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# Impact of Madden-Julian oscillations on the Indian summer monsoon sub-divisional rainfalls

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**सार –** भारतीय ग्रीष्मकालीन मानसून वर्षा से 2–7 वर्षों के समय के पैमानों में अंतः मौसमी परिवर्तनों का पता चलता है। ये परिवर्तन द्विवार्षिक कल्प दोलनों और एल नीनो दक्षिणी दोलन परिघटना तथा एम. जे. ओ. की सक्रियता से संबद्ध 30–60 दिनों के समय के पैमानों में अंतः मौसमी परिवर्तनों से भी जुड़े हुए हैं। ये निम्न आवृति दोलनों के अन्य मोडों के अलावा भारतीय ग्रीष्मकालीन मानसून वर्षा के अंतः मौसमी दोलनों के प्रमुख मोड के रूप में उभर कर आए हैं। इस परिप्रेक्ष्य में 29 मौसम विज्ञानिक उपखंडों में हुई वर्षा के अंतः और अंतर मौसमी परिवर्तनों की जाँच संचयी उपखंडीय ग्रीष्मकालीन मानसून वर्षा (1979–2000) से हिंद महासागर, प्रशांत महासागर और अटलांटिक महासागर के अन्तर्गत आने वाले 10 विभिन्न देशांतरों के एम. जे. ओ. के सूचकांकों से जोड़ते हुए की गई है। इस शोध पत्र में इस अध्ययन से प्राप्त हुए परिणामों का विवेचन किया गया है।

**ABSTRACT.** Indian summer monsoon rainfall exhibits inter-seasonal variations in the time scales of 2-7 years which are linked to quasi-biennial oscillations and El nino-Southern Oscillation phenomenon and also intra-seasonal variations in the time-scale of 30-60 days which are linked to activity of MJO which emerged as a dominant mode of intra-seasonal oscillations of Indian summer monsoon rainfall in addition to the other modes of low frequency oscillations. In this scenario, the inter and intra seasonal variability of 29 meteorological sub-divisional rainfalls has been investigated by correlating the MJO indices at 10 different longitudes covering Indian, Pacific and Atlantic Oceans with cumulative sub-divisional summer monsoon rainfall (1979 – 2000). The results were discussed.

**Keywords** – Madden Julian oscillations, Velocity potential, Zonal wind, Circulation cells.

## 1. Introduction

In the early 1980s, Madden Julian Oscillations (MJO) which were named after, Roland Madden and Paul Julian, gained prominence. The global significance of those oscillations was understood and several taken up this phenomenon for studies. In the year 1971, Roland Madden and Paul Julian discovered 40-50 day oscillations or 30-60 day oscillations in the zonal wind anomalies over tropical Pacific. The MJO is considered to be a global westward propagating 40 to 50 day oscillations seen in the 850 hPa zonal wind and 700-150 hPa temperatures (Madden and Julian 1971, 1994). In upper air, these are characterized by eastward propagation of atmospheric features with maximum amplitudes in the Eastern Hemisphere (Wang and Rui, 1990). MJO affects most of the troposphere but is more evident over Indian and Pacific oceanic regions for the reason that the convective anomalies associated with the intra-seasonal oscillation are strongest over the Indian Ocean, Maritime Continent and warm pool region of the west Pacific. The MJO are seen as variations in the wind, cloudiness, rainfall and as well as sea surface temperature in the tropics. Spectral studies of monsoonal parameters like cloudiness (Yasunari, 1979) and precipitation (Hartmann and Michelson, 1989) showed a 30–40 day period oscillations. The period of oscillation is approximately the same as that of the Madden–Julian oscillation and termed as the Intra-Seasonal Oscillation (ISO).

## 2. Data and methodology

The sub-divisional rainfall data for the 29 meteorological sub-divisions has been obtained from COLA and the India rainfall data was compiled by Parthasarathy (Parthasarathy *et al.*, 1995), Indian Institute of Tropical Meteorology, Pune. The MJO indices for ten time-lagged longitudes were obtained from Climate Prediction Center (CPC), NOAA data sets. The ten MJO indices were constructed by regressing the daily data onto the ten patterns of the first EEOF obtained from the analysis of pentad velocity potential at 200 hPa for ENSO neutral and weak ENSO winters (November – April) for the period 1979-2000 during which the MJO activity is prominent. The MJO indices are for longitudes (80° E, 100° E, 120° E, 140° E, 160° E, 120° W, 40° W, 10° W, 20° E and 70° E) for the period 1979 - 2000 are used in this study. The time-longitude cross-section of MJO as above reveal the propagation, amplitude and location of the MJO related features. The monthly MJO indices for the period 1979 - 2000 were computed based on the daily CPC MJO indices. Both data sets were correlated to visualize the impact of MJO phases during different months at different longitudes on 29 meteorological sub-divisional summer monsoon rainfalls and also to understand the inter-seasonal and intra-seasonal variability of sub-divisional rainfalls associated with MJO phenomenon.

## 3. Results and discussion

MJO influences the global circulation, intensity and break monsoon conditions of the summer monsoon rainfall considering that monsoon is normally active during the monsoon period of four months from June to September. During the summer months, low-frequency variability in the tropics is dominated by inter-annual variations associated with ENSO and by intra-seasonal variations such as the MJO. The MJO can have a significant impact on regions that experience rainy seasons both during winter and summer seasons. The study of extreme events of precipitation over California (Jones, 2000) indicated that the frequency of extreme events are more common when tropical activity associated with the MJO is high, as opposed to periods of quiescent phases of the oscillation. Second, a slight preference for a higher number of events is observed when convective anomalies are located in the Indian ocean. Many studies on intra-seasonal oscillations of Indian summer monsoon rainfall also indicated its close association with the Madden Julian oscillations (Dakshinamurti and Keshavamurthy, 1976; Sikka and Gadgil, 1980; Keshavamurthy, 1973; Krishnamurti and Bhalme, 1976; Murakami and Frydrych, 1974; Ramaswamy, 1962; Murakami, 1976).

Indian summer monsoon rainfall is localized to certain extent and is often convective type. The summer monsoon rainfall is marked by wet and dry periods. During dry periods (break monsoon conditions) the easterly jet at the upper levels is stronger and shifts northward and the meridional component of the wind over the northern parts of India is from the north in the middle troposphere and from the south in the upper troposphere. The direction of the meridional winds is just the opposite during the wet periods (active monsoon conditions). From the observed patterns in rainfall distribution and circulation, it can be inferred that the break monsoon conditions are associated with a northward shift of the normal meridional circulation and the occurrence of enhanced convective activity near the southern tip of India. Most of India lies under the descending branches of the two thermally forced meridional circulations with ascending branches near the foothills of the Himalayas and the extreme southern tip of India. The wind anomalies associated with MJO activity cause oceanic disturbances and alter the sea surface temperatures over the Indian, Pacific and Atlantic Oceans thereby creating convective anomalies over Oceans. In suppressed convection, the clear skies allow more incoming shortwave radiation that increases sea surface temperature and associated stronger than normal trade winds cause more evaporation. The convective anomalies associated with MJO alter the general circulation pattern. The MJO index is a measure of OLR at that longitude and a high value of OLR is indicative of cloud free atmosphere and low OLR value is indicative of convection and cloud formation. It is observed that the OLR pattern is organized into concentrated areas and move eastward starting from Indian Ocean toward Pacific Ocean. The MJO is said to have a dipole nature, with enhanced convection over Indian Ocean and a suppressed convection over Pacific Ocean and *vice versa*. In this scenario, the influence of these eastward moving convective anomalies on the sub-divisional rainfall of Indian summer monsoon rainfall was investigated and results are discussed below.

MJO activity is stronger during northern hemispheric boreal winter and prominent over the eastern hemisphere than western hemisphere and stronger when the sea surface temperatures are near normal over Pacific Ocean. MJO dynamics suggests that the zone of suppressed convection is characterized by clear skies, high sea surface temperature and high evaporation. The zone of alternative enhanced convection is characterized by cloudiness, low sea surface temperature, low evaporation and moisture convergence. Anomalous circulation develops around the region of enhanced convection with zonal winds blowing away from the zone of suppressed convection towards region of enhanced convection. The super cloud clusters move eastward with slow speed with MJO wave. The MJO wave has a wave number is 1-2 suggesting presence of one or two enhanced convective zones around the globe. The MJO wave at the western Indian Ocean takes 30 – 60 days period to complete one single cycle. The MJO activity is found to modify the general circulation. The cloudiness/rainfall associated with zone of enhanced convection propagate slowly eastward with a period of 30-60 days and alters the sea surface temperatures during progression of the MJO wave. The sub-divisional rainfalls

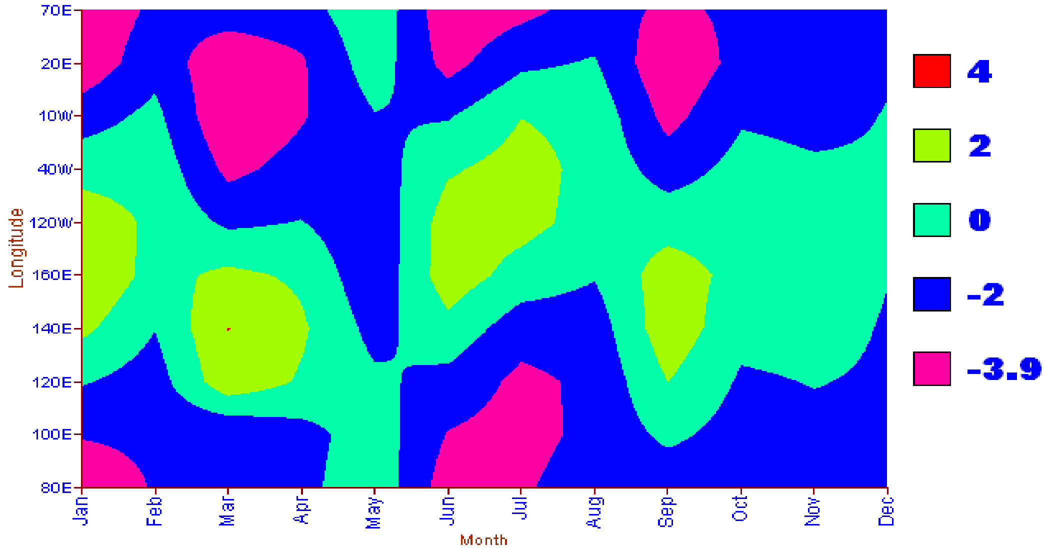


**Fig. 1.** Showing longitude wise distribution of average (1979-2002) monthly MJO activity

that showed correlations with MJO index at different longitudes were a result of propagation of MJO wave and the MJO influences entire tropical troposphere. The average (1979-2002) monthly MJO activity was presented in Fig. 1. The average distribution suggests a suppressed convective activity zone (approximately 120° E to 40° W) between two enhanced convective activity zones. The first enhanced convective activity zone is approximately between 80° E - 120° E in all the months from January to December except for the month of May and another approximately at 10° W and between 20° E - 70° E in all the months except for the month of May. In the month of May it is seen that the enhanced convective activity was extending westwards. It indicates that the variability in MJO activity in tropics, leads to shifting of enhanced/suppressed convective activity zones in tropics altering the general circulation, walker's circulation through anomalous circulations that develop around the enhanced (suppressed) convective activity zones changing rainfall pattern over India. The present study of correlations between meteorological sub-divisional rainfalls and MJO indices centered at various longitudes suggest the extent of rainfall variability due to MJO variability.

The spatial and temporal distribution of mean monthly MJO activity at various longitudes is presented in Fig. 1. The spatial distribution of CCs observed between MJO activity at various longitudes and summer monsoon sub-divisional rainfalls is presented in Figs. 2 to 13 month-wise. The observed spatial distribution of CCs is a result of the association between the strength of MJO activity at various longitudes and the summer monsoon sub-divisional rainfall.

From Fig. 1, it is seen that a suppressed convective activity zone is sandwiched between two enhanced convective activity zones. The two regions are shown as filled contours. The positive and negative or near zero correlations depicted in Figs. 2 to 13 are in various regions and are in accordance with the association between strength of MJO activity at various longitudes. As the strength of MJO activity varied month-wise at different longitudes so do the correlation coefficients. Fig. 1 suggests that in the month of January, enhanced convective activity zone was between 10° W - 120° E with much stronger activity between 20° E - 100° E. At the same time a suppressed convective activity zone was observed between 120° E - 10° W.

In Fig. 2, the spatial distribution of CCs between sub-divisional rainfalls and MJO activity at various longitudes in the month of January is presented. From Fig. 2, it can be seen that the correlation coefficients are opposite in sign with respect to enhanced/suppressed convective activity zones. The sub-divisional rainfalls of north Assam to Bihar plains showed negative CCs with respect to enhanced convective zone and positive with respect to suppressed convective activity zone. The other sub-divisional rainfalls in the same figure suggested negative or near zero CCs with respect to suppressed convective activity zone and positive or near zero CCs with respect to enhanced convective zone. The propagation of super cloud clusters associated with enhanced convective activity zones and their movement along the MJO influenced the certain sub-divisional rainfalls and its influence is limited to certain zone of sub-divisional rainfalls.

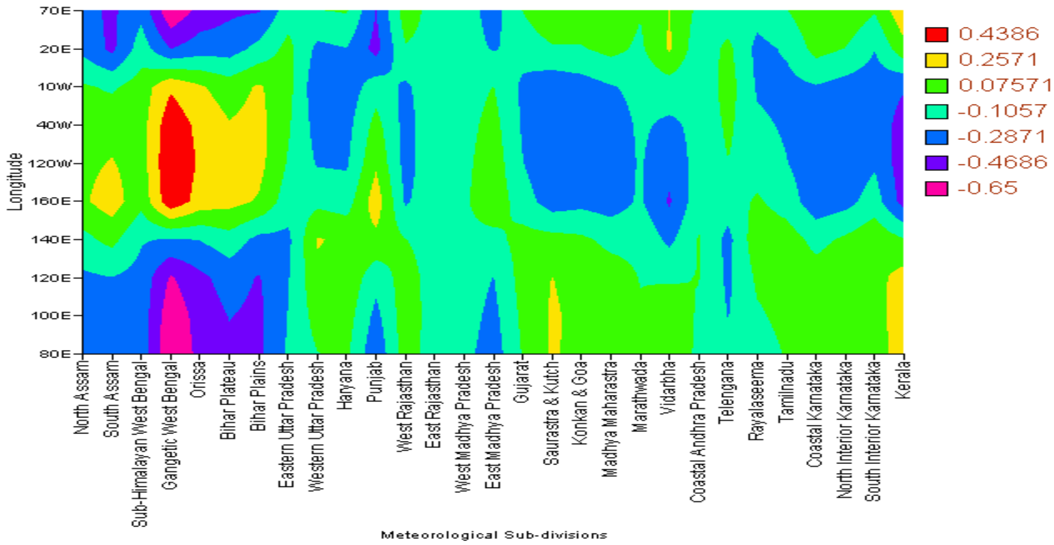


**Fig. 2.** Showing distribution of CCs between January MJO activity at various longitudes and summer monsoon sub-divisional rainfall (1979-2000)

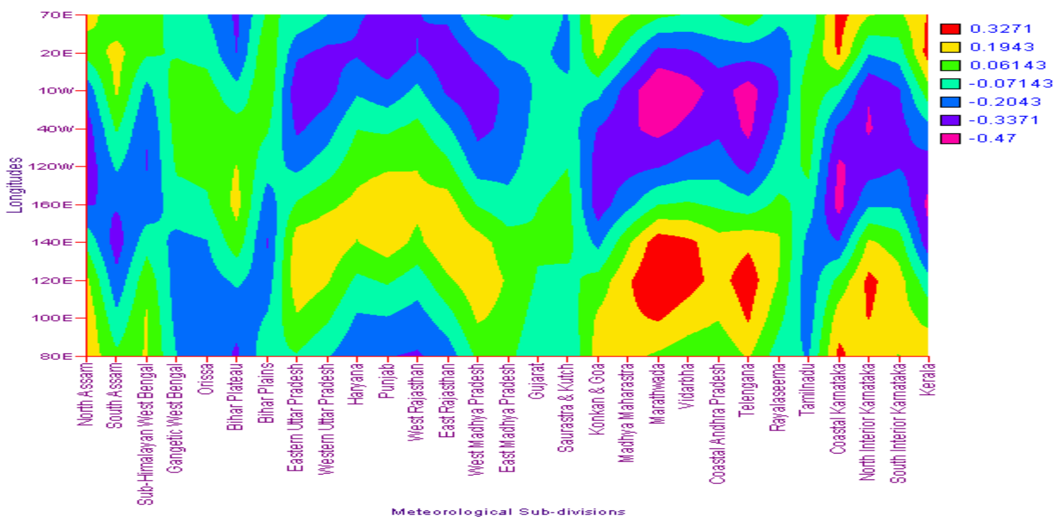


**Fig. 3.** Showing distribution of CCs between February MJO activity at various longitudes and summer monsoon sub-divisional rainfalls (1979-2000)

From Fig. 1, it is seen that for the month of February enhanced convective activity zone shifts slightly eastward and was between 20° E - 140° E. The suppressed convective activity zone was between 140° E - 20° E. The strength of MJO activity in these zones observed to be lesser than the month of January.

In Fig. 3, the spatial distribution of CCs between MJO activity at various longitudes and sub-divisional rainfalls are presented. The change in CCs distributions for the month of February, in comparison, with the month of January is due to variation in the strength of MJO activity at specified longitudes. However, the pattern of CCs suggests again the opposite influence of enhanced/suppressed convective activity on the sub-divisional rainfalls. Significant positive CCs were found between sub-divisional rainfalls from Konkan & Goa to Telangana and also from coastal Karnataka to Kerala with enhanced convective activity zone between 20° E - 140° E and significant negative CCs with suppressed convective activity between 140° E - 20° E. The pattern of CCs further suggests that enhanced convection within 20° E - 140° E increases sub-divisional rainfalls from Konkan & Goa to Telangana and from coastal Karnataka to Kerala and so do the suppressed convection within 140° E - 20° E. The sub-divisional rainfalls of east Uttar Pradesh,

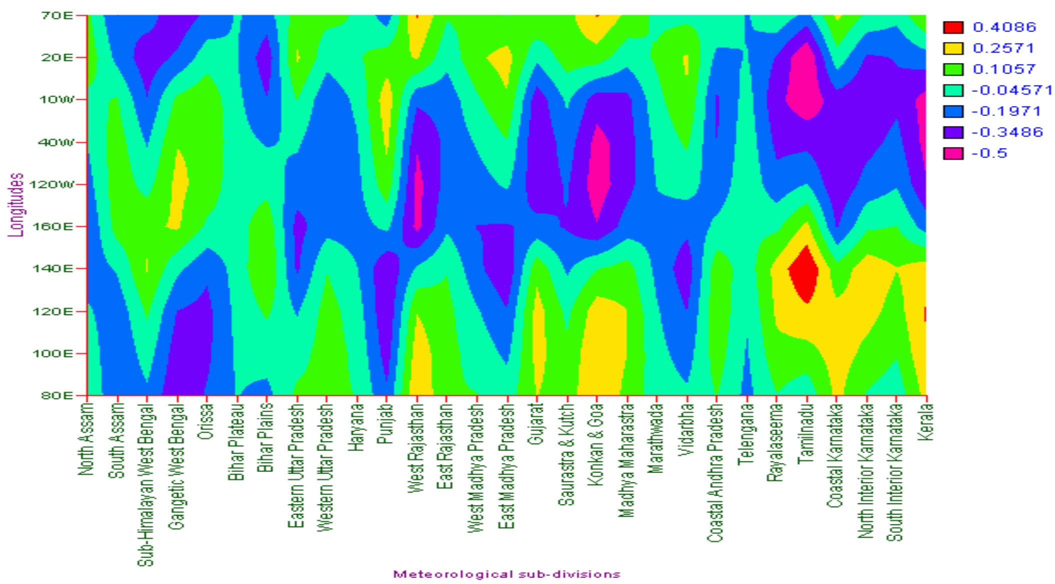


**Fig. 4.** Showing distribution of CCs between March MJO activity at various longitudes and summer monsoon sub-divisional rainfalls (1979-2000)

west Uttar Pradesh and west Madhya Pradesh have similar relationship with MJO activity. However, the sub-divisional rainfalls of Haryana, Punjab, west Rajasthan and east Rajasthan have negative CCs or near zero CCs with enhanced convective activity between 20° E - 140° E and positive CCs or near zero CCs with suppressed convective activity between 140° E - 20° E. The zone of positive CCs shifted slightly westwards and south or southwestwards in comparison with the month of January. It is seen from Fig. 3 that the spatial extent of impact on sub-divisional rainfall reduced and only seen from Gangetic West Bengal to Bihar plateau due to reduced strength of MJO activity between 10° W - 120° E.

For the month of March (Fig. 1) it is noted that, again, the enhanced convective activity zone extended westwards up to 120° W and the zone lay between 120° W - 120° E approximately with strong enhanced convective activity between 40° W - 20° E. The suppressed convective activity zone lay between 120° E - 120° W with the strength of suppressed convection increased between 120° E - 160° E. The resulting spatial distribution of CCs between mean monthly MJO activity at various longitudes and sub-divisional rainfalls for the month of March is presented in Fig. 4.

From Fig. 4 it is seen that enhanced/suppressed convective activity at various longitudes have shown opposite impact on sub-divisional rainfalls. The sub-divisional rainfalls of west Rajasthan, Gujarat, Konkan & Goa, coastal Karnataka and Kerala have shown positive CCs with enhanced convective activity between 80° E - 120° E. The sub-divisional rainfall of Tamilnadu has shown positive CC with suppressed convective activity between longitudes 120° E - 160° E. That means, the suppressed convective activity over the above region reduces the sub-divisional rainfall of Tamilnadu. Again, it is seen that the strong enhanced convective activity between 40° W - 20° E have shown significant negative CCs with sub-divisional rainfall of Tamilnadu indicating any increase in enhanced convective activity over this region results in reduction of sub-divisional rainfall of this sub-division. Rest of the sub-divisions has shown only negative CCs with MJO activity at various longitudes considered in this study.

The mean monthly MJO activity for the month of April was presented in Fig. 1. From the figure we can see that the mean monthly enhanced MJO activity was between 120° W - 100° E and the mean monthly suppressed MJO activity was between 100° E - 120° W. The strength of MJO activity between 100° E - 120° W was lesser than the strength of MJO activity for the month of March.

The distribution of CCs found between the sub-divisional rainfalls and the mean monthly MJO activity for the month of April was presented in Fig. 5. It is seen from the figure that the sub-divisional rainfalls of west Uttar Pradesh, Haryana, Punjab, west Rajasthan, Gujarat, Saurastra & Kutch, Konkan & Goa, Marathwada, Rayalaseema, coastal Karnataka, north & south interior Karnataka, Orissa, Bihar Plateau, north Assam and Sub-Himalayan West Bengal have positive CCs with mean monthly suppressed MJO activity between 100° E & 120° W indicating that the suppressed convective activity

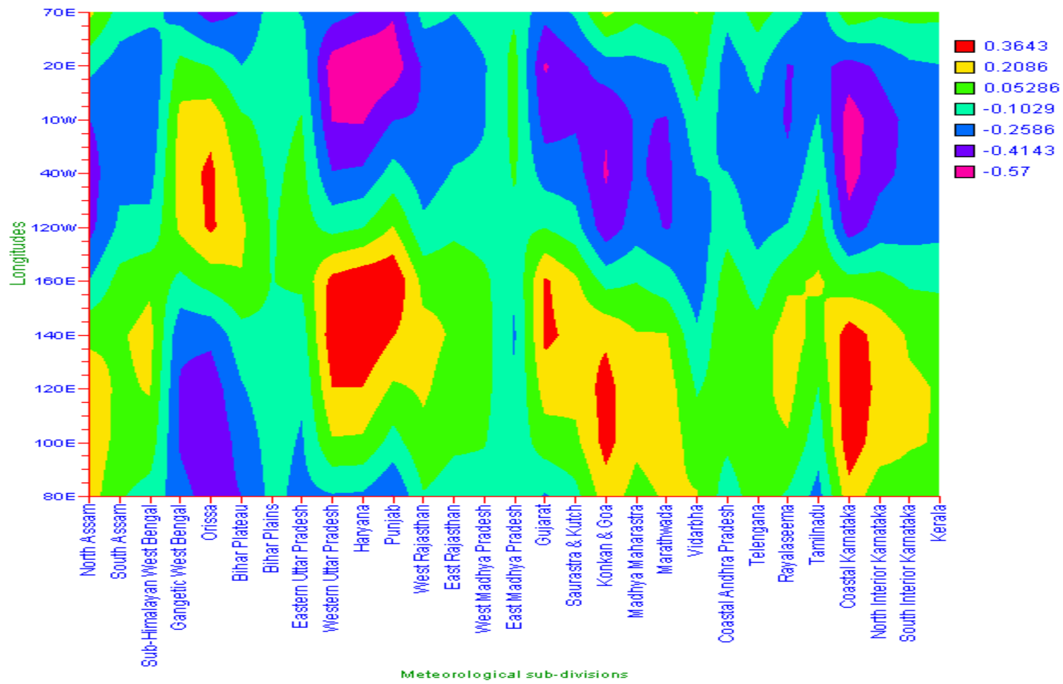


**Fig. 5.** Showing distribution of CCs between April MJO activity at various longitudes and summer monsoon sub-divisional rainfalls (1979-2000)

between these longitudes increases the sub-divisional rainfalls of the above. Moreover, Konkan & Goa, Madhya Maharastra, Marathwada, coastal Karnataka, north & south interior Karnataka also have positive CCs with mean monthly enhanced MJO convective activity between 80° E - 100° E indicating the increase in sub-divisional rainfalls with increase in enhanced convective activity within these longitudes. The sub-divisional rainfalls that have negative CCs with mean monthly MJO activity at various longitudes for the month of April indicating suppressed/enhanced convective activity increases/decreases sub-divisional rainfalls were also shown in Fig. 5.

The Mean monthly MJO activity at various longitudes for the month of May was presented in Fig. 1. From this figure, it can be seen that the enhanced convective activity extended further westwards up to 120° E from 10° W and suppressed convective activity was seen between 10° W - 120° E. The observed mean monthly MJO activity was different from the mean monthly MJO activity seen in the months from January to April. No strong enhanced MJO activity was also seen in the month of May as seen in the months of January and March.

The distribution of CCs observed between mean monthly MJO activity for the month of May and the sub-divisional rainfalls was presented in Fig. 6. It can be seen from this figure that the sub-divisional rainfalls of north Assam, Sub-Himalayan West Bengal, Bihar Plains, Haryana, Punjab, Saurastra & Kutch, Marathwada and Vidarbha have positive CCs with enhanced convective activity between 10° W - 120° E indicating increase in the enhanced convective activity in this region increases these sub-divisional rainfalls. Moreover, it is also seen that the sub-divisional rainfalls from Gangetic West Bengal to west Rajasthan and from Gujarat to Telangana, coastal Karnataka, south interior Karnataka and Kerala have negative CCs with enhanced convective activity between 120° E - 120° W indicating decreased sub-divisional rainfalls of these sub-divisions with increased enhanced convective activity over this region. The other observed negative CCs shown in Fig. 6 indicate that the suppressed/enhanced convective activity at various longitudes increases/decreases the sub-divisional rainfalls.

Again, from Fig. 1, the mean monthly MJO activity for the month of June can be seen and the figure suggests that a strong enhanced convective activity lies over the region 20° E - 100° E and the overall enhanced convective activity over 10° W - 120° E. The suppressed convective activity lies between 120° E - 10° W with strong suppressed convective activity between 140° E - 120° W.

The resulting distribution of CCs found between 29 sub-divisional rainfalls and mean monthly MJO

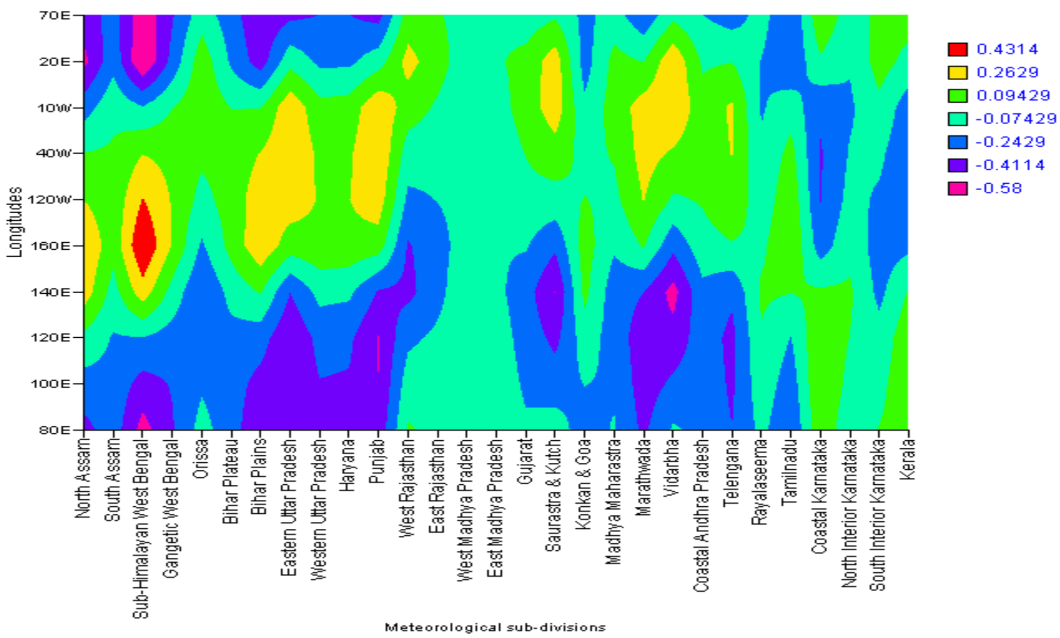


**Fig. 6.** Showing distribution of CCs between May MJO activity at various longitudes and summer monsoon sub-divisional rainfalls (1979-2000)

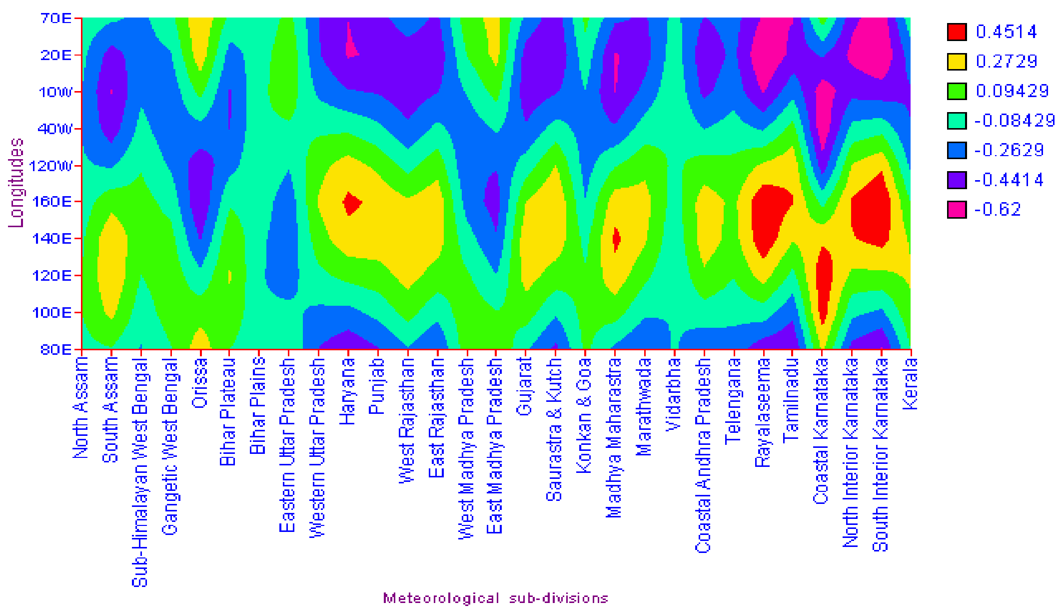


**Fig. 7.** Showing distribution of CCs between June MJO activity at various longitudes and summer monsoon sub-divisional rainfalls (1979-2000)

activity for the month of June was shown in Fig. 7. From this figure, it can be seen that the sub-divisional rainfalls of south Assam & coastal Karnataka have positive CCs with enhanced convective activity between 80° E - 120° E. The sub-divisional rainfalls of Haryana, Punjab, west Rajasthan, Gujarat, Madhya Maharastra, coastal Andhra Pradesh, Rayalaseema, Tamilnadu, coastal Karnataka, north & south interior Karnataka and Kerala have positive CCs with suppressed convective activity between 120° E - 120° W indicating that increased suppressed convective activity increases these sub-divisional rainfalls. Moreover, the sub-divisional rainfalls

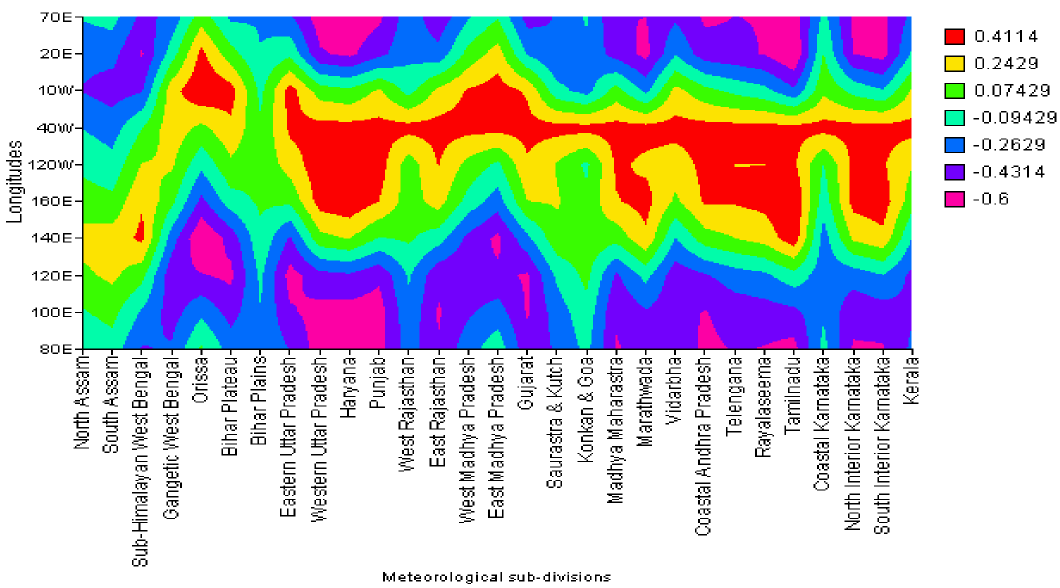


**Fig. 8.** Showing distribution of CCs between July MJO activity at various longitudes and summer monsoon sub-divisional rainfalls (1979-2000)

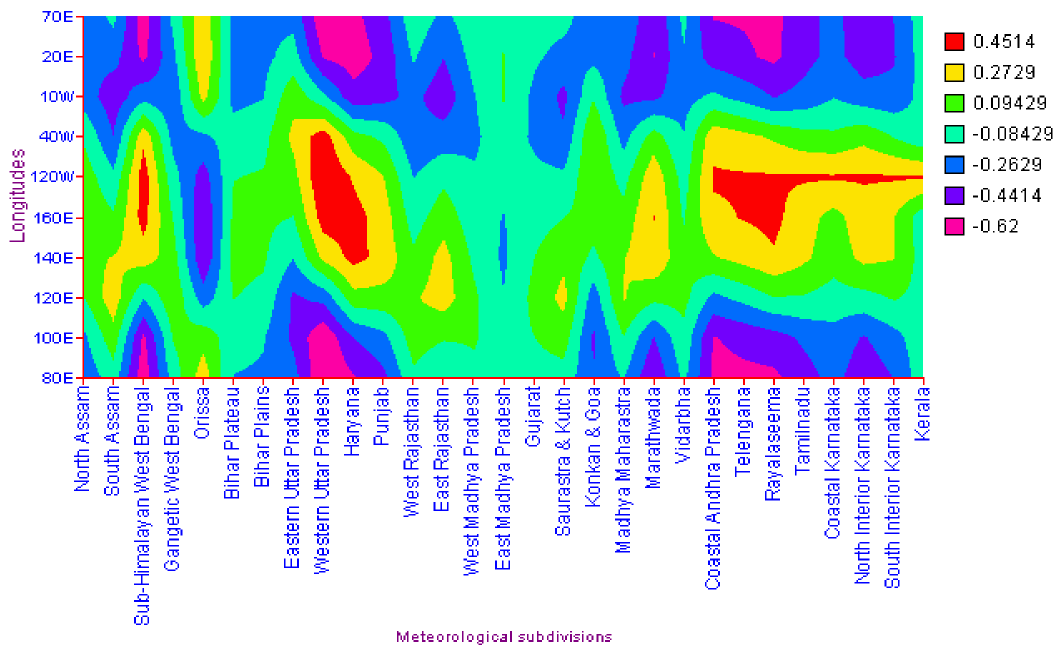


**Fig. 9.** Showing distribution of CCs between August MJO activity at various longitudes and summer monsoon sub-divisional rainfalls (1979-2000)

of north & south Assam, Sub-Himalayan West Bengal to Bihar plateau, western Uttar Pradesh to Marathwada, coastal Andhra Pradesh to Kerala shown negative CCs with suppressed MJO convective activity between 10° W - 140° E indicating increased suppressed convective activity between 10° W - 140° E decreases these sub-divisional rainfalls. The other negative CCs shown in Fig. 7 indicate increased/decreased enhanced convective activity between 10° W - 100° E decreases sub-divisional rainfalls.

The mean monthly MJO activity for the month of July was presented in Fig. 1. It can be seen from this

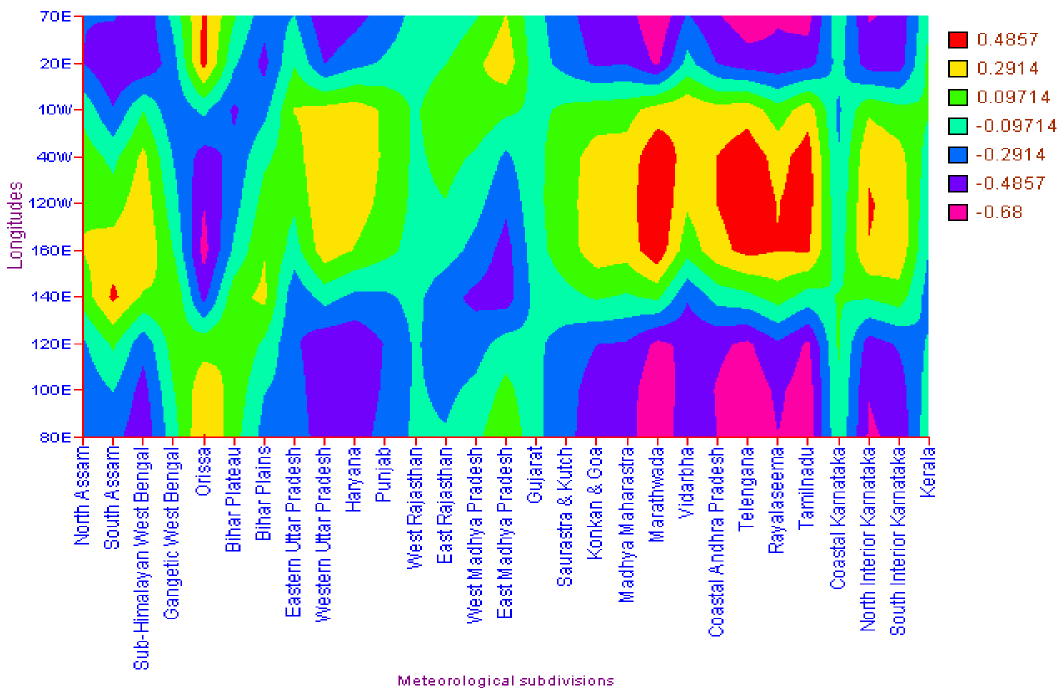


**Fig. 10.** Showing distribution of CCs between September MJO activity at various longitudes and summer monsoon sub-divisional rainfalls (1979-2000)

figure that the enhanced MJO convective activity shifted eastward in comparison with the month of June and lies between 20° E - 140° E with strong MJO enhanced convective activity between 20° E - 120° E. Moreover, the suppressed MJO convective activity was seen between 140° E - 20° E with strong suppressed MJO convective activity between 140° E - 40° W.

The distribution of CCs observed between mean monthly MJO activity of July and the summer monsoon sub-divisional rainfalls is presented in Fig. 8. The figure suggests that the sub-divisional rainfalls of north & south Assam and Orissa have positive CCs with enhanced MJO convective activity between 20° E - 140° E indicating increased enhanced convective activity within 20° E - 140° E increases the sub-divisional rainfalls of these three. Again, the sub-divisional rainfalls of Sub-Himalayan West Bengal, Orissa and sub-divisional rainfalls from eastern Uttar Pradesh to Kerala have positive CCs with suppressed MJO convective activity within 140° E - 10° W indicating increased suppressed convective activity increases these sub-divisional rainfalls. The negative CCs shown in figure, other than discussed above, indicate that the increased enhanced/suppressed convective activity within 20° E - 140° E reduces the sub-divisional rainfalls.

The average monthly MJO activity for the month of August was presented in Fig. 1. The Fig. 1 suggests that the mean monthly enhanced convective activity slightly extended westwards and lies within 20° E - 160° E and the suppressed convective MJO activity between 160° E - 20° E. No strong enhanced or suppressed convective activity was seen in this month as observed in the months of June and July.

The distribution of CCs observed between mean monthly MJO activity for the month of August and the summer monsoon sub-divisional rainfalls was shown in Fig. 9. This Fig. 9 suggests that the sub-divisional rainfalls have both positive and negative CCs with both enhanced MJO convective and suppressed MJO convective activity. The sub-divisional rainfalls of south Assam, Sub-Himalayan West Bengal, east Uttar Pradesh to Punjab, Madhya Maharastra, Marathwada, coastal Andhra Pradesh to Kerala have positive CCs with enhanced convective MJO activity between 120° E - 160° E and also with suppressed MJO convective activity between 160° E - 40° W indicating increased enhanced MJO convective activity increases and decreased suppressed MJO convective activity decreases these sub-divisional rainfalls. The negative CCs indicated in Fig. 9 further suggest that the increased enhanced convective MJO activity at various longitudes decreases and increased suppressed convective MJO activity at various longitudes decreases those sub-divisional rainfalls.

The average monthly MJO activity at various longitudes for the month of September was presented in

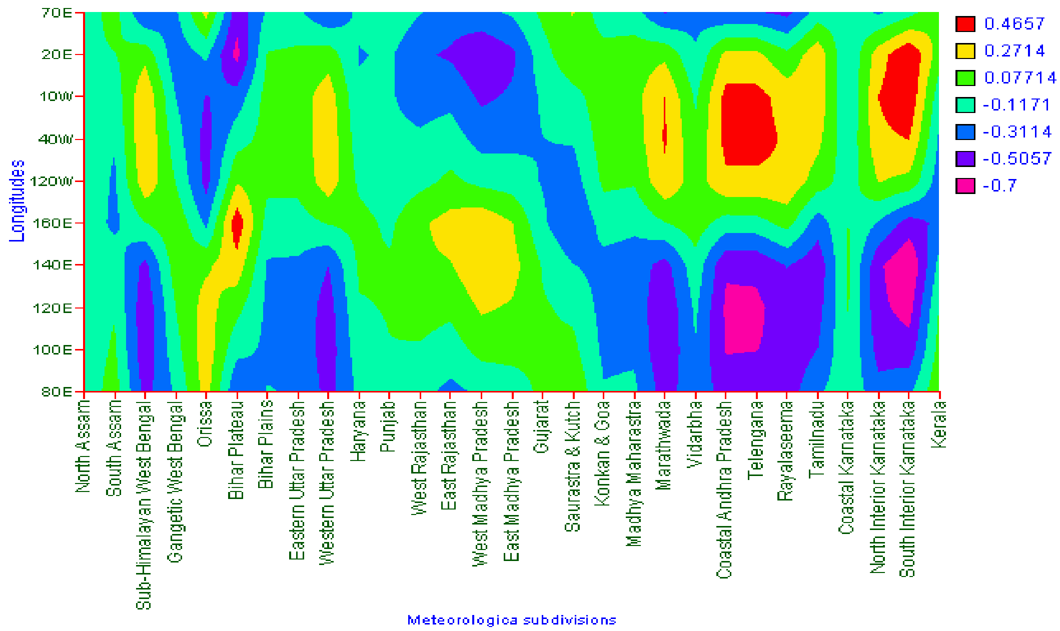


**Fig. 11.** Showing distribution of CCs between October MJO activity at various longitudes and summer monsoon sub-divisional rainfalls (1979-2000)

Fig. 1. From this Fig. 1, it can be seen that the average enhanced MJO convective activity shifted eastwards and seen within 40° W - 100° E and the suppressed average MJO convective activity within 100° E - 40° W with strong suppressed MJO convective activity between 120° E - 160° E and strong enhanced convective activity between 10° W - 70° E.

The distribution of observed CCs between average monthly MJO activity at various longitudes for the month of September and the sub-divisional rainfalls considered in this study was shown in Fig. 10. From Fig. 10 it can be seen that the sub-divisional rainfall of Orissa has got positive CC with enhanced MJO convective activity and negative CC with suppressed MJO convective activity. It can also be seen that the sub-divisional rainfalls of north & south Assam, Sub-Himalayan West Bengal have positive CCs with suppressed average MJO convective activity and negative CCs with enhanced average MJO convective activity. However, it is seen that the remaining sub-divisional rainfalls have both positive and negative CCs with both enhanced and suppressed mean monthly MJO convective activity for the month of September at various longitudes.

The mean monthly MJO activity for the month of October, November was presented in Fig. 1. From Fig. 1, it can be seen that the enhanced MJO convective lies between 10° W - 120° E and the suppressed MJO convective activity between 120° E - 10° W. From the Fig. 1, it can also be seen that for the month of December, the enhanced MJO convective activity extended slightly westwards up to 140° E and lies over 10° W - 140° E with suppressed MJO convective activity within 140° E - 10° W. No strong MJO activity was observed from October to December either in enhanced MJO convective activity or in suppressed MJO convective activity.

The distribution of CCs found between average monthly MJO activity at various longitudes and the sub-divisional rainfalls for the month of October was shown in Fig. 11. From this Fig. 11, it was seen that sub-divisional rainfalls of east Rajasthan and west Madhya Pradesh have positive CCs with suppressed MJO convective activity and negative CCs with enhanced MJO convective activity and further the distribution of CCs suggests that the other sub-divisional rainfalls shown have both positive and negative CCs with both enhanced and suppressed MJO convective activity at various longitudes.

Again, the distribution of CCs found between average monthly MJO activity for the month of November and the sub-divisional rainfalls was presented in Fig. 12. From this Fig. 12, it was seen that only the sub-divisional rainfalls of north & south Assam have positive CCs with suppressed MJO convective activity and negative CCs with enhanced MJO convective activity. The distribution of CCs suggests further that other sub-divisional rainfalls have both positive and negative CCs with both enhanced and suppressed MJO convective activity for this month.

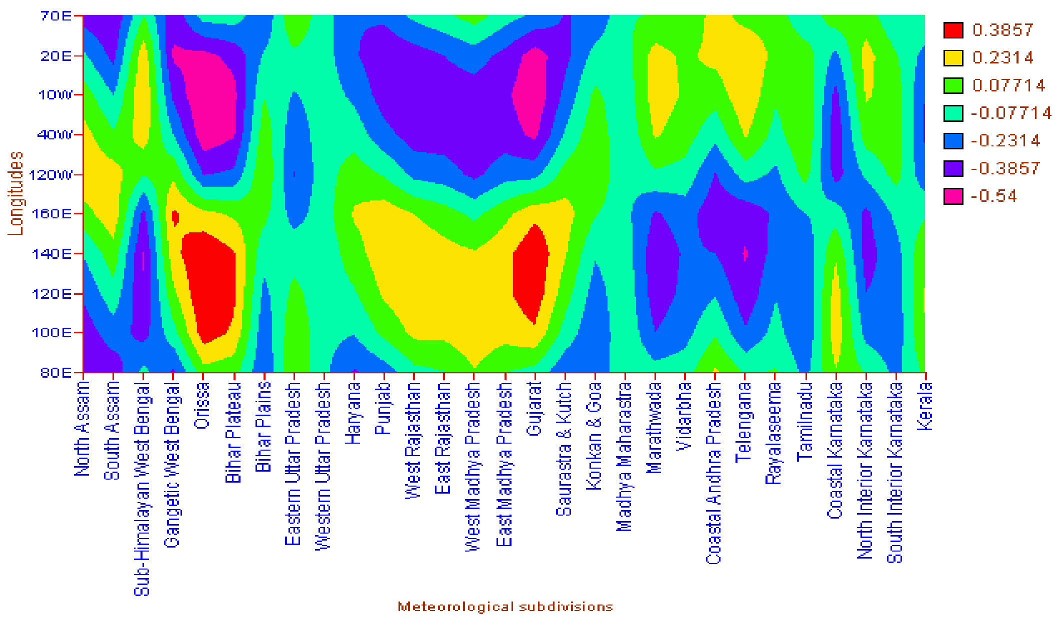


**Fig. 12.** Showing distribution of CCs between November MJO activity at various longitudes and summer monsoon sub-divisional rainfalls (1979-2000)

Furthermore, the distribution of CCs observed between average monthly MJO activity for the month of December at various longitudes and the sub-divisional rainfalls was shown in Fig. 13. From this Fig. 13, it can be seen that the sub-divisional rainfalls of north & south Assam and Sub-Himalayan West Bengal have positive CCs with suppressed MJO convective activity and negative CCs with enhanced MJO convective activity. The other sub-divisional rainfalls shown in the same figure suggests that they have both positive and negative CCs with both the enhanced and suppressed MJO convective activity as in the months of October and November.

From the study of distribution of correlation coefficients (Figs. 2 to 13), it is seen that the highest correlation found between MJO index and sub-divisional rainfall was 0.68 that explain 46% variance and the lowest correlation was 0.43 that explain 18% of the variance. The observed variance even though trivial or feeble may be important depending on the situation. As in the present study, the correlation was between MJO index and cumulative sub-divisional rainfall and if the variance explained is of 10% or more, it may be considered as significant because the predictor was rainfall which is above or below normal. Moreover, the cumulative seasonal rainfall was from June to September, the May month MJO index that correlates with sub-divisional rainfall be considered as pre-cursive as it indicates the progression of MJO wave towards the east. The observed correlations also suggest dipole nature of the MJO wave with enhanced suppressed convections on opposite sides. During near normal sea surface temperatures, the MJO wave over Pacific Ocean modifies the Walker/Hadley circulations by generating anomalous wind patterns thereby influencing rainfall over Indian meteorological sub-divisions. The enhanced convection over 10° W - 100° E (Atlantic/Indian Ocean) and associated cloudiness/rainfall suggest propagation of MJO eastwards with slow speed.

The study of the observed correlations for north Assam suggests that the suppressed/enhanced convection over the 20° E Longitude (African, Indian Ocean region) decreases/increases rainfall over this sub-division and is pre cursive to the summer monsoon rainfall over this sub-division. Similarly, the other observed correlation at 160° E for the month of May indicates the opposite relationship between the convective anomalies over east Indian Ocean/west Pacific and the convective anomalies of west Indian Ocean (Africa region). The Madden Julian oscillations exhibit Kelvin-Rossby mixed mode of propagation in the eastern Hemisphere. The super cloud clusters that are associated with enhanced convection move eastward/pole ward with the movement of Madden-Julian Wave (MJW). Therefore, suppressed/enhanced convection over 20° E Longitude (African, Indian Ocean region) influences the sub-divisional rainfall due to generation and propagation of super cloud clusters that moves with MJW. Again, for south Assam the observed correlations suggest an opposing effect of convective anomalies over east Indian Ocean and Atlantic/west

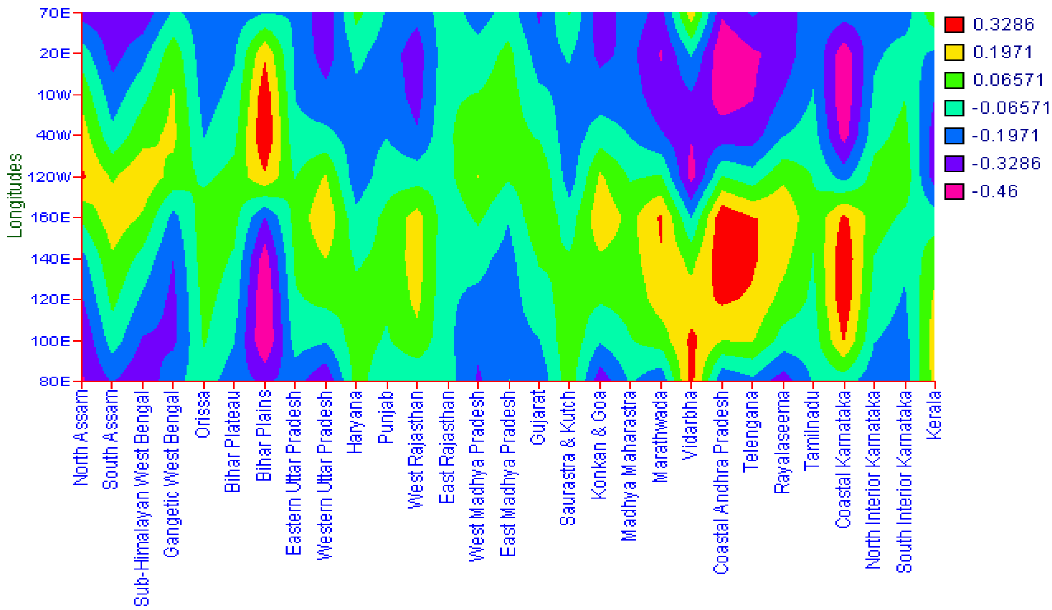


**Fig. 13.** Showing distribution of CCs between December MJO activity at various longitudes and summer monsoon sub-divisional rainfalls (1979-2000)

Indian Oceans for the month of September. The cumulative sub-divisional rainfall is either decreased or increased with suppressed or enhanced convection over Atlantic/west Indian Ocean (African region) and *vice versa* with convection over east Indian Ocean. The observed correlations also suggest negative correlation with Australian, Polynesian rainfalls and positive correlation with African rainfall. The suppressed (enhanced) convection over Indian Ocean region decreases (increases) this sub-divisional cumulative rainfall as a consequence of modification in the Hadley circulation. Further more, the observed inverse relationship between this sub-divisional rainfall and MJO indices at 20° E, 70° E & 80° E for the month of May indicate a pre cursive relationship between the two. Similarly, the positive correlation with MJO indices at 140° E for the month of June, at 160° E for the months of August, September and at 120° W for the month of August indicates that the positive convective anomalies over Western and Central Pacific Ocean decreases cumulative rainfall over this sub-division.

The study for Gangetic West Bengal showed negative correlation with MJO indices from 70° E to 120° E for the month of January and a positive correlation with MJO indices from 160° E, 120° W, 40° W and 10° W for the month of January. The observed correlations suggest opposing influences of convective anomalies over Indian Ocean region and the convective anomalies over Pacific and Atlantic Oceans on the cumulative summer monsoon rainfall and these correlations are pre cursive to the Summer Monsoon rainfall. January month's suppressed convection over west Indian Ocean leads to less cumulative rainfall and suppressed convection over Pacific/Atlantic Oceans lead to more cumulative rainfall over this sub-division.

The Orissa sub-divisional rainfall showed inverse relationship with MJO index at 140° E for the month July, at 160° E for the months of June to September and 120° W for the month of September. The sub-divisional rainfall also showed direct relationship with MJO index at 20° E for the months of July to September, at 70° E for the months of June, September and 10° W for the month of July. It is also seen that positive correlations exist between MJO indices at 100° E, 120° E, 140° E for the month of November and negative correlation between 40° W, 10° W & 20° E for the same month. The observed correlations suggest that the summer monsoon rainfall is influenced by the Western/Central Pacific convective anomalies and enhanced/suppressed convection over this region lead to increased/decreased cumulative rainfall over this sub-division and the enhanced/suppressed convective anomalies over Atlantic Ocean/west Indian Ocean decrease/increase cumulative rainfall over this sub-division. The sub-divisional rainfall of Bihar plateau showed a positive correlation with MJO index at 10° W and a negative correlation with MJO index at 120° E for the month of July. The July month's correlations suggest that enhanced convection over east Indian Ocean decreases cumulative rainfall over this sub-division and enhanced convection over Atlantic Ocean increases cumulative rainfall. The Bihar plains sub-division showed no significant correlation between MJO indices of monsoon months with the cumulative sub-divisional rainfall.

The east Uttar Pradesh sub-division showed negative correlation with MJO index at 120° E and positive correlation with MJO indices at 40° W and 10° W for the month of July. The relationship indicates the influence of July month's enhanced convection in parts of the East Indian Ocean and suppressed convection over Atlantic Ocean on the sub-divisional cumulative rainfall. The enhanced convection over east Indian Ocean cumulative and suppressed convection over Atlantic Ocean lead to increased rainfall. Negative correlations were found between MJO indices and cumulative sub-divisional rainfall of west Uttar Pradesh at 70° E, 80° E & 100° E for the months of July to September, at 20° E for the month of August, at 120° E for the month of September. Positive correlations were found between MJO indices and cumulative sub-divisional rainfall at 120° W & 40° W for the months of July to September, at 160° E for the months of July, August, at 140° E for the month of April. The study suggests that the suppressed convection over Pacific and Atlantic Oceans and enhanced convection over Indian Ocean lead to increased cumulative sub-divisional rainfall.

The study for the Haryana sub-division showed significant negative correlations between MJO indices and sub-divisional cumulative rainfall at 10° W for the month of April, at 20° E for the months of April, June to August, at 70° E for the months of June to August, at 80° E for the months of July, August, at 100° E for the months of July, September and at 120° E for the month of September. The observed positive correlations were between MJO indices at 140° E for the April, August, at 160° E for the months of April, June to August, 120° W for the months of July, August and 40° W for the months of July, September. The study, again, revealed opposite influence of convection over Indian Ocean and Pacific/Atlantic Oceans. The enhanced convection over Indian Ocean during monsoon months increases the cumulative sub-divisional rainfall and enhanced convection over Pacific and Atlantic Oceans decrease the cumulative sub-divisional rainfall. The negative correlations between sub-divisional rainfall and MJO indices at 10° W, 20° E for the month of April and positive correlations between the two at 140° E for the month of April suggest that increased convection over Atlantic/Indian Ocean (African region) and decreased convection over west Pacific/east Indian Ocean are pre cursive to the summer monsoon rainfall over the sub-division.

In the study of Punjab sub-division, negative correlations were found between MJO indices and cumulative sub-divisional rainfall for the month of July at 70° E, 80° E & 100° E and at 20° E for the month of April. Moreover, positive correlations were found between MJO indices and cumulative sub-divisional rainfall at 120° W, 40° W for the month of July and at 160° E for the month of April. The observed correlations suggest that the suppressed convection over west Indian Ocean and enhanced convection over Pacific/Atlantic Oceanic regions for the month of July reduce the sub-divisional rainfall. Furthermore, the enhanced convection over west Indian Ocean (African region) and suppressed convection over west Pacific region in the month of April lead to increased sub-divisional summer monsoon rainfall.

This sub-division of west Rajasthan has shown no significant relationship with MJO indices. This suggests that the summer monsoon rainfall is not influenced by Oceanic convections. In the study of east Rajasthan sub-division, positive correlation was found between MJO index and cumulative sub-divisional summer monsoon rainfall at 40° W for the month of July, negative correlation at 20° E for the month of October. This is indicative of the fact that enhanced convection over Atlantic Ocean reduces this sub-divisional rainfall. The lag-correlation suggests that enhanced convection over west Indian Ocean (African region) succeeds increased sub-divisional rainfall.

The study of cumulative sub-divisional rainfall of west Madhya Pradesh showed a positive correlation with MJO index at 10° W for the month of July. The positive correlation with MJO index at 10° W for the month of July indicates that the suppressed convection over Atlantic Ocean increases the cumulative sub-divisional rainfall. The cumulative sub-divisional summer monsoon rainfall for east Madhya Pradesh showed negative correlation with MJO index at 140° E and a positive correlation with MJO index at 10° W for the month of July. The enhanced convection over east Indian Ocean and suppressed convection over Atlantic Ocean during the month of July increases sub-divisional rainfall over this sub-division.

The study of sub-divisional cumulative summer monsoon rainfall of Gujarat showed a positive correlation with MJO index at 40° W, negative correlation with MJO indices at 100° E, 120° E for the month of July, positive correlation with MJO indices at 10° W, 20° E, negative correlation with MJO indices at 120° E, 140° E for the month of November and a negative correlation with MJO index at 20° E for the month of April. The study indicates that enhanced convection over east Indian Ocean and a suppressed convection over Atlantic Ocean for the month of July increase sub-divisional rainfall. The enhanced convection over Indian Ocean (African region) in the month of April is a pre cursive to summer monsoon rainfall and indicates a direct relationship between African rainfall for the month of April and this sub-divisional cumulative rainfall during summer months. The cumulative sub-divisional rainfall Saurastra & Kutch showed negative correlation with MJO index at 20° E and a positive correlation with MJO index at 160° E for the month of June indicating enhanced convection over west Indian Ocean (African region) and a suppressed convection over west Pacific lead to increased rainfall and also a direct relationship with African rainfall for the month of June.

The cumulative sub-divisional rainfall Konkan & Goa showed only negative correlation with MJO index at 120° W for the month of March and with MJO index at 40° W for the month of April indicating an enhanced convection in the east Pacific in the month of March and an enhanced convection in the Atlantic Ocean in the month of April lead to increased rainfall over this sub-division during summer monsoon months.

The study indicated that negative correlations were found between cumulative sub-divisional rainfall of Madhya Maharastra and MJO indices at 70° E, 80° E for the month of July, at 10° W, 20° E for the month of June and also positive correlation between sub-divisional rainfall and MJO index at 120° W for the month of July. The observed correlations indicate enhanced convection over Atlantic/west Indian Ocean in June/July months and suppressed convection over west Pacific Oceanic region increase cumulative sub-divisional rainfall. The cumulative sub-divisional rainfall Marathwada showed negative correlation with MJO indices at 20° E, 70° E for the months of July to September, with MJO index at 80° E for the months of August, September, with MJO indices at 100° E, 120° E for the months of September, October. The cumulative sub-divisional rainfall also showed positive correlation with MJO indices at 120° E for the month of February, at 140° E for the month of August, at 160° E for the months of July, August & September, at 120° W, 40° W for the months of September, October, at 10° W for the month of October. The study showed that enhanced convection over Indian Ocean during different monsoon months increases the cumulative rainfall and the opposite with the convection over Pacific Ocean/Atlantic Ocean. The enhanced convection over east Indian Ocean at 120° E in the month of February leads to an increased cumulative sub-divisional summer monsoon rainfall. The sub-divisional rainfall of Vidarbha showed a negative correlation with MJO index at 120° E for the month of September, 140° E for the month of May and a positive correlation with MJO index at 10° W for the month of September indicating enhanced convection over east Indian Ocean and a suppressed convection over Atlantic Ocean in the month of May lead to increased sub-divisional rainfall. The negative correlation with MJO index at 140° E for the month of May suggests enhanced convection over west Pacific in this month increases sub-divisional rainfall and is a pre cursive relationship with sub-divisional monsoon rainfall.

The study of sub-divisional rainfalls of coastal Andhra Pradesh showed negative correlations between cumulative sub-divisional rainfall and MJO indices at 70° E, 80° E for the months of July, August & September, at 100° E for the months of July to October, at 120° E for the months of September, October, at 160° E for the months of July, December, at 120° W for the months of July to October, at 40° W for the months of September, October and at 10° W for the month of October. The observed correlations suggest that the enhanced convection Indian Ocean during different monsoon months increases cumulative summer monsoon rainfall and suppressed convection in Pacific and Atlantic Oceans in different monsoon months also increases summer monsoon rainfall over this sub-division. The sub-divisional rainfall of Telangana showed negative correlation with MJO indices at 70° E for the months of July, August & September, at 80° E for the months of August, September, at 100° E for the months of September, October, at 120° E for the months of September, October and at 140° E for the month of October. Again, the sub-divisional rainfall showed positive correlations with MJO indices at 160° E for the months of July, August, September, at 120° W for the months of August, September & October, at 40° W for the months of September, October, at 10° W for the month of October. The observed relationships are indicative of enhanced convection of Indian Ocean in different months increase sub-divisional rainfall and suppressed convection over Pacific and Atlantic Ocean in different monsoon month increases cumulative sub-divisional rainfall. The study indicated that the cumulative sub-divisional rainfall of Rayalaseema showed negative correlations with MJO indices at 10° W for the month of June, at 20° E, 70° E for the months June to September, at 80° E for the months of August, September, at 100° E, 120° E for the months of September, October. The cumulative sub-divisional rainfall also showed positive correlations with MJO indices at 140° E for the months of October, at 160° E for the months of July to September, at 120° W for the months of August, September, at 120° W for the months August to October, at 40° W for the month of October. The correlations suggest enhanced convection over Atlantic/Indian Ocean in different monsoon months and a suppressed convection over Pacific Ocean during different monsoon months increases sub-divisional cumulative rainfall.

The study, in this paper, indicated sub-divisional cumulative summer monsoon rainfall of Tamilnadu showed negative correlation with MJO indices at 10° W for the month of March, at 20° E for the month of July, at 70° E, 80° E for the months of June, July & September, at 100° E, 120° E for the month of September, at 140° E for the month of October. The sub-divisional cumulative summer monsoon rainfall of Tamilnadu has also shown positive correlations with MJO indices at 140° E for the month of July, 160° E for the months of June, July & September, at 120° W for the month of July, at 40° W for the month of September. The observed correlations suggest opposite influence of convection over Indian Ocean and Pacific Ocean on the cumulative sub-divisional rainfall. The enhanced convection over Indian Ocean and suppressed convection over Pacific Ocean during different monsoon months increase the cumulative sub-divisional rainfall. The found negative correlation between cumulative sub-divisional rainfall and MJO index at 10° W is pre cursive and an enhanced convection over Atlantic Ocean in the month of March leads to increased cumulative sub-divisional summer monsoon rainfall.

The distribution of CCs in this study indicated positive correlations between sub-divisional rainfall of coastal Karnataka and MJO indices at 100° E for the month of April, June, at 120° E for the months of June, December, at 140° E for the months of April, December. Negative correlations were also found between cumulative sub-divisional rainfall and MJO indices at 40° W for the months of April, June, at 10° W for the months of June and December. The observed correlations indicate that a pre-cursive relationship exists between cumulative sub-divisional rainfall and MJO indices at 100° E, 140° E and 40° W for the month of April and enhanced convection over East Indian Ocean and Atlantic Ocean during the month of April leads to decreased sub-divisional rainfall. The suppressed convection in the east Indian Ocean and enhanced convection in the Atlantic Ocean during the month of June leads to increased sub-divisional rainfall. In this study, the cumulative sub-divisional rainfall of north interior Karnataka showed negative correlations with MJO indices at 80° E for the months of July, September, at 100° E for the month of September, at 120° E, 140° E for the month of October and showed positive correlation with MJO indices at 140° E for the month of June, at 160° E for the months of June, July & September, at 120° W for the months of July, September, at 40° W for the month of September, at 10° W for the month of October. The observed correlations suggest enhanced convection over east Indian Ocean and suppressed convection over west/central Pacific Ocean in different monsoon months increases sub-divisional rainfall. The study also indicates opposite influence of convections over east Indian Ocean and west/central Pacific Ocean on cumulative sub-divisional rainfall. In case of south interior Karnataka the study indicated positive correlations were found between cumulative sub-divisional rainfall and MJO indices at 140° E for the month of June, 160° E for the months of June, July & September, at 120° W for the months of July, September, at 40° W, 10° W, 20° E for the month of October. Negative correlations were found between cumulative sub-divisional rainfall and MJO indices at 20° E for the months of June, July, at 70° E, 80° E for the months of June, July & September, at 100° E for the month of October, at 120° E for the month of November. The observed correlations indicated opposite influence of convections over Indian Ocean and Pacific/Atlantic Oceans during different months on the cumulative sub-divisional rainfall. The enhanced convection over Indian Ocean in different monsoon months and suppressed convection over Pacific/Atlantic Oceans increase cumulative sub-divisional rainfall. Further, the observed lag-correlations suggest enhanced convection over east Indian Ocean during the months of October, November and suppressed convection over Atlantic/west Indian Ocean (African region) in the month of October following increased sub-divisional summer monsoon rainfall.

The study of distribution of CCs suggested that the cumulative sub-divisional summer monsoon rainfall of Kerala has shown positive correlation with MJO index at 120° E for the month of March indicating a pre-cursive relationship between convection over east Indian Ocean in the month of March and sub-divisional rainfall. The enhanced convection over east Indian Ocean in the month of March leads to decreased cumulative sub-divisional rainfall and also suggests pre-monsoon rains in the month of March over Polynesian islands and Australian region have an inverse relationship with sub-divisional rainfall.

The association of 29 sub-divisional rainfalls with MJO activity was described above. The significant lead-lag correlations found, in this paper, re-iterates the influence of MJW on the summer monsoon rainfall of these meteorological sub-divisions. The MJW exhibits two distinct patterns in the low-level and upper-level atmospheric circulations. In this paper, the upper-level atmospheric circulation was considered to find out the influence of MJO on sub-divisional rainfalls. The MJO activity would be strong a year in advance of the El-nino activity and the activity of MJO manifests itself in the variations of wind, sea-surface temperatures and rainfall. The MJO propagates eastward from the date line of Africa and has different modes in Eastern and Western Hemispheres and the activity is strong in Northern

Hemisphere. The observed significant correlations could be explained in terms of the mode of propagation and generation super cloud clusters that move along the MJW. The propagation of MJW in the atmosphere induces anomalous circulations in the East-West and North-South general circulations. In the zone of suppressed convection, skies would be clear, stronger than normal trade winds are seen, more shortwave radiation would the reach the sea-surface, warmer sea-surface temperature are observed and more evaporation from the seas are resulted. In the adjacent zones of enhanced convection, easterly trade winds weaken, large low-level moisture convergence would take place and this causes generation of Super Cloud cluster (SCC) over the enhanced convective activity zones. These SCC s move along the MJW in the tropics causing rainfall variability.

## 4. Conclusions

(*i*) MJO associated convective anomalies at different longitudes influence sub-divisional rainfalls differently.

(*ii*) The rainfall variability at different sub-divisions depends on the status of MJO as MJO induces anomalous circulations.

(*iii*) The study indicates that MJO explains variance of 45% to 18% in sub-divisional summer monsoon rainfalls.

(*iv*) As Indian summer monsoon rainfall is influenced by other inter-annual, inter and intra seasonal oscillations, extreme events like Elnino/Lanina and internal dynamics, the explained variance is considered as significant. Moreover, the MJO activity exhibits inter-annual variations and is not always present.

(*v*) The MJO associated anomalous circulations alter the regional circulation pattern and as a consequence alter the rainfall patterns over tropics. The variability in MJO activity in tropics is also one of the reasons for summer monsoon meteorological sub-divisional rainfall variability.

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**References**

Dakshinamurti, J. and Keshavamurty, R. N., 1976, “On oscillations of period around one month in the Indian summer monsoon”, *Indian J. Met. & Geophys.*, **27**, 201-203.

Hartmann, D. L. and Michelsen, M. L., 1989 “Intra-seasonal periodicities in Indian rainfall”, *Journal of Atmospheric Science*, **46**, 2838-2862.

Jones, C., 2000, “Occurrence of extreme precipitation events in California and relationships with the Madden-Julian Oscillation”, *J. Climate*, **13**, 3576-3587.

Keshavamurty, R. N., 1973, “Power spectra of large scale disturbances of Indian southwest monsoon”, *Indian J. Met. & Geophys.*, **24**, 117-124.

Krishnamurti, T. N. and Bhalme, H. N., 1976, “Oscillations of a monsoon system Part I : Observational aspects”, *Journal of Atmospheric Science*, **33**, 1937-1954.

Madden, R. A. and Julian, P. R., 1971, “Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific”, *Journal of Atmospheric Science*, **28**, 702-708.

Madden, R. A. and Julian, P. R., 1994, “Observations of the 40-50 day tropical oscillation : A review”, *Mon. Wea. Rev*., **122**, 814-837.

Murakami, M. and Frydrych, M., 1974, “On the preferred period of upper wind fluctuations during the summer monsoon”, *Journal of Atmospheric Science*, **31**, 1549-1555.

Murakami, M., 1976, “Analysis of summer monsoon fluctuations over India”, *Journal of Meteorological Society*, Japan, **54**, 15-31.

Parthasarathy, B., Munot, A. A. and Kothawale, D. R., 1995,” Monthly and seasonal rainfall series for all-India homogeneous regions and meteorological sub-divisions : 1871-1994”, Contributions from Indian Institute of Tropical Meteorology, Research Report RR-065, August 1995.

Ramaswamy, C., 1962, “Breaks in the India summer monsoon as a phenomenon of interaction between easterly and the subtropical westerly jet streams”, *Tellus*, **14**, 337-349.

Sikka, D. R. and Gadgil, S., 1980, “On the maximum cloud zone and the ITCZ over Indian longitudes during the southwest monsoon”, *Mon. Wea. Rev*., **108**, 1840-1853.

Wang, B. and Rui, H., 1990, “Synoptic climatology of transient tropical intra-seasonal convection anomalies: 1975 - 1985”, *Journal of Meteorology and Atmospheric Physics*, **44**, 43-61.

Yasunari, T., 1979, “Cloudiness fluctuations associated with the Northern Hemisphere summer monsoon”, *Journal of Meteorological Society of Japan*, **57**, 227-242.