Spatial–Intensity Variations in Extreme Precipitation in the Contiguous United States and the Madden–Julian Oscillation

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ABSTRACT

The spatial–intensity variability of extreme precipitation over the contiguous United States (CONUS) during boreal winter and relationships with the Madden–Julian oscillation (MJO) are investigated. Daily gridded precipitation is used to define two types of contiguous regions of extreme precipitation (CREPs): the intensity and spatial extent exceeding the 75th and 90th percentiles of frequency distributions. Extreme precipitation occurs twice as frequently when the MJO is active than inactive. Joint probabilities of the fractional area of CONUS sectors when the MJO is active are 2.0–2.5 higher than probabilities during inactive days for both 75th and 90th percentile CREPs (similar for the intensity of CREPs). Probabilities of the fractional area of 75th percentile CREPs when the MJO is active in neutral ENSO are higher than during warm or cold ENSO. Joint probabilities of the fractional area during MJO and warm ENSO are higher than MJO and cold ENSO and statistically significant over southern sectors. Results are similar for joint probabilities of intensity exceedance and MJO activity in warm and cold ENSO phases. Proportions of 75th and 90th percentile CREPs for each sector and phase of the MJO are predominantly large when MJO convective signals are over the central Indian Ocean or western Pacific. Probabilities of the fractional area of 90th percentile CREPs conditioned on MJO phases, however, do not show clear predominance. This indicates that the MJO is not the sole player in the occurrences of CREPs. Last, this study concludes that probabilities of the fractional area and intensity of 75th and 90th percentile CREPs in the CONUS do not depend on the amplitude of the MJO.

1. Introduction

The Madden–Julian oscillation (MJO) is the most prominent mode of tropical intraseasonal variability in the climate system (Madden and Julian 1994; Lau and Waliser 2005; Zhang 2005; Jones and Carvalho 2006; Pohl and Matthews 2007; Jones 2009; Jones and Carvalho 2011a). The influence of the MJO has been demonstrated in monsoon systems (Hendon and Liebmann 1990; Goswami and Mohan 2001; Higgins and Shi 2001; Carvalho et al. 2002a; Jones and Carvalho 2002), upper-ocean variability (Matthews and Meredith 2004; Waliser et al. 2005; Isoguchi and Kawamura 2006; Matthews et al. 2007), tropical–extratropical teleconnection patterns (Matthews et al. 2004; Kiladis et al. 2005), tropical cyclones and hurricane frequency (Maloney and Hartmann 2000; Sobel and Maloney 2000), and interactions with El Niño–Southern Oscillation (ENSO) (Weickmann 1991; McPhaden 1999, 2004; Lau 2005).

Additionally, important linkages have been found between the MJO and precipitation variability, including occurrences of extreme events (Jones et al. 2004b; Donald et al. 2006). Significant signals have been shown over Canada (Lin et al. 2010), the contiguous United States (CONUS) (Mo and Higgins 1998b,a; Mo 1999; Higgins et al. 2000a; Jones 2000; Bond and Vecchi 2003; Becker et al. 2011; Ralph et al. 2011; Zhou et al. 2012), Mexico (Mo and Higgins 1998b; Cavazos and Rivas 2004), the Caribbean (Martin and Schumacher 2011), South America (Nogues-Paegle et al. 2000; Carvalho et al. 2002b; Carvalho et al. 2004; Liebmann
et al. 2004; De Souza and Ambrizzi 2006; Gonzalez et al. 2008), Africa (Pohl and Camberlin 2006a, b; Pohl et al. 2007), Australia (Wheeler et al. 2009), Asia (Barlow et al. 2005; Jeong et al. 2005, 2008; Zhang et al. 2009), and Indonesia (Hidayat and Kizu 2010).

Nevertheless, many aspects of the MJO have yet to be fully explored, particularly in relation to subseasonal potential predictability and improvements in forecast skill in the extended ranges (e.g., weeks 3 and 4). For instance, although previous studies have provided insightful analyses on the role of the MJO and precipitation variability (including extremes), all aforementioned studies have investigated this aspect with composite analyses (or variations of). While those diagnostic methods are informative, they are of limited use in providing quantitative information on the probability of precipitation when the MJO is active. This is especially the case if one wishes to further improve forecasts in the extended range, which, given the chaotic nature of the problem, have to be probabilistic by construction. The second feature that has not been previously investigated relates to the importance of the MJO in influencing the spatial characteristics of extreme (or heavy) precipitation. Typically, the frequency of extreme events has been studied using gridded precipitation data without taking into account the spatial extent of extremes (Higgins et al. 2000a; Jones 2000; Bond and Vecchi 2003; Jones et al. 2004b).

The present study focuses on the MJO and occurrences of precipitation over the CONUS during boreal winter. This problem is investigated by considering two joint properties: intensity and spatial extent. The focus of this work is on precipitation events associated with large intensity and large areas, given that these types of occurrences typically cause major environmental and socioeconomic impacts. More specifically, the following questions are investigated: 1) What is the probability of extreme precipitation over the CONUS when the MJO is active? 2) Does the spatial–intensity probability of extreme precipitation associated with the MJO significantly vary with ENSO? 3) Do probabilities of spatial–intensity characteristics of extreme precipitation over the CONUS vary with MJO phases? 4) Are large amplitudes of the MJO associated with high probabilities of extreme precipitation over the CONUS? The paper is structured in the following way. Section 2 describes datasets and characterizes the life cycle of the MJO. Section 3 defines extreme events and analyzes the spatial–intensity characteristics of contiguous regions of extreme precipitation. Section 4 investigates probabilities of extreme precipitation and the activity of the MJO, including interannual variations associated with ENSO. Summary and conclusions are presented in section 5.

2. Data

Daily gridded precipitation from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) unified gauge (CPC-uni) (Higgins et al. 2000b; Chen et al. 2008) is used to investigate the variability of extreme events. The CPC-uni dataset uses an optimal interpolation technique to reproject precipitation reports to a grid. In this work, data with 0.5° in latitude and longitude are used for the period 1 January–31 December 1979–2010. Figure 1 shows the mean daily precipitation over the CONUS during boreal winter seasons defined from 1 November to 31 March (1979–2010). In the western CONUS, mean precipitation exceeds 2 mm day$^{-1}$ and shows large gradients associated with topographic features over the coastal
ranges, Sierra Nevada, and Rocky Mountains. In contrast, the mean winter precipitation in the eastern CONUS shows smooth horizontal gradients and maximizes over the southeastern states. To make the presentation manageable, the CONUS is divided into six sectors: Southwest (SW), central-south (CS), Southeast (SE), Northwest (NW), central north (CN) and Northeast (NE) (Fig. 1). The division is arbitrary but intends to have all sectors with comparable areas and the least possible crossings of state boundaries. The spatial–intensity characteristics of extreme precipitation, their probabilities of occurrence, and the importance of the MJO are aggregated in each sector over the CONUS.

To identify MJO events, daily averages of zonal wind components at 850-hPa (U850) and 200-hPa (U200) from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) are used (1 January–31 December 1979–2010). Daily averages of outgoing longwave radiation (OLR) (Liebmann and Smith 1996) are used to characterize convective anomalies associated with the MJO. To isolate the MJO signal, the seasonal cycle is first removed and filtered in the frequency domain to retain intraseasonal variations (20–200 days). This procedure follows Matthews (2000, 2008), who determined that the wide 20–200-day band more accurately represents isolated MJO events. Note that the wide bandpass filter is applied after removing the seasonal cycle (Jones 2009; Jones and Carvalho 2011a).

MJO events are identified with combined empirical orthogonal function (EOF) analysis (Wilks 2006) of equatorially averaged (15°S–15°N) U200 and U850 bandpass-filtered anomalies. The first two EOFs (see Fig. 1 in Jones 2009) are in good agreement with Wheeler and Hendon (2004), and the phase diagram of the first two normalized principal components (PC1, PC2) approximately follows the convention of the real-time multivariate MJO (RMM) index. Since the focus of this study is on estimating the MJO influence on probabilities of occurrence of extreme precipitation, we use the index based on bandpass-filtered anomalies rather than the RMM index because 1) the RMM index is significantly more noisy than the bandpass-filtered index (not shown) and 2) the bandpass filtering is a better estimate of intraseasonal signals associated with the MJO. In addition, it is important to clarify some critical aspects in the identification of MJO events. Two fundamental characteristics of the MJO determined from the PC1/PC2 phase diagram are large amplitudes, \( (PC1^2 + PC2^2)^{0.5} \), and eastward propagation. Large amplitude is a necessary but not a sufficient condition in the identification of events. Eastward propagation is determined by counterclockwise rotation in the phase diagram. Published studies based on the Wheeler and Hendon (2004) RMM index typically specify a minimum amplitude of 1.0 to identify MJO days. Note that solely using the criterion of amplitudes \( \geq 1.0 \) is incorrect and can result in spurious signals in the diagnostic analysis of the MJO.

A third aspect that it is important to note is that, once an MJO event starts and propagates eastward, the amplitude varies and sometimes can reach values below the threshold, if it is too large. Detailed discussions and examples of this issue are found in Matthews (2000, 2008) and Pohl and Matthews (2007). Therefore, MJO events in this study are defined according to the following criteria: 1) the phase angle between PC1 and PC2 systematically rotates counterclockwise, indicating eastward propagation at least to the Maritime Continent (phase 5); 2) the amplitude is always larger than 0.35; 3) the mean amplitude during the event is larger than 0.9; and 4) the entire duration of the event lasts between 30 and 90 days. These conditions are comparable to the criteria used in Matthews (2000, 2008) and have been used in Jones (2009) and Jones and Carvalho (2011b,a).

A total of 81 MJO events are identified during 1 November–31 March (1979–2010). Some events did not start and end entirely within the winter season (November–March). The conclusions of this study, however, are not affected by this, since the relationships between the MJO and extreme precipitation investigated here do not depend on the actual dates of initiation and termination of events.

Fig. 2 shows the canonical life cycle of the MJO based on composites of bandpass-filtered OLR anomalies and indicates enhancement of convective anomalies in the tropical Indian Ocean, intensification, and eastward propagation to the western Pacific. Convective anomalies are also observed over tropical Africa and South America.

To characterize the extratropical changes during the MJO life cycle, Fig. 3 shows anomalies in the Northern Hemisphere geopotential height at 500 hPa composited on the same dates as the MJO events (H500; only the seasonal cycle removed). The enhancement of convection over the tropical Indian Ocean (phase 1, Fig. 2) is associated with negative H500 anomalies in the North Pacific, eastern CONUS, and North Atlantic (phase 1, Fig. 3). As tropical convective anomalies propagate eastward, negative H500 anomalies nearly cover the entire CONUS (phase 2, Fig. 3) and then weaken in phases 3 and 4 (Fig. 3). Eastward propagation of H500 anomalies are subsequently observed from eastern Asia toward western North America (phases 4–8, Fig. 3). The phase composites of OLR and H500 anomalies are used to estimate the probabilities of extreme precipitation...
over the CONUS associated with the MJO life cycle. Other studies provide additional discussions about the MJO and extratropical responses (Mo and Higgins 1998b,a; Matthews and Kiladis 1999; Higgins et al. 2000a; Moon et al. 2011).

3. CREP

The spatial–intensity variability of extreme precipitation in the CONUS is analyzed by first identifying extreme events in daily gridded precipitation. Gamma distributions (Wilks 2006) are fitted to the time series of precipitation in each winter month separately (only values $\geq 0.1 \text{ mm day}^{-1}$ are used in the fitting). Two thresholds of daily precipitation intensity are defined: exceeding the 75th and 90th percentiles of the monthly gamma frequency distribution. Below threshold values are set to zeroes in the dataset. Next, regions of spatially connected grid points in which precipitation exceeds the 75th or 90th percentiles are identified. The spatial connection is determined by the four sides or corners of the grid points. The frequency distribution of sizes of spatially connected grid points varies from one isolated grid point up to extreme cases in which the spatially connected region of extreme precipitation covers a large area of the CONUS. To focus on extremes, two thresholds for size are used: 5 and 25 connected grid points. These thresholds correspond to the 75th and 90th percentiles, respectively, of the frequency distribution of sizes of connected grid points of extreme precipitation. In summary, two types of contiguous regions of extreme precipitation (CREP) are analyzed: type 1, the intensity

**FIG. 2.** Phase composites of bandpass-filtered OLR anomalies. Light (dark) shading indicates positive (negative) anomalies. Contour interval is $2.5 \text{ W m}^{-2}$; zero contours are omitted.

**FIG. 3.** Phase composites of H500 anomalies. Light (dark) shading indicates positive (negative) anomalies. Contour is $10 \text{ m}$; zero contours are omitted.
of precipitation and size exceeds the corresponding 
75th percentiles of frequency distributions; and type 2, 
the intensity and size exceed the 90th percentiles of the 
frequency distributions.

Fig. 4 shows the daily precipitation on 10 January 1995 
and illustrates examples of CREPs. The months of 
January and March 1995 were characterized by active 
MJO variability as well as high frequency of intense 
storms and above-average precipitation over most of the 
western CONUS. Those events also caused extensive 
property damage and loss of life. Estimates showed over 
$3\text{ billion}$ in damages and 27 lives claimed by flooding 
(e.g., Masutani and Leetmaa 1999; Jones 2000). The 75th 
percentile CREP (top) shows one large area of extreme 
precipitation over California and parts of Nevada, Or-

egon, Washington, Montana, and Wyoming. Three ad-

ditional but smaller CREPs are observed over Nevada, 
North Dakota, and Wisconsin. The center ("X") of each 
CREP is defined by the weighted average of extreme 
precipitation within the CREP, calculated as

\[
I_C = \frac{\sum_{i,j} j P_{ij}}{\sum_{i,j} P_{ij}}, \quad J_C = \frac{\sum_{i,j} i P_{ij}}{\sum_{i,j} P_{ij}},
\]

where \((I_C, J_C)\) are the coordinates of the center "X", 
\((i, j)\) and \(P_{ij}\) are the coordinates and precipitation, re-

spectively, in each grid point within the CREP. The in-
tensity is defined by the total precipitation within each 
CREP \((\Sigma P_{ij})\).

As the thresholds for intensity and size increase, the 90th 
percentile extremes (bottom) show three large CREPs 
with centers over California, Idaho, and Washington State; 
note the small CREPs over Nevada, North Dakota, and 
Wisconsin are removed. Additional discussions about dy-
namical mechanisms associated with severe storms during 
January 1995 are provided in Masutani and Leetmaa 
(1999), including forcing on the Northern Hemisphere 
atmospheric circulation by interannual sea surface tem-
perature anomalies in the tropical Pacific Ocean.
The spatial distributions of 75th and 90th percentile CREPS are shown in Fig. 5. The counts are assigned to the center of each CREP. Since the winter mean precipitation is largest over the western and eastern CONUS (Fig. 1), the counts of both types of extremes are also more frequent in those regions. The total numbers of 75th and 90th percentile CREPs are 26,138 and 5,600, respectively (about 817 and 175, respectively, mean number of events per season).

In the following analyses, the variability of CREPs is examined separately during active and inactive (or quiescent) MJO days. The MJO was active 69.6% of the time out of 4,689 days during 1 November–31 March 1979–2010. Figure 6 shows the proportions of both types of extremes (75th and 90th percentiles) during active and inactive MJO days and sectors in the CONUS. The centers of CREPs were assigned to each CONUS sector and proportions were calculated by counting the number of CREPs in the sector divided by the total number of CREPs. The results clearly demonstrate that extreme precipitation occurs more frequently when the MJO is active than inactive (more than twice). Differences are statistically significant at the 5% level for both types of extremes and all sectors.

4. The MJO and probabilities of CREPs

The previous results highlight the importance of the MJO on the variability of CREPs. This section presents a quantitative analysis of probabilities of CREP occurrences and relationships with the MJO, including interannual variations associated with ENSO. To make the presentation more manageable, the results are aggregated for each CONUS sector. We define the fractional area as the area of the sector covered by CREPs divided by the total area of the sector. Note that...
oftentimes CREPs can cover more than one sector. The calculation for each sector considers the area of the CREP contained within the sector. Likewise, intensity is defined as the total precipitation associated with CREPs falling in each sector. These two variables are computed separately for the 75th and 90th percentiles.

Fig. 7 shows joint probabilities that the fractional area in each sector associated with the 75th percentile CREPs exceeds specific thresholds (horizontal axis) and the MJO is active (in any phase). Similarly, joint probabilities for fractional area exceedance and inactive MJO days are plotted. Over the NW CONUS, for instance, the probability that the MJO is active and the sector is covered by more than 10% with 75th percentile CREPs is about 0.33. In contrast, the joint probability for the NW sector being covered by more than 10% CREPs during inactive MJO days is ~0.14. As the thresholds of fractional area increase, the joint probabilities decrease. The joint probabilities are significantly higher when the MJO is active and in inactive days. Moreover, joint probabilities decrease slower over the NW, NE and SE sectors relative to the CN and CS sectors, probably because precipitation over the central CONUS is not too intense during winter and weather systems quickly move eastward over those regions. Joint probabilities of the fractional area associated with 90th percentile CREPs and active (inactive) MJO days show similar patterns (Fig. 8), although the magnitudes are evidently smaller than for 75th percentile CREPs. It is also interesting to note that the influence of the MJO on probabilities of fractional areas in the SE and NE sectors is even slightly higher than in the SW CONUS.

Joint probabilities of precipitation intensity and active (inactive) MJO days associated with 75th and 90th percentile extremes are shown in Figs. 9 and 10, respectively. The joint probabilities are at least twice as high when the MJO is active than during inactive days. The results above demonstrate quantitatively that the MJO has a substantial influence on both the spatial and intensity characteristics of extreme precipitation over the CONUS during winter.

Significant linkages have been found between interannual variations in the MJO and ENSO (Weickmann 1991; Hendon et al. 1999; McPhaden 1999; Slingo et al. 1999; McPhaden 2004; Pohl and Matthews 2007). In general, as tropical waters warm (cool) in the Pacific during ENSO events, the MJO tends to propagate farther eastward (or being more confined to the west) (Kessler 2001; Jones et al. 2004a). The mean location of tropical convective anomalies associated with MJO events may differ considerably between warm and cold ENSO phases and, consequently, in the precipitation variability downstream in the teleconnection patterns (Moon et al. 2011).

Thus, an important question to ask is how the probabilities of CREP occurrences associated with the MJO change during different phases of ENSO. To investigate this question, we use the definition of ENSO phases by the NCEP Climate Prediction Center for the period 1979–2010 (http://www.cpc.ncep.noaa.gov). Joint probabilities of fractional area exceedance and MJO days (in any phase) during warm, neutral, and cold ENSO seasons are estimated. Figure 11 shows joint probabilities for 75th percentile CREPs. In general, the joint probabilities of MJO days in neutral ENSO are always higher than during warm or cold phases except over the SW and CS sectors. This is consistent with Higgins et al. (2000a), who show that extreme precipitation over the CONUS occurs at all phases of ENSO but tends to be higher during neutral phases before the onset of warm events. This is likely associated with increased tropical intraseasonal variability during neutral phases (Higgins et al. 2000a; Jones et al. 2004a). Another interesting finding is that joint probabilities of the fractional area for MJO and warm ENSO are always higher than MJO and cold ENSO. Note, however, that differences are only statistically significant over the southern sectors of the CONUS (except over the NW for a fractional area >5%). This is also consistent with the fact that the
southern CONUS tends to be wetter (drier) during warm (cold) ENSO phases (e.g., Ropelewski and Halpert 1986).

Fig. 12 shows joint probabilities of 75th percentile precipitation exceedance and active MJO (in any phase) during warm, neutral, and cold ENSO phases. Similar
findings are observed such that joint probabilities over the southern sectors during MJO and warm ENSO are always statistically higher than joint probabilities in MJO and cold phases. Similar results are obtained for joint probabilities of fractional area and intensity of 90th percentile extremes (not shown), although the
The distribution during active MJO days shows small differences among phases: 7.1% (phase 1), 8.7% (phase 2), 12.1% (phase 3), 8.3% (phase 4), 8.2% (phase 5), 8.0% (phase 6), 10.5% (phase 7), and 6.8% (phase 8). To gain further insight on how CREPs are distributed in each MJO phase and sector, proportions of CREPs are computed as the number of CREPs in each phase divided by the total number of CREPs in the sector. Every CREP is assigned to a given sector depending on the location of its center. Therefore, even though CREPs may extend over more than one sector, each CREP is counted only once. Figure 13 shows the proportions of 75th and 90th percentile CREPs for each sector and phase of the MJO. A somewhat consistent pattern emerges such that the proportions of CREPs are predominantly large in phases 3 and 7 relative to other phases. This is in agreement with previous studies that indicated that the influence of the MJO on precipitation over the CONUS happens when convective signals are over the Indian Ocean or western Pacific (Mo and Higgins 1998b; Higgins et al. 2000a; Jones 2000; Becker et al. 2011). Note, however, that previous studies analyzed the influence of the MJO on precipitation variability from composites point of view, whereas this study investigates probabilities of extremes characterized by two joint properties: area and intensity. We recall that extreme precipitation with spatial extents less than the 75th percentile of the frequency distribution of areas are excluded from the analysis (e.g., isolated grid points).

Probabilities of fractional area conditioned on MJO phases are shown in Fig. 14 for 90th percentile CREPs and each CONUS sector. Since differences among the probabilities are not particularly large, only phases 3 (triangles) and 7 (squares) are highlighted so that the plots are not overcrowded with symbols. Likewise,
probabilities of precipitation intensity for 90th percentile CREPs conditioned on MJO phases are plotted in Fig. 15. The results in Figs. 13–15 indicate that CREPs occur in all phases of the MJO but with higher frequencies in phases 3 and 7. However, the probabilities of area and intensity of CREPs conditioned on the MJO do not appear to have preferential phases. This is not too surprising and suggests that the MJO is not the sole player in the occurrences of CREPs and other physical processes on large, synoptic and meso scales are equally important in determining the magnitudes of area and intensity of CREPs. The conclusions are similar for conditional probabilities of 75th percentile CREPs (not shown).

The last question investigated in this study is whether probabilities of fractional area and intensity of CREPs in the CONUS depend on the amplitude of the MJO. In principle, one could expect that MJO events with large amplitudes would force large extratropical responses and increase the probability of extreme precipitation. This question is investigated by stratifying the data in subsamples of MJO amplitude above or below the median amplitude (also 0.75 and 1.25 times the median amplitude). Joint probabilities of fractional area and MJO amplitudes are computed (similarly for joint probabilities and intensity and MJO amplitudes). The results, however, indicate no statistically significant differences with MJO amplitudes above or below the median value (not shown). This finding indicates that, although the MJO is the main mode of tropical intraseasonal forcing for extreme precipitation occurrences over the CONUS, the MJO is not the only player.

5. Summary and conclusions

This paper investigates the spatial–intensity of extreme precipitation over the CONUS during boreal winter and relationships with the MJO. Two types of contiguous regions of extreme precipitation (CREPs) are defined: intensity and spatial extent exceeding the 75th and 90th percentiles of frequency distributions of daily precipitation and areas, respectively. A detailed discussion of the procedure to identify the MJO events is provided. The importance of the oscillation in the occurrence of CREPs over six CONUS sectors is summarized as follows.

Fig. 12. Joint probabilities of 75th percentile CREPs during active MJO days and ENSO phases. Panels are for each sector in the CONUS. Solid lines show joint probabilities that precipitation intensity in the sector due to 75th percentile CREPs exceeds a given threshold (horizontal axis; mm day$^{-1}$) and the MJO being active during neutral ENSO. Solid lines with squares show joint probabilities that the precipitation intensity in the sector exceeds a given threshold and the MJO being active during warm ENSO. Solid lines with triangles show joint probabilities that the precipitation intensity in the sector exceeds a given threshold and the MJO being active during cold ENSO. Symbol ‘*’ indicates that the joint probabilities of MJO active and warm ENSO are statistically greater (5% level) than joint probabilities of MJO active and cold ENSO.
The probability of CREPs during active and inactive MJO days is investigated. The MJO was active 69.6% during 1 November–31 March 1979–2010. Extreme precipitation occurs nearly twice as frequently when the MJO is active than inactive. For each sector, joint probabilities of the fractional area when the MJO is active are about 2.0–2.5 higher than probabilities of the fractional area during inactive days for both 75th and 90th percentile CREPs. Likewise, joint probabilities of 75th and 90th percentile CREPs intensity during active MJO days are significantly higher than in inactive cases. The second aspect is the dependence of probabilities of CREPs associated with the MJO on different phases of ENSO. Probabilities of the fractional area associated with 75th percentile CREPs when the MJO is active in neutral years are always higher than during warm or cold phases except over the SW and CS sectors. Additionally, joint probabilities of the fractional area for MJO and warm ENSO are always higher than MJO and cold ENSO and statistically significant over the southern sectors. Results are similar for joint probabilities of CREPs intensity exceedance and MJO active in warm and cold ENSO phases. The third aspect investigated shows that the proportions of 75th and 90th percentile CREPs for each sector and phase of the MJO are predominantly large in phases 3 and 7 relative to other phases. These phases are associated with convective signals over the central Indian Ocean or western Pacific. Probabilities of the fractional area of 90th percentile CREPS conditioned on MJO phases, however, do not show clear predominance (similarly for probabilities of precipitation intensity conditioned on MJO phases). This indicates that, although the MJO is the main mode of tropical intraseasonal forcing on precipitation variability over the CONUS, the MJO is not the sole player in the occurrences of CREPs. Other physical processes on large, synoptic and meso scales are equally important in determining the area and intensity of CREPs. Last, this study concludes that probabilities of the fractional area and intensity of 75th and 90th percentile CREPs in the CONUS do not depend on the amplitude of the MJO. The importance of the MJO is further appreciated by its influence on the predictability of extreme precipitation (Jones et al. 2004b). Jones et al. (2011b), for instance, investigated the MJO and forecast skill of extreme precipitation over the CONUS during boreal winter. The forecast skill is higher when the MJO is active and has enhanced convection occurring over the
FIG. 14. Conditional probabilities of 90th percentile CREPs during active MJO days. Panels are for each sector in the CONUS. Lines show probabilities that the fractional area of the sector due to 90th percentile CREPs exceeds a given threshold (horizontal axis; percentages), conditioned that the MJO is active and in a given phase. Solid lines with triangles (squares) are for MJO in phase 3 (phase 7).

FIG. 15. Conditional probabilities of 90th percentile CREPs during active MJO days. Panels are for each sector in the CONUS. Lines show probabilities that the intensity in the sector due to 90th percentile CREPs exceeds a given threshold (horizontal axis; mm day$^{-1}$), conditioned that the MJO is active and in a given phase. Solid lines with triangles (squares) are for MJO in phase 3 (phase 7).
Western Hemisphere, Africa, and/or the western Indian Ocean. Heidke skill scores (HSSs) (Wilks 2006) greater than 0.1 extend to lead times of up to two weeks in these situations. When the MJO is active, approximately 10%–30% of the CONUS have HSSs greater than 0.1 at all lead times from 1 to 14 days (Jones et al. 2011b). In addition, Jones et al. (2011a) used a simple decision model and showed that the relative value of deterministic forecasts of extreme precipitation is significantly higher and extends to longer leads (2 weeks) during an active MJO.

The findings of this study are consistent with previous works (Mo and Higgins 1998b; Higgins et al. 2000a; Jones 2000; Bond and Vecchi 2003; Jones et al. 2004b; Becker et al. 2011; Ralph et al. 2011; Zhou et al. 2012). However, the novel aspect of this paper is that the spatial–intensity characteristics of extreme precipitation are jointly analyzed and that the probabilities of extreme events are estimated. While the probability of CREPs is presented here with MJO events identified with bandpass-filtered data, the same methodology can be easily applied to the Wheeler and Hendon (2004) RMM index and, therefore, develop useful diagnostic tools for real-time applications. Probability curves similar to the ones presented in this study could be used in quantitative probabilistic forecasts of the spatial–intensity characteristics of extreme precipitation over the CONUS in the extended range (e.g., 3–4 weeks), which could be very useful in hazard assessments.

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REFERENCES


——, ——, and B. Liebmann, 2002b: Extreme precipitation events in southeastern South America and large-scale convective patterns in the South Atlantic convergence zone. J. Climate, 15, 2377–2394.


