
"burst" is used here, it is applied broadly as the method technically describes rapid rainfall increases in the Australian tropics, with no metric accounting for the low-level flow pattern. Examples of the area-averaged AWAP data from three seasons are shown in Figs. 1b–d, with annotations denoting bursts detected using the AWAP rainfall criteria. A time series of the 500–1000-hPa pressure-weighted, layer-averaged zonal wind at Darwin is overlaid to allow comparison with previous studies and an annotation is added to indicate the monsoon onset date as defined by Drosdowsky (1996). Although there is clear burst–break behavior in the area-averaged rainfall in all the examples there are pronounced season-to-season variations. Note that not all of the high-amplitude rainfall peaks shown are identified as bursts [e.g., near 20 December 1988 (Fig. 1b)] as they do not meet the change in amplitude or time scale criteria required. In general, the peaks in area-averaged rainfall correspond with peaks in the lower-tropospheric zonal winds at Darwin, indicating that the monsoon bursts as defined here broadly conform to periods of an active monsoon defined in previous studies. It is interesting to note that in the three examples shown in Figs. 1b–d the monsoon onset as defined by Drosdowsky (1996) does not coincide with a monsoon burst.

Once the bursts are identified, the antecedent synoptic conditions are characterized by composites of reanalysis data. The data chosen come from the European Centre for Medium range Weather Forecasts (ECMWF)
ERA-Interim (ERAI) dataset. This dataset has a 1.5° horizontal resolution with 37 pressure levels between 1000 and 10 hPa. The data used are for the period 1979–2010 inclusive. Only the 0000 UTC analysis time is used here to avoid complicating the interpretation by the diurnal cycle. Because the analysis is conducted over a 7-month period spanning the wet season, the composites are created by computing anomalies from a smooth, time-varying basic state for the period 1979–2010. This climatology is valid at the 0000 UTC analysis time of each day, defined in the same way as the AWAP rainfall climatology, by retaining the first six harmonics of the seasonal cycle. The anomalies from each monsoon burst are calculated and the fields shown are the composite mean of all the events.

The role of lower-tropospheric fronts is examined using the objective front dataset generated by Berry et al. (2011) from the same ERAI dataset as the monsoon burst composites. The objective front locations were computed using several functions of the 850-hPa wet-bulb potential temperature ($\theta_w$) field and the horizontal wind components [described in detail in Hewson (1998)] combined with an automated line-joining algorithm. At any single analysis, time fronts are only present at a small number of the total grid points, which means a spectroscopically smoothed daily climatology cannot be computed in the same manner as the ERAI dataset. Therefore, front count anomalies in this study are defined using their respectively monthly means.

The large-scale conditions at the time of the monsoon burst are characterized by three climate indices. The state of the MJO during each burst is determined using the real-time multivariate MJO (RMM) index provided by the Australian Bureau of Meteorology, following Wheeler and Hendon (2004). The state of El Niño–Southern Oscillation (ENSO) is determined using the Southern Oscillation index (SOI) and the southern annular mode (SAM) is characterized using the SAM index, both provided by the Bureau of Meteorology.

3. Results

a. Monsoon burst statistics

Using the AWAP dataset for the period October–May 1979–2010, the occurrence of monsoon bursts as per the definition described in the methodology are determined. In total there are 218 individual monsoon bursts during the study period. Figure 2a displays the number of bursts detected in each of the seasons. In this figure the label 1979 refers to the period October 1979–April 1980, and so forth. On average there are seven monsoon bursts per season, with a standard deviation of 1.7 events. The fewest events occur in 1990 and 1991 (4 events each) and the
most occur in 1996 and 1998 (10 events each). The time interval (return period) between consecutive monsoon bursts is shown by the bar chart in Fig. 2b. There is a peak in the return period near 13 days. The distribution is skewed toward higher values, with 38% of the total falling in return periods of between 10 and 20 days. A secondary peak in the return periods exists between 30 and 40 days (accounting for 18% of the cases), which presumably reflects the influence of the MJO. The seasonality of the monsoon bursts is shown by Fig. 2c, where the number of events against calendar date is displayed. Although monsoon bursts occur throughout the whole wet season, they are most frequent between mid-November and mid-December, prior to the average monsoon onset date, which is generally accepted to be near the end of December (Drosdowsky 1996). Based on the subjectively defined periods shown in Fig. 1a, there are 62 cases during premonsoon, 47 during monsoon onset, 70 during peak monsoon, and 39 during the monsoon retreat period.

### b. Synoptic composites

Lag composites of various fields from ERAI are computed using the date of each monsoon burst. The fields are calculated as deviations from the harmonically smoothed daily mean and the resultant composite anomaly from the 218 cases is shown here. The evolution of the mean sea level pressure (MSLP) and 925-hPa wind anomalies in the lead up to the composite monsoon burst are plotted in Fig. 3, as is the mean magnitude of the 200-hPa wind (i.e., not anomalous wind speed) in order to show the relationship with upper-tropospheric jet streams. On the day of the burst (Fig. 3a), the MSLP anomaly is negative throughout northern Australia, consistent with the occurrence of deep convection. This tropical MSLP anomaly is part of an anomalous trough that extends along the eastern coast of the Australian continent into an anomalous low center that is positioned in the Tasman Sea, approximately equidistant between Australia and New Zealand. Consistent with the MSLP anomalies, anomalous northerlies extend from near 10°S to poleward of 60°S, on the eastern side of the trough, implying large-scale meridional transport. In the Great Australian Bight there is a positive MSLP anomaly and associated anticyclonic circulation at 925 hPa centered on approximately 40°S, 125°E. On the eastern flank of the positive MSLP anomaly, anomalous southerlies extend from near 50°S to 15°S, again emphasizing the tropical–extratropical interaction. Upstream of the Australian continent, there are a series of alternating high and low MSLP anomalies between 30° and 60°S extending from the Atlantic basin to the middle of the Indian Ocean (approximately 90°E). The 200-hPa jets have a complicated structure over the Australian
region; the midlatitude jet (MLJ) peaks over the Indian Ocean near 60°E, then decelerates to the southwest of the Australian continent. Over the Australian continent itself, there is a subtropical jet (STJ) centered near 30°S, which extends eastward from near the west coast of Australia into the Pacific Ocean. At the time of the monsoon burst, the low center in the Tasman Sea is positioned in the relatively weak flow between the 200-hPa jet cores and the anticyclone in the Great Australian Bight is positioned in the equatorward exit of the MLJ and the poleward entrance of the STJ. The pattern of MSLP anomalies in the Australian sector resembles that in the composite of Davidson et al. (2007) for 2 days after the monsoon onset (their Fig. 13f), suggesting that, in general, the dynamics of the monsoon onset is likely similar to the bursts that occur throughout the wet season.

Two days prior to the composite monsoon burst (Fig. 3b) a large, well-defined anomalous low pressure center is located near 50°S, 140°E, with cyclonic flow anomalies that extend well into the Australian tropics, across the latitudes of both the MLJ and STJ. The tilt of the center of this disturbance has changed from a positive tilt at day 0 (i.e., orientated northwest–southeast) to a negative tilt at day −2 (i.e., orientated northeast–southwest). This cyclonic feature is flanked by two well-defined anticyclonic anomalies: one to the south of New Zealand and a smaller anticyclonic anomaly center over Australia. This smaller anticyclonic anomaly lies between the MLJ and STJ, in a region quasigeostrophic theory would predict descent. At day −4 (Fig. 3c) the pattern is shifted farther upstream, with the main cyclonic negative MSLP anomaly centered near 120°E, with a pronounced negative tilt. At this time, the negative MSLP anomaly extends from the MLJ to the STJ, suggesting that the composite disturbance could be interacting with both jets. One interpretation of this change in tilt and wide latitudinal extent could be that the extratropical disturbance interacts with the heat low; previous studies have shown that the heat low intensifies during periods of widespread rainfall over the tropics (e.g., Davidson 1984). At this lag, a clear wave packet can be observed in the MSLP anomaly field, extending from 30° to 160°E. At day −6 (Fig. 3d), the cyclonic MSLP anomaly that reaches Australian at day 0 is not well defined. However, the upstream components of the wave packet, consisting of an anticyclonic anomaly near 80°E and the next cyclonic anomaly near 40°E, are clearly seen at the latitude of the MLJ. The largest amplitude anomalies at day −6 are these upstream anomalies, suggesting that downstream development is occurring during the course of the composite evolution. At day −8 (Fig. 3e), the overall pattern is less distinct, as might be expected in the construction of a lag composite, although at the latitude of the MLJ an anticyclonic anomaly in the Indian Ocean is present near 70°E, with a cyclonic anomaly near 15°E. The relative amplitude of these anomalies supports the notion of downstream development.

Although the composites are based on sudden increases in tropical Australian rainfall, the MSLP fields shown in Fig. 3 show a clear pattern of midlatitude and subtropical disturbances propagating into the region in the week leading up to extreme tropical rainfall. From the MSLP anomaly fields, it is clear a burst in the Australian monsoon is preceded by the arrival of a wave packet that can be detected near the Greenwich median on the MLJ approximately 8 days earlier. On reaching the longitudes of the Australian continent at the end of the MLJ a significant cyclonic anomaly extends into the tropics, perhaps linked to the changing jet structure or even due to an interaction with the surface heat low. At the start of a monsoon burst a cyclonic anomaly is positioned between Australia and New Zealand with a trough of anomalously low surface pressures extending into the monsoon region.

A more succinct view of the Rossby wave propagation is given by the Hovmöller space–time diagram in Fig. 4.
which shows the composite MSLP anomaly field averaged in the latitude band 20°–60°S as a function of time lag. A wave packet can be seen to propagate from the vicinity of the Greenwich meridian at ~8 days to the longitudes of the Australia at day 0. The phase velocity of the individual anomalies within the packet is of order 8 m s⁻¹, whereas the clear downstream development of the next anomaly reveals a group velocity is of the order 20 m s⁻¹. After the monsoon burst at day 0, there is little evidence that this composite wave packet proceeds farther downstream, perhaps as a consequence of the slowing of the MLJ (see, e.g., Fig. 3a) or the interaction with the South Pacific convergence zone, or more simply a range of subsequent synoptic evolutions in each of the cases that average together to produce a noncoherent result.

The evolution of the synoptic conditions leading up to a monsoon burst is examined now in a potential vorticity (PV) framework. Figure 5 shows the potential temperature and wind anomalies on the dynamic tropopause [defined as the −2 potential vorticity unit (PVU) surface; 1 PVU = 10⁻⁸ K kg⁻¹ m⁻² s⁻¹] alongside the 925-hPa temperature, wind, and specific humidity anomalies. The left column of Fig. 6 shows that along the dynamic tropopause, a negative potential temperature anomaly propagates from southwest of western Australia at day −5 to near southeastern Australia on the day of the monsoon burst. Comparing with the evolution shown by the MSLP anomalies previously shown in Fig. 2, it is clear that the cyclonic disturbance tilts toward the west with increasing height, consistent with the expected structure of a deepening midlatitude cyclone. The right-hand column of Fig. 6 shows the development of significant moisture and temperature anomalies at 925 hPa over the continent as the composite midlatitude disturbance approaches northern Australia prior to the monsoon burst. Cold and dry anomalies occur where there are anomalous southerlies whereas warm, moist anomalies occur where there are anomalous northerlies, consistent with that expected from meridional advection. At day −4 (Fig. 6h), a continental-scale warm anomaly is over Australia. By day −3 this warm anomaly becomes elongated north-northwest–south-southwest and is collocated with positive moisture anomalies. Given the prevailing trade easterlies equatorward of about 30°S, based on the 925-hPa flow anomalies, it likely that the source of this moisture anomaly is the tropical oceans surrounding the northern part of Australia. Over the following few days this anomalous warm, moist plume extends farther poleward, stretching from the Australian tropics to the Southern Ocean, poleward of New Zealand. This feature strongly resembles the wintertime “northwest cloud band” phenomena described by Tapp and Barrell (1984) or the warm conveyor belts associated with midlatitude cyclones. From day −3 onward a stationary local maximum in the mixing ratio anomaly develops just south of the Gulf of Carpentaria (near 20°S, 135°E) and peaks in amplitude at day −1, just prior to the composite burst of rainfall in the monsoon region.

Comparing the anomalous 925-hPa temperature fields with the MSLP field (Fig. 3) shows that the anticyclonic anomalies are associated with cold anomalies and the cyclonic anomalies overlay warm anomalies. Before the monsoon burst, a very strong (anomalous) temperature gradient between the anomalous high and low pressure centers (see Fig. 3) propagates across the continent, reaching the northern parts of Australia at the time of the monsoon burst. One interpretation of this pattern is the intrusion of a midlatitude synoptic front into the tropics. This interpretation is examined using the objective front dataset on the 850-hPa level from Berry et al. (2011). As noted by these authors, an individual front detected by this diagnostic need not correspond directly with the traditional textbook schematic of (midlatitude) fronts. The algorithm detects linear airmass boundaries at a single level in the lower troposphere and thus, although referred to as fronts henceforth, a myriad of synoptic features can be detected. These data are available for the period 1989–2009; thus, a subset comprising of 150 monsoon burst cases is used. The front frequency anomaly during the monsoon burst cases is shown in Fig. 6. A coherent pattern of front frequency anomalies propagate across the Australian continent prior to a monsoon burst. At day −2 (Fig. 6) a positive front frequency anomaly is present over central Australia, which is followed to the west by a negative frequency anomaly. Comparing Fig. 6 with Fig. 2b shows that the positive front frequency anomaly lies along an anomalous trough in the MSLP field, whereas the negative front frequency is centered on an anomalous anticyclone, consistent with the structure of a synoptic cold front. Over the following few days, the positive front frequency anomaly propagates to the north and east, reaching the monsoon region on the composite burst date (day 0). The strength of the fronts at 850 hPa in the monsoon burst case, as determined by the magnitude of the ϑw gradient at 850 hPa, are not significantly stronger or weaker than their climatology.

From the sequence of composite mixing ratio anomalies (Fig. 5) it appears that at low levels in the tropics there is moistening from the adjacent ocean by the anomalous convergence in the warm conveyor-belt-like structure that is rooted in the midlatitudes. This moistening process is examined with Fig. 7, which shows the composite mixing ratio flux convergence anomaly, averaged over the entire monsoon region (the area shown by the inset in Fig. 1a) as a function of pressure level and
FIG. 5. (a)–(f) Time-lagged composite potential temperature anomalies (K, color shading) with wind anomalies (m s\(^{-1}\), vectors, reference vector shown in top right of each panel) and total wind speed (m s\(^{-1}\), black contours) on the dynamic tropopause, defined as the −2-PVU surface. (g)–(l) Time-lagged composite anomalies of 925-hPa specific humidity (g kg\(^{-1}\), shaded), wind (m s\(^{-1}\), vectors, reference vector shown in top right of each panel), and temperature (K, black contours with dashed negative). Maps are shown every day from (top) −5- to (bottom) 0-day lag.
lag. Ten days before a monsoon burst there is moisture flux divergence over the entire troposphere with anomalous easterlies throughout, consistent with the definition of the burst being a change from very dry to very wet conditions. In the period leading up to the monsoon burst there is an abrupt change to moisture flux convergence over the entire troposphere. This moistening begins at low levels (below the 800-hPa

**Fig. 6.** Time-lagged composite front frequency anomalies (%, color shading) shown every day from (a) −2 to (d) +1-day lag.

**Fig. 7.** Composite mixing ratio flux convergence (shaded, \(10^{-9}\) g kg\(^{-1}\) s\(^{-1}\)) and wind anomalies (m s\(^{-1}\), vectors, reference vector shown in top right) averaged over the region 10°–20°S, 120°–150°E (see inset in Fig. 1a), shown as a function of days time lag and pressure level.

**Fig. 8.** Composite convective available potential energy (solid line, J kg\(^{-1}\)) and convective inhibition (dashed line, J kg\(^{-1}\)) averaged over the region 10°–20°S, 120°–150°E (see inset in Fig. 1a), shown as a function of days time lag.
level) approximately 4 days prior to the composite burst date as the wind anomalies begin to exhibit a northerly component. The time at which moistening begins is delayed with increasing height, consistent with a westward tilted midlatitude cyclone and front moving through the region. At all levels the moistening is coincident with a weakening of the anomalous easterly flow and the development of a northerly component.

The integrated effect of the deep moistening on the likelihood of convection is indicated by the calculation of convective available potential energy (CAPE) and convective inhibition (CIN), which is displayed in Fig. 8. These calculations are confined to the land area only in the region 10°–20°S, 125°–145°E (inset map on Fig. 1a). Both composite CAPE and CIN begin to increase before the monsoon burst. The CAPE begins to increase continually from day –7 onward to a peak at day –1, after which it falls dramatically, presumably as convection in the burst begins. During this period, the area mean CAPE almost doubles from its value 10 days prior to the monsoon burst. The CIN also increases just prior to the monsoon burst; between days –4 and –1 the CIN increase by approximately 50%, before reducing as the burst begins.

Although midlatitude cyclones transit Australian longitudes regularly throughout the year, monsoon bursts are irregular (see, e.g., Figs. 1 and 2), implying that the passage of cyclone south of the Australian continent does not guarantee a monsoon burst. Whether or not a midlatitude disturbance triggers a monsoon burst may depend on the large (hemispheric) scale conditions. This possibility is examined here using several common climate indices. The impact of the MJO is assessed using the RMM phase diagnostics developed by Wheeler and Hendon (2004), which uses the amplitude of the first two empirical orthogonal functions of the combined near-equatorial wind and outgoing longwave radiation fields. Following Wheeler and Hendon (2004), the state of the MJO at the start of the monsoon bursts is shown by the scatterplot in Fig. 9. This diagram indicates that monsoon bursts occur in any phase of the MJO, including when the MJO is weak (indicated by the center circle in the figure). Climatologically, the MJO phases are evenly distributed, with 37% of days falling into the weak category and approximately 8% in each of the 8 RMM phases. In the monsoon burst cases, there are slightly fewer weak cases compared with climatology (32% of total) and more cases fall in phases 4–7 (44% of the total) than in phases 1–3 and 8 (25% of the total). Overall, this indicates that monsoon bursts are more likely (but not exclusive to) when the envelope of MJO convection is in the vicinity of the Australian continent, consistent with previous studies concerned with monsoon onset (e.g., Hung and Yanai 2004).

Caution must be exercised in interpreting these statistics as the RMM index uses temporal filtering. Consequently, the outgoing longwave radiation signature from the monsoon burst could be aliased onto the RMM phase diagnostics, potentially resulting in circular reasoning. Given that the composite view of the MJO is a broad area of tropical convection that propagates eastward around the globe (Madden and Julian 1971), the time evolution of the MJO will reveal if aliasing is a
problem. Using the monsoon burst dates, the RMM phase is displayed in Fig. 10 as a percentage versus lag time. Here the weak cases (inner circle in Fig. 9) are included by assigning them to their appropriate phases, although the inclusion of the weaker cases does not change the essential result. From Fig. 10, it is clear that there is a preferred progression of the MJO phase over the 20 days prior to the composite monsoon burst. Approximately 20 days before the monsoon burst, the RMM is most frequently in phase 2 (convection centered in the central Indian Ocean, with suppressed convection over Australia). The RMM shifts to phases 3 and 4 (convection in the eastern Indian Ocean) 10 days before the burst, reaching phase 5 and 6 (convection centered on Australian longitudes) at day 0. This progression through the RMM phases is consistent with the expected geographical progression of the MJO convection, showing that there is a genuine connection with the occurrence of monsoon bursts, although the presence of the active phase of the MJO does not guarantee a monsoon burst will occur.

Australian rainfall in the tropics is commonly linked with ENSO and rainfall in the extratropics is commonly linked with the SAM (see, e.g., Risbey et al. 2009). These phenomena can be characterized using simple indices—namely, the SOI (e.g., McBride and Nicholls 1983) and the SAM index (Kidson 1999). Histograms of the SOI and SAM index in each of the monsoon burst cases are shown in Figs. 11a and 11b. In terms of ENSO (Fig. 11a), the majority of monsoon bursts occur when the SOI indicates neutral conditions (i.e., between minus and plus one standard deviation), although they occur across the entire range of SOI values. There are two major peaks in the distribution: they lie at $-0.75$ and $+1.25$ standard deviations, and overall slightly more than half of the monsoon bursts (55.7%) occur when the SOI is negative (corresponding to El Niño conditions). There is, however, apparently no strong preference for monsoon bursts in either El Niño or La Niña conditions. The occurrence of monsoon bursts with respect to the SAM index (Fig. 11b) is similarly distributed around neutral conditions, with monsoon bursts found at extreme high and low values of the index. Unlike the SOI, the SAM index is skewed, with almost two thirds (61.8%) of the monsoon bursts in the positive phases of SAM, although most cases occur when the magnitude of the index is small. At the Australian longitudes a positive SAM index during December–February (DJF) occurs when the mean subtropical ridge is shifted poleward of its mean position (see, e.g., Hendon et al. 2007), implying that the midlatitude storm track is also shifted poleward.

4. Discussion and concluding remarks

In this study, the composite evolution of monsoon bursts has been examined for 218 cases during the period October–April 1979–2009. The monsoon bursts have been defined as changes in the area-averaged rainfall over tropical north Australia from drier-than-average to wetter-than-average conditions over a 7-day period. Analysis of the individual seasons and the statistics of monsoon bursts has shown that there is pronounced year-to-year variability in the character of the area-averaged rainfall in this region. There is a large spread in the number of bursts and the return period of consecutive events (see Fig. 2a), which is similar to the characteristics of coherent PV maxima in the Australian tropics noted by Berry et al. (2012). Indeed, some of the
218 cases may be linked to the presence of coherent PV maxima in the Australian tropics, although this does not mean that the role of midlatitude features suggested by the lag composites is irrelevant in these cases. It has been found that some coherent PV maxima are formed as debris from midlatitude wave breaking along the eastern coast of Australia (Berry et al. 2012) and that fronts are always marked by lines of cyclonic PV; thus, the presence of fronts and PV maxima are not mutually exclusive. The temporal distribution of monsoon bursts (Fig. 2c) shows that they occur throughout the entire warm season but are slightly more frequent in the period when the climatological rainfall is increasing rapidly (Fig. 1a), prior to what is generally accepted as the monsoon onset (on average around 28 December; e.g., Drosdowsky 1996). A series of extratropical intrusions were noted by Davidson et al. (2007) prior to the onset of the Australian monsoon and described as either “preconditioning” the tropics or “false” onsets. A distinction between pre-onset and post-onset has not been made in this study as the bursts are defined relative to a seasonally evolving climatology of rainfall. The weak preference for the monsoon bursts to occur prior to onset could be an artifact of the burst definition [linked to the lower standard deviation early in the season (see Fig. 1a)] or the intrusion of extratropical features is...
made more difficult by a well-established, large-scale monsoon circulation.

The composite lower-tropospheric temperature, moisture, and front frequency anomalies suggests that a lower-tropospheric-front-like feature is an important ingredient for the development of monsoon bursts in the Australian tropics. The lag composites show that as an extratropical cyclone moves through Australian longitudes, its associated front pushes across the center of the continent into the tropics. Further analysis of individual cases (not shown) suggests that in many instances the airmass boundary detected is reminiscent of drylines found in regions such as North America or northern and central Australia (Arnup and Reeder 2007, 2009), rather than the tropospheric deep frontal structures associated with midlatitude cyclones. Ahead of this front there are anomalous northerlies that advect relatively warm, moist air from the surrounding oceans onto the landmass. The composite CAPE approximately doubles prior to the monsoon burst, indicating that the degree of conditional instability changes, potentially in response to the approach of the low-level front. A distinct plume of moisture orientated northwest–southeast from the tropics into the extratropical cyclone is formed, effectively becoming the warm sector of the composite extratropical cyclone and, in so far as the moisture anomaly is a proxy for cloud, is consistent with the general description of the wintertime northwest cloud bands (Tapp and Barrell 1984). Those fronts connected with monsoon bursts are not significantly different from their climatology in terms of strength.

Davidson et al. (2007) concluded that the STJ was key to the propagation of extratropical Rossby waves into the tropics, through the provision of deep westerlies to relatively low latitudes, a conclusion supported by ray tracing calculations. These authors suggested that baroclinic or barotropic development of the midlatitude disturbance on the STJ did not occur in their monsoon onset cases. It is important to note that during the analysis period used here (October to April) there are significant changes to the upper-level jet structure in the vicinity of Australia. Figure 12a shows the mean 200-hPa wind speed from ERAI, averaged 90°–170°E, as a function of latitude and date. Figures 12b–e shows time mean, longitudinally averaged vertical cross sections of wind speed in different phases of the monsoon evolution, defined on the basis of the AWAP climatology shown in Fig. 1a.

In the premonsoon period (Fig. 12b) both the STJ and MLJ are present; the STJ has higher wind speeds, but is vertically confined between 400 and 100 hPa, whereas the MLJ extends from the lower troposphere to levels above 50 hPa. Both jets weaken during the monsoon onset phase (Fig. 12c) and during the peak monsoon there is only the MLJ near 50°S, with no evidence of the STJ at these longitudes (Fig. 12d). During the retreat phase (Fig. 12e) the STJ reemerges, resulting in the double jet structure similar to the premonsoon period. Given the changing nature of the basic state, the propagation of Rossby waves to low latitudes is likely to be different at different points in the season. To examine this, the 218 cases in the synoptic composite are divided according to the four monsoon phases. Figure 13 shows...
the composite MSLP anomaly with anomalous 925-hPa wind vectors and 200-hPa wind speed 2 days before a monsoon burst for cases in each monsoon phase. In the first three phases (premonsoon to peak monsoon) the MSLP and low-level flow anomalies are very similar to one another (and the combined composite in Fig. 3), with an anomalous cyclone over southeastern Australia, an anticyclonic anomaly in the Great Australian Bight, with anomalous southwesterly flow directed into the tropics. The pattern during the retreat period (Fig. 13d) still exhibits an anomalous anticyclone in the Great Australian Bight and a trough extending from the tropics toward southeastern Australia but also shows a large-scale cyclone in the monsoon region and synoptic-scale cyclonic centers in the tropical Indian Ocean. The most significant changes are in the upper troposphere, with the 200-hPa STJ absent during the peak and retreat phases, as suggested by Fig. 12. Even with these large changes at upper levels, the evolution of the flow at low levels is similar and monsoon bursts still occur. This suggests that the upper-level STJ does not strongly influence monsoon bursts in the manner hypothesized by Davidson et al. (2007) for the monsoon onset. Instead, it is contended that monsoon bursts are linked to the progression of fronts associated with transient mid-latitude disturbances.

It might be anticipated that the ability of a front associated with an extratropical cyclone to penetrate the Australian tropics during the warm season is adversely affected by the boundary layer mixing forced by strong sensible heating over the interior of the continent and the meridional distance over which the front must propagate. As monsoon bursts do not develop with the passage of every midlatitude cyclone further work is required to determine what factors are important in permitting a front to reach these low latitudes.

Relatively weak links are found between the occurrence of monsoon bursts and common climate indices. Monsoon bursts occur in all phases of the three commonly used indices examined here, with only weak tendencies toward particular phases. However, the phase of the MJO may dictate the ensuing amount of rainfall and the large-scale dynamic response as the phase of the MJO is linked to large-scale ascent, tropospheric humidity, etc., in the vicinity of the Australian continent (Kiladis et al. 2005). Thus, it appears that an active MJO moving through Australian longitudes increases the probability of a monsoon burst, all else being equal. It is speculated that early in the summer (before the monsoon circulation is established) that there are reasonably frequent incursions of extratropical systems into the tropics and their timing with respect to the MJO phase determines the magnitude of the convective response. In the dry phase of the MJO, extratropical fronts would produce little or short-lived rainfall, corresponding to “false onsets,” whereas in the wet MJO phase, fronts would trigger widespread convection; the first time this occurs in the season of sufficient magnitude to feed back on the large-scale flow would be termed the monsoon onset. The coincidence of extratropical systems and an active phase of the MJO during monsoon onset has been reported by Hung and Yanai (2004) and is consistent with the variability of the onset dates (Holland 1986).

In summary, this study has shown that monsoon bursts are regulated by the passage of extratropical disturbances and their associated fronts. A midlatitude Rossby wave (and associated surface cyclone) reaching the west coast of Australia decelerates in the MLJ exit, causing the Rossby wave to expand meridionally and potentially break, allowing the disturbance to extend to lower latitudes. The lower-tropospheric flow associated with the surface cyclone (and front) alters the airmass source for the continent, advecting relatively warm, moist air onshore, thereby promoting convection. With the active phase of the MJO in the vicinity, a supply of tropospheric deep moisture is more readily available, increasing the probability of convection over a large area. This mechanism differs slightly from the monsoon onset mechanism suggested by Davidson et al. (2007), who emphasized the role of the STJ in refracting mid-latitude upper-tropospheric disturbances toward the tropics. It was suggested in previous studies that extratropical disturbances regulate convection through the secondary circulation controlling upper-level divergence, it is speculated here that low-level advection connected to the penetration of frontal features is key.

Perhaps the most surprising result here is the very distinct extratropical pattern that is the precursor of monsoon bursts; it might be expected that when averaged over 218 cases the composite produced would be smeared out as a result of slight differences in phase speed. Instead, it is found that the composite MSLP pattern (Figs. 3 and 4) shows a wave packet developing in the extratropics near the Greenwich meridian approximately one week before a monsoon burst. Open questions still remain regarding the monsoon bursts. It has been shown here that these bursts are coincident with the arrival of extratropical of cyclones over the southern parts of Australia, the extension of fronts into the tropics, and the resultant advection of warm, moist air onto the Australian landmass. However, it is not known why only some of the extratropical cyclones result in monsoon bursts. From the lag composites (Figs. 3 and 5), no large-scale anomalies can be seen in the strength or position of the upper-tropospheric jets or the
low-level flow in the tropics; away from the synoptic systems the flow anomalies are generally less than 1 m s\(^{-1}\), consistent with the finding that the SAM and SOI indices are well distributed over the cases. For this reason, it is suggested that the probability of a monsoon burst depends on characteristics of the antecedent synoptic disturbance, such as its amplitude, the manner in which it interacts with the upper-level jets (particularly Rossby wave breaking), the nature of its associated fronts, as well as the availability of moisture in the tropics. Future work should focus on identifying if the precursor midlatitude disturbances have attributes that are distinct from the general population of disturbances in order to advance forecasting abilities in the Australian region. The relationship between the characteristics of the extratropical system, the nature of the MJO, and the intensity of the resulting burst should also be analyzed. Connected to this is the need to examine climate projections to determine if the physical mechanisms producing rainfall in the current climate match the results shown here and, if so, how these mechanisms will change in the future climate, in order to understand how tropical rainfall is likely to be affected.

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