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Key Points:
- The Madden-Julian Oscillation (MJO) modulates tropical Australian rainfall
- This response is enhanced in El Niño periods
- The effect of ENSO on the MJO-rainfall connection is independent of the MJO-ENSO statistical connection

Supporting Information:
- Supporting Information S1
- Table S1

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Joint Modulation of Intraseasonal Rainfall in Tropical Australia by the Madden-Julian Oscillation and El Niño-Southern Oscillation

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Abstract Rainfall in tropical Australia is a critical resource for the agricultural sector. However, its high variability implores improvements in our understanding of its variability. Australian tropical rainfall is influenced by both the Madden-Julian Oscillation (MJO) on intraseasonal time scales and El Niño-Southern Oscillation (ENSO) on interannual time scales. This study examines the joint relationship between the MJO, ENSO, and tropical Australian rainfall variability. We analyze daily precipitation data from stations across tropical Australia during the wet season (November to April). The wet season rainfall response to the MJO is found to be greater during El Niño than La Niña. We demonstrate that this relationship is not due to the statistical relationship between the MJO and ENSO indices but instead due to differences in how the MJO modulates the large-scale circulation during El Niño versus during La Niña.

Plain Language Summary This manuscript presents studies of the simultaneous relationship between tropical Australian rainfall variability and two modes of climate variability: the Madden-Julian Oscillation (MJO) and El Niño-Southern Oscillation (ENSO). We analyze daily rainfall at 43 long-record (1942–2011) weather stations across tropical Australia during the wet season (November to April). The MJO is shown to increase rainfall in certain phases (phases 5 and 6) and decrease it in other phases (phases 2 and 3), but more importantly, this signal is enhanced during El Niño as compared to La Niña. This is demonstrated to be due to how the MJO influences atmospheric circulation differently in El Niño versus La Niña wet seasons. These results are significant in demonstrating that the MJO and ENSO do not act independently on rainfall; the state of both climate modes need to be known in order to better predict rainfall variability. Agricultural decisions are highly dependent on knowledge of rainfall variability, from crop management on intraseasonal scales to crop types on interannual scales. Overall, the results of this study provide a better understanding of wet season rainfall and its potential predictability in tropical Australia, a major exporter of agriculture and livestock, with implications for improved agricultural decision-making.

1. Introduction

Many sectors of the Australian economy are sensitive to the frequency and amount of rainfall. Extreme rainfall can cause flooding in major population centers, such as the 2010–2011 Queensland floods (King et al., 2013). Skillful probabilistic climate forecasts can aid decision-making in agriculture around the timing and strategies for planting and harvesting. This is particularly true for tropical regions, where climatic variability has direct impacts on production (Hammer et al., 1987). Fluctuations in agricultural production are often compounded throughout the local economy (White, 2000) and can influence export prices and terms of trade. We expect a better understanding of rainfall variations and their prediction to provide clear benefits (Meinke & Stone, 2005).

For tropical Australia, most rainfall occurs from November to April, and significant variability of this rainfall occurs on both interannual (Nicholls et al., 1997) and intraseasonal (Wheeler & McBride, 2012) time scales. On interannual time scales, the El Niño-Southern Oscillation (ENSO) is the dominant driver of rainfall variability (Risbey et al., 2009), with El Niño and La Niña bringing drier and wetter conditions, respectively. On intraseasonal time scales, the Madden-Julian Oscillation (MJO) is the dominant driver of variability (Wheeler & McBride, 2012), bringing increased or decreased rainfall as the MJO's convective anomalies propagate across the tropics. Using the Wheeler and Hendon (2004) phase definition of the MJO, increased rainfall occurs in phases 5 and 6 and reduced rainfall occurs in phases 1 and 2 (Wheeler et al., 2009). These MJO-related variations are often associated with burst and break periods in the monsoon, with monsoon bursts more likely to occur when the MJO's enhanced convective phase passes over tropical Australia (Berry & Reeder, 2016).

Climate variations can be modulated independently by ENSO and the MJO, but in some regions ENSO acts jointly with the MJO to modulate climate on intraseasonal time scales. For example, precipitation and temperature anomalies over South America (Shimizu & Ambrizzi, 2015) and anomalies in tropical cyclone activity in several basins (Klotzbach & Oliver, 2015) are known to experience MJO-associated variations with a different magnitude during El Niño versus La Niña. The MJO itself varies on interannual time scales with ENSO. For example, Pohl and Matthews (2007) show that the lifetime amplitude of the MJO varies with ENSO, and Tam and Lau (2005) show that during El Niño there is an eastward shift in convective anomalies and the speed of propagation of the MJO decreases. However, there is no significant contemporaneous, or zero lag, relationship between ENSO and MJO strength (Hendon et al., 2007; Hendon et al., 1999). A partial explanation is that this could be due to central Pacific and eastern Pacific-type El Niño events enhancing and suppressing MJO amplitudes differently (Feng et al., 2015; Gushchina & Dewitte, 2012). Nevertheless, gaps remain in understanding the joint modulation of tropical Australian rainfall by the MJO and ENSO. When examining the modulation of the MJO-rainfall connection with ENSO, it is important to isolate the distinction between ENSO-driven variations in the MJO itself and independent ENSO-driven variations in the *impact* of the MJO. An example of the latter could include ENSO-related variations in the strength and location of the Walker circulation that facilitate or suppress the connection mechanisms between the MJO and rainfall.

Through this study we address the question of the joint modulation of tropical Australian rainfall by the MJO and ENSO. We analyze daily precipitation observations from 43 long-record stations. We find that the MJO modulation of rainfall is stronger during El Niño than La Niña. We also use a double-significance test to demonstrate that this result is largely not due to the statistical relationship between the MJO and ENSO indices themselves. Rather, ENSO significantly modulates the rainfall response to the MJO, which has implications for the prediction of rainfall across tropical Australia.

2. Data

2.1. Rainfall Observations

We obtained daily precipitation data from the Australian Bureau of Meteorology (BoM) for 43 stations. These stations were chosen as they were long enough to have observed many variations in ENSO state. These were stations within tropical Australia (north of the Tropic of Capricorn, 23.44°S) and were at least 80% complete over 1 January 1942 to 31 December 2011 (70 years). This same analysis period was defined for all records to ensure the same background climate. See Table S1 in the supporting information for details on station names, locations, and completeness.

2.2. MJO Index

We define the MJO amplitude and phase using the historical reconstruction of the Wheeler and Hendon (2004) Real-time Multivariate MJO (RMM) index by Oliver and Thompson (2012). The index, denoted IHR (Index Historical Reconstruction), is a reconstruction of the RMM index from 1905 to 2011 based on multiple linear regression of Twentieth-Century Reanalysis (20CR) (Compo et al., 2011) surface pressure time series onto the RMM index, which starts in 1974. The 20CR surface pressures are then used to hindcast the RMM index back to 1905.

An active MJO is defined when the IHR amplitude is $\geq$1. MJO phases from 1 through 8 describe the longitudinal location of the region of active MJO convection in the tropics. The IHR index allows us to better examine interannual variations in MJO-related rainfall associated with ENSO.

2.3. ENSO Index

We define ENSO using the Troup Southern Oscillation Index (SOI) (Troup, 1965) obtained from the BoM. The SOI represents the standardized anomaly of the mean sea level pressure difference between Tahiti and

Darwin. We smooth the monthly values with a 3 month running average, then convert to daily values by assigning each monthly value to all days in that month. El Niño and La Niña periods are defined when the smoothed, daily SOI index is <-8 and $>+8$, respectively.

2.4. Twentieth-Century Reanalysis

The 20CR data (Compo et al., 2011) are used to evaluate how large-scale atmospheric fields are modulated by the combination of ENSO and the MJO. The 20CR assimilates synoptic observations of surface pressure and monthly observations of sea surface temperature and sea ice from which it produces 6-hourly estimates of the global atmospheric state. We obtained daily fields of surface precipitation rate, midlevel relative humidity (at 600 hPa), and upper level vertical motion (ω; at 300 hPa) over the 1942–2011 period.

3. Methods

We restrict our analysis to the wet season defined here as November to April. The upper tercile of daily rainfall during the wet season is used as the minimum level for “wet conditions,” and this value varies from station to station. Nominally, the probability of exceeding the upper tercile is 33%. However, some stations in drier areas receive rainfall on fewer than one in every 3 days, and at those stations the upper tercile is equal to zero and the probability of exceeding this upper tercile value is therefore <33% (see Figure S1 in the supporting information). We therefore define a baseline probability as the actual probability of exceeding the upper tercile, which will be <33% at some stations (see Figure S2 in the supporting information). We then calculate the probability of daily rainfall exceeding the upper tercile conditioned on MJO phase, regardless of ENSO state. This conditional probability is presented as a ratio to the baseline probability, following Wheeler et al. (2009). A ratio value of 1 indicates no change in the probability of upper tercile rainfall relative to the baseline probability, while a value of 0.5 indicates a halving of the probability of upper tercile rainfall. We then include the influence of ENSO by performing the above analysis but restricting it to days which are classified as El Niño or La Niña and calculating the eight-phase MJO composites separately for each ENSO state.

Statistical significance of results is tested using a Monte Carlo technique, whereby we simulate 50,000 randomizations of the MJO phase vector (Wheeler et al., 2009). Each iteration consists of randomly shifting the MJO phase vector relative to the precipitation time series in steps of 7 days and recalculating the results. The shifts allowed in the method are a minimum of 50 days and a maximum of total length minus 50 days. A confidence interval is then built from these iterations. This technique preserves the statistical properties of the MJO such as its serial correlation. This test tells if rainfall probabilities, by MJO phase, are greater or less than expected given random weather variations.

If changes in the MJO-rainfall relationship are observed as a function of ENSO state, these changes could be due to one or both of two factors: (1) changes in the rainfall response to the MJO due to ENSO-related changes in the climate system and/or (2) changes in the MJO itself due to its statistical relationship with ENSO. It has been suggested that the second possibility might manifest through a change in the frequency distribution of MJO phases with ENSO state (Pohl & Matthews, 2007). Therefore, we perform a double-significance test to discern between these two possibilities. First, we perform the basic test described above which tests if anomalies are significant relative to random climate variations (regardless of ENSO state). Second, we repeat this test but restrict the simulated Monte Carlo phase vector to only values that occurred during the ENSO state of interest. This ensures that the changing distribution of MJO phases in El Niño and La Niña (i.e., the statistical relationship between the MJO and ENSO indices) are implicitly taken into account. By performing the Monte Carlo double-significance test using only MJO phase values from the ENSO state of interest, we preserve the MJO-ENSO statistical relationship as part of the test. Therefore, any significant results are those which exceed any influence of this relationship. Both tests are carried out at the 5% significance level, and if both tests prove the composites to be statistically significant, then they could not have arisen due to the MJO-ENSO statistical relationship alone. Consequently, they reflect a real change in the MJO-rainfall relationship.

We note that rainfall may be part of the MJO in certain regions of Australia, with stronger rainfall anomalies indicating a stronger MJO event. Therefore, in those regions it cannot be said that the MJO causes such rainfall anomalies but rather that these anomalies are part of the MJO itself. However, for the purposes of this study we discuss rainfall as being external to the MJO, i.e., responding to variations in the MJO due to its interaction with ENSO.

4. Results

4.1. Joint Response of Rainfall to the MJO/ENSO Across Tropical Australia

We begin by showing the spatial coherence of the rainfall response to the MJO and ENSO by studying the probability of upper tercile rainfall with MJO phase across all 43 stations, separately for El Niño (Figure 1) and La Niña (Figure 2). Generally, across tropical Australia, phases 4–6 are wetter while phases 8, 1, and 2 are drier. However, the range of the rainfall response to the MJO is clearly stronger in El Niño as compared to La Niña. This difference in response is particularly strong in wet phases 5 and 6 and dry phase 2, and is more pronounced for the coastal stations than inland.

During both El Niño and La Niña periods, upper tercile rainfall probabilities are generally significantly increased in MJO phases 5 and 6 (Figures 1e, 1f, 2e, and 2f, open circles), consistent with previous studies (Wheeler et al., 2009). During El Niño, the MJO effectively doubles the probability of upper tercile rainfall in phases 5 and 6 along much of the coast and the interior of Queensland, and shows a clear progression from Western Australia to Queensland. During La Niña by comparison, increases in these phases are weaker, typically showing a ratio of less than 1.4 compared to the aforementioned doubling in El Niño. Furthermore, the presence of many bold circles in El Niño (Figures 1e and 1f) suggests that the rainfall response is significantly stronger than expected from variability within El Niño periods, especially along the entire coastline of tropical Australia. The same is not true of La Niña, meaning the MJO response of rainfall is within the range of variability of those periods, shown by an absence of many bold circles (Figures 2e and 2f).

El Niño periods also show a strong impact in the dry MJO phases, with several bold circles in MJO phase 2 (Figure 1b). The MJO during El Niño typically decreases the probability of upper tercile rainfall by about one half in phases 8, 1, and 2. This is most prominently observed in phase 2, across the interior as well as closer to the coast of the Northern Territory and Queensland. During La Niña, however, there is an inconsistent mix of increases and decreases of rainfall probabilities. Several stations had a decrease in rainfall probability during dry MJO phases that was significantly greater than expected for La Niña periods, with bold circles in phases 7, 8, 1, and 2 (Figures 2g, 2h, 2a, and 2b). However, the decrease in rainfall probability is not statistically significant against random climate fluctuations when tested against the Monte Carlo distribution over the whole study period (i.e., these stations often also have a cross in Figure 2).

Overall, Figure 2 shows a smaller magnitude of variation across MJO phases and fewer bold circles than Figure 1, suggesting that the response of rainfall to the MJO in La Niña is weaker and less often statistically significant when compared to El Niño. The larger-magnitude response to the MJO in El Niño occurs in both wetter and drier MJO phases.

We tested our results for the cases of upper tercile thresholds computed independently for El Niño and La Niña. In these cases, there are more stations with ratios of daily rainfall probabilities that are not statistically significant when tested against the entire analysis period (see Figures S3 and S4 in the supporting information, crossed circles). However, the overall conclusion that there is a stronger rainfall response to the MJO in El Niño than in La Niña remains unchanged.

4.2. Range of Rainfall Response to the MJO

The magnitude of rainfall response at each station is defined as the difference between the probabilities of exceeding upper tercile rainfall in MJO phases 4–6 (wet phases) and 8–2 (dry phases). The largest and smallest probabilities from phases 4–6 and 8–2 were chosen, respectively, for the calculation of the difference. Analysis of the magnitudes (Figure 3) clearly highlights the greater response of rainfall to the MJO in El Niño compared with La Niña. Under the double-significance test, 12 of the 43 stations show a significant response in El Niño (Figure 3a, bold circles). In comparison, only seven stations have a significant response in La Niña (Figure 3c, bold circles). This difference is notable particularly in Queensland. The magnitude of rainfall response in La Niña (Figure 3c) is less than the response observed even when not stratified by ENSO state (Figure 3b), particularly around Darwin and several stations along the coast of Queensland. The stark difference in the rainfall response between El Niño and La Niña over Queensland could be associated

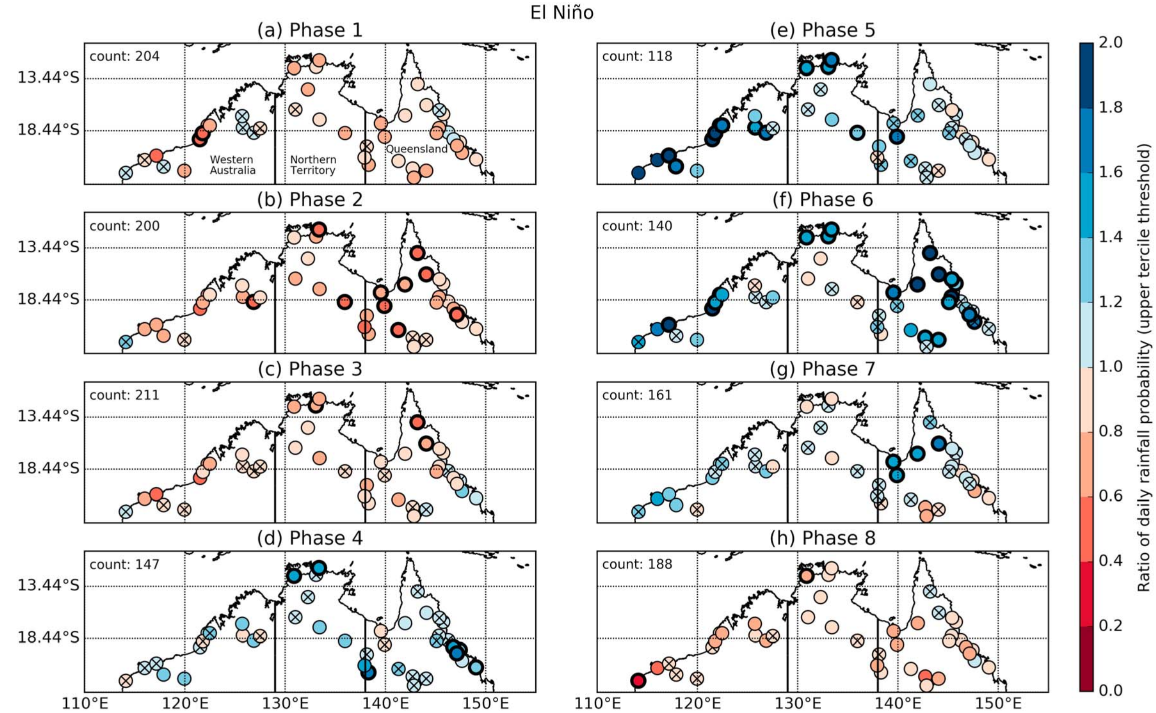

Figure 1. (a–h) Probability of extended wet season daily rainfall above the upper tercile for MJO phases 1–8 during El Niño, expressed as a ratio between the probability itself and the probability of upper tercile rainfall across all El Niños. Crossed-out circles are not significant at the 5% level over the analysis period regardless of ENSO state. Bold circles are significant at the 5% level over the analysis period when restricted to El Niño only.

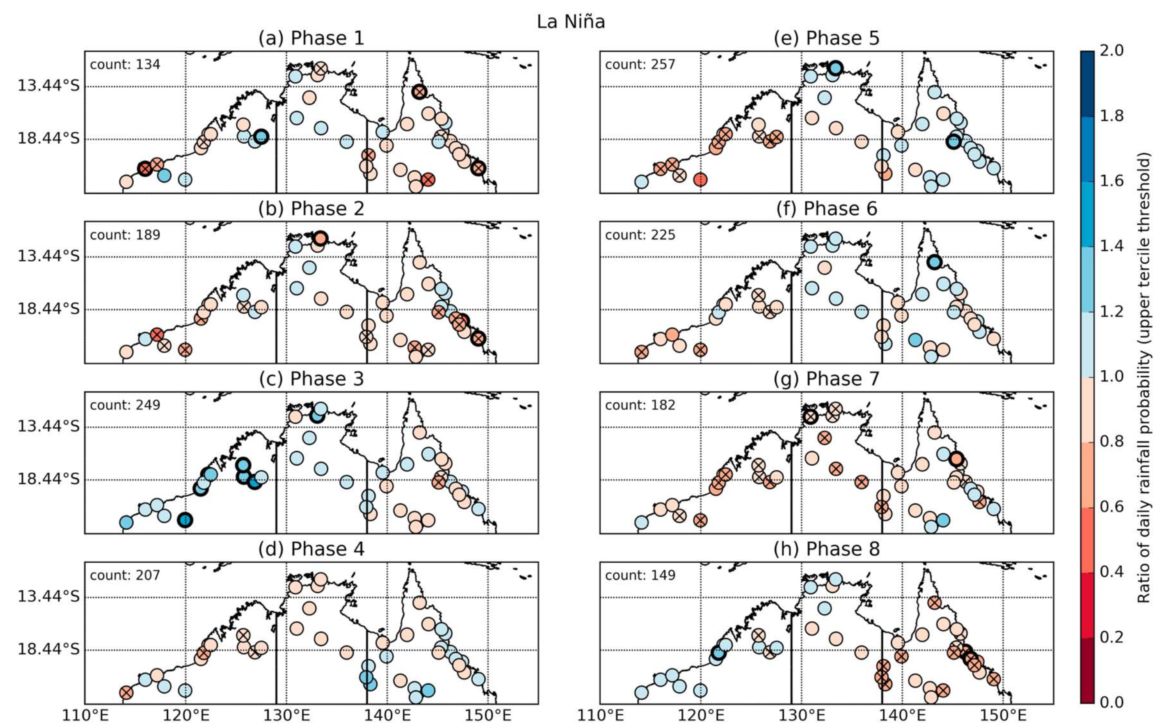

Figure 2. (a–h) Same as in Figure 1 but for La Niña.

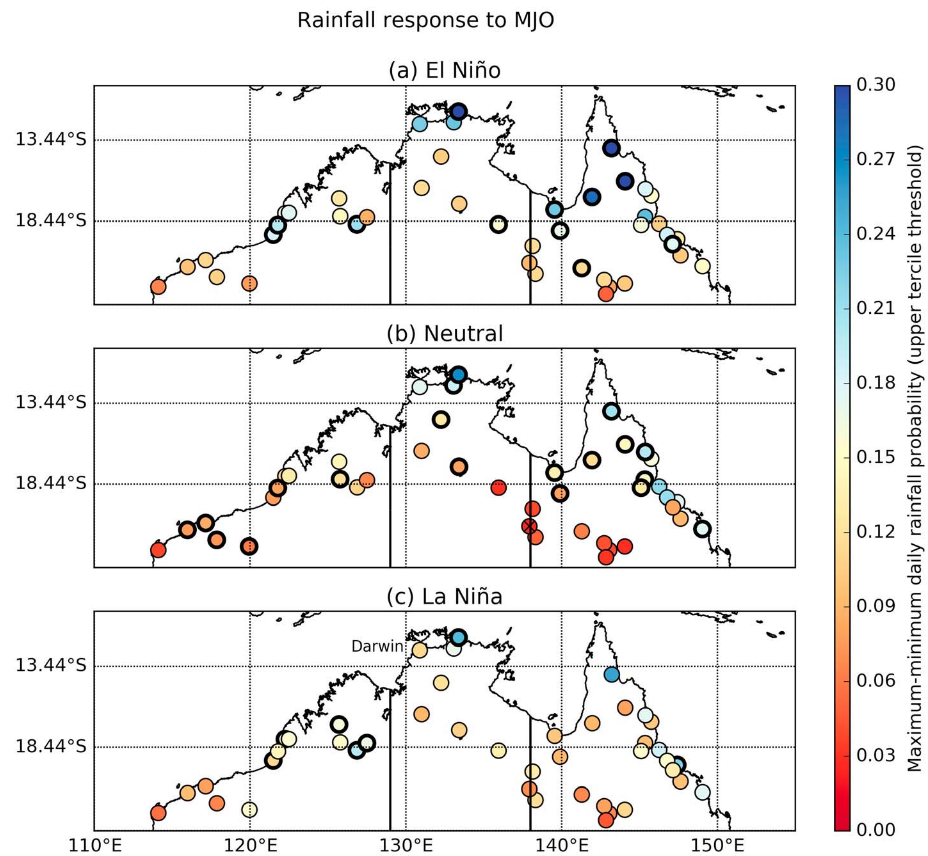

Figure 3. Magnitude of extended wet season rainfall response to the MJO. The magnitude is shown for (a) El Niño, (b) neutral, and (c) La Niña periods. Crossed-out circles are not significant at the 5% level over the analysis period in any of the eight MJO phases. Bold circles are when the largest or smallest anomalies during phases 4–6 or 8–2, respectively, are significant at the 5% level over both the complete analysis period and when restricted to the specific ENSO state.

with the much shallower convection that characterizes the dry phases of the MJO there relative to the rest of northern Australia (Murphy et al., 2016).

We also analyze the ratio of maximum to minimum probabilities of daily rainfall above the upper tercile (as calculated for Figures 1 and 2 but restricted to the wet and dry MJO phases as in Figure 3) under different ENSO states, and show that the impact of the MJO on rainfall is demonstrably much stronger in El Niño than in La Niña. The ratios of rainfall probabilities in El Niño are higher than those in La Niña for 41 of the 43 stations (Figure S5 in the supporting information). This is most clearly observed in Queensland and Western Australia. Disregarding the Exmouth Gulf station (westernmost station), which we consider to have an exceptionally large value (5.9), the ratios of rainfall probabilities in El Niño to La Niña have a mean factor of 1.8 and a single-station maximum of 3.6.

4.3. MJO-ENSO Statistical Relationship

The double-significance test demonstrated that, in contrast to La Niña, the relatively wet conditions in MJO phases 5 and 6 and dry conditions during phase 2 for El Niño are both statistically significant compared to random climate variations and due to more than just the MJO-ENSO statistical relationship. However, we now test the possibility that the amplitude of the MJO across MJO phases varies by ENSO state.

The amplitude of IHR is greater in El Niño than La Niña across all MJO phases except phase 5 (Figure S6 in the supporting information). However, the ratio of IHR amplitudes between El Niño and La Niña is never greater than 1.17 (Table S2 in the supporting information). This slight difference in IHR amplitudes is not sufficient to explain the rainfall impact differing by a factor of up to 3.6 between El Niño and La Niña. While there is a possibility of nonlinearity, it would have to be strong to account for the observed results.

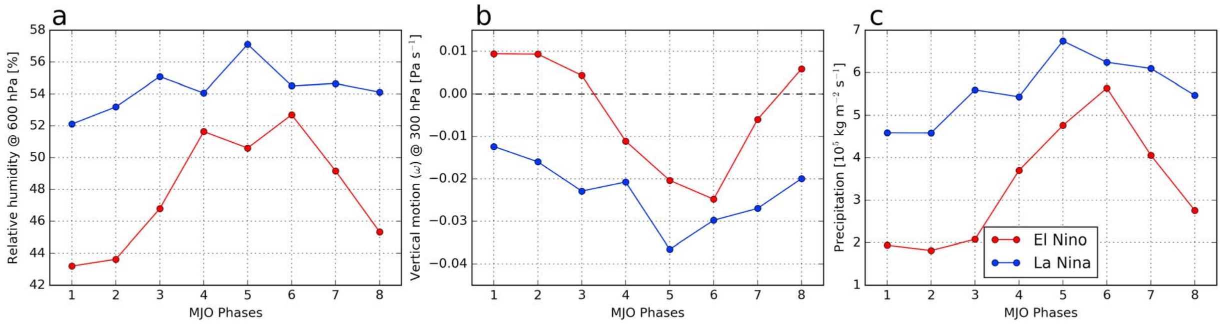

Figure 4. Average (a) 600 hPa relative humidity, (b) 300 hPa vertical motion, and (c) daily precipitation observed during the extended wet season and stratified by ENSO and MJO phase over the region from 10–20°S, 110–160°E.

In summary, our analysis of the statistical significance of the relationship between rainfall, the MJO and ENSO, and the variation of average MJO amplitudes with ENSO indicate that the MJO itself is not changing with ENSO in a manner large enough to drive the observed rainfall changes. Instead, the MJO impacts on rainfall itself are changing with ENSO state.

4.4. Possible Physical Mechanism

We use the 20CR to briefly investigate physical mechanisms that may be at work to drive these observed changes in precipitation. We calculate composites of 20CR precipitation, relative humidity, and vertical motion by MJO phase, using only data over land cells. The composites were calculated separately for each grid cell and then averaged spatially over 110–160°E and 10–20°S. The reanalysis successfully replicates the observed station changes in precipitation that were discussed previously; in that, there are larger MJO-driven modulations in precipitation in El Niño than La Niña (Figure 4c). Both midlevel relative humidity and upper level vertical motion also show considerably larger modulations in El Niño than La Niña, indicating that the MJO drives more atmospheric variability in an overall drier background base state over tropical Australia in El Niño (Figures 4a and 4b). During La Niña, the enhanced Walker circulation appears to reduce the impacts of the MJO on the large-scale atmospheric circulation over tropical Australia, thereby reducing observed precipitation variability. Alternatively, during El Niño the eastward shifted and weaker Walker circulation allows for much stronger large-scale atmospheric and associated precipitation modulations by the MJO. In addition, during El Niño the MJO is able to more strongly modulate rainfall by lowering rainfall probabilities during dry phases rather than by raising them during wet phases. These results are consistent with those calculated over 1958–2011 using the Japanese 55-year Reanalysis (Figure S7 in the supporting information).

The period covered by this study (November to April) includes the premonsoon, monsoon, and postmonsoon periods, each associated with distinct types of convection (Murphy et al., 2016; Pope et al., 2009), which in turn exhibit different convectional and hence rainfall responses to the MJO (Murphy et al., 2016). There may be possibly significant differences in the ENSO modulation of the MJO-rainfall relationship between these individual submonsoonal periods, which merit further investigation.

5. Conclusions

This study has found that wet season rainfall in tropical Australia responds to the MJO much more strongly during El Niño than La Niña. El Niño acts to strengthen the MJO-rainfall relationship, particularly during dry phases, while La Niña acts to suppress it. In addition, the magnitude of the rainfall response to the MJO during El Niño is statistically significant when tested against the entire study period as well as against variations that would typically be expected in El Niño. The same rainfall response and statistical significance is not observed in La Niña. This difference in rainfall response to the MJO is not due to the MJO-ENSO statistical relationship, and hence must be due to the effects of ENSO on the physical mechanism by which the MJO influences rainfall variability.

By highlighting the effects of the MJO and ENSO on tropical Australian rainfall variability, we build on existing literature concerning the MJO-ENSO relationship and its relevance to intraseasonal rainfall variability. Previous studies have found different ways by which the MJO interacts with ENSO to affect atmospheric conditions. For example, enhanced springtime MJO activity is suggested to produce favorable conditions for El Niño 8 months later (Hendon et al., 2007). Enhanced MJO activity has been found to weaken the atmospheric response to ENSO ocean temperatures (Hoell et al., 2014). Furthermore, the lifetime of the MJO is also found to be dependent on ENSO state, increasing under La Niña (Pohl & Matthews, 2007).

Our findings have implications for the prediction of tropical Australia's summer rainfall on intraseasonal time scales, in relation to ENSO phase. We show that ENSO acts to modulate interannually the intraseasonal response of rainfall due to the MJO. This demonstrates that the MJO and ENSO do not act independently on rainfall; there is a joint interaction, whereby the state of both climate modes must be considered. Agricultural decisions across temporal scales are dependent on knowledge of climatic variability, from logistics and tactical crop management at intraseasonal scales to crop types and sequencing at interannual scales (Meinke & Stone, 2005). These results provide a better understanding of wet season rainfall in tropical Australia, with the potential to improve agricultural decision-making.

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