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RESEARCH ARTICLE

Influence of the Madden–Julian oscillation on Costa Rican mid-summer drought timing

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The Central American mid-summer drought (MSD) is the decline of precipitation during the middle of the wet season (July and August) over Central America and southern Mexico. It affects agriculture and favours the initiation of bushfires in Costa Rica's national parks, particularly during El Niño years. The MSD is a seasonal phenomenon that varies in intensity and timing inter-annually. The Madden–Julian oscillation (MJO) has been shown to influence Costa Rican rainfall on intra-seasonal time scales, and therefore may be important to the MSD. In this study we use rainfall data from seven stations in Costa Rica to analyse the MJO's influence on the timing of the onset and end of the MSD. We find that the MSD is more likely to start and end in MJO Phases 1 and 8, respectively. Our findings indicate enhanced MSD predictability on intra-seasonal time scales, which could be beneficial to agricultural planning in Costa Rica.

KEYWORDS
Costa Rica, Madden–Julian oscillation, mid-summer drought

1 | INTRODUCTION

Over the southern part of Mexico and the majority of Central America, the rainy season is characterized by a bimodal distribution with peaks during May–July and August–October, and a relative minimum during July and August (Coen, 1973; Ramírez, 1983; Alfaro, 2014). The relatively dry July–August period is known as the "Mid-Summer Drought" (MSD), also called the "Canícula" in Spanish. Because of the economic consequences of rainfall on agriculture, understanding and improving the predictability of the onset and decay of the MSD from year-to-year is likely to be of considerable value to the agricultural sector in Central America.

Rainfall across the Pacific Coast of Costa Rica is broadly characterized by a rainy season from May to October and a dry season from November to April of the following year (Hastenrath, 1967; Alfaro, 2014). However, like much of Central America, Costa Rica also experiences the bimodal rainfall MSD phenomenon which affects a large part of its countryside and agriculture. Economically, agriculture makes up 6% of the national gross domestic product of Costa Rica and the success of its major economic crops, such as pineapple, coffee and rice, are highly dependent on the characteristics of the rainy seasons (Horn and Kennedy, 2006). These features make Costa Rica an excellent case study country to investigate and understand the large-scale climatic relationships affecting the timing of MSD onset and decay (end).

There is no consensus in the literature regarding the dynamics of the MSD or the cause of its existence. Small *et al*. (2007) pointed out that the MSD is not a real drought (i.e., with nearly zero precipitation for an extended period), but rather a decline by up to 40% of the wet season rainfall making it distinct from the true dry season. Mosiño and García (1966) identified the basic spatial distribution of the MSD and proposed that it was caused by dry northerly winds, themselves caused by a combination of high surface pressure systems over the southeast part of Central America, and a mid-atmospheric cyclonic circulation over the Gulf of Mexico during July and August. However, this has not really been supported by observations to this point in time. Magaña *et al*. (1999) suggested that the double crossing of Central America by the Intertropical Convergence Zone (ITCZ) caused the MSD, with ITCZ crossings corresponding to increased rainfall and inter-crossing periods leading to the MSD. However, Mosiño and García (1966) confirmed that the MSD could exist in locations where the double crossing of the ITCZ could not be detected. Mapes *et al*. (2005) suggested that the onset of the Indian Monsoon might also be associated with the MSD. Furthermore, Magaña *et al*. (1999) suggested that intense deep convection initiated at the start of the rainy season, causing a corresponding subtropical lower-tropospheric cyclonic circulation anomaly. Then the cyclonic cycle weakens, corresponding to an anticyclonic acceleration, which could strengthen the trade winds over Central America and the onset of the MSD. However, while this theory went some way to potentially explaining the MSD over Central America, it still does not explain the MSD over the Caribbean islands.

An important notable feature of the MSD is that it varies in intensity and timing on both intra-seasonal and inter-annual time scales. Higgins *et al*. (1999) proposed that the MSD was strong in the summer before El Niño and weak in summers associated with La Niña. They also suggested that the northern annual mode (i.e., Arctic oscillation) could influence the MSD by changing the variation of sea surface temperature. Alfaro (2014) also noted that strong MSD events were more likely during El Niño years and weaker MSD events were more likely during La Niña years.

The climate signal associated with the MSD is complex and may be modulated by a variety of regional forcing factors. A widely accepted theory suggests that the intensification and expansion of the north Atlantic subtropical high pressure cell could induce stronger trade winds, cooler sea surface temperature, increased subsidence, and diminished Caribbean rainfall, and its intensification and expansion could induce the MSD (Hastenrath, 1976, 1978, 1984; Granger, 1985; Knaff, 1997; Giannini *et al.,* 2000). The Caribbean low-level jet (CLLJ) is also shown to have the potential to influence the MSD (Wang, 2007; Wang and Lee, 2007). The CLLJ has semi-annual variability, characterized by two maxima in summer and winter and two minima in autumn and spring. Observations suggest that the maxima of the CLLJ could induce relatively low rainfall over Central America, corresponding to the duration of the MSD, which could also be associated with a minimum of tropical cyclogenesis.

The present study investigates the role of the Madden–Julian oscillation (MJO) on the timing of the MSD over Costa Rica. Amador *et al*. (2006) propose that the intra-seasonal variability of precipitation over Central America may influence the MSD. As the dominant mode of intra-seasonal variability in the global Tropics, the MJO is a likely candidate for predictable intra-seasonal variability of the MSD. Importantly, the MJO has been shown to impact rainfall over Central America (Barlow and Salstein, 2006; Martin and Schumacher, 2011; Brito *et al*., 2014). Here we demonstrate that the MJO brings higher rainfall in Phases 1, 2 and 8, leading to increased probability of MSD onset and end in these periods. We also demonstrate that the mechanism is the regional atmospheric circulation, dominated by wind anomalies associated with the MJO.

2 | DATA AND METHODS

In this study we analyse station observations of rainfall in Costa Rica and use an index of the MJO to identify the MJO's influence on the timing of onset and decay of the MSD over Costa Rica. We implement an algorithmic method proposed by García-Martínez (2015) to identify the onset and end dates of the MSD, and use statistical techniques to analyse the relationship with MJO variability.

2.1 | Precipitation

Rainfall data used in this study are daily observations from seven stations in Costa Rica (Table 1). They are located across Costa Rica including the Pacific coast, the Central Valley and the Caribbean coast, and have record lengths ranging from 18 to 74 years.

TABLE 1 Location and record length details of the seven daily rainfall stations in Costa Rica analysed in this study (data provided by the National Institute of Meteorology of Costa Rica)

Rainfall station	Code	Periods (years)	Altitude (m)	Longitude	Latitude	Missing data (%)
Llano Grande	74020	1976–2012	80	85°32′23″	10°35′54″	2.23
Aerop. Liberia Oeste 07	74051	1999–2015	89	85°33′07″	10°35′20″	4.30
Limon	81003	1943–2015	5	84°42′10″	09°59′59″	1.70
Aerop. Limon	81005	1998–2015	5	84°42′10″	09°59′59″	5.25
Aerop. Juan Santamaria	84169	1974–2015	932	84°10′52″	09°59′28″	2.33
Pocares	90001	1942–2015	6	84°14′42″	09°31′28″	4.29
Coto 49	100062	1987–2015	13	82°59′00″	08°38′00″	2.01

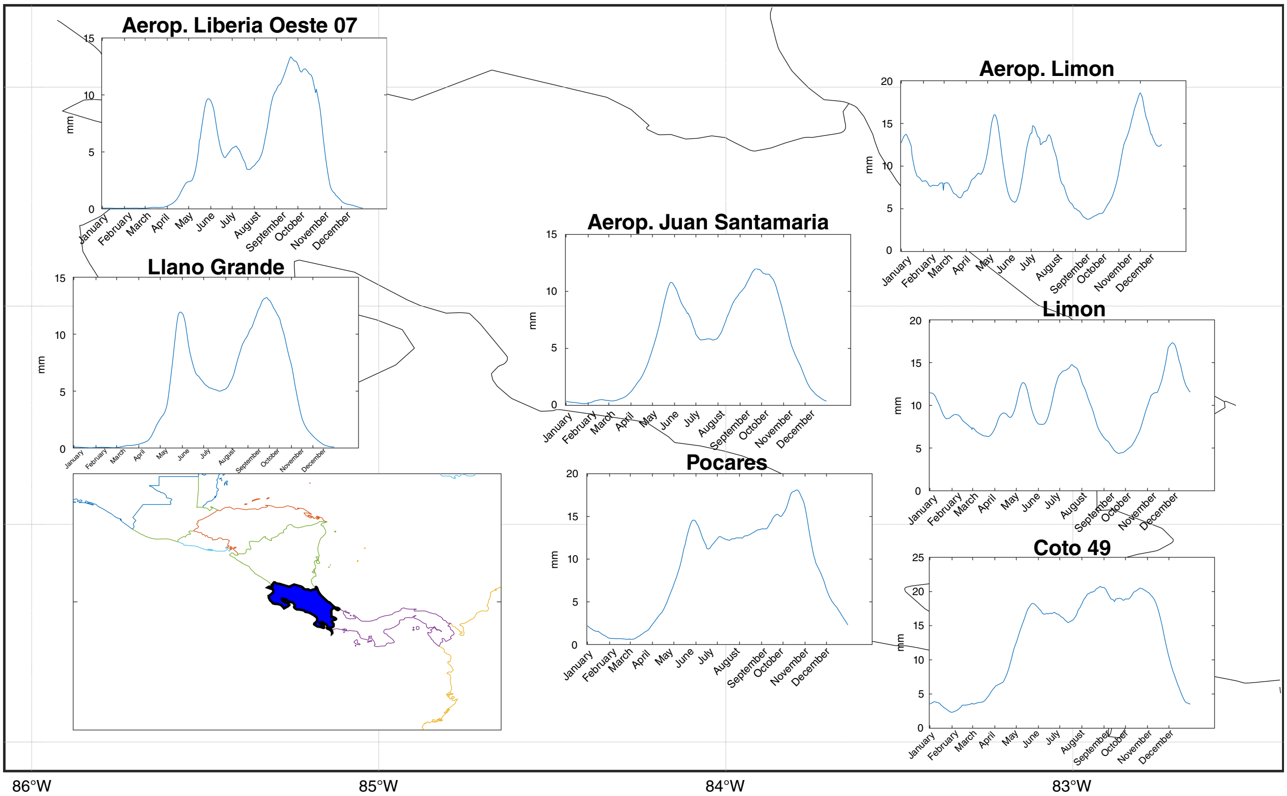

FIGURE 1 Daily climatologies of precipitation for each of the seven rainfall stations. Each sub-panel is positioned approximately over that station location [Colour figure can be viewed at wileyonlinelibrary.com]

2.2 | The MJO index

The most widely used MJO index is the bivariate index developed by Wheeler and Hendon (2004) (WH04 index). This index is based in part on satellite observations of outgoing long-wave radiation and thus does not cover the pre-satellite period. Therefore, we use the historical reconstruction of the WH04 index back to 1905 developed by Oliver and Thompson (2011) (OT11 index) to characterize the MJO over the full period of our data. The OT11 index is based on time series of surface air pressure from the twentieth century reanalysis (Compo *et al.,* 2011) as predictors of the observed index from Wheeler and Hendon (2004) in a multivariate linear regression model. The OT11 index is consistent with the WH04 index in both temporal and spectral properties over the common period (1979–2008) and its relationships with other properties (cloud cover, surface wind, precipitation and sea level) are shown to be consistent with corresponding results from the WH04 index over the early period (1905–1978). The OT11 index consists of two real-time multivariate (RMM) MJO indices (RMM_1 and RMM_2), roughly in quadrature, from which we calculate the daily MJO phase (1, 2, …, 8) and amplitude ($RMM_1^2 + RMM_2^2$).

2.3 | Defining the MSD

The method of García-Martínez (2015) is used here to identify the onset and end dates of the MSD. García-Martínez (2015) identified the MSD as the period between two peaks of precipitation, where the first peak occurs between May 15–July 15 and the second peak between August 15 and October 15. If either period lacks a precipitation peak, the year would be identified as having no MSD. Otherwise, the dates of these peaks are defined as the start and end dates of the MSD.

The intensity of the MSD is also quantified by García-Martínez (2015). The mean precipitation between the two peaks is calculated and it is identified as P_{msd}. Then the larger one of the two peaks is identified as P_{max}. Therefore, the intensity of the MSD (I_{msd}) is defined by the equation:

$$I_{msd} = \frac{P_{max} - P_{min}}{P_{max}}.$$

Before applying this method to our data, we firstly use a 31-day triangle window to average the daily time series and perform the MSD detection on this smoothed series. Smoothing with a 31-day window was found to be necessary to detect the MSD onset and end (i.e., a persistent change in seasonal rainfall levels, rather than simply to detect the odd day of heavy rain) but still retain the characteristic intra-seasonal variability.

2.4 | Reanalysis data

We also analysed daily fields of surface (10 m) wind and precipitation rate for the period 1979–2010 obtained from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR; Saha *et al.,* 2010). These data were obtained over the Central America region (100°–70°W, 5°–25°N) at a resolution of ca. 0.3° ×

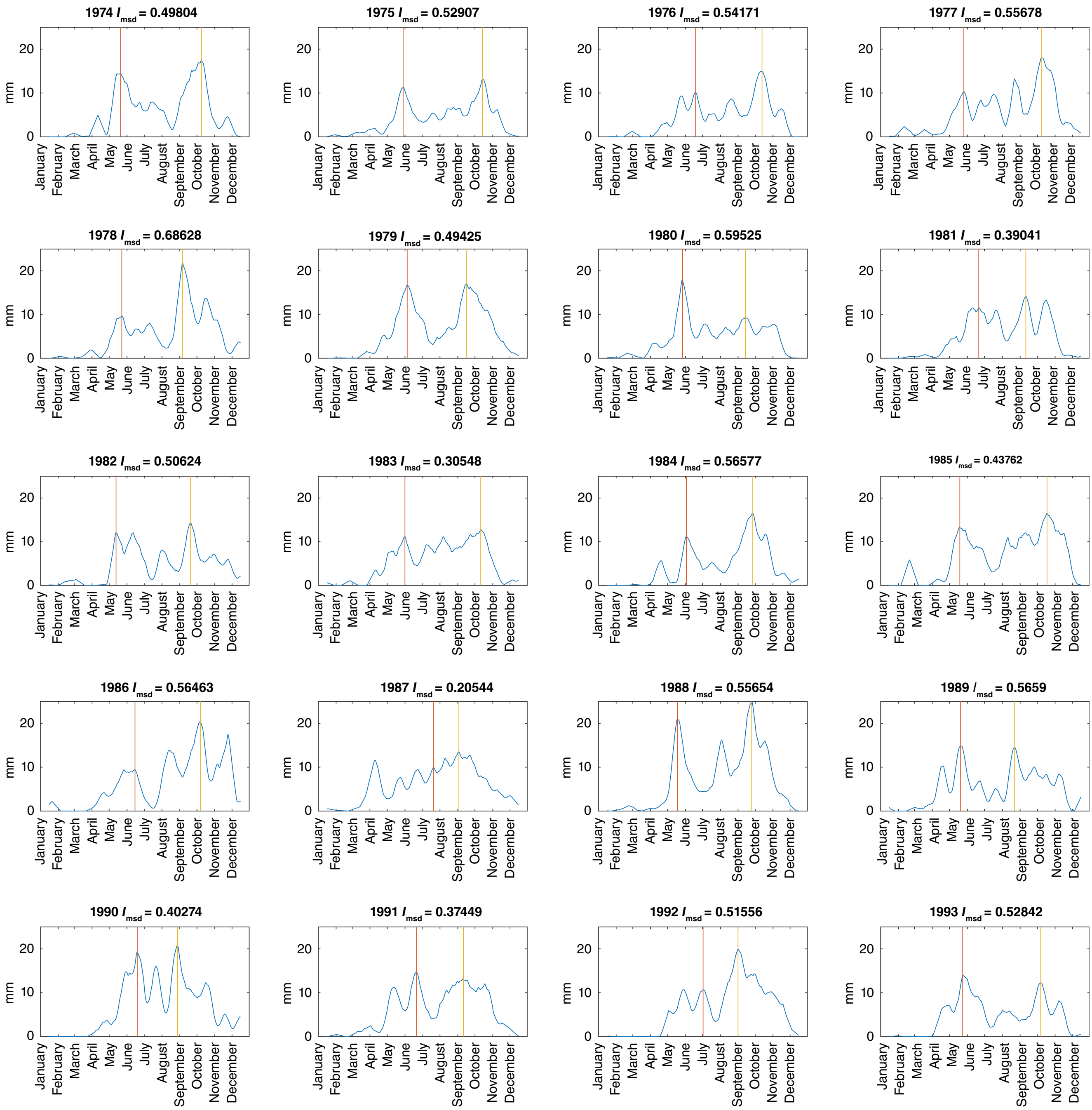

FIGURE 2 The 31-day smoothed daily rainfall at *Aerop. Juan Santamaria* for each year from 1974 to 1993. The horizontal axis tick indicates the first day of corresponding month. Vertical orange lines identify the onset and end dates of the MSD in each year. The year and associated *I*msd are labelled in each panel [Colour figure can be viewed at wileyonlinelibrary.com]

0.3°. Composite means were calculated by MJO phase (for MJO amplitudes >1) for each variable in order to statistically analyse the relationship between the MJO and Central America's regional circulation and rainfall.

3 | RESULTS

3.1 | Climatology

Daily rainfall climatologies from the seven stations show that the MSD is present at most locations (Figure 1). The MSD is most obvious at the northwestern Pacific coast (e.g., *Aerop. Liberia Oeste 07* with I_{msd} = 0.48 and *Llano Grande* with I_{msd} = 0.46) and in the Central Valley (e.g., *Aerop. Juan Santamaria* with I_{msd} = 0.31). The MSD is weakly evident at the central Pacific coast station (*Pocares* with I_{msd} = 0.25) and is absent from the southern Pacific coast station (*Coto 49*) and from the Caribbean coast stations (*Limon* and *Aerop. Limon*). In Figure 2, it is clear that there are large spatial variations in the seasonal cycle of rainfall across Costa Rica. In the western part, the rainfall is characterized by a relatively bimodal distribution with variable

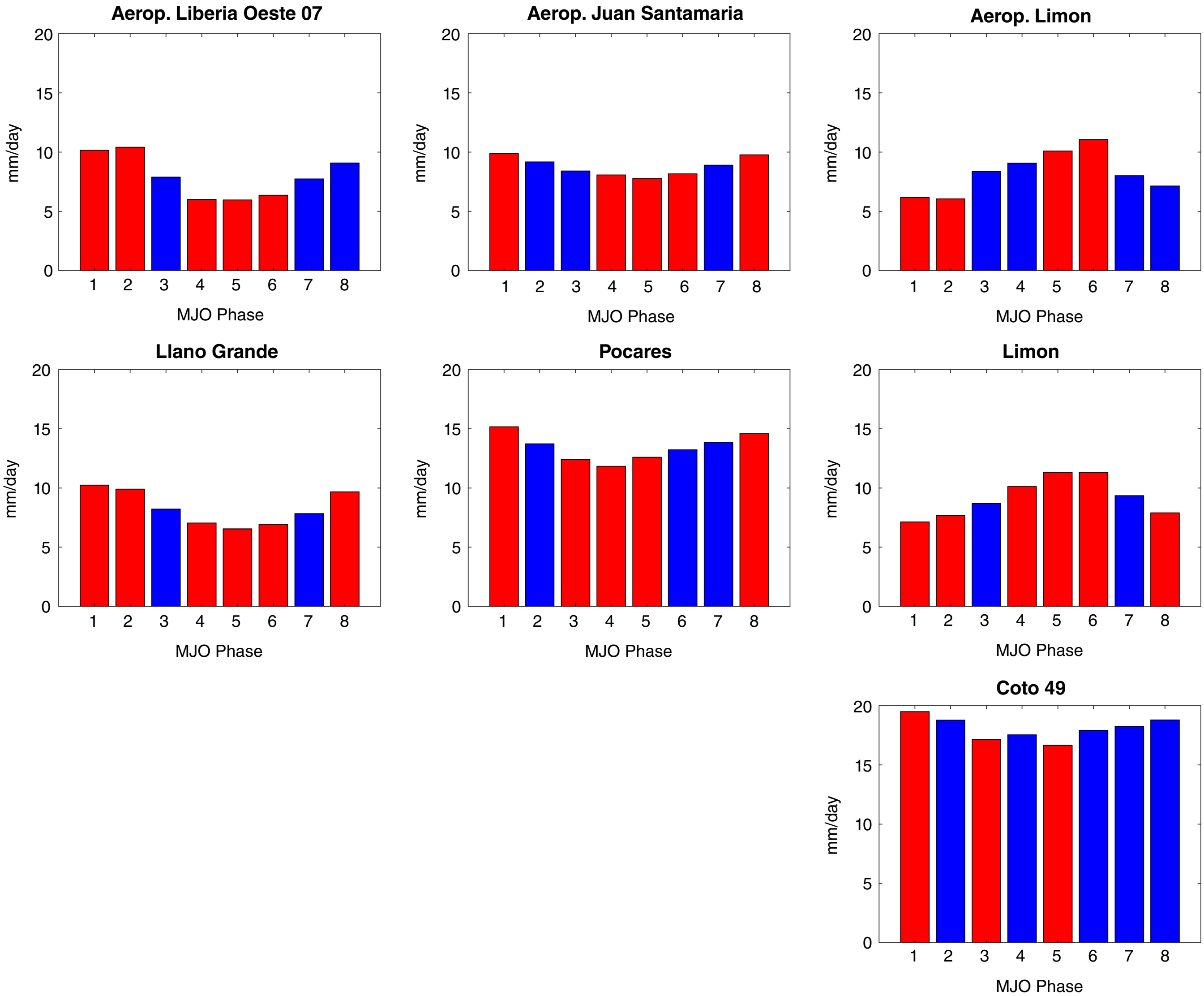

FIGURE 3 A composite mean of the 31-day smoothed wet season rainfall rates (mm/day) at each of the seven stations for each of the eight MJO phases. Red bars indicate statistically significant results (at the 5% level, i.e., <2.5% or >97.5%) [Colour figure can be viewed at wileyonlinelibrary.com]

intensity, while at the coastal Caribbean stations the MSD could not be detected and in fact the climatology exhibits quite a complex pattern, devoid of a two-peak seasonal variation or even a classic one-peak wet-and-dry cycle.

3.2 | Year-to-year variability of daily precipitation over Costa Rica

The smoothed daily rainfall for Aerop. Juan Santamaria is shown for each year in Figure 2, including the start and end dates of the MSD, based on the method of García-Martínez (2015). We selected data from Aerop. Juan Santamaria for the period 1974–1993 as an example to demonstrate our technique. While the start and end of the MSD tends to occur around the same time of the year throughout the record, we nevertheless note intra-seasonal variations in the exact onset date.

The start and end dates of the MSD were calculated based on the method of García-Martínez (2015), and identified in the plot as two solid vertical lines for each year. The duration of the MSD is simply the elapsed time between start and end dates. The absence of an MSD (not applicable for this station and record period) in some years is due to the absence of clear precipitation peaks that are able to be identified following the definition given by García-Martínez (2015).

Most years from 1974 to 1993 showed a relatively obvious bimodal distribution indicative of the MSD. Some years (e.g., 1980 and 1987) were identified as having an MSD but did not show a clear relative minimum in precipitation during July and August. Some other years (1981, 1986, 1990) showed a tri-modal distribution with an extra peak between November and December after the MSD. However, considering this unclear detection is caused by technical definition, we decided to still consider them as potential MSD year for following analysis.

3.3 | Interaction between the MJO and the MSD

The averaged wet season (periods during May–October) daily precipitation rate in every MJO phase (Figure 3) is

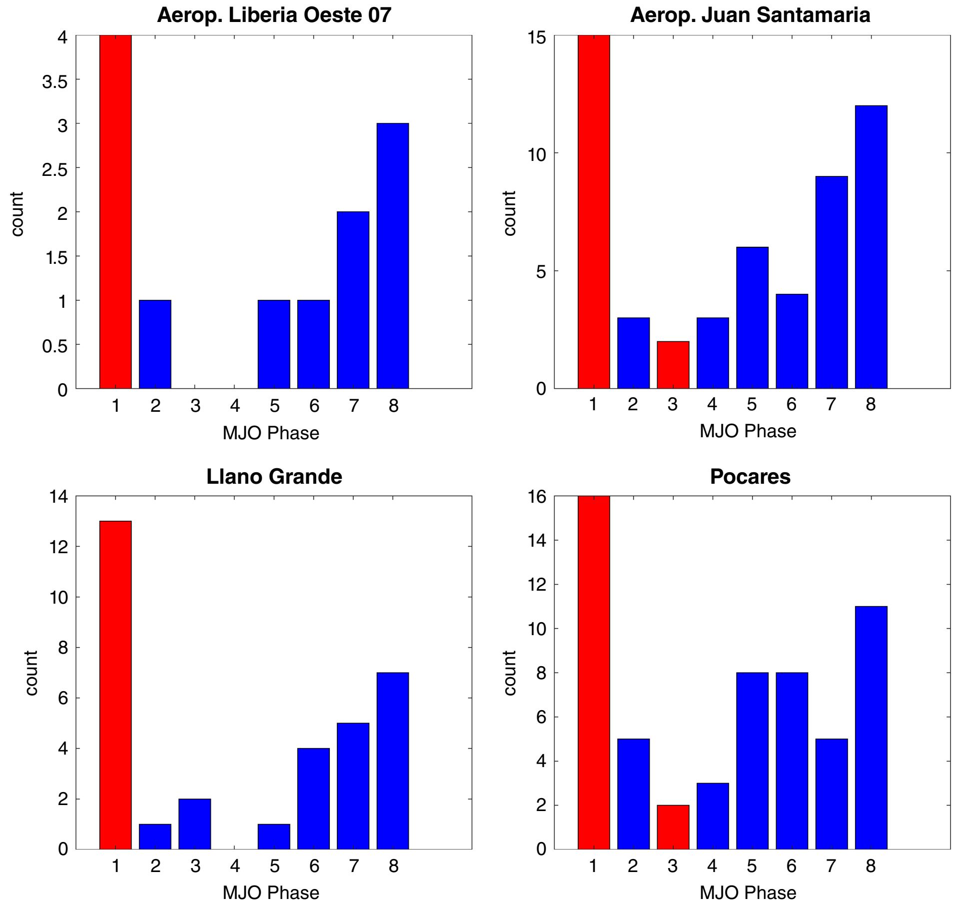

FIGURE 4 MSD onset counts as a function of MJO phase, for each of the four rainfall stations which exhibited an MSD. Red bars indicate statistically significant relationships (at the 5% level, i.e., <2.5% or >97.5%). All bars of zero height are statistically significant (i.e., <2.5%) [Colour figure can be viewed at wileyonlinelibrary.com]

calculated for each station by temporally averaging the daily precipitation rates corresponding to MJO phase, and the statistical significance for each station is determined by a K-state first-order Markov Chain through Monte Carlo method, following a similar approach to that applied by Riddle *et al.* (2013). In this test, we generated 1000 first-order Markov Chains for each station and averaged wet season rainfall rates larger than 97.5th or smaller than 2.5th percentile, determined to be statistically significant. The modulation of wet season rainfall by the MJO is shown at all seven stations. At the five Pacific coast stations and in the Central Valley, rainfall generally increased during MJO Phases 1, 2 and 8 and decreased during MJO Phases 4–6. At the two Caribbean coast stations, we see the opposite pattern: rainfall generally increased during MJO Phases 4–6 and decreased during MJO Phases 1, 2 and 8. From west to east, the MJO–rainfall relationship tends to transform from a quasi-parabolic distribution at the west coast to a unimodal distribution at the east coast, corresponding to the movement of high precipitation from Phases 1 and 8 to Phases 4 and 5.

Figures 4 and 5 show the counts of MSD onset and end dates, respectively, corresponding to each of the MJO phases. Statistical significance here is determined following the same method as above. Results are only shown for the four stations that exhibit an MSD in their climatological mean, that is, the northwest Pacific coast and Central Valley stations. Typically, the onset and end dates of the MSD occurred significantly more often in MJO Phases 1 and 8, which also correspond to the wettest MJO phases shown in Figure 3. The dry MJO Phases (4–6) in Figure 3 tended to exhibit the significantly fewer MSD onset and end dates.

3.4 | Regional circulation

The MJO is known to impact the regional circulation over Central America (Barlow and Salstein, 2006; Brito *et al.*, 2014). For example, the MJO composites presented in Wheeler and Hendon (2004) show that zonal wind and convection anomalies over Central America are out of phase with the anomalies over the Maritime Continent (figs 8 and 9 in Wheeler and Hendon, 2004). MJO composites of surface wind and precipitation from NCEP CFSR allowed us to examine the atmospheric response to the MJO over Central America in more detail. Surface wind anomalies tend to flow across Central America from the Pacific to the Caribbean coasts during MJO Phases 1 and 2, and from the Caribbean to the Pacific coasts through MJO Phases 4–7 (Figure 6, arrows). Due to the steep topography over much of Central America, this leads to

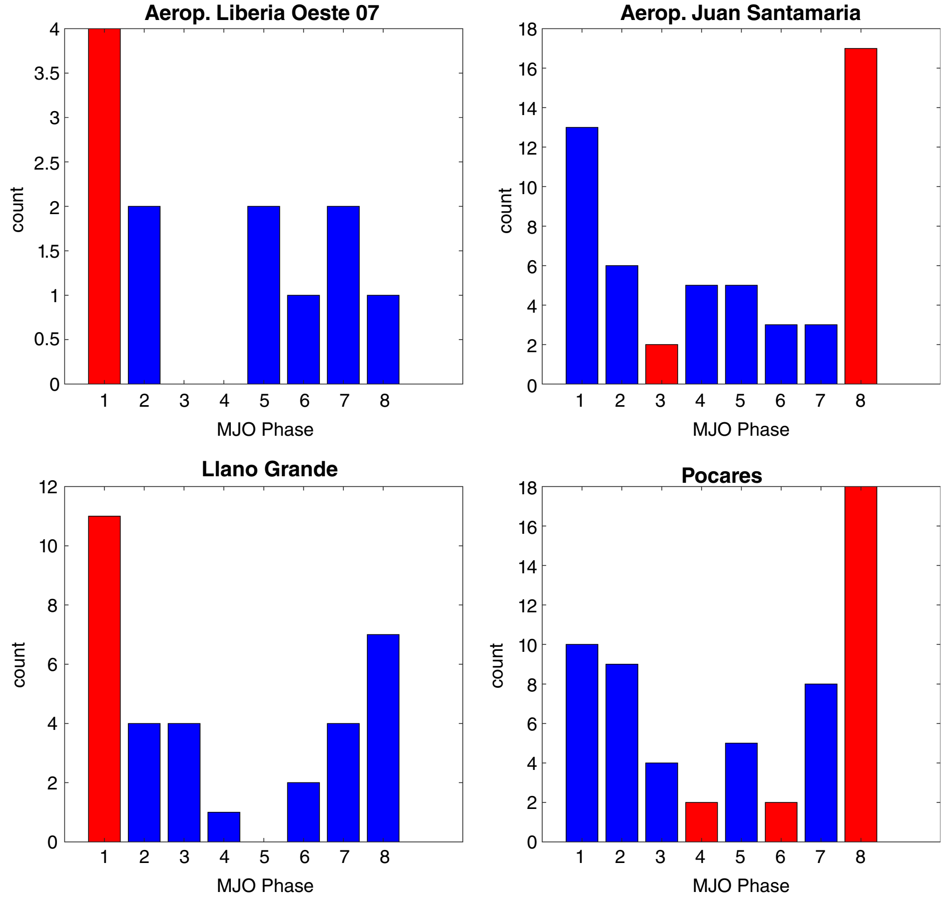

FIGURE 5 MSD end counts as a function of MJO phase, for each of the four rainfall stations which exhibited an MSD. Red bars indicate statistically significant relationships (at the 5% level, i.e., <2.5% or >97.5%). All bars of zero height are statistically significant (i.e., <2.5%) [Colour figure can be viewed at wileyonlinelibrary.com]

orographic upward (downward) motion at the Pacific (Caribbean) coast during Phases 1 and 2, and therefore enhanced (suppressed) rainfall there (Figure 6, colours). During Phases 4–7 the opposite occurs, with orographic upward (downward) motion at the Caribbean (Pacific) coast and therefore enhanced (suppressed) rainfall there. The timing of enhanced and suppressed rainfall at the Pacific coast of Central America during Phases 1–2 and 4–7 is consistent with our results above. Therefore, we hypothesize that it is the regional circulation associated with the MJO which leads to anomalous wet and dry conditions during these phases, setting up the conditions for preferential start and end dates for the MSD.

4 | DISCUSSION AND CONCLUSIONS

Our analysis has shown clear and statistically significant relationships between the MJO and wet season rainfall over the northwest and Central Valley regions of Costa Rica. Specifically, we have shown that the west and northwest Pacific coasts of Costa Rica receive higher rainfall than average in MJO Phases 1–2 and 8 and less than average in Phases 4–6. These results are supported by the recent work of Brito *et al.* (2014), who found that there is more precipitation in the Pacific slope of Costa Rica in Phases 1 and 2 of the MJO associated with the highest rainfall period (August–October) in Costa Rica. For the four stations located at the Pacific coast and Central Valley regions, our results have shown that the MSD has a statistically significantly higher probability of starting in MJO Phases 1 and 8, while the end of the MSD is also more probable in these phases (Figure 4). This is caused by peaks of precipitation during the wet season in MJO Phases 1 and 8, which would bring greater rainfall corresponding to onsets or ends of the MSD. The proposed mechanism for this phenomenon is the regional circulation, which tends to induce enhanced and suppressed rainfall during Phases 1–2 and 4–7 in the Pacific Coast.

It is notable that the most intense anomalies of precipitation occur off the Caribbean coast of Costa Rica (~100 km offshore; Figure 6, Phases 4–7), which is far away from the mountainous regions in central Costa Rica. This could be caused by two possible mechanisms:

1. In Phases 4–7 (Figure 6), the MJO produces easterly winds which hit the high mountains of Costa Rica (extending from north to south along Costa Rica). The easterly winds are uplifted when approaching the mountains, discharging most of the humidity as precipitation. A major proportion of the dry wind passes to the Pacific

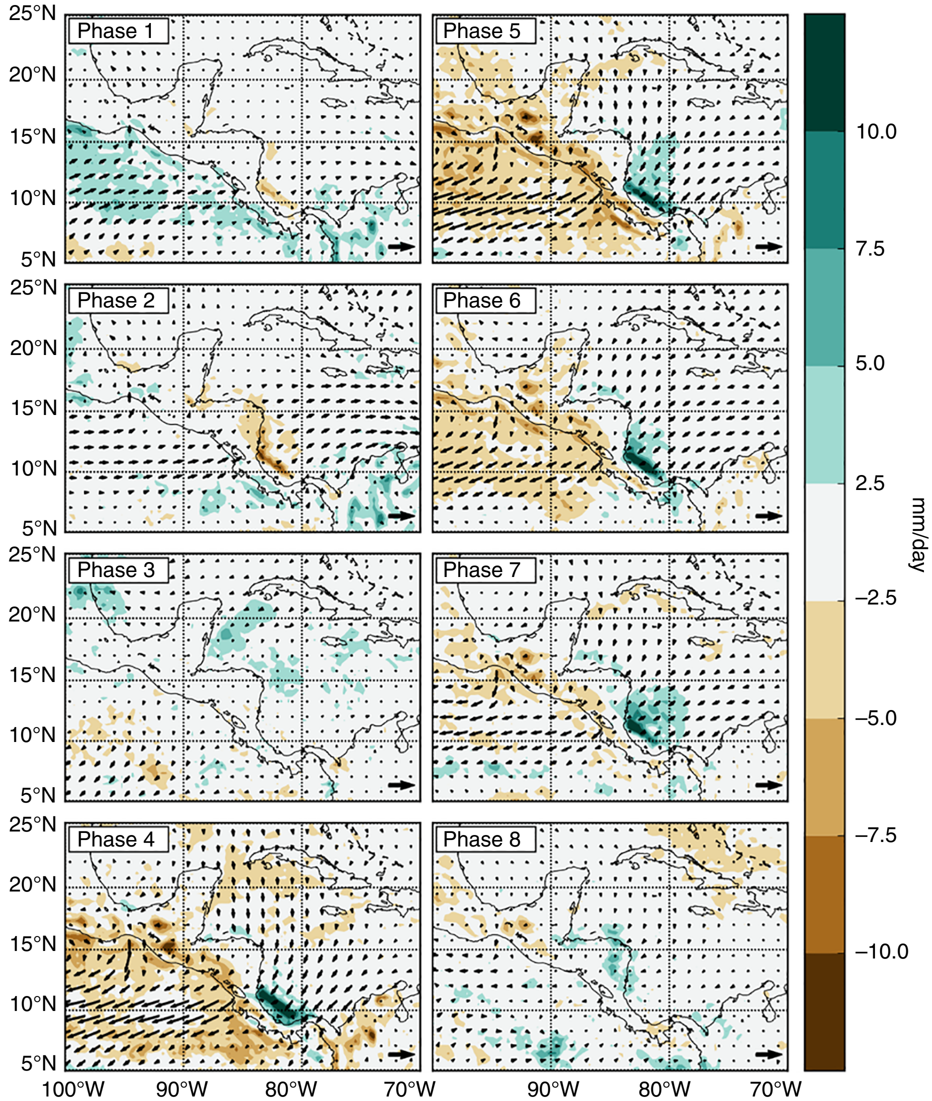

FIGURE 6 Composite mean regional circulation and rainfall across Central America with the MJO. Arrows and colours indicate composite anomalies of NCEP CFSR surface winds and precipitation, respectively, by MJO phase. A reference arrow indicating a wind speed of 5 m/s is shown in the lower right of each panel [Colour figure can be viewed at wileyonlinelibrary.com]

slope and part of it is reflected to the Caribbean as westerly winds that encounter the prevailing easterly winds producing a low level convergence zone. This corresponds to relatively low pressures, generating positive anomalies of precipitation off-shore in the Caribbean Sea. This returned wind circulates at low levels leaving part of its humidity in the mountains. Considering this is a fine-scale local feature, it may not be captured by the coarser spatial scale of the reanalysis data.

Interestingly, a band of negative anomalies of precipitation is observed off-shore in the Caribbean Sea in Phases 1 and 2 (Figure 6). In this case, the MJO produces westerly winds and dry conditions in the Caribbean slope, particularly off-shore in the Caribbean Sea. The westerly winds are dry after passing the mountains and they get drier as they propagate eastward in the ocean reaching a minimum in humidity off-shore in the Caribbean Sea. The band shape matches with the longitudinal extension of mountains in Costa Rica, while there are gaps in the mountains to the north and south of Costa Rica.

2. Marine breeze may be a less likely possibility. During the nights and early in the mornings, a marine breeze is produced and winds blow from land to the Caribbean Sea. This westerly wind encounters the easterly winds enhancing the convergence zone discussed in Point 1. However, the marine breeze is a short-time scale phenomenon (<24 hr) and is unlikely to influence the local climate on MJO time scales (intra-seasonal time scales).

Our results have implications for understanding the influence of the MJO on regional climate, particularly the MSD here, and the predictability of the MSD. Mountainous regions in central Costa Rica separate the land into Pacific and Caribbean regions with different climates, implying the potential that the west and east of Costa Rica could have different responses to large-scale forcing, particular MJO as shown here. As our results show, MJO Phases 1 and 8 could induce flows of surface wind anomalies over Central America from the Pacific to Caribbean coasts during this period, which could bring relatively high precipitation rates to the Pacific coast, contributing to the onset of the MSD there. This finding highlights the tight connection between the MJO and variations in the onset and end of the MSD in Costa Rica, implying that predictability of the MJO leads to predictability of the MSD. For example, if a strong MJO Phase 1 or 8 was predicted, we could expect large precipitation rates and an increased likelihood of onset or end of the MSD in this period.

Several forecast methods for the MJO exist, including both statistical and dynamical methods. In 2004, an Experimental MJO Prediction Project (EMPP; Waliser *et al.,* 2006), in which one of the fundamental components is the prediction of the MJO with lead times of 2–4 weeks, was organized to provide real-time weather and climate information and predictions for a variety of applications. EMPP provided forecasts from nine prediction systems, including Global Climate Model (GCM) ensembles, coupled GCMs, and statistical models such as multiple linear regression. Additionally, Oliver and Thompson (2016) used a statistical technique based on a damped harmonic oscillator model to estimate MJO predictability at ~3 weeks. The MJO was also simulated (Seo and Wang, 2010) and predicted (Wang *et al.,* 2014) in the NCEP climate forecast system. These prediction methods for the MJO could contribute to the prediction of the MSD as implied by findings from our analysis. Improved forecasts could then be used to better plan and manage agriculture, which is sensitive to rainfall, particularly in the dry regions of northwestern Costa Rica. This can have implications for the economy, development and food security of this Central American nation. These results could also contribute to the research of potential mechanisms of the MSD over Costa Rica, as well as its characteristics in different phases.

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Conflict of interest

The authors declare no conflict of interest.

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