Chapter 3

The Influence of Madden Julian Oscillation in the Genesis of North Indian Ocean Tropical Cyclones

3.1 Introduction

The relation between MJO and tropical cyclones can be attributed to the deep convection in the convective phase and the associated strengthening of equatorial lower tropospheric westerly wind towards the west of the area of convection (Rui and Wang, 1990). Such a situation leads to an increase in cyclonic vorticity in the atmospheric boundary layer of the low latitude regions north and south of the equator. MJO is also characterized by enhanced upper level divergence associated with the convective phase.

Liebmann et al (1994) observed that the cyclones preferentially occur during the convective phase of MJO, and cluster around the low-level cyclonic vorticity and upper level divergence anomalies that appear poleward and westward of the large-scale convective anomaly along the equator. Later studies have shown the importance of eddy kinetic energy associated with the convective phase of MJO in the formation of cyclones. Maloney and Hartman (2001) noticed that when 850 hPa wind anomalies of MJO are westerly, small-scale slow-moving eddies
grow through barotropic eddy kinetic energy conversion from the mean flow and these growing eddies, together with strong surface convergence, 850 hPa cyclonic wind shear (vorticity) and high mean SST, create a favourable environment for tropical cyclone formation. Leroy and Wheeler (2008) developed a statistical scheme to predict the tropical cyclone activity in the southern hemisphere using five predictors in which two represents the eastward propagation of the MJO, two represents the leading patterns of interannual SST variability in the Indo-Pacific Oceans and one represent the climatological seasonal cycle of tropical cyclone activity in each zone. They found that inclusion of indices of the MJO as predictors leads to increased skill out to about three weeks.

Roundy (2008) discussed in detail the interaction of convectively coupled Kelvin wave with MJO in North Indian Ocean basin and has shown that the MJO phase modulates the intensity of moist deep convection associated with the Kelvin waves. The role of convectively coupled waves like MJO, convectively coupled equatorial Rossby, Kelvin, and mixed Rossby-gravity waves in the modulation of south Indian Ocean tropical cyclones were analysed by Besafi and Wheeler (2006) who studied the dynamical controls of these waves on tropical cyclone through wave-induced perturbations to the dynamical fields of low-level vorticity, vertical shear, and deep convection. They have shown that large-scale atmospheric variability caused by MJO and equatorial Rossby waves is important for the modulation of tropical cyclones in south Indian Ocean and can be used for prediction purposes extending up to few weeks.

The cyclones having their genesis in the area bounded by latitudes 0° to 15°N and longitudes 60°E to 100°E has been studied as outside this area very few cyclones have their genesis in the pre-monsoon and post-monsoon seasons. In the Indian summer monsoon season (June to September) monsoon depressions (cycloic systems weaker than tropical cyclones) are formed and their genesis area is north of the area chosen for the study. During the monsoon season very few of the cycloic systems formed develop into cyclone intensity due to the prevailing high VWS in the environment, with LLJ in the lower troposphere and the TEJ in the upper troposphere.
3.2 Methodology

The MJO days can be clustered into 8 phases (P1, P2, P3,..., P8 hereafter) depending on the phase angle variations in the phase space created by the RMM1 and RMM2 indices (Wheeler and Hendon, 2004). Each phase represents the geographical location of the enhanced convection of the MJO with respect to the phase space. On this, the phases P1, P2, P3 and P4 represent the convective phase of MJO where the equatorial Indian Ocean is dominated by convection. Similarly the phases P5, P6, P7 and P8 represent the period when convection is suppressed in the equatorial Indian Ocean. The genesis dates of cyclones are clustered into these 8 groups based on the MJO phase in which a cyclone genesis date resides. The genesis date of a cyclone is defined as the first day of the cyclone reported in the IBTrACS dataset. Following Hall et al (2001) a statistical analysis of the significance of the number of tropical cyclone in each MJO category is done. Here a Z statistic is calculated for the 8 phases of MJO taking the null hypothesis that cyclones are equally distributed in all the phases. The statistic is given as

\[ Z = \frac{P - P_0}{\sqrt{P_0 \left(1 - \frac{P_0}{N}\right)}} \]  

(3.1)

Where \( P \) and \( P_0 \) are expected and observed proportion of cyclogenesis days within a particular MJO category respectively and \( N \) is the number of days in the category. It was tested at the 95%, 98% and 99% levels, using a two-tailed test, with critical values of \( Z = \pm 1.96, \pm 2.326 \) and \( \pm 2.576 \) respectively.

3.3 Results and discussion

3.3.1 Genesis and distribution of cyclones

From IBTrACS cyclone data, cyclonic systems with maximum sustained wind speed of 34 knots or above, which is the criteria used by India Meteorological Department for North Indian Ocean cyclones; are used in the study. Using this criteria, 118 cyclones were identified which satisfy the intensity criteria for North Indian Ocean basin from 1979 to 2008. Out of the 118 cyclones selected, 96
Table 3.1: Summary of the distribution of cyclones from January to December. Here the first row represents the total 118 cyclones formed during the period of study (1979 to 2008). The second row shows the distribution of 96 cyclones which formed in the genesis area selected for the study (0-15°N, 60°E-100°E).

<table>
<thead>
<tr>
<th>Total</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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</thead>
<tbody>
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<td>5</td>
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<td>0</td>
<td>3</td>
<td>16</td>
<td>32</td>
<td>11</td>
</tr>
</tbody>
</table>

cyclones had their genesis in the study region. Figure 3.1 gives the distribution of the genesis points of cyclones in which the area inside the box (0-15°N and 60°E-100°E) represents the area of cyclogenesis selected for the study. Figure 3.1a represents the total 118 cyclones formed and figure 3.1b gives the cyclones which originated during June to September (JJAS). It can be seen that majority of the JJAS cyclones had their genesis outside the study area. The month-wise distribution of the total 118 cyclones selected and the 96 cyclones having their genesis located in the study region are given in table 3.1. It may be seen that during the monsoon season (June to September) very few cyclones have formed. Similarly there are few cyclones in February and March. Cyclone prone months are April and May and October to December which account for the majority of cyclogenesis in the area.

A phase space diagram is created using the RMM1 and RMM2 index to represent the different phases of MJO. The phase space diagram along with the distribution of cyclones is given by figure 3.2. In figure 3.2 the circle in the center of phase space with radius 1 represents days with MJO amplitude 1 and less. The back dots represent the date of cyclogenesis. Any day falling inside this circle is considered as a weak MJO day. From the phase-space diagram, it can be seen that cyclogenesis dates are clustered on the convective phase of MJO (P1 to P4). Although cyclogenesis occurred in the suppressed convection phases of MJO, majority of the days are under MJO amplitude 1.

The distributions of cyclones in different MJO categories were studied by setting different amplitudes of MJO. The MJO amplitudes, total number of cyclones
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Figure 3.1: Tropical cyclone genesis location (dots) for the three decades from 1979 to 2008. The rectangular area marked in the figure shows the region selected for the study (0-15°N, 60°E-100°E) (a) Total 118 cyclones formed during 1979 to 2008 (b) Cyclones which formed from June to September.

formed under each amplitude and distribution of cyclones in each MJO phase are given in table 3.2. The first column in table 3.2 represents the MJO amplitude and the second column gives the total number of cyclones for the corresponding phase. Columns from 3 to 10 give the distribution of genesis days within the eight phases of MJO. The MJO amplitude 0.5 covers approximately 89% of the total days selected which include the majority of the cyclogenesis days and accounts for 83 cyclones out of the total 96 cyclones formed in the study area. Out of this 83 cyclones, 7 (8.4%) formed in P1, 15 (18%) in P2, 22 (26.5%) in P3, 20 (24.1%) in P4. For MJO amplitude 1, which includes approximately 61% of the total days, 54 cyclones are formed. Out of this 54 cyclones, 5 (9.3%) formed in P1, 10
Table 3.2: Summary of the distribution of tropical cyclone genesis days in the different categories of MJO for the various amplitudes taken. Here the first column represents the MJO amplitude and the second column gives the total number of cyclones for the corresponding amplitude. Columns from 4 to 7 give the distribution of genesis days within the four categories of MJO.

<table>
<thead>
<tr>
<th>MJO Amplitude</th>
<th>No. of Cyclones</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
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<td>1</td>
</tr>
</tbody>
</table>

(18.5%) in P2, 13 (24.1%) in the P3, 16 (29.3%) in the P4. Convective phase of MJO (P1, P2, P3 and P4) accounts for 44 (81.5%) of cyclones formed under MJO amplitude 1. Using the statistic defined earlier the number of cyclones phases P3 and P4 are found to be significantly high at 98% significance level. For MJO amplitude of 1.5 which includes 33.4% of the total days 27 cyclones formed. Here 22 out of 27 cyclones originated in the convective phase of MJO. In all cases, it is seen that the number of cyclogenesis days are more in the convective phase compared with the suppressed convection phases.

The month wise distribution of the tropical cyclone genesis in each phase is given in table 3.3. As seen from table 3.3, the monthly distributions of cyclones within the MJO phases are also showing the bimodal structure similar to the general North Indian Ocean cyclone variability. As we can see the bimodal peak has its largest amplitude during November to December which accounts for 25 cyclones followed by May-June accounting 20 cyclones. For P3 more number of cyclones formed in May-June period; but for P4, majority of cyclones are formed in November-December period. Thus we have two distinct periods (May-June and November-December) of cyclogenesis for each MJO phase which is used to analyze the prevailing synoptic conditions for the phases.

The spatial distribution of cyclogenesis with the genesis points and tracks of tropical cyclones in each MJO phases are shown in figure 3.3. Here only the days with MJO amplitude 1 or above is considered. Figure 3.3a to figure 3.3d
Figure 3.2: Phase amplitude diagram constructed with the principal components RMM1 and RMM2 of MJO from 1979 to 2008. The black dots represent the cyclogenesis days. Eight categories are defined according to the phase angle in which a day resides. The circle in the center with amplitude 1 represents days with weak MJO activity.

represents the convective phases of MJO and figure 3.3e to figure 3.3h represents the suppressed convection phase. For phases P1 and P2 although the number of tropical cyclones are less, they are distributed almost equally in the Arabian Sea and Bay of Bengal. But for phases P4 and P5, more cyclones are formed in the Bay of Bengal comparing with Arabian Sea. For phases P5 to P8 the cyclogenesis occurred mainly in the Bay of Bengal. The spatial distributions of cyclones are found to be highly influenced by the synoptic conditions associated with the MJO categories. A detailed discussion about the synoptic conditions leading to cyclogenesis and distribution during the phases are given in the following section.
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Figure 3.3: Tropical cyclone genesis location (dots) and tracks (lines) for different MJO Phases.

(a) P1, (b) P2, (c) P3, (d) P4, (e) P5, (f) P6, (g) P7, (h) P8
Table 3.3: Month wise distribution of cyclones in each phase of MJO. Here the first column represents the MJO Phase. Columns from 2 to 13 give the distribution of genesis days with in the eight categories of MJO. The last row gives the total distribution of cyclones (above MJO 1 amplitude) in the 12 months.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Jan</th>
<th>Feb</th>
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<td>1</td>
<td>2</td>
<td>21</td>
<td>4</td>
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3.3.2 Synoptic conditions

Synoptic conditions associated with each phase of MJO are studied by compositing the different parameters related with cyclogenesis such as OLR, SST, 850 hPa wind flow, 850 hPa vorticity and the VWS between 200 hPa and 850 hPa. SST of the study region has remained higher than 28°C in all the MJO phases during November-December. In May-June SSTs are still higher. Our study has shown that SST is not an important factor for cyclogenesis in the study region with respect to the phases of MJO. However, the large scale circulation patterns and associated changes in environmental parameters such as 850 hPa relative vorticity and VWS are important in modulating the tropical cyclone activity over the ocean basins (Chand and Walsh, 2009; Belanger et al, 2010). Composites of these fields were analysed in the study to bring out the favourable conditions which led to cyclogenesis. For each phase, the days having MJO amplitude 1 or above is composited for the months under consideration. The anomalies were calculated from these fields by subtracting the climatological mean of the months from 1979 to 2008.
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Figure 3.4: OLR anomaly composites of November-December associated with MJO phases 1 to 8. The negative contours are shaded and the positive anomaly contours are hatched. The contour interval is 7.5 Wm$^{-2}$.

The OLR anomaly patterns for November-December are given in figure 3.4. The eight phases of MJO convection is depicted in the figure which shows the temporal varying patterns for the season. It is seen that during the phases P1 to P4, the area of convection is located over the Indian Ocean. During P1 the convection is in its initial phase with a small patch extends over the Arabian Sea. During P2 the convection has shifted to central Indian Ocean and from there it has shifted to eastern Indian Ocean during P3. This convection further extends in P4 covering the entire eastern Indian Ocean and maritime continent. During P5 the convection over maritime continent strengthens but there is suppressed convection.
generating over the western Indian Ocean. This suppressed convection follows the same development pattern as in the convective phase of MJO by subsequent development of suppressed convection from P5 to P8. The May-June convection patterns for the same phases are given in figure 3.5 which is identical with those given in Wheeler and Hendon (2004). Similar to P1 of November-December, the first phase (P1) of MJO consists of weak convection over the Arabian Sea. During P2 this further extends into central Indian Ocean. In P3 convection covers the entire Indian Ocean and reaches up to the maritime continent. This convection moves further eastward during P4 with a slight northward movement with an elongated patch reaching Western Pacific and covering the entire Indian Ocean. From P5 to P8, suppression phase of MJO exists over the Indian Ocean with its

Figure 3.5: Same as figure 3.4, but for May-June.
Figure 3.6: Composite 850 hPa wind and vorticity anomalies of November-December associated with MJO phases. Wind magnitude and direction is shown by the arrows. Reference vector is given in the upper right corner. Contours of cyclonic vorticity are also shown as shaded. Vorticity values are scaled by $1 \times 10^{-5}$ and the contour interval is $1 \times 10^{-5} \text{s}^{-1}$. The cyclogenesis points are given as black dots.

development patterns similar to the convective phases.

Wind anomaly patterns associated with the MJO convection during November-December is given in figure 3.6. The cyclone genesis points are also given in the figure for each phase as black dots. Only the positive vorticity anomaly (cyclonic vorticity) regions are shown in the diagram as shaded regions. It is seen that the cyclones are clustered around the cyclonic vorticity anomaly formed during the passage of MJO convection. In P1, as the convective region is generated over Arabian Sea, easterly wind anomaly exits over the North Indian Ocean. Two cy-
clones had genesis in the equatorial Arabian Sea and Bay of Bengal near areas of cyclonic vorticity. As the convection moves eastward in P2, anomalous westerly flow is generated in the North Indian Ocean especially in Arabian Sea and the cyclones get formed in the cyclonic vorticity region associated with this. As the MJO convection shifts further eastward during P3 the westerly flows enter the Bay of Bengal creating a favourable vorticity region for the genesis of cyclones there. The anomalous westerly flow is strengthened further in the entire North Indian Ocean during P4, which account for 10 cyclones formed in its cyclonic vorticity region. As the convection moves to the western Pacific the westerly wind strengthens over the Bay of Bengal and 5 cyclones are formed. Thus P5 is favourable for cyclogenesis in North Indian Ocean particularly the Bay of Bengal although the convection is suppressed there. In effect the phases P1 to P5.

Figure 3.7: Same as figure 3.6, but for May-June.
Figure 3.8: Composite VWS associated with MJO phases during November-December. The cyclogenesis points are given as black dots.

favours cyclogenesis in North Indian Ocean. From P6 to P8 although vorticity is favourable, the other environmental factors like suppressed convection and VWS (discussed later) inhibit cyclogenesis in North Indian Ocean.

Composites for May-June are shown in figure 3.7. Similar to November-December, the westerly wind anomalies are generated which moved eastwards along with the convection. Westerly wind maximum occurs during the phases P3 and P4 which accounts for the maximum cyclogenesis in North Indian Ocean. During P3 vorticity maximum exits over the Arabian Sea and Bay of Bengal accounting for 8 cyclones. In P4 the vorticity maximum region shifts eastwards and 5 cyclones are formed in the Bay of Bengal. During the phase P5, cyclonic vorticity is strong over Bay of Bengal but there is no cyclogenesis. In phases P5
to P8 there is little cyclogenesis as both vorticity and VWS (discussed later) are unfavourable along with the suppressed convection existing over North Indian Ocean.

Figure 3.8 and figure 3.9 represents the VWS composites for November-December and May-June seasons respectively. During November-December the VWS is found to be favourable for the study region in MJO phases P2 to P5 and cyclogenesis occurs with VWS less than 8 ms$^{-1}$. In the other phases VWS is more that 8 ms$^{-1}$ and there is very little cyclogenesis in the study area. Comparing with November-December, the VWS over the study region is higher during the May-June. Cyclones have occurred in large numbers during the phases P3 and P4. In these phases VWS is in the order of 8 to 16 ms$^{-1}$. Cyclones have occurred with these high shear values in this season, most likely due to the high
cyclonic vorticity available there at 850 hPa (See figure 3.7).

3.4 Conclusion

Formation of cyclonic storms over North Indian Ocean in the area bounded by latitudes 0 and 15°N and longitudes 60°E and 100°E during the period 1979 to 2008 have been studied with respect to the eastward passage of Madden-Julian Oscillation. In this study, MJO intensity with amplitude 1 and above is considered, which includes 61.24% days of the whole period. There were a total of 118 cyclones in the three decades out of which 96 formed in the study region. The relationship between these cyclones with the different phases of MJO has been studied.

The cyclones are clustered in eight phases of MJO and have been analysed by selecting different amplitude criteria. The number of the MJO days for each amplitude varies significantly from one to another. However irrespective of the amplitudes chosen, it is observed that cyclogenesis over North Indian Ocean basin preferentially occurred during the convective phase of MJO (P1 to P4). By selecting MJO amplitude 1 and above 81.5% of the cyclones formed was under the convective phase of MJO. Further increasing the amplitude to 1.5, convective phase of MJO dominates by accounting 22 out of the 27 cyclones formed. The study has also shown that P3 and P4 of MJO have the highest favourable environment for cyclogenesis in Bay of Bengal.

The spatial distribution of the cyclogenesis is seen to be highly associated with the synoptic conditions existing over the North Indian Ocean during the phases. Phases P1 and P2 are associated with the initial phase of the MJO cycle where active convection occurs over equatorial Indian Ocean. This active convection area will induce strong equatorial westerlies to its west and associated cyclonic vorticity. The cyclogenesis location is seen to be distributed in the Arabian Sea and Bay of Bengal almost equally. In the next three phases of the MJO cycle (P3 to P5) the equatorial area of active convection has moved to the Bay of Bengal and the adjoining western Pacific and the associated westerlies in the lower troposphere cover the whole of equatorial Indian Ocean and is particularly strong over the equatorial areas south of Bay of Bengal. These phases are thus
most favourable for cyclogenesis in the Bay of Bengal. The cyclogenesis locations are seen to be distributed more in the Bay of Bengal comparing with Arabian Sea. In phases P6 to P8 the equatorial convection has moved further east and the subsiding motion in the North Indian Ocean leads to suppressed convection and thereby develops unfavourable conditions for cyclogenesis.

The cyclogenesis parameters were composited and analysed for the different phases of MJO particularly 850 hPa wind and vorticity. The cyclonic vorticity appearing the north and south of the flow induced by the westerly phases of MJO are significantly influencing the cyclogenesis. The axis of the 850 hPa wind maxima particularly the zonal component is seen to be shifting from Arabian Sea to Bay of Bengal changing the location of cyclogenesis. Vertical shear of zonal wind is found to be favorable during the P3 and P4 phases of November-December and May-June seasons which account for the maximum number of cyclone formation in those phases.

In this study intensification trends or the direction of movement of tropical cyclones in any category were not examined. Although the convective phase of MJO is found to be favourable for cyclogenesis, further studies are needed for using MJO as an effective predictor of cyclogenesis in North Indian Ocean.