On the linkage between extreme rainfall and the Madden–Julian Oscillation over the Indian region

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Abstract
The relationship between extreme rainfall events (ERE) and the Madden–Julian Oscillation (MJO) over the Indian Subcontinent is intriguing. In this regard, the study investigates in detail the association between the ERE and the MJO. Daily Tropical Rainfall Measuring Mission (TRMM) data were used for the period 1998–2015. The real-time multivariate MJO index was applied to classify active and suppressed phases of the MJO. The percentile-based threshold indices, change in probability, logistic regression models and composite analysis were used to understand the statistical and atmospheric circulation features. The results suggest that the frequency and rainfall contribution of the ERE were found to be higher during the active phases of the MJO across the seasons over the geographically distinct regions. The profound influence of the MJO on the ERE was found during the post-monsoon over the southern Indian peninsula and Bay of Bengal regions. During the Indian Summer Monsoon (ISM), the prominent signals of the MJO are limited to the south of 20°N. The logistic regression and cumulative probability changes affirm the above results. The composite analysis of various diagnostic parameters reveals the background synoptic conditions during the post-monsoon and the propagation of the Rossby convective lobe during the ISM might facilitate the occurrences of the ERE during the active phases of the MJO. The study highlights the space–time evolution of the ERE and the relative influence of the MJO across the seasons. Besides, its insights have practical implications for the understanding and prediction of sub-seasonal rainfall extremes over the Indian Subcontinent.

KEYWORDS
extreme rainfall events, Indian Summer Monsoon, logistic regression, Madden–Julian Oscillation, Tropical Rainfall Measuring Mission (TRMM)

1 | INTRODUCTION
Precipitation extremes are ubiquitous across the world from the long past. However, substantial evidence shows that the occurrence of extreme rainfall events (ERE) and their associated floods are escalated (Stott, 2016). These ERE have a large spatio-temporal variability and often influenced by the large-scale oceanic and atmospheric
coupled phenomena. One such dominant feature in the Tropics is the Madden–Julian Oscillation (MJO), which affects the weather and climate across the globe at an intraseasonal timescale (Madden and Julian, 1972; Zhang, 2005; Konda and Vissa, 2019). For instance, 55% of tropical weather was influenced by the MJO (Roxy et al., 2019) across the various meteorological scales. Thus, the slow eastward-propagating MJO with strong convective systems can either enhance or suppress the convection through the scale interactions (Rauniyar and Walsh, 2011; Krishnamurti et al., 2016; Anandh et al., 2018). Besides, there is evidence that the presence of the MJO can trigger weather extremes (Zhang, 2013; Peng et al., 2019; Roxy et al., 2019). For example, the precipitation extremes increased two-fold during the active phases of the MJO than inactive phases over the United States (Jones and Carvalho, 2012). Xavier et al. (2014) reported that the MJO influences both the spatial distribution as well as the probability of occurrence of the ERE over the Southeast Asian regions. Similarly, over the East Asia (Jeong et al., 2008), China (Jia et al., 2011), South America (Shimizu et al., 2017) and African regions (Sossa et al., 2017) as well as globally (Jones et al., 2004), the influence of the MJO on the ERE has been reported. The impact of the MJO on the rainfall characteristics and the ERE is inevitably evident in the above-mentioned studies.

In the Indian context, the occurrences of high-impact weather events and the ERE are escalated not only during the Indian Summer Monsoon (ISM) but also in other seasons (Roxy et al., 2017; Boyaj et al., 2018; Goswami et al., 2019). Significant efforts have been made to understand how the primary climate mode such as the El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) influences the ERE (Gadgil et al., 2004; Ajayamohan and Rao, 2008; Krishnaswamy et al., 2015). However, little attention is given to understanding the influence of the MJO on precipitation extremes. The earlier studies have primarily focused on either particular seasons or regions (Goswami et al., 2003; Joseph et al., 2009). Recently, Singh and Bhatla (2019) reported that MJO phases 3–5 are associated with intense rainfall events over the Indo-Gangetic plains during the ISM. However, comprehensive evaluation of various aspects of the statistical, dynamic and thermodynamic influence of the MJO on the ERE over the Indian Subcontinent is still warranted across the seasons and regions. Thus, profound attention is required to investigate the influence of the MJO on the characteristics of the ERE. With this rationale, the present study aims to understand the relationship between the MJO and the ERE over the Indian Subcontinent for all seasons using the various statistical and dynamic characterization of the ERE.

2 | DATA AND METHODOLOGY

2.1 | Data

This study uses the Tropical Rainfall Measuring Mission (TRMM)-based Multi-satellite Precipitation Analysis (TMPA) 3B42 version 7 (Huffman et al., 2007) daily rainfall (mm-day⁻¹) product available at a spatial resolution of 0.25 × 0.25° for the period 1998–2015. Data were processed for the study area encompassing the geographical coordinates 0–38 °N and 65 °E – 98 °E, as shown in Figure S1 in the additional supporting information. Regarding the validation of the TRMM data with the rain gauge data, previous research about the reliability of TRMM over the Indian region is well documented. Recently, Gupta et al. (2019) compared the TRMM and other satellite products such as Climate Hazards Group InfraRed Precipitation and Soil Moisture to Rain satellite data validated with India Meteorological Department (IMD) gridded data during the ISM. Their study evaluates the standard extreme precipitation indices, and the findings suggest that the TRMM daily data are found to be closer to the IMD than other satellite products. The TMPA is validated over the continental and oceanic regions with the IMD rain gauge and gridded data. In the continental regions over lower altitudes, the TMPA products perform reasonably well (e.g. Rahman et al., 2009; Prakash et al., 2015, 2016a, 2016b); however, over the higher altitudes (> 3,000 masl) the overestimation of TMPA products is reported (e.g. Bharti and Singh, 2015). Over the oceanic region, Prakash and Gairola (2014) validated the daily TMPA 3B42 with the The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction buoy array of rain gauge data over the Bay of Bengal (BoB). Their findings reveal that the TMPA rainfall is well correlated with buoy locations during the ISM; however, a positive (negative) bias of the TMPA rainfall is evident for light (heavy) rain of intensity less (higher) than 0.5 (100) mm·day⁻¹.

To determine the circulation and dynamic features of the ERE, high spatial resolution (0.25 × 0.25°) of the daily European Center for Medium Range Weather Forecasts (ECMWF) interim reanalysis data products is used. The various parameters such as zonal (u) and meridional (v) winds, geopotential heights (GPH) at 850 hPa, and vertically integrated moisture flux divergence (MFD) are used for the period 1998–2015 (Dee et al., 2011). Daily interpolated outgoing long wave radiation (OLR) of spatial resolution 2.5 × 2.5 ° was obtained from the National
Oceanic and Atmospheric Administration (NOAA) (Liebmann and Smith, 1996), and the best tracks for cyclones and depressions were obtained from the IMD (2008) (http://www.rsmcnewdelhi.imd.gov.in) for the period 1998–2015.

2.2 Characterization of precipitation extremes

The precipitation extremes show large variations in time and space. Especially over the Indian Subcontinent, disparity in rainfall is high over geographically distinct regions (Rajeevan et al., 2012). Therefore, a fixed threshold for the entire Indian Subcontinent to delineate the ERE would not be appropriate owing to the different climatic zones (Kothawale et al., 2010; Du et al., 2013). In this regard, the present study employs the percentile-based statistical method to characterize the ERE over the Indian Subcontinent. Many previous studies have successfully demonstrated the robust nature of the percentile method to detect the rainfall extremes over India and other parts of the world (Krishnamurthy et al., 2009; Boers et al., 2019).

In the present study period (1998–2015), the ERE are defined as rainfall events exceeding the 95th percentile (R95) of the daily rainfall distribution. The R95 threshold calculated at each grid point for the individual season is as defined by the IMD (winter: January–February; pre-monsoon: March–May; ISM: June–September; post-monsoon: October–December). Thus, the frequency and threshold of extreme rainfall is calculated based on the R95 at each grid point seasonally. The ratio of the sum of the total extreme rainfall to the seasonal total rainfall at each grid gives the extreme rainfall contribution (ERC) (Krishnamurthy et al., 2009; Mishra and Singh, 2010). The extreme rainfall intensities are calculated from the ratio of the accumulated ERE rainfall to the total number of ERE, and the corresponding ERE intensity anomalies were computed by subtracting the MJO extreme rainfall intensity with the seasonal extreme rainfall intensity at each grid point.

2.3 Delineation of the MJO phases over the Indian Subcontinent

The real-time multivariate MJO index (RMM index) developed by Wheeler and Hendon (2004) defines the strength and phase (1–8) of the MJO. In the present study, the active and suppressed phases of the MJO are defined based on the presence of active convective centres over the Indian Ocean (Fujita et al., 2011; Pai et al., 2011; Mishra et al., 2017; Anandh et al., 2018). Active phases of the MJO are classified for RMM phases 2–5, and phases 1 and 6–8 are classified as suppressed phases of the MJO. The RMM amplitude (RMM1 + RMM2) > 1 is considered for the analysis in both the active and suppressed phases of the MJO, where RMM1 and RMM2 are the leading pair of principal components. For detailed descriptions about the RMM index computation and its applications, see Wheeler and Hendon (2004). The characteristics of the ERE are examined for the days of the active and suppressed phases of the MJO. The mean and composite anomalies of the zonal and meridional winds, GPH and MFD for the seasonal, active and suppressed phases of the MJO are analysed. Total active and suppressed days of the MJO during the study period are given in Table 1.

2.4 Probability of changes in the ERE

The probabilities of ERE occurrences during the MJO phases were investigated using the change in the cumulative probability of rainfall. The percentage of changes in the probability signifies relative influences of the MJO phases on ERE occurrences. The positive (negative) probabilities indicate the high (low) influence of the MJO on ERE occurrences. The change in probability is computed as follows (Xavier et al., 2014):

\[
\Delta P_{mjo} = \frac{P_{mjo}(r \geq R95) - P_{all}(r \geq R95)}{P_{all}(r > R95)} \times 100
\]

where \(\Delta P_{mjo}\) is the percentage change in the cumulative probability of extreme rainfall; \(P_{mjo}\) is the cumulative probability of rainfall exceeding the R95 threshold, but only for the phases of the MJO; \(P_{all}\) is the same, but for all rainy days in a season exceeding the R95 percentile threshold; and \(r\) is rainy days.

2.5 Logistic regression

The logistic regression is employed to examine the statistical relationship between the frequency of the ERE and the MJO over the Indian Subcontinent across the seasons. It is a type of probabilistic forecasts model that describes the relationship between the independent variables “\(x\)” with the dependent dichotomous binary variables “\(y\)”. The advantage of this model forecast is that the probability neither exceeds “1” nor decreases below “0” (Leroy and Wheeler, 2008). In the present study for an ERE, the RMM amplitude is used to define the dichotomous binary variables for the active and suppressed
The phases of the MJO. Previous studies have successfully demonstrated the logistic regression technique in order to understand the relationship between tropical cyclones (TC) and the ENSO (Leroy and Wheeler, 2008; Villarini and Denniston, 2016; Khouakhi et al., 2017).

The MJO phases are considered as independent variables (x) and the probability of occurrence of the ERE during particular phases is considered as dependent variables (y). The binary response of dependent variables (y) on independent variables (x) is modelled as follows:

\[
\log \left( \frac{\pi}{1-\pi} \right) = \beta_1 + \beta_2 x
\]

whereas \(\pi\) denotes the probability of success; \(\beta_1\) and \(\beta_2\) are regression coefficients; and \(x\) is the MJO phases.

### 2.6 | Statistical significance test

The occurrences of TC and tropical depressions (TD) during the active (suppressed) phases of the MJO are evaluated by using a Z-test (Hall et al., 2001; Klotzbach, 2014). Based on the study, the null (alternate) hypothesis defined as the distribution of the TC and TD was equally (unequally) distributed across the phases of the MJO. The Z-statistics are then given based on:

\[
Z = \frac{P - P_e}{\sqrt{P_e(1-P_e)/N}}
\]

where the observed fractions \(P\) is defined as the ratio of the total number of TC (TD) days in the particular phase to the total number of the MJO days of the phase. Similarly, the expected fractions \(P_e\) is given by the ratio of the total number of TC and TD days during the active and suppressed phases of the MJO to the sum of the total number of active and suppressed MJO days. \(N\) is the total number of days in the particular phases of the MJO category. By using a two-tailed test, the critical Z-value at a 95% confidence level is 1.96. The positive (negative) value of Z exceeding the 95% confidence level indicates the more (less) likelihood for the occurrences of the TC or TD than expected during the active and suppressed phases of the MJO (Barrett and Leslie, 2009).

### 3 | RESULTS

#### 3.1 | Seasonal spatial distribution of the ERE thresholds

The spatial distributions of the R95 thresholds for all seasons are shown in Figure 1. The R95 thresholds show the large spatial heterogeneity.

##### 3.1.1 | Oceanic regions

Over the BoB, widespread higher R95 (> 80 mm day\(^{-1}\)) are evident during the pre-monsoon (Figure 1b), ISM (Figure 1c) and post-monsoon (Figure 1d) seasons. During the pre-monsoon and ISM, the higher R95 thresholds are evident over the central and northeast BoB, whereas during the post-monsoon season, higher R95 thresholds are to be seen over the western BoB. On the contrary, during the winter (Figure 1a), higher R95 intensities (60–80 mm day\(^{-1}\)) seen over the southwest BoB, east-central BoB and north-central parts of equatorial Indian Ocean (EIO). Over the Arabian Sea (AS), peak R95 (about 80 mm day\(^{-1}\)) thresholds are concentrated over the west-central AS during the pre- and post-monsoon seasons.

##### 3.1.2 | Land and coastal regions

Over the west coast and Western Ghats (WG), a narrow band of high R95 thresholds (> 100 mm day\(^{-1}\)) is evident during the ISM season. Over the east coast and Eastern Ghats (EG), high R95 thresholds (about 80–100 mm day\(^{-1}\)) are prominent during the post-monsoon seasons. Over the Arakan and eastern Himalayas, higher R95 thresholds are noticed during the pre-monsoon, ISM and post-monsoon seasons. However, over the western Himalayan peak, high R95 thresholds are evident during the winter. The thresholds of R95 over the ocean and land regions are consistent with the
seasonal peak rainfall. Similarly, the ERE intensity anomalies for the active and suppressed phases of the MJO are given in Figure S2 in the additional supporting information. However, the ERE intensities during the active (suppressed) phases of the MJO show large spatial heterogeneity without any clear pattern. This analysis also affirms that the presence of the MJO influences the frequency and contribution of the ERE over Indian region, whereas it does not influence the extremes intensity (Subudhi and Landu, 2019).

3.2 Statistical characteristics of the ERE during the MJO phases

3.2.1 Frequency of the ERE events

The spatial distribution of the total number of ERE during all seasons (Figure 2a, d, g, j) and the corresponding normalized ERE number (NEN) of active (Figure 2b, e, h, k) and suppressed (Figure 2c, f, i, l) phases of the MJO are analysed.

Over oceanic regions

Occurrences of the ERE are high over the northeastern EIO and southern BoB during all seasons. However, during the ISM (Figure 2g), a large number of ERE are occurring over the central, northern BoB and southeastern AS regions. The frequency of the ERE shows significant differences during the active and suppressed phases of the MJO. Higher NEN are noticed during the active phases of the MJO, specifically over the eastern coastal regions, eastern AS and southern BoB regions. Interestingly, over the northeastern BoB, higher NEN are evident during the suppressed phases of the MJO. However, over the northern BoB (AS), higher NEN during the winter and pre-monsoon seasons are due to the lesser number of seasonal ERE.

Over the land and coastal regions

Large spatial heterogeneity in occurrences of the ERE is shown in Figure 2a, d, g, j. Over the North-East India (NEI), a large number of ERE are evident during all seasons, in concurrence with the peak R95 thresholds and the peak occurrence of the ERE (> 100) which is evident during the ISM (Figure 2g) followed by the pre-monsoon (Figure 2d), post-monsoon (Figure 2j) and winter (Figure 2a). Over the windward side of the WG and Arakan mountains, a narrow band of high ERE is evident, whereas over the peaks of the EG and central India, a large, widespread ERE is seen during the ISM (Figure 2g). Over the Gangetic West Bengal, a large
number of ERE (> 50) are seen during the ISM (Figure 2g) and pre-monsoon season (Figure 2d). Over the Himalayan arc and the foothills of the western and central Himalaya, a significant number of events are evident during the ISM, pre-monsoon and winter seasons. In contrast to other regions, over the Deccan Plateau and eastern side of southern India, there are a large number of events occurring during the post-monsoon seasons. During the active phases of the MJO, a high NEN (about 0.3–0.5) is found over the WG, central India, west coast of India and northern part of the east coast of India and Himalayan regions during the ISM (Figure 2h, i). During the post-monsoon (Figure 2k, l), a high NEN is seen over southern India. On the contrary, during the pre-monsoon (Figure 2f) and ISM (Figure 2i) over the NEI and the Arakan mountains, a high NEN (about 0.4–0.5) is occurring during the suppressed phases of the MJO. Previous studies have reported enhanced convection and rainfall during the suppressed phases of the MJO during the ISM over the NEI (Pai et al., 2011; Mishra et al., 2017; Anandh et al., 2018). The present study also highlights that the occurrences of the ERE are also high over the NEI during the suppressed MJO phases. Besides, during the post-monsoon and winter over the Himalayas arc, large occurrences of the ERE are evident during the suppressed phases of the MJO, which is in agreement with the findings of Cannon et al. (2017).

3.2.2 | ERE contribution to the season totals

The total and normalized ERE contribution (ERC) to the season, active and suppressed phases of the MJO are shown in Figure 3. A significant feature that differentiates the total number of ERE and ERC over the EIO are
large number of ERE are associated with a relatively low ERC (about 20–30%) for all seasons (Figure 3a, d, g, j). However, over the west-central BoB and central AS, a lesser number of ERE attributes a high ERC during all seasons, prominently during the ISM (Figure 3g) and pre-monsoon season (Figure 3d). Over the major rainfall zones of the Indian Subcontinent, extremes are contributing nearly 20–30% to the season totals during all seasons. During the pre-monsoon season over central and north-west India, the ERC gives nearly 50% to the season total, though occurrences of the ERE are low. During the active (Figure 3b, e, h, k) and suppressed (Figure 3c, f, i, l) phases of the MJO, the normalized ERC variations are nearly in concurrence with the number of ERE during all seasons. For instance, over the ocean and the land regions, the seasonal ERC is mostly attributed from the active phases of the MJO (Figure 3b, e, h, k). However, over the regions of the NEI, Arakan mountains, northern BoB as well as over the northwestern regions of India, the ERC is relatively high during the suppressed phases of the MJO (Figure 3c, f, i, l). During the pre-monsoon and winter, the higher normalized ERC over the north-west Indian regions are attributed from fewer ERE occurrences during the suppressed phases of the MJO.

### 3.3 Probability of extreme rainfall during the MJO phases

It is important to understand the relationship between the active (suppressed) phases of the MJO and the occurrences of the ERE for the realistic prediction of intra-seasonal extremes (Xavier et al., 2014; Lee et al., 2017). To investigate this, the percentage change in the cumulative probability of extreme rainfall is computed for the active (suppressed) phases of the MJO (Figure 4). Notably, the percentage change in the cumulative probability of rainfall was found to be significant in both the active
(Figure 4a–d) and suppressed (Figure 4e–h) phases of the MJO over different areas of the Indian Subcontinent. The maximum positive change in the probability found over the south of 20°N was during the active phases of the MJO. During the ISM (Figure 4c), the cumulative change in probability (>100%) is found to be significant during the active phases of the MJO, and the results are consistent with Subudhi and Landu (2019). During the post-monsoon (Figure 4d), the presence of active MJO anomalies enhances the occurrences of the ERE by about 25–50%. Besides, the strong spatial coherence is noticed between the regions of the maximum ERE and ERC, with the areas of positive $\Delta P_{\text{mjo}}$. This signifies that the MJO might be a major precursor for the occurrences of the ERE over these regions, namely the east coast of India, southern BoB (AS) and EIO regions. The large spatial heterogeneity found in $\Delta P_{\text{mjo}}$ values over the north Indian regions, especially during the winter (Figure 4a, e) and pre-monsoon (Figure 4b, f), might be attributed to the low frequency of the ERE. Thus, the high positive and negative values over certain regions and seasons are due to the low values of $P_{\text{mjo}}$ and $P_{\text{all}}$, which might resulted in a high percentage of change in the probability. The frequency and probability of the ERE that occurred during the non-MJO phases (i.e., RMM amplitude < 1 irrespective of the phases) are shown in Figure S3 in the additional supporting information. During the non-MJO periods across the seasons, the lesser number of events and probability are seen over the south of 20°N.

### 3.4 Logistic regression models for the ERE and MJO phases

Figure 5 summarizes the results of the logistic regression, which shows the relationship between the occurrences of the ERE and the active (suppressed) MJO phases. A perusal of the results reveals the strong association between the ERE and the MJO over certain regions across the seasons. The $\beta_2$ coefficient and significances $(p)$ are used to evaluate the results. The $\beta_2$ coefficient is classified based on the significance, that is, $p < 0.05$, which is highly significant. Over the grid locations, the influence of active (blue) and suppressed (red) phases of the MJO on the ERE indicate the large spatial heterogeneity across the seasons. During the winter (Figure 5a), the influence of the MJO on the ERE is restricted to the EIO, southern AS and BoB; however, over the continental regions, no significant influence on the ERE is evident. During the pre-monsoon (Figure 5b), over the southern BoB a significant influence of the active (blue) phases of the MJO is seen over most regions. On the contrary, over the AS and northeastern Himalayan range and adjoining regions, the impact of the suppressed (red) phases of the MJO is significant. However, during the

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**Figure 4** Percentage change probability of the extreme rainfall events (ERE) during the active and suppressed phases of the phases for winter (a, e); pre-monsoon (b, f); Indian Summer Monsoon (ISM) (c, g); and post-monsoon (d, h)
ISM (Figure 5c) over the large regions, the significant influence of the MJO on the ERE is found over central India, and the findings are consistent with the statistical analysis of Singh and Bhatla (2019). Interestingly, during the post-monsoon (Figure 5d) over the BoB, east coast of India, eastern AS and NEI, the active phases of the MJO show a significant relationship with the ERE. The results of logistic regression analysis are consistent with the ERE frequencies and the ERC of the active and suppressed phases of the MJO.

3.5 Contextual synoptic characteristics during the active and suppressed phases of the MJO

The relationship between the MJO phases and the ERE characteristics are inevitably evident over the Indian Subcontinent. To substantiate the results of previous sections, the synoptic conditions during the active (suppressed) phases of the MJO are assessed by using diagnostic variables such as the GPH, winds, MFD and OLR. Analysing the mean state of the large-scale fields can provide the precursors for evolving the ERE of a particular season (Hunt et al., 2018). The mean and composite anomalies of the GPH and wind vectors at 850 hPa are shown in Figure 6. Over the EIO during the active (suppressed) phases of the MJO, seasonal westerly winds are enhanced (weakened) in all seasons, and these are associated with negative (positive) GPH anomalies. This feature is pronounced during the winter (Figure 6b), pre-monsoon (Figure 6e) and post-monsoon (Figure 6k). During the ISM (Figure 6h, i), a weak anomalous low (high) is evident during the active (suppressed) phases of the MJO over the eastern AS. However, during the suppressed phases of the MJO, westerlies are predominant in the north of 18°N with enhanced convection. There is cyclonic (anticyclonic) circulation over the eastern AS and easterlies (westerlies) over central India during the active (suppressed) phases of the MJO in ISM (Figure 6h, i). This synoptic feature signifies the propagation of wet (dry) Rossby lobes that have emanated from the maritime continent (Karmakar and Krishnamurti, 2019).

Similarly, the OLR and vertically integrated MFD of the season, active and suppressed phases of the MJO are shown in Figure 7. Low values of OLR (< 220 W m⁻²)
are evident over the regions of the southern BoB and eastern EIO during all seasons, notably over the southern BoB during the pre-monsoon (Figure 7d) and post-monsoon (Figure 7j) seasons, whereas it is over the northern BoB during the ISM (Figure 7g). Over the AS regions, low OLR values are dominant during the ISM (Figure 7g); however, they are limited to the southeastern AS during the post-monsoon (Figure 7j). Over the continents, a large spatial heterogeneity of the OLR variation is evident in the seasonal mean (Figure 7a, d, g, j); however, the decrease of the OLR from northwest India to southern BoB for all seasons is evident. During the active (suppressed) phases of the MJO, enhanced (weekend) convection, that is, negative (positive) anomalies of the OLR, is observed over the oceanic regions during all seasons. During the ISM (Figure 7h), the migration of the monsoon trough to the south (north) of 18° N during the active phases of the MJO is evident, and the findings are in concurrence with Pai et al. (2011) and Mishra et al. (2017). Over the NEI and northern BoB, enhanced (weakened) convection is evident during the suppressed (active) phases of the MJO in the pre-monsoon (Figure 7e, f) and ISM (Figure 7h, i). During the post-monsoon (Figure 7k, l), the influence of the MJO is evident over the southern BoB and east coast of India.

The spatial distribution of the mean MFD (Figure 7a, d, g, j) during all seasons is in concurrence with the season rainfall distribution. During the active (suppressed) phases of the MJO, large negative (positive) anomalies of the MFD are evident over the regions of the BoB in all seasons, whereas it is pronounced during the ISM (Figure 7h, i). During the active phases of the MJO, composite anomalies of the MFD indicate the transport of moisture from the surrounding seas to the continent, in concurrence with the wind composites (Figure 6). This feature is evident during the post-monsoon season over the BoB, during active moisture transport is from the offshore.

![Figure 6](image_url)  
**Figure 6** Geopotential heights (GPH) (m$^2$ s$^{-2}$) overlaid by 850 hPa wind vectors (m s$^{-1}$) for the seasonal (a, d, g, j), active (b, e, h, k) and suppressed (c, f, i, l) phases of the Madden–Julian Oscillation (MJO) for the winter, pre-monsoon, Indian Summer Monsoon (ISM) and post-monsoon seasons, respectively.
3.6 Plausible synoptic rain-bearing systems for the ERE

On a daily time scale, convective cloud clusters embedded in synoptic systems can occasionally produce excessive rainfall. Over the South Asian region, extreme rainfall or convection is a well-organized manifestation of more frequent non-extreme rain-bearing systems (Romatschke et al., 2010). Most of the ERE arises from the severe thunderstorms that are highly unevenly distributed in space (e.g. Goswami et al., 2019) and from the TC (Prat and Nelson, 2016). Goswami et al. (2019) suggested that the occurrences of the ERE are primarily controlled by the large-scale set-up of thermodynamics and circulation features. The present study provides the most frequent rain-bearing systems over the Indian Subcontinent that would occur over a distinct geographical region during different seasons, which are summarized in Table S1 in the additional supporting information. The east coast of India, southern India, BoB and central India and other neighbouring countries, namely, Myanmar, Sri Lanka and Bangladesh, are the regions most affected by the passage and landfall of the TC and TD. Over the north Indian Ocean, especially over the BoB, the frequency of the TC shows a significant bimodal character, with peaks during the pre- and post-monsoon (Li et al., 2013; Vissa et al., 2013). However, during the ISM over the head (northwest) BoB, synoptic-scale monsoon depressions can produce extreme rainfall over the east coast and central India (e.g. Goswami et al., 2006, 2019;
The tracks of the TC and TD during the seasonal, active and suppressed phases of the MJO for the pre-monsoon, ISM and post-monsoon are shown in Figure 8. Winter tracks are not shown owing to the lesser number (three) of occurrences of the TC and TD in the north Indian Ocean during the study period. During the active phases of the MJO (Figure 8b, e, h), the total of 38 TC and 33 TD occurred during the study period (1998–2015) over the north Indian Ocean. Similarly, for the suppressed phases of the MJO (Figure 8c, f, i), 12 TC and 17 TD are reported. From this analysis, it is clear that nearly 53% (21) of the low-pressure systems occurred

| Phases of the MJO | Days in the pre-monsoon | Days in the ISM | Days in the post-monsoon |
|------------------|-------------------------|----------------|-------------------------|
|                  | TC          | TD     | TC        | TD     | TC        | TD     |
| Active           | 32          | 2      | 28        | 53**   | 121**     | 66**   |
| Suppressed       | 19          | 3      | 15        | 21++   | 33+++     | 14+++  |

Note: TC or TD during the active (suppressed) phases of the MJO with a 95% confidence level are denoted as **(++).
during the active (suppressed) phases of the MJO. Besides, nearly 26% of the low-pressure systems occurred during non-MJO days. The significance test (Table 2) affirms the above results. Thus, the TC (TD) formed during the post-monsoon and the TD during the ISM are statistically significant at a 95% confidence level. Overall, the results are in concurrence with the findings of Krishnamohan et al. (2012) and Girishkumar et al. (2015). Recently, Bhardwaj et al. (2019) reported that the presence of a large-scale convective environment during the active phases of the MJO plays a vital role in the genesis of a low-pressure system over the North Indian Ocean, and the findings from the present study support their hypothesis.

4 | DISCUSSIONS AND CONCLUSIONS

In recent decades, the escalated occurrences of extreme rainfall events (ERE) have been reported over the Indian Subcontinent (e.g. Roxy et al., 2017), and these ERE are majorly associated with severe floods. The composite tracks of the low-pressure systems (tropical cyclones and depressions) indicate that 53% of these have occurred during the active phases of the Madden–Julian Oscillation (MJO). Moreover, future climate projections suggest that MJO-related precipitation events are intensifying under global warming scenarios (e.g. Subramanian et al., 2014; Maloney et al., 2019). Though individual MJO events can act differently, a composite analysis of the ERE and large-scale environmental conditions can provide the broader aspects of its influence. Thus, the study focuses on the characterization of the ERE and its linkage with the propagation of the MJO.

The analysis revealed that the occurrences and characterization of the ERE were more pronounced during the active phases of the MJO. Over the oceanic and continental regions, a large number of ERE and a significant contribution to the seasonal rainfall is prominent during the active phases of the MJO. However, over northeast India and northern Bay of Bengal (BoB), a large number of ERE and extreme rainfall contributions (ERC) is evident during the suppressed phases of the MJO. Another notable finding from the analysis is that the influence of the MJO on the ERE is prominent south of 20° N. The logistic regression model substantiates this, and the probability of the ERE occurrences is strongly associated with the active phases of the MJO during the Indian Summer Monsoon (ISM) and post-monsoon over the east coast of India. The composite results are in agreement with the variations in the ERE during the active and suppressed phases of the MJO. Krishnamurti et al. (2016) proposed that the passage of an active MJO can only trigger convection and clouds; the succeeding growth of the clouds involves synoptic-scale disturbances. The present study indicates that a large-scale environmental set-up during the passage of the active MJO can favour the initiation of meso- and synoptic-scale convection.

A future scope of the study is to investigate the distinctive thermodynamic and circulation features of the ERE by considering both north- and eastward-propagating intraseasonal oscillations over a quasi-homogeneous climate zones (about 10° × 10°). Further, the study advocates that in the prediction of the ERE, numerical weather prediction models should consider the dominant intraseasonal oscillations. The findings from the study will help to validate ocean–atmosphere-coupled models.

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REFERENCES

Ajayamohan, R.S. and Rao, S.A. (2008) Indian Ocean dipole modulates the number of extreme rainfall events over India in a warming environment. Journal Meteorological Society of Japan, 86, 245–252. https://doi.org/10.2151/jmsj.86.245.
Anandh, P.C., Vissa, N.K. and Broderick, C. (2018) Role of MJO in modulating rainfall characteristics observed over India in all seasons utilizing TRMM. International Journal Climatology, 38, 2352–2373. https://doi.org/10.1002/joc.5339.
Barrett, B.S. and Leslie, L.M. (2009) Links between tropical cyclone activity and Madden–Julian Oscillation phase in the North Atlantic and Northeast Pacific basins. Monthly Weather Review, 137, 727–744. https://doi.org/10.1175/2008MWR2602.1.
Bhardwaj, P., Singh, O., Pattanaik, D.R. and Klotzbach, P.J. (2019) Modulation of Bay of Bengal tropical cyclone activity by the Madden–Julian Oscillation. Atmospheric Research, 229, 23–38. https://doi.org/10.1016/j.atmosres.2019.06.010.
Bharti, V. and Singh, C. (2015) Evaluation of error in TRMM 3B42V7 precipitation estimates over the Himalayan region. Journal of Geophysical Research: Atmospheres, 120, 12458–12473. https://doi.org/10.1002/2015JD023779.
Boers, N., Goswami, B., Rheinwalt, A., Bookhagen, B., Hoskins, B. and Kurths, J. (2019) Complex networks reveal global pattern of extreme-rainfall teleconnections. *Nature*, 566, 373–377. https://doi.org/10.1038/s41586-018-0872-x.

Boyaj, A., Ashok, K., Ghosh, S., Devanand, A. and Dandu, G. (2018) The Chennai extreme rainfall event in 2015: the Bay of Bengal connection. *Climate Dynamics*, 50, 2867–2879. https://doi.org/10.1007/s00382-017-3778-7.

Cannon, F., Carvalho, L.M., Jones, C., Hoell, A., Norris, J., Kiladis, G.N. and Tahir, A.A. (2017) The influence of tropical forcing on extreme winter precipitation in the western Himalaya. *Climate Dynamics*, 48, 1213–1232.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Herschbaumer, H., Holm, E. V., Isaksen, L., Källberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.J., Park, B.K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.N. and Vitart, F. (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137, 553–597. https://doi.org/10.1002/qj.828.

Gupta, V., Jain, M.K., Singh, P.K. and Singh, V. (2019) An assessment of global satellite-based precipitation datasets in capturing precipitation extremes: a comparison with observed precipitation dataset in India. *International Journal of Climatology*, 1–22. https://doi.org/10.1002/joc.6419.

Hall, J.D., Matthews, A.J. and Karoly, D.J. (2001) The modulation of tropical cyclone activity in the Australian region by the Madden–Julian Oscillation. *Monthly Weather Review*, 129, 2970–2982. https://doi.org/10.1175/15200493(2001)129<2970:TMOTC2.0.CO;2.

Huffman, G.J., Bolvin, D.T., Nelkin, E.J., Wolff, D.B., Adler, R.F., Gu, G., Hong, Y., Bowman, K.P. and Stocker, E.F. (2007) The TRMM multisatellite precipitation analysis (TMPA): quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *Journal of Hydrometeorology*, 8, 38–55. https://doi.org/10.1175/JHM560.1.

Hunt, K.M.R., Turner, A.G. and Shaffrey, L.C. (2018) Extreme daily rainfall in Pakistan and north India: scale-interactions, mechanisms, and precursors. *Monthly Weather Review*, 146, 1005–1022. https://doi.org/10.1175/MWR-D-17-0258.1.

India Meteorological Department. (2008) *Tracks of Cyclones and Depressions in the Bay of Bengal and Arabian Sea 1891–2007*. Electronic Version 1.0/2008. Chennai: IMD.

Jeong, J.H., Kim, B.M., Ho, C.H. and Noh, Y.H. (2008) Systematic variation in wintertime precipitation in East Asia by MJO-induced extratropical vertical motion. *Journal of Climate*, 21, 788–801. https://doi.org/10.1175/2007JCLI1801.1.

Jia, X., Chen, L., Ren, F. and Li, C. (2011) Impacts of the MJO on winter rainfall and circulation in China. *Advances in Atmospheric Sciences*, 28, 521–533. https://doi.org/10.1007/s00376-010-9118-z.

Jones, C. and Carvalho, L.M. (2012) Spatial-intensity variations in extreme precipitation in the contiguous United States and the Madden–Julian oscillation. *Journal of Climate*, 25, 4898–4913. https://doi.org/10.1175/JCLI-D-11-00278.1.

Konda, G. and Vissa, N.K. (2019) Intraseasonal convection and air–sea fluxes over the Indian monsoon region revealed from the bimodal ISO index. *Pure and Applied Geophysics*, 176, 3665–3680. https://doi.org/10.1007/s00024-019-02119-1.
Sossa, A., Liebmann, B., Bladé, I., Allured, D., Hendon, H.H., Peterson, P. and Hoell, A. (2017) Statistical connection between the Madden–Julian Oscillation and large daily precipitation events in West Africa. *Journal of Climate*, 30, 1999–2010. https://doi.org/10.1175/JCLI-D-16-0144.1.

Stott, P. (2016) How climate change affects extreme weather events. *Science*, 352, 1517–1518. https://doi.org/10.1126/science.aaf7271.

Subramanian, A., Jochum, M., Miller, A.J., Neale, R., Seo, H., Waliser, D. and Murtugudde, R. (2014) The MJO and global warming: a study in CCSM4. *Climate Dynamics*, 42, 2019–2031. https://doi.org/10.1007/s00382-013-1846-1.

Subudhi, A.K. and Landu, K. (2019) Influence of convectively coupled equatorial waves and intra-seasonal oscillations on rainfall extremes over India. *International Journal of Climatology*, 39, 2786–2792. https://doi.org/10.1002/joc.5987.

Villarini, G. and Denniston, R.F. (2016) Contribution of tropical cyclones to extreme rainfall in Australia. *International Journal of Climatology*, 36, 1019–1025. https://doi.org/10.1002/joc.4393.

Vissa, N.K., Satyanarayana, A.N.V. and Prasad Kumar, B. (2013) Intensity of tropical cyclones during pre- and post-monsoon seasons in relation to accumulated tropical cyclone heat potential over Bay of Bengal. *Natural Hazards*, 68, 351–371. https://doi.org/10.1007/s11069-013-0625-y.

Wheeler, M.C. and Hendon, H.H. (2004) An all-season real-time multivariate MJO index: development of an index for monitoring and prediction. *Monthly Weather Review*, 132, 1917–1932. https://doi.org/10.1175/1520-0493(2004)132<1917:AARMMI>2.0.CO;2.

Xavier, P., Rahmat, R., Cheong, W.K. and Wallace, E. (2014) Influence of Madden–Julian Oscillation on Southeast Asia rainfall extremes: observations and predictability. *Geophysical Research Letters*, 41, 4406–4412. https://doi.org/10.1002/2014GL060241.

Zhang, C. (2005) Madden–Julian Oscillation. *Reviews of Geophysics*, 43, RG2003. https://doi.org/10.1029/2004RG000158.

Zhang, C. (2013) Madden–Julian Oscillation (2013) Bridging weather and climate. *Bulletin of the American Meteorological Society*, 94, 1849–1870. https://doi.org/10.1175/BAMS-D-12-00026.1.

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