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Modulation of cyclonic disturbances over the north Indian Ocean by Madden - Julian oscillation

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सार – इस शोध पत्र में एम. जे. ओ. सूचकांक के 33 वर्षों (1975–2007) के आँकड़ों और भारत मौसम विज्ञान विभाग (आई. एम. डी.) द्वारा विकसित चक्रवाती विक्षोभ (CDs) के सर्वोत्तम पथ का उपयोग करते हुए मदान – जूलियन दोलन (एम. जे. ओ.) सहित उत्तरी हिंद महासागर में चक्रवाती विक्षोभों (CDs) की उत्पत्ति और उनकी तीव्रता के मध्य संबंधों की जाँच की गई है। इसके लिए बहिर्गामी दीर्घ तरंग विकिरण (ओ. एल. आर.) पर आधारित एम. जे. ओ. सूचकांक और ऊपरी (200 hPa तथा निचले (850 hPa) क्षोभमंडल (वीलर और हैंडल 2004) में कटिबंधीय पवन का उपयोग किया गया है।

एम. जे. ओ. उत्तरी हिंद महासागर में चक्रवात विक्षोभों की उत्पत्ति और उसकी तीव्रता को बहुत कम करती है। तथापि उत्तरी हिंद महासागर में चक्रवात को उत्पन्न करने वाले अन्य कारक हैं, जबकि मानसून ऋतु और मानसून पश्च ऋतुओं के दौरान लगभग 60 प्रतिशत चक्रवात की उत्पत्ति एम. जे. ओ. के साथ उल्लेखनीय रूप से संबंधित नही है जबकि मानसून ऋतु के दौरान चक्रवात उत्पत्ति की संभावना चरण 4 और 5 समुद्रवर्ती प्रायद्वीप में एम. जे. ओ. के साथ अधिक होती है यद्यपि चरण 3 और 4 (पूर्वी हिंद महासागर और निकटवर्ती और समुद्रवर्ती प्रायद्वीप) में एम. जे. ओ. के साथ मानूसन पश्च ऋतु में अधिक होती है। इससे यह पता चलता है कि मानूसन ऋतु के दौरान उत्पत्ति की संभावना चरण 1, 7 और 8 (अफ्रीका, पश्चिमी गौलार्घ और प्रशांत महासागर के निकटवर्ती भागों में सक्रिय एम. जे. ओ. के साथ उल्लेखनीय रूप से दमित रहती हैं, मानूसन पश्च ऋतु के दौरान चरण 1, 7 और 8 में उत्पत्ति और सक्रिय एम. जे. ओ. के मध्य कोई उल्लेखनीय संबंध नही है। चरण 4 और 5 में एम. जे. ओ. से संबंद्व बंगाल की खाड़ी के मध्य और उत्तरी भाग के निचले स्तरों पर असंगत चक्रवाती संचरण मानसून ऋतु के बंगाल की खाड़ी में चक्रवात की उत्पत्ति की संभावना को बढ़ाता है। चरण 1 में एम. जे. ओ. से संबंद्व असंगत पूर्वी हवाएँ और चरण 7 और 8 में एम. जे. ओ. से संबंद्ध दक्षिण भारत में असंगत रिज का विकास कमजोर मानसून के लक्षण होते हैं जिससे इस ऋतु के दौरान उत्तरी हिंद महासागर में चक्रवात उत्पत्ति दमित होती है। चरण 3 और 5 में सक्रिय एम. जे. ओ. के दौरान इस क्षेत्र में दक्षिणी महोर्मि से सबंद्व बंगाल की खाड़ी के दक्षिण पश्चिमी / पश्चिमी मध्य भाग में चक्रवाती परिसंचरण में अंतः स्थापित पूर्वी हवाओं में असंगत उत्तर – दक्षिणी द्रोणी संवहन को अधिकतम अनुकलतम रूप से प्रभावित करता है और मानसून – पश्च ऋतु के दौरान उत्तरी हिंद महासागर में चक्रवात बनने की सभावना को बढ़ाता है।

चक्रवात विक्षोभों की उत्पत्ति आयाम की अपेक्षा चरण के प्रति अधिक संवेदनशील होती है जबकि चक्रवात विक्षोभों की तीव्रता एम.जी.ओ. के आयाम पर अधिक निर्भर होती है मानसून और मानसून पश्च ऋतुओं की तुलना करने पर मानसून पश्च ऋतु की अपेक्षा मानूसन ऋतु के दौरान एम.जी.ओ. द्वारा चक्रवात विक्षोभों की उत्पत्ति के अनुकरण, उनकी तीव्रता और अवधि अधिक होती है।

ABSTRACT. The relationship of genesis and intensity of cyclonic disturbances (CDs) over the north Indian Ocean with the Madden – Julian Oscillation (MJO) has been examined using 33 years (1975 - 2007) data of MJO index and best track of (CDs) developed by India Meteorological Department (IMD). The MJO index based on outgoing long wave radiation (OLR) and zonal wind in upper (200 hPa) and lower (850 hPa) troposphere (Wheeler and Hendon, 2004) has been used for this purpose.

The MJO strongly modulates the genesis and intensity of CDs over the north Indian Ocean. However there are other factors contributing to cyclogenesis over the north Indian Ocean, as about 60% of cyclogenesis during monsoon and post-monsoon seasons are not significantly related with MJO. While the probability of cyclogenesis during monsoon season is higher with MJO in phase 4 and 5 (Maritime Continent), that during post-monsoon season is higher with MJO in phase 3 and 4 (east Indian Ocean and adjoining Maritime Continent). It indicates that while possibility of genesis during monsoon season is significantly suppressed with active MJO at phase 1, 7 and 8 (Africa, western Hemisphere and adjoining Pacific Ocean), there is no significant relationship between genesis and active MJO at phase 1, 7 and 8 during post-monsoon season. The anomalous cyclonic circulation at lower levels over central and north Bay of Bengal in association with MJO at phase 4 and 5 favours enhanced probability of cyclogenesis over the Bay of Bengal during monsoon season. The anomalous easterlies in association with MJO at phase 1 and development of anomalous ridge over south India in association with MJO at phase 7 and 8 which are weak monsoon features lead to suppressed cyclogenesis over north Indian Ocean during this season. The anomalous north-south trough in easterlies embedded with cyclonic circulation over the south west/west central Bay of Bengal in association with southerly surge over the region during active MJO in phase 3 and 4 most favourably influences the convection and enhances the probability of cyclogenesis over the north Indian Ocean during post-monsoon season.

The genesis of CDs is more sensitive to phase than the amplitude while the intensification of CDs is more dependent on the amplitude of MJO. Comparing monsoon and post-monsoon seasons, the modulation of genesis, intensification and duration of CDs by the MJO is more during the monsoon season than the post-monsoon season.

Key words – Cyclonic disturbances, North Indian Ocean, Madden-Julian Oscillation.

1. Introduction

The climatology of cyclonic disturbances (CDs) over the north Indian Ocean region (Fig. 1) indicates that virtually the entire Bay of Bengal and Arabian Sea are susceptible to the destructive landfalling CDs. More complete climatologies may be found in Cyclone e-Atlas published by India Meteorological Department (IMD, 2008). Over the Sea, wind strength at the surface level is used as a criterion for classification of different intensities of cyclonic disturbances. As per the criteria of IMD, a CD is a depression if the wind speed is 17 - 27 knot (kt), a deep depression if the wind speed is 28 - 33 kt, a cyclonic storm if the wind speed is 34 - 47 kt, a severe cyclonic storm if the wind speed is 48 - 63 kt, a very severe cyclonic storm if the wind speed is 64 - 119 kt and a super cyclonic storm if the wind speed is 120 kt or more. Tropical cyclone (TC) is a generic name for all the storms with wind speed of 34 kt or more (IMD, 2003).

The origins of the vast majority of CDs in the north Indian Ocean region can be found in the vicinity of the inter tropical convergence zone (ITCZ). Some of the CDs develop from the westward moving remnants from the northwest Pacific Ocean (Saha *et al*., 1981). The situation with cyclogenesis is more problematic than the movement forecasting. In this case, mechanisms such as complex scale interactions, processes at the air-sea interface, and diabatic heating profiles-all of which must be parameterized in current dynamical models-become critical and dominant factors. Accordingly, there is little skill involved in this aspect of forecasting based on dynamical models, especially in the medium range.

Although the short lead time guidance is vital in the interests of saving lives, there is no doubt that guidance of expected CD activity in medium range (during 5-20 days in the future) would be a valuable asset. This is particularly true in the Bay of Bengal region, where CD formation close to the coasts can lead to rapidly developing threats. In these situations a level of preparation prior to the storm's development is important, as there is often insufficient time once the storm has been identified. As dynamical prediction models do not currently provide much guidance at these lead times, a different approach is required. One possibility is through the establishment of relationships between long-period oscillations of the atmosphere and CD numbers. Less work has been undertaken on the modulation of CDs at the intra-seasonal timescale. Yet for many years there has been abundant evidence that CD formation is strongly modulated at these timescales as well. Gray (1979) studied each of the world's CD basins, and found that the formation of TC is not evenly distributed in time within any particular season. Rather, cyclogenesis appears to occur in clusters. Periods of 1 or 2 weeks of active formation may produce as many as 10 cyclones, whereas the inactive periods of similar length may see no cyclones forming at all. The Madden-Julian oscillation (MJO) is a dominant mode of oscillation of the tropical troposphere at 30-50 day timescale (Madden and Julian, 1994) and explains a significant amount of variability in the circulation and convection on intra-seasonal timescale. The MJO can be summarized as an eastward-propagating disturbance of the tropical troposphere with zonal wave number 1 (Mathews, 2000). In the Eastern Hemisphere, it also interacts strongly with deep convection, with enhanced convective activity at all scales in the ''wet'' phase, and correspondingly suppressed convection in the ''dry'' phase (Hendon and Liebmann, 1994). A distinct hierarchy of convective organization has been observed within the active phase of the MJO, with eastward-propagating supercloud clusters with diameters of the order of 3000 km forming an envelope of enhanced mesoscale cloud cluster activity (Nakazawa 1988; Hendon and Liebmann 1994). As all CDs are initially formed from these convective cloud clusters (Kalsi, 2002), the modulation of activity during MJO passage is likely to be an important factor to cyclogenesis. However, the effect of the MJO on the dynamical parameters may also have an important role to play.

Forecasters are aware of intra-seasonal variability in CD activity associated with the MJO, and do take this into account subjectively (Hanstrum *et al*., 1999). However, little quantitative research has been undertaken into the relationship. Storch and Smallegange (1991) and Hall *et al.* (2001) found significant modulation of TC numbers in

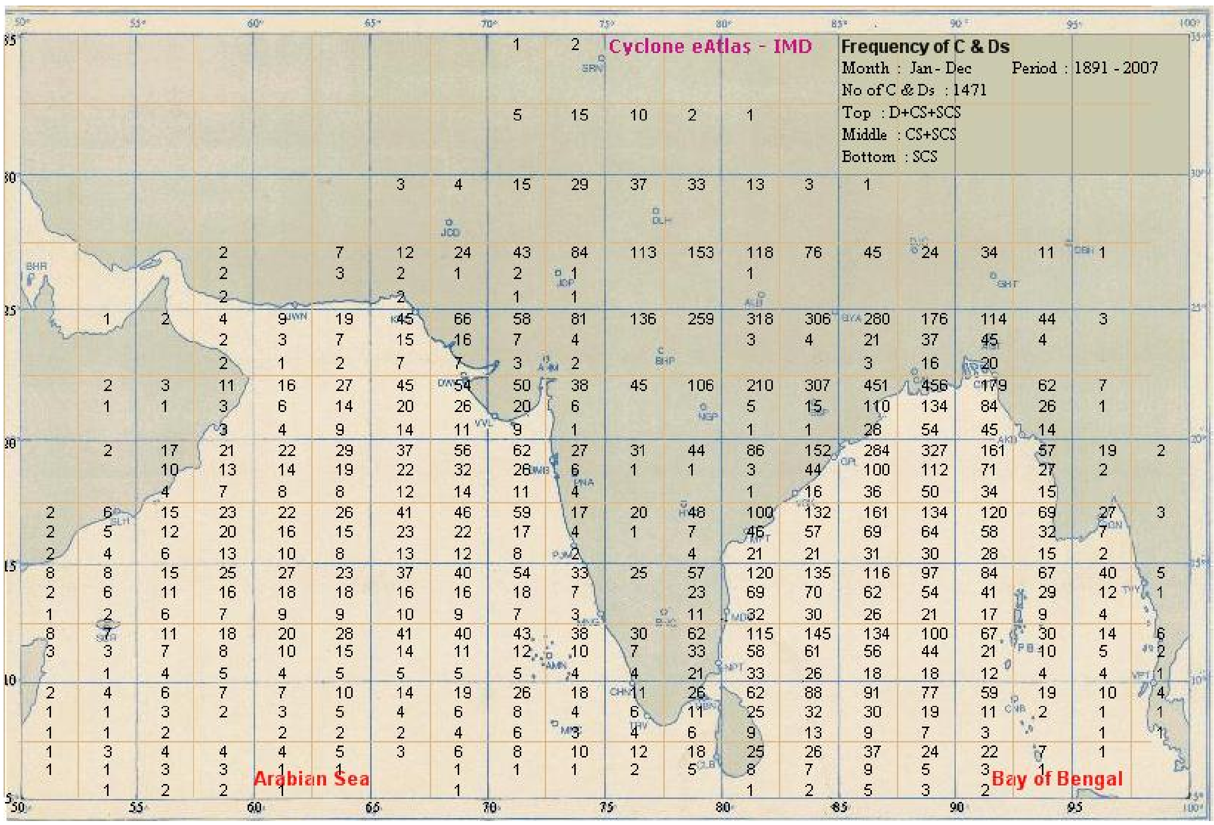


Fig. 1. Frequency of tropical cyclonic disturbances over the north Indian Ocean

the South Indian and North and South Pacific Oceans by the MJO. Liebmann *et al*. (1994) based on data of 10 years also found increases and decreases in TC activity over north Indian Ocean and northwest Pacific Ocean between 60° E and 180° E that appeared to be consistent with the phase of the MJO. Further, they found that the ratio of storm and typhoon formed per depression are the same in the convective phase as the dry phase of MJO and hence, the intensification from depression to storm is not more likely during wet phase of MJO. Maloney and Hartmann (2001) found significant modulation of eastern north Pacific hurricane numbers and intensities by the MJO. Using low pressure systems (low + depression + cyclone) data for 40 years, Goswami *et al*. (2003) have found that dry and wet spells of monsoon over India indeed arises from a space time clustering of the LPS and that the clustering is caused by a modulation of the large scale monsoon circulation by the intra seasonal oscillation including MJO. While Goswami *et al*. (2003) deal with LPS during monsoon season, Liebman *et al*. (1994) deal with the cyclonic disturbances during the year as a whole. The cyclonic disturbances mostly develop during monsoon (June - September) and post-monsoon (October - December) seasons over the north Indian Ocean. The disturbances developing in these two seasons are different from each other corresponding to area of genesis, circulating patterns and the intensification of the system. The aims of this study are to investigate into the modulation of formation and intensification of CDs on the north Indian Ocean by the MJO during monsoon season, post-monsoon season and the year as a whole. Although the major focus is on cyclogenesis (formation of depression), preliminary investigations into the intensification of depression into cyclone are also made. An observational, compositing approach is adopted, based on 33 years (1975 - 2007) of data for the above purpose. A particular goal of the study is to select an optimum temporal resolution of the MJO to allow these TC genesis patterns to be observed, while ensuring that the MJO evolution is slow enough to set a basic state for cyclogenesis. If the current intense research into the MJO produces techniques to improve its prediction, then such a relationship would have obvious benefits to forecasting of CDs over North Indian Ocean.

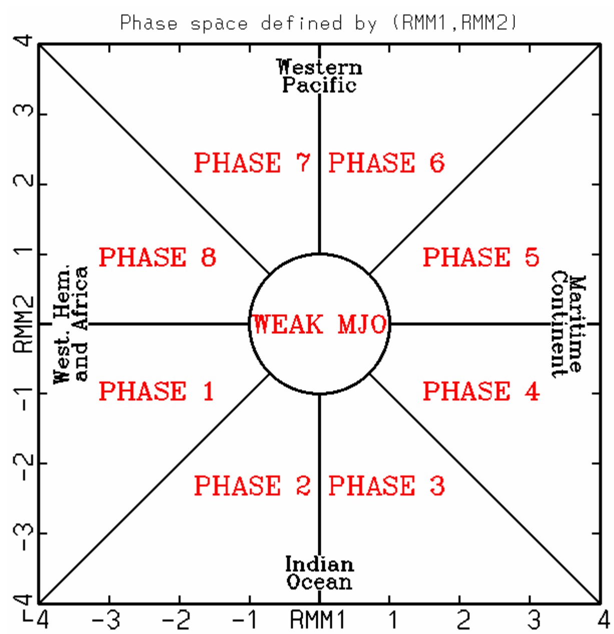


Fig. 2. Different phases of MJO (after Wheeler and Hendon, 2004)

2. Data and methodology

In our study, we have taken MJO data from the Centre for Australian Weather and Climate Research, Australia (http://www.cawcr.gov.au). The MJO index is developed using Outgoing Longwave Radiation (OLR) and zonal wind (u) in upper (200 hPa) and lower (850 hPa) troposphere (Wheeler and Hendon, 2004). The OLR data is taken as the daily averaged values from the polar orbiting satellites of National Oceanic and Atmospheric Administration (NOAA). Zonal wind data is taken from National Centre for Environmental Prediction (NCEP)-National Center for Atmospheric Research (NCEP-NCAR). Seasonal effect is removed from the MJO value. The empirical orthogonal function (EOF) analysis of the three fields, *viz*., OLR, Zonal wind at 850 hPa level (u850) and Zonal wind at 200 hPa level (u200) is done and two main principal components (PCs) of the two dominant EOFs are taken as Real-time Multivariate MJO series 1 (RMM1) and Real-time Multivariate MJO series 2 (RMM2). Considering MJO as eastward propagating system with lead-lag behavior of RMM indices, the status of MJO is described by a vector Z in two dimensional phase space diagram defined by RMM1 and RMM2.

$$Z(t) = [RMM1(t), RMM2(t)]$$

Amplitude (A) and angle φ of MJO is defined as (Matthews, 2000)

$$A(t) = [RMM1^2(t) + RMM2^2(t)]^{1/2}$$

$$\Phi(t) = \tan^{-1}[RMM2(t)/RMM1(t)]$$

According to the angle of the MJO, eight different phase zones are defined. Angular width of each zone is 45°. At each day, the MJO is assigned a phase number depending on the location of the MJO and amplitude depending on the strength of the MJO. Hence at any day, the MJO will be within one of the eight phase zones. According to Wheeler and Hendon (2004), phase 2 and 3 corresponds to Indian ocean (Fig. 2), phase 4 and 5 corresponds to Maritime Continent, phase 6 and 7 for western pacific and phase 1 and 8 corresponds to western hemisphere and Africa.

In this study, the MJO index data of each day, *i.e*., MJO signal Amplitude and phase of each day are taken from 1975 to 2007 excluding the period from 17th March 1978 to 31st December 1978 when index was not available due to non availability of OLR data. A time series is prepared with amplitude and phase of the MJO index for each day during the period 1975-2007.

The region under consideration for the study of cyclogenesis, *i.e*., Bay of Bengal and Arabian Sea is shown in Fig. 1. The statistics of CD over the Bay of Bengal and the Arabian Sea from 1975 to 2007 have been taken from the best track data-set published as Cyclone E-Atlas by IMD (2008). From these data-set a daily time series of the occurrence of CDs with different intensities have been prepared for the period of 1975-2007 (33 years). For this purpose, when there is no CD over north Indian Ocean, it is considered as 0 for that day. The occurrence of depression/deep depression (D) and cyclonic storms (C) have been considered as 1 and 2 respectively. Here depression and deep depression are considered as single category D and the occurrence of severe cyclonic storms (S) is considered as 3. The severe cyclonic storms also include very severe cyclonic storms and super cyclonic storms. Intensity of CD at 0300 UTC of a day is considered as the intensity of CD for that day.

To know whether there is any bias for cyclogenesis and intensity towards a particular phase of MJO, statistical Z test is conducted following Hall *et al.* (2001) and Bessafi and Wheeler (2005). Assuming the hypothesis that cyclogenesis and intensity are uniformly distributed among all the days irrespective of the MJO phase of a particular day, the statistical Z test is applied to know whether any MJO phase has significantly (*i*) more or less number of cyclogenesis and (*ii*) higher/less no. of cyclone

TABLE 1

Number and probability of cyclogenesis (formation of D) in different phases of MJO

MJO Phase (α)	Year as a whole			Monsoon Season			Post-monsoon Season		
	Days with α	No.	Probability (%)	Days with α	No.	Probability (%)	Days with α	No.	Probability (%)
1	1526	25*	1.64*	666	10*	1.50*	342	13	3.80
2	1627	45	2.77	638	20	3.13	380	18	4.74
3	1421	50	3.52	418	17	4.07	370	26*	7.03*
4	1475	63*	4.27*	465	28*	6.02*	379	26#	6.86#
5	1509	60*	3.98*	513	30*	5.85*	399	23	5.76
6	1406	41	2.92	459	22	4.79	353	11	3.12
7	1438	26*	1.81*	362	13	3.59	393	13	3.31
8	1417	25*	1.76*	410	10	2.44	351	12	3.42
Total	11819	335	22.66	3931	150	31.40	2967	142	38.03
Average	1477.37	41.87	2.83	491.37	18.75	3.92	370.88	17.75	4.75

* : Number of cyclogenesis and their probability significantly different from the average at 95 % level of confidence according to Z test.
\# : Same as * but at 90 % level of confidence.

days than expected. The Z - test as computed separately for each category is given below:

$$Z = \frac{\left(P_0 - P_e\right)}{\left[P_e\left(1 - P_e\right)/ N\right]^{1/2}}$$

Considering cyclogenesis, P_o and P_e are the observed and expected fraction of days of cyclogenesis respectively in each phase of MJO and N is the number of days in that phase. Expected fraction of cyclogenesis is determined by dividing the total number of cyclogenesis by the total number of days. Similarly expected fraction of different intensities like D, C and S are determined by dividing the total number of D / C / S days by the total number of days.

To analyse the relation between genesis and amplitude of MJO, the first day of occurrence of D, C, S and corresponding MJO amplitudes at different phases have been considered from the above mentioned two time series of MJO index and occurrence of CDs. Mean amplitudes of MJO at different phases with respect to genesis of D are calculated and compared with average amplitude of MJO in corresponding phases. Similarly, mean amplitudes of MJO at different phases with respect to all the days of D, C, S, C+S and D+C+S have been found out and compared with average amplitude at corresponding phases to analyse the relation between intensity and MJO. Student's *t*-test has been applied for each phase of MJO to know whether the amplitudes of MJO vary significantly with respect to genesis and intensity of CDs from the average MJO amplitudes at corresponding phases. Further, the range of amplitude favourable for genesis and different intensities of CDs has also been found out and analysed.

The genesis and intensity of CDs over the North Indian Ocean during monsoon season (June - September), post monsoon season (October - December) and year as a whole with respect to MJO have been analysed and discussed here in the above manner. The results obtained from the study are presented and analysed in Section 3 and broad conclusions of the study are presented in Section 4.

3. Result and discussion

Cyclogenesis in relation to phase and amplitude of the MJO index is presented in section 3.1 and 3.2 respectively. The intensity of CDs in relation to phase and amplitude of MJO index is presented in section 3.3 and 3.4 respectively.

3.1. *Cyclogenesis in relation to phase of MJO*

Considering the first day when the system intensifies into a D as the day of cyclogenesis, the cyclogenesis days and the probability of cyclogenesis (fraction of cyclogenesis days to total number of days) corresponding to eight phases of MJO are calculated and analysed. The results are shown in Table 1. There is significant modulation in the temporal distribution of cyclogenesis

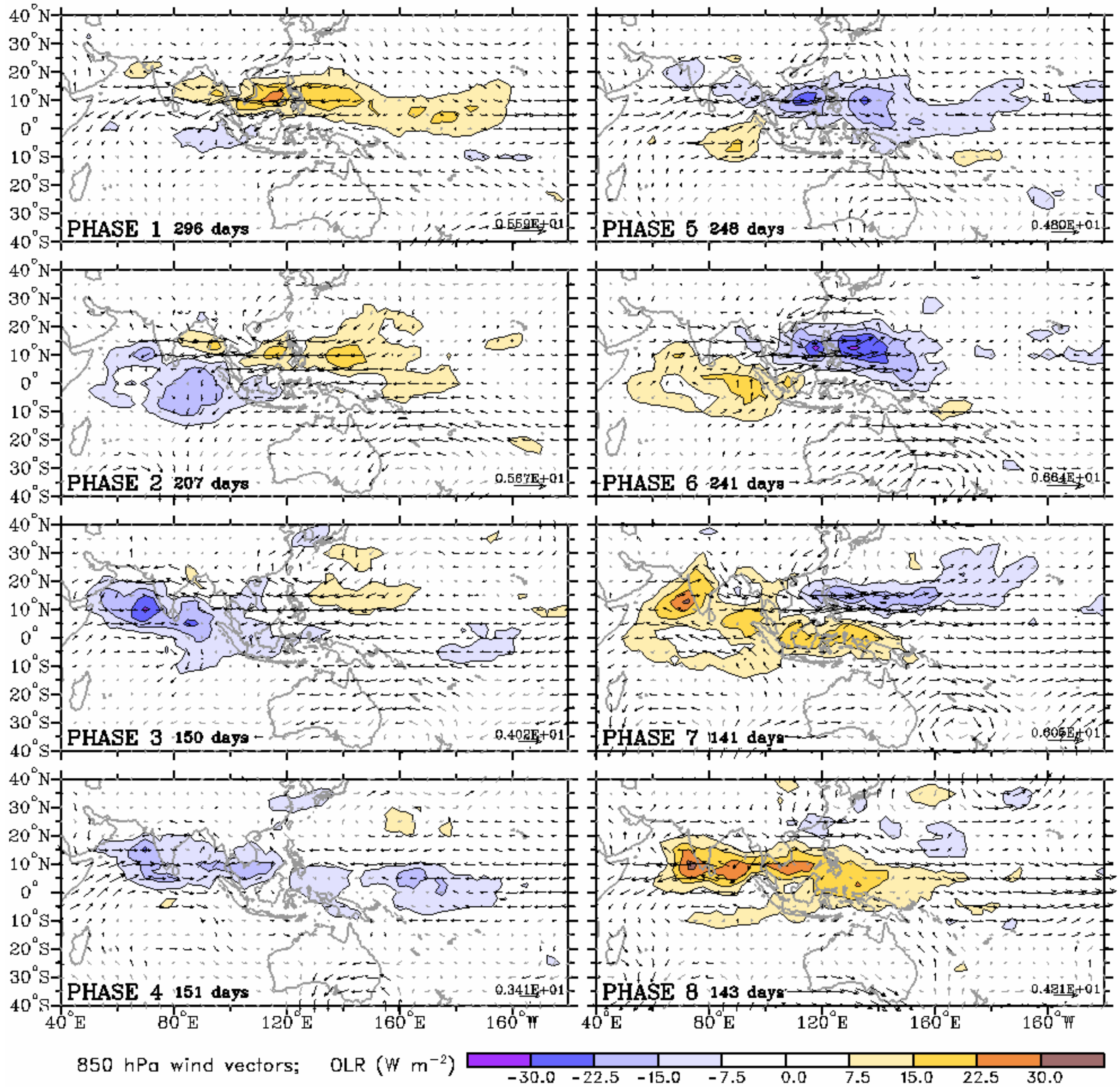


Fig. 3. Composites of anomalies of OLR (W/m²) and 850hPa wind (m/s) for June, July and August (after Wheeler *et al*., 2009)

during different phases of MJO. Out of total 335 genesis as D during the year as a whole, lowest number of cyclogenesis is associated with phase 1 and 8 (25 each) followed by phase 7 (26) and highest number of cyclogenesis is associated with phase 4 (63) followed by phase 5 (60) and phase 3 (50). According to the null hypothesis that all the events of cyclogenesis are uniformly distributed over the eight phases of MJO, the average probability of genesis is 2.83%, 3.92% and 4.75% during year as a whole, monsoon season and post monsoon season respectively. However, the cyclogenesis probabilities at phase 4 and 5 are significantly higher for year as a whole and monsoon season and at phase 3 and 4 for post monsoon season. Considering phases 4 and 5 together, the genesis of 123 out of 335 (37%) Ds take place in these phases for year as a whole. However, it is found that probability of cyclogenesis in phase 1, 7 and 8 are much below the average and significant at 95% level of confidence. Similarly considering the unfavourable phases of MJO, *viz*., 1, 7 and 8 together, about 23% (76 out of 335) of total genesis of Ds takes place in these phases. The cyclogenesis is significantly less at 95% level

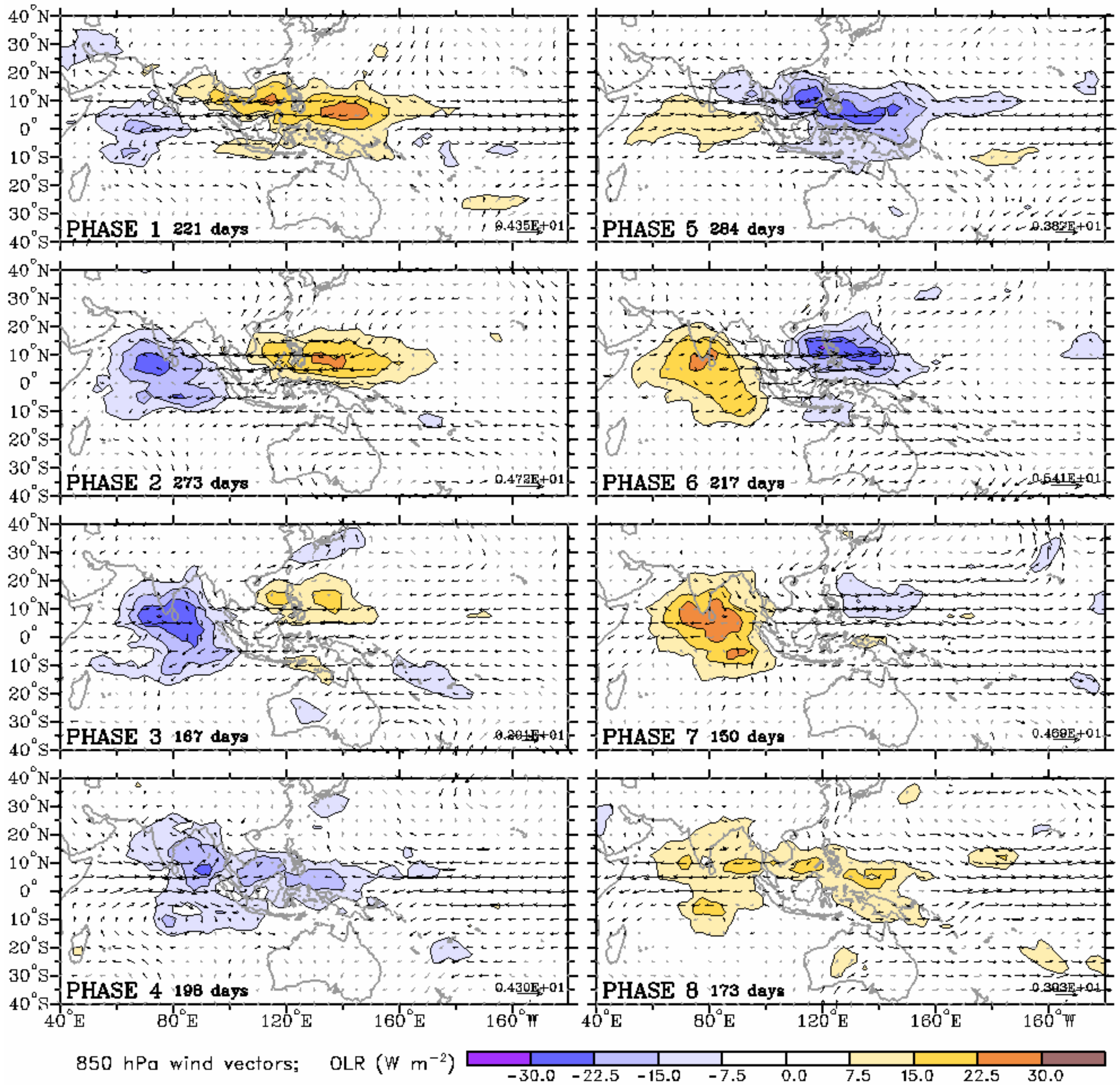


Fig. 4. Composites of anomalies of OLR (W/m²) and 850hPa wind (m/s) for September, October and November (after Wheeler *et al*., 2009)

of confidence with active MJO over phase 1 for the monsoon season. Only 10 cyclogenesis have taken place out of 150 with MJO in phase 1 and about 22% genesis takes place with MJO in phase 1, 7 and 8. However out of total 150 cyclogenesis, about 58 (39%) takes place during active phase of MJO lying in phase 4 and 5. Considering post monsoon season, active MJO in phase 3 and 4 contribute to 52 genesis out of 142 (37%) whereas active MJO over other phases is not significantly related to cyclogenesis unlike that during monsoon season and year as a whole. It indicates that while possibility of genesis during monsoon season is significantly suppressed with active MJO at phase 1, 7 and 8, there is no significant relationship between genesis and active MJO in phase 1, 7 and 8 during post-monsoon season.

All the above results indicate that though the MJO modulates the cyclogenesis pattern, there are other factors contributing to cyclogenesis, as about 60% of total genesis are not significantly related with the MJO phases.

To analyse the physical processes behind the relationship between MJO index and genesis, the composite OLR anomalies and 850 hPa wind (Wheeler *et al.*, 2009) corresponding to different phases of MJO have been analysed and presented in section 3.1.1 and 3.1.2 for monsoon and post-monsoon seasons respectively.

3.1.1. *Circulation pattern during monsoon season in association with MJO*

The representative composite OLR anomaly and 850 hPa wind distribution for the months of June - August representing monsoon season are shown in Fig. 3. During phase 1, easterly anomalies prevail over Indian region at 850 hPa level with ITCZ near about 10° S resulting in enhanced convection over southern hemisphere and suppressed convection over Indian region. As the MJO propagates to phase 2, similarly easterly anomalies prevail over Indian region, but with ITCZ and associated convection moving northward near to the equator. At the same time, easterly anomaly reduces near Somalia coast. With MJO at phase 3, cross equatorial south westerly flow increases over the Arabian Sea and ITCZ lies near 10° N across extreme south peninsula, leading to further northward propagation of convection near to this region. An embedded cyclonic circulation lies over south east and adjoining east central Arabian Sea, which may lead to cyclogenesis over this region. The cross equatorial flow further strengthens with MJO at phase 4, as a result the strong south westerlies prevail over Arabian Sea up to 15° N with axis of ITCZ lying along 18° N. An anomalous cyclonic circulation at 850 hPa level develops also over the west central Bay of Bengal at this phase. As the MJO moves to phase 5, the cross equatorial south westerly flow continues to be stronger and spread up to northern part of central Arabian Sea and ITCZ roughly runs along 20° N. The anomalous cyclonic circulation then lies over north Bay of Bengal and adjoining east central India. With MJO at phase 6, the ITCZ moves further north lying close to 25° N. Accordingly westerly anomalies prevail over the entire north Indian Ocean suppressing development of any circulation over the oceanic region. It also leads to reduction in convection over the monsoon trough region in Bay of Bengal unlike that with phase 4 and 5. The persistent convection in association with the cyclonic circulation is the essential condition for cyclogenesis over this oceanic region (IMD, 2003). The circulation pattern becomes further unfavourable for cyclogenesis with MJO at phase 7 and 8, as a ridge appears over the peninsular India. It leads to dry and cold mid-latitude westerlies penetrating into central and north Bay of Bengal which inhibits cyclogenesis over this region (Rao, 1976; Ramamurthy, 1969). Hence the circulation patterns associated with phase 4 and 5 are most favourable for cyclogenesis over north Indian Ocean, especially over the central and northern part of Bay of Bengal. These findings on the associated circulation pattern and convections during different phases of MJO endorse the earlier findings of Pai *et al*. (2009).

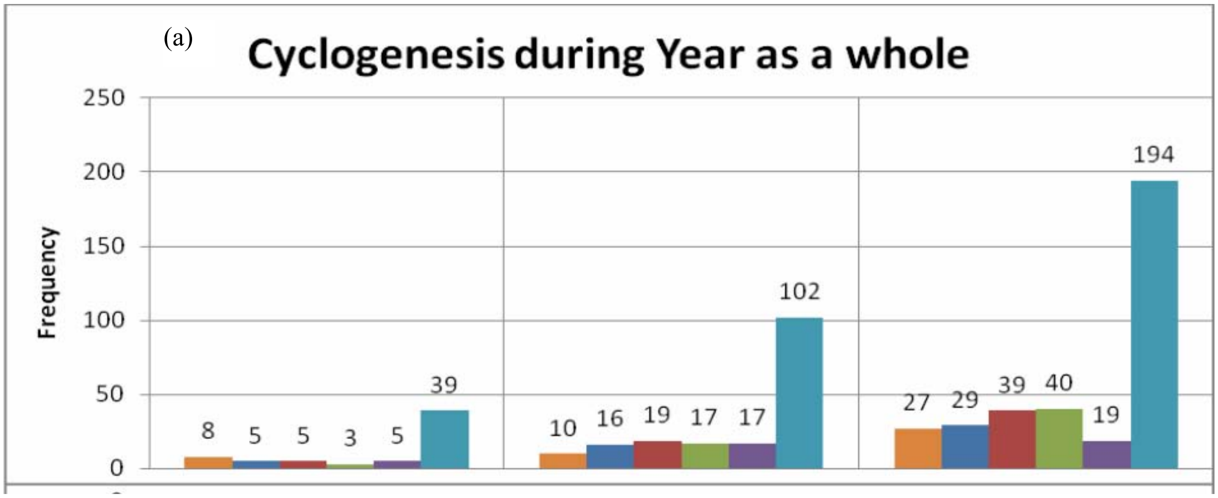
TABLE 2

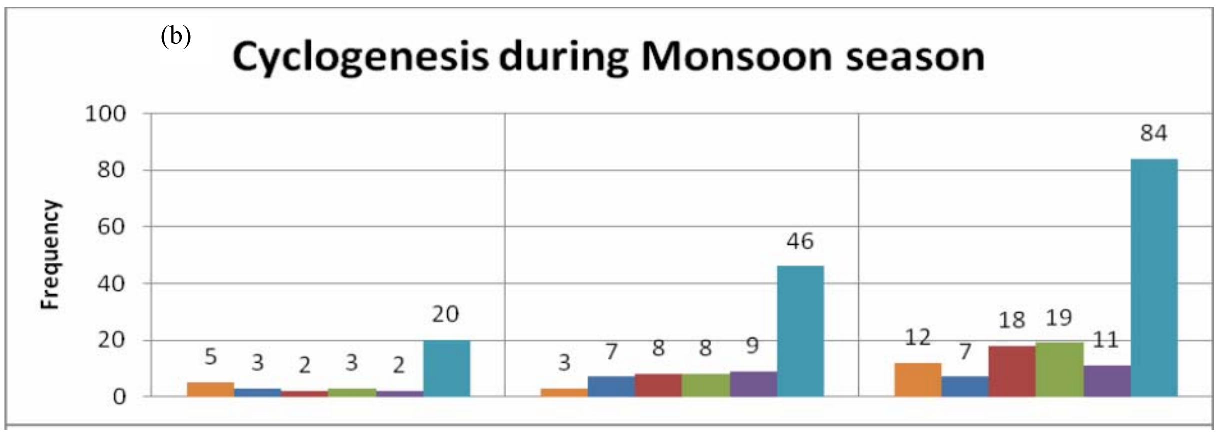
Average amplitude of MJO at different phases during cyclogenesis days

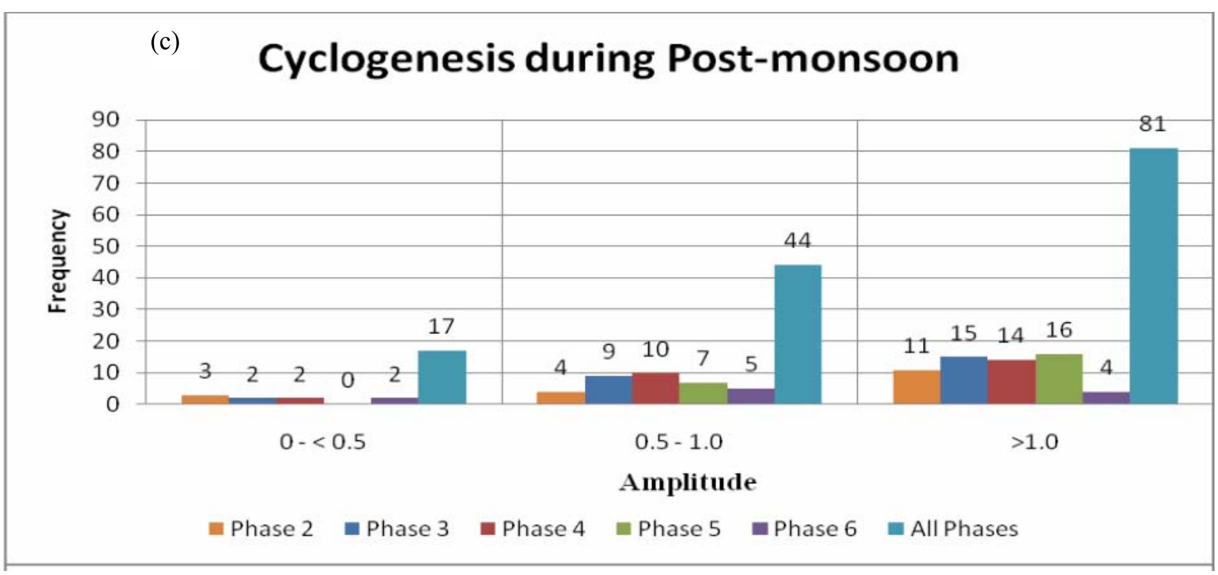
MJO Phase	Average amplitude during		
	Year as a whole	Monsoon season	Post-monsoon season
1	1.17	1.11	1.28
2	1.12	1.02	1.23
3	1.28	1.01	1.29
4	1.25	1.19	1.29
5	1.33	1.28	1.38
6	1.2	1.3	1.06
7	1.04	1.09	0.99
8	0.91	0.89	0.86
Mean	1.2	1.14	1.21

3.1.2. *Circulation pattern during post-monsoon season in association with MJO*

Strong easterly anomalies prevail over north Indian Ocean in association with phase 1 of MJO during post monsoon season (Fig. 4) like that during monsoon season and the ITCZ lies roughly along 5° S over Indian Ocean. Similar circulation pattern continues with MJO in phase 2 but ITCZ lying along 5° N over the west equatorial Indian Ocean. An embedded trough extends from west equatorial Indian Ocean to central Arabian Sea. As the MJO moves to phase 3, the ITCZ over Arabian Sea moves to about 12° N and extends to southwest Bay of Bengal across southern peninsula. Also the north-south trough runs from southwest Bay of Bengal to north peninsula. The easterly wind anomaly over the Bay of Bengal changes to southerlies. When the MJO lies in phase 4, ITCZ further moves to 20° N over the Arabian Sea and extends to southwest Bay of Bengal across peninsular India. An anomalous cyclonic circulation lies over south west and adjoining west central Bay of Bengal. In its association southerly to southwesterly anomalies prevail over the Bay of Bengal. Strong southerly surges over the Bay of Bengal leads to cyclonic circulation in association with northward propagation of ITCZ and these are the pre-requisites for the development of cyclogenesis (IMD, 2003). With the MJO in phase 5, the ITCZ moves further north, strong westerly anomalies prevail over north Indian Ocean







Figs. 5(a-c). Frequency distribution of cyclogenesis with respect to amplitude of MJO at phase 2, 3, 4, 5, 6 and all phases together during (a) year as a whole, (b) monsoon and (c) post-monsoon season

TABLE 3(a)

Number of days and probability of different intensities of CDs with respect to different phases of MJO during year as a whole

MJO Phase (α)	No. of days with α	D days		C days		S days		C+S days	
		No. of days	Probability (%)	No. of days	Probability (%)	No. of days	Probability (%)	No. of days	Probability (%)
1	1526	59*	3.87*	15#	0.98#	18	1.18	33	2.16
2	1627	124	7.62	25	1.54	22	1.35	47	2.89
3	1421	133*	9.36*	32*	2.25*	21	1.48	53*	3.73*
4	1475	163*	11.05*	33*	2.24*	32*	2.17*	65*	4.41*
5	1509	181*	11.99*	34*	2.25*	24	1.59	58*	3.84*
6	1406	137*	9.74*	20	1.42	19	1.35	39	2.77
7	1438	66*	4.59*	10*	0.70*	7*	0.49*	17*	1.18*
8	1417	67*	4.73*	15	1.06	11	0.78	26*	1.83*
Total	11819	930		184		154		338	
Mean	1477	116.2	7.87	23	1.56	19.3	1.30	42.3	2.86

* : Number of days and probability significantly different from the average at 95% level of confidence according to Z test.
# : Same as * but at 90% level of confidence.

TABLE 3(b)

Number of days and probability of different intensities of CDs with respect to different phases of MJO during monsoon season

MJO Phase (α)	No. of days with α	D days		C+S days	
		No. of days	Probability (%)	No. of days	Probability (%)
1	666	28*	4.2*	9	1.35
2	638	55*	8.62*	6	0.94
3	418	68*	16.27*	8	1.91
4	465	76*	16.34*	17*	3.66*
5	513	90*	17.54*	9	1.75
6	459	85*	18.52*	8	1.74
7	362	45	12.43	0	0
8	410	32*	7.8*	0	0
Total	3931	479		57	
Mean	491.37	59.88	12.72	7.125	1.42

* : Number of days and probability significantly different from the average at 95% level of confidence according to Z test.

TABLE 3(c)

Number of days and probability of different intensities of CDs with respect to different phases of MJO during post monsoon season

MJO Phase (α)	No. of days with α	D days		C days		S days		C+S days	
		No. of days	Probability (%)	No. of days	Probability (%)	No. of days	Probability (%)	No. of days	Probability (%)
1	342	27*	7.89*	7	2.05	6	1.75	13*	3.8*
2	380	56	14.74	16	4.21	13	3.42	29	7.63
3	370	59*	15.95*	17	4.59	17#	4.59#	34*	9.19*
4	379	68*	17.94*	18	4.75	16	4.22	34#	8.97#
5	399	76*	19.05*	19	4.76	13	3.26	32	8.02
6	353	31*	8.78*	10	2.83	9	2.55	19	5.38
7	393	18*	4.58*	6*	1.53*	7	1.78	13*	3.31*
8	351	29*	8.26*	13	3.7	7	1.99	20	5.7
Total	2967	364		106		88		194	
Mean	370.88	45.5	12.15	13.25	3.55	11	2.95	24.25	6.5

* : Number of days and probability significantly different from the average at 95 % level of confidence according to Z test.
\# : Same as * but at 90 % level of confidence.

against the climatological easterlies. The westerly anomaly continues and becomes stronger over the north Indian Ocean with an anomalous anticyclonic circulation over southeast Arabian Sea during phase 6 of MJO. This anticyclonic circulation anomaly moves northward and lies over central part of Arabian Sea and adjoining peninsula during phase 7 of MJO. As a result, the mid latitude dry and cold westerlies prevail over the Oceanic region which supress the cyclogenesis. Similar pattern continues in phase 8 of MJO with further northward movement of anticyclonic circulation anomaly and reappearance of easterlies up to southern part of Bay of Bengal and Arabian Sea without any embedded north-south trough. The ITCZ (the north equatorial trough) also continues to be absent over north Indian Ocean region through phase 6 - 8 like that in phase 1. The associated convection strengthens/weakens and propagates northward in accordance with the variation of circulation pattern as discussed above. It all indicates that the anomalous north-south trough in easterlies embedded with cyclonic circulation over the south west/west central Bay of Bengal in association with southerly surge over the region during active MJO in phase 3 and 4 most favourably influences the convection and enhances the probability of cyclogenesis over the north Indian Ocean during post-monsoon season.

3.2. *Cyclogenesis in relation to amplitude of MJO*

The mean amplitudes of MJO in different phases with respect to cyclogenesis days during monsoon season, post monsoon season and year as a whole are analysed and salient results are presented in Table 2. It indicates that the mean amplitude for any phase of MJO is >1 during the cyclogenesis days except for phase 8 during monsoon season and phase 7 and 8 during post monsoon season.

To find out further the favourable ranges of amplitude associated with genesis, the amplitude of MJO has been split into three ranges, *viz*., (*i*) 0 - < 0.5, (*ii*) 0.5 to 1.0 and (*iii*) > 1.0. Number of cyclogenesis days for each interval is calculated for each phase separately. However, the results for the phases 2, 3, 4, 5 and 6 are presented [Figs. 5(a-c)]. It is found that quite a significant number of cyclogenesis takes place with the weak MJO (amplitude < 1) in different phases as described by Wheeler and Hendon (2004). The cyclogenesis also takes place even with weak amplitude of MJO in favourable phases. More than one third (36%) of total genesis in phase 4 and 5 for the monsoon season occurs with amplitude < 1. It indicates that the phase is more important than amplitude of MJO. Further it indicates that

TABLE 4(a)

Mean amplitudes of MJO with respect to different intensities of CDs during year as a whole

MJO Phase	Mean amplitude of MJO			
	All Days	C days	S days	C+S days
1	1.24	1.04*	1.27	1.16
2	1.21	1.13	1.8*	1.44*
3	1.3	1.23	1.57*	1.37
4	1.22	1.36#	1.37*	1.37*
5	1.29	1.62*	1.54*	1.58*
6	1.3	1.22	1.31	1.26
7	1.26	0.7*	0.73*	0.71*
8	1.3	1.17	1.01#	1.1*

* : Amplitude significantly different at 95 % level of confidence according to student's *t*-test from the mean amplitudes of the respective phases.
\# : Same as * but at 90 % level of confidence.

TABLE 4(b)

Mean amplitudes of MJO with respect to different intensities of CDs during monsoon season

MJO Phase	Mean amplitude of MJO	
	All days	C+S days
1	1.2	1.26
2	1.09	1.68*
3	1.02	1.26#
4	1.03	1.44*
5	1.28	1.7*
6	1.25	1.89*
7	1.11	No C/S
8	1.17	No C/S

* : Amplitude significantly different at 95 % level of confidence according to student's t test from the mean amplitudes of the respective phases.
\# : Same as * but at 90 % level of confidence.

the genesis is less dependent on amplitude during post-monsoon season compared to monsoon season, as about 44% of total genesis in association with favourable phases (3 & 4) during post-monsoon season occur with amplitude < 1. However, when the amplitude of MJO is less than 0.5, the frequency of cyclogenesis over north Indian Ocean is very negligible as 10% of total genesis occurs in the favourable phase of 4 and 5 in monsoon and 3 and 4 in post-monsoon season.

TABLE 4(c)

Mean amplitudes of MJO with respect to different intensities of CDs during post-monsoon season

MJO Phase	Mean amplitude of MJO			
	All days	C days	S days	C+S days
1	1.2	1.09	1.02	1.05#
2	1.23	1.11	1.92*	1.5*
3	1.32	1.18	1.69*	1.44
4	1.21	1.29	1.38#	1.34#
5	1.29	1.34	1.42	1.37
6	1.29	1.19	1.38	1.28
7	1.12	0.49*	0.73*	0.62*
8	1.18	1.05	0.76*	0.95*

* : Amplitude significantly different at 95 % level of confidence according to student's t test from the mean amplitudes of the respective phases.
\# : Same as * but at 90 % level of confidence.

3.3. *Intensity of CDs in relation to MJO phases*

The intensity of CD with respect to MJO has been analysed by calculating the number of days of CD with different intensities like D, C and S with respect to different phases of MJO during year as a whole, monsoon season and post monsoon season. The results are summarized in Tables 3(a-c). There is strong modulation in the distribution of intensity of CD during the different phases of MJO. There are 1268 CD days out of total 11819 days considered for the study. If the CD days would have been distributed uniformly, the percentage of occurrence of these days would have been 10.73% [(1268/11819)*100)] for all phases (not shown) during a year. Similarly, if D, C, S and C+S days would have been distributed uniformly, the percentage of occurrence of these days would have been 7.87%, 1.56%, 1.30% and 1.86% respectively during year as a whole. But it is found that phase 3, 4, 5 and 6 have significantly higher percentage of occurrence whereas phase 1, 7 and 8 have significantly lower percentage of occurrence of D days during year as a whole according to *Z* test [Table 3(a)]. Similarly, probability of C days is higher in phase 3, 4 and 5 and less in phase 1 and 7. The number of S days significantly increases in association with phase 4 and decreases in association with phase 7 of MJO. Considering both C and S days together (C+S days), they have preference to phase 3, 4 and 5. There is significantly lower probability of occurrence of these days at phase 7 and 8. About 52% of total C and S days occur in association with phase 3, 4 and 5 and 22% occur in phase 1, 7 and 8. Hence, the probability of intensification of a

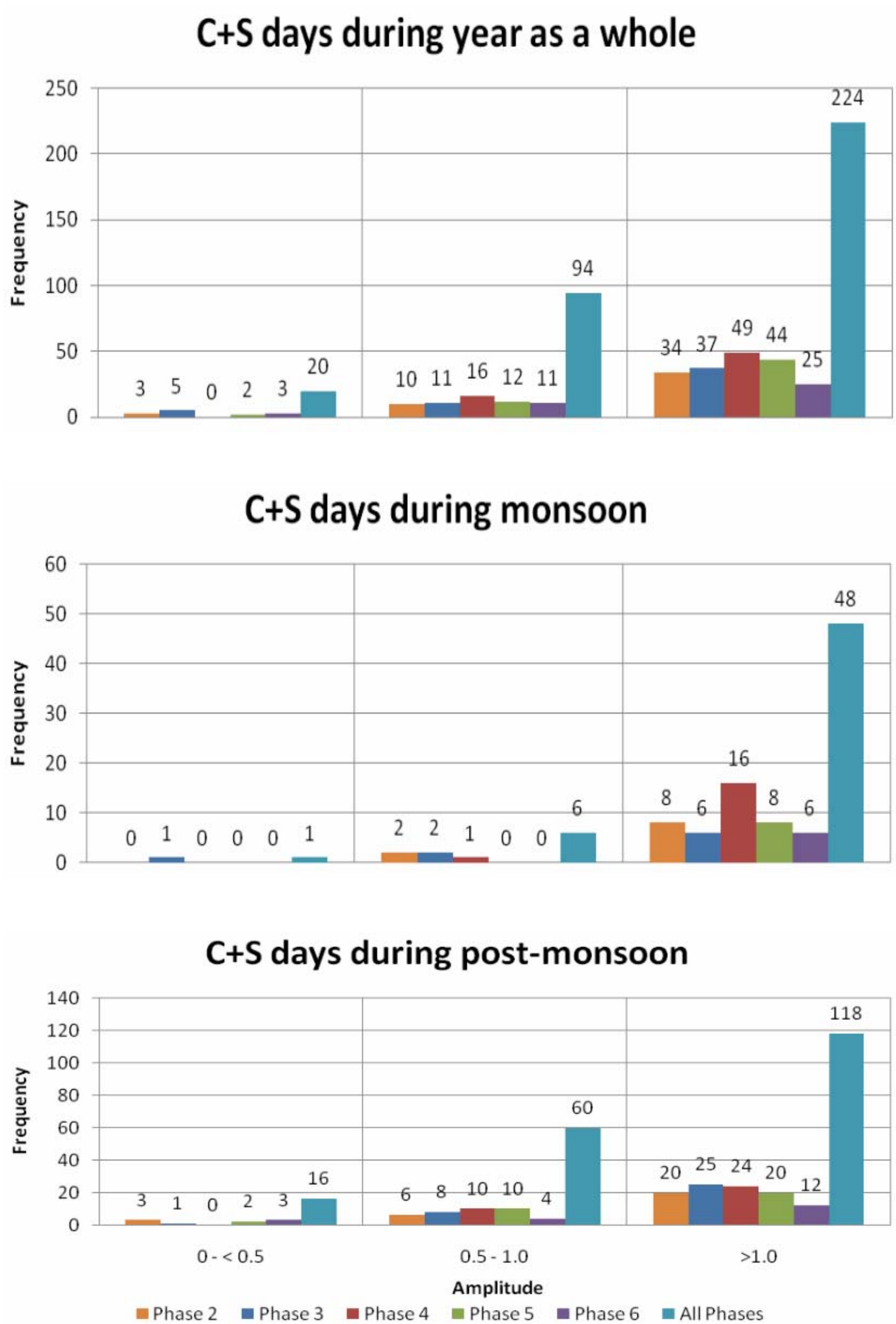


Fig. 6. Frequency distribution of C+S days with respect to amplitude of MJO at phase 2, 3, 4, 5, 6 and all phases together during year as a whole, monsoon and post monsoon season

depression into a cyclonic storm is higher with MJO in phase 3, 4 and 5 and less with MJO in phase 1, 7 and 8. The possibility of intensification into a severe cyclone (S) is higher with MJO in phase 4 and less with MJO in phase 7. Further, it indicates that like genesis, the intensity of the CDs are governed by some other factors apart from MJO.

During monsoon season, the frequency of C and S are very less, as only 21 Cs and 9 Ss developed during the period under study. Similarly, the number of C days and S days during monsoon season are also very less, being 36 and 21 respectively. Hence the sample is not sufficient enough to analyse the characteristics of MJO association with the intensification of the system into severe cyclonic storm. Therefore, the total number of C and S days and hence the intensification of D into C/S has been considered and analysed for the monsoon season. The number of D days is significantly higher with MJO in phase 3, 4, 5, 6 and less with MJO in phase 1, 2 and 8 during monsoon season. The probability of intensification from D to C is significantly higher with MJO in phase 4 [Table 3(b)]. There have been no C or S days in association with phase 7 and 8. Hence MJO at phase 7 and 8 during monsoon season completely suppresses the intensification of D into C.

Considering post-monsoon season Table 3(c), number of C+S and S are 63 and 44 respectively. There are 106 C days, 88 S days and 194 C+S days during the post-monsoon season. Hence, it is a good sample to present the result. The number of D days is significantly higher with MJO in phase 3, 4, 5 and less with MJO in phase 1, 6, 7, 8 during this season. The number of C+S days is significantly higher with MJO in phase 3 & 4 and less with MJO in phase 1 & 7. It indicates that probability of intensification and the average duration in C/S stage and hence life period of the cyclone is higher with MJO in phase 3 and 4 and less with MJO in phase 1 and 7 during post-monsoon season.

3.4. *Intensity of CDs in relation to MJO amplitudes*

Summary of mean amplitudes of MJO with respect to D, C and S days during year as a whole, monsoon season and post monsoon season are shown in Tables 4(a-c). Considering C days, the amplitude is significantly less than the normal at phase 1 & 7 and higher at phase 4 & 5 during year as a whole [Table 4(a)]. The amplitudes are significantly higher than the normal amplitude at phase 2, 3, 4 & 5 and less at phase 7 & 8 in case of S days. Considering monsoon season, the mean amplitude is significantly higher in phase 2, 3, 4, 5 and 6 during C+S days [Table 4(b)]. Hence higher amplitude of MJO in phase 2, 3, 4, 5 and 6 may lead to intensification of D into C/S during monsoon season. Significantly higher amplitude in phase 2, 3 and 4 and less amplitude (< 1.0) in phase 7 and 8 leads to intensification of D into S during post-monsoon season. There is no significant difference in amplitude for intensification of D into C except that the lower amplitude at phase 7 can lead to intensification of D to C during this season [Table 4(c)].

Considering different ranges of amplitude, the C+S days with amplitude of MJO less than 0.5 is negligible in case of monsoon season (Fig. 6). There is only 1 C+S day (2%) out of total 55 C+S days for the whole monsoon season. Only 6 (11%) C+S days occur within the amplitude range 0.5 to 1.0. But 48 (87%) C+S days occur when amplitude is greater than 1.0. So for the monsoon season, it may be assumed that the favourable range of amplitude for intensification is >1.0.

In the post-monsoon season, 16 (8%), 60 (31%) and 118 (61%) C+S days occur in the amplitude range <0.5, 0.5 – 1.0 and >1.0 respectively. So unlike monsoon season, the intensification of the D into C/S can occur with lower amplitudes (<1.0) during post-monsoon season.

4. Conclusions

Following broad conclusions are drawn from the above results and discussion:

(*i*) The MJO strongly modulates the genesis and intensity of CDs over the north Indian Ocean. However, there are other factors contributing to cyclogenesis over the north Indian Ocean, as about 60% of cyclogenesis during monsoon and post-monsoon seasons are not significantly related with MJO.

(*ii*) While the probability of cyclogenesis during monsoon season is higher with MJO in phase 4 and 5 (Maritime Continent), that during post-monsoon season is higher with MJO in phase 3 and 4 (east Indian Ocean and adjoining Maritime Continent). It indicates that while possibility of genesis during monsoon season is significantly suppressed with active MJO at phase 1, 7 and 8, there is no significant relationship between genesis and active MJO at phase 1, 7 and 8 during post-monsoon season.

(*iii*) The anomalous cyclonic circulation at lower levels over central and north Bay of Bengal in association with MJO at phase 4 and 5 favours enhanced probability of cyclogenesis over the Bay of Bengal during monsoon season. The anomalous easterlies in association with MJO at phase 1 and development of anomalous ridge over south India in association with MJO at phase 7 and 8 which are weak monsoon features lead to suppressed cyclogenesis over north Indian Ocean during this season. The anomalous north-south trough in easterlies embedded with cyclonic circulation over the south west/west central Bay of Bengal in association with southerly surge over the region during active MJO in phase 3 and 4 most favourably influences the convection and enhances the probability of cyclogenesis over the north Indian Ocean during post-monsoon season.

(*iv*) The genesis of CDs is more sensitive to phase than the amplitude. Further genesis is less dependent on amplitude during post-monsoon season than monsoon season. About 36% and 44% of total cyclogenesis in the favourable phases as mentioned above can occur with amplitude < 1 for monsoon and post-monsoon season respectively. However, the frequency of cyclogenesis is negligible (about 10% of total genesis) with amplitude of MJO < 0.5 in the favourable phases.

(*v*) The probability of intensification and C+S days are more dependent on amplitude than on phase. The probability of intensification and C+S days are higher with higher amplitude of MJO in phase 2, 3, 4, 5 & 6 and lies with higher amplitude of MJO at phase 7 and 8 during monsoon season. About 87% of total number of C/S days occurs with the amplitude > 1 during monsoon season. The higher amplitude in phase 2, 3, 4 and less amplitude in phase 7 and 8 are favourable for intensification of D into C/S & higher C+S days during post-monsoon season. However, the intensification can occur with lower amplitude (<1.0) as about 47% of total C and S days occuring with amplitude of < 1.0 in the phase 2, 3, 4 and 5 during this season. Hence like the genesis, the intensification and duration of the CDs are less dependent on the amplitude during post-monsoon season than the monsoon season.

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