The impact of the Madden-Julian Oscillation on the formation of the Arabian Sea Monsoon Onset Vortex

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Abstract

During some years, a synoptic scale vortex called the Monsoon Onset Vortex (MOV) forms within the northward advancing zone of precipitating convection over the Arabian Sea. The MOV does not form each year and the reason is unclear. Since the Madden-Julian Oscillation (MJO) is known to modulate convection and tropical cyclones in the tropics, we examined its role in the formation of the MOV. While the convective and transition phases of the MJO do not always lead to MOV formation, the suppressed phase of the MJO hinders the formation of the MOV more consistently. This non-linear relationship between the MJO and MOV can be partially explained by the modulation of the large-scale environment, measured by a tropical cyclone genesis index. It also suggests that the Arabian Sea is generally near a critical state that is favorable for MOV formation during the monsoon onset period.

Key Points:

- The MOV's response to the MJO phases is non-linear.
- A convectively active MJO is neither a necessary nor a sufficient condition for the formation of the MOV.
- The GPI is a useful metric for studying MOV formation.

Plain Language Summary

The MOV is a cyclonic vortex, which forms in the Arabian Sea in some years during the onset of the Indian Summer Monsoon. It often intensifies into a tropical cyclone. The MJO is an eastward-moving band of clouds and rainfall near the equatorial regions, having a cycle of 30-60 days. The MJO enhances the formation of tropical depressions and tropical cyclones worldwide. This study shows that the wet phase of the MJO is neither a necessary nor a sufficient condition for the MOV to form over the Arabian Sea. Additionally, the peak dry phase of the MJO is least likely to witness the formation of a MOV.

1 Introduction

A variety of synoptic-scale disturbances originate within the monsoon regions of the globe. One of them is a synoptic-scale vortex that forms over the Arabian Sea during the onset of the Indian summer monsoon (Krishnamurti et al., 1981). This monsoon onset vortex (MOV) is typically described as a low-pressure system at the leading edge of the monsoon current (Deepa & Oh, 2014). The MOV's socio-economic impact is substantial. In some years, it intensifies into a tropical cyclone and leads to widespread damage and casualties (Evan & Camargo, 2011). Additionally, the presence of a MOV may also impact the progression of the monsoon (Srivastava et al., 2008; P. P. Baburaj et al., 2022). Compared to the monsoon depressions of the Bay of Bengal, relatively less attention has been devoted to the MOV in the published literature.

Early work on the MOV focused on the possibility that the MOV arises from the hydrodynamic instability of the low-level Somali jet (Krishnamurti et al., 1981; Mak & Kao, 1982). These studies employed highly idealized numerical models that lacked crucial physical mechanisms such as boundary layer dynamics and feedback from moist convection and radiation. It is unclear whether the instability of the Somali jet is the primary mechanism for the MOV origin. Additional work is needed to address this knowledge gap.

During late May and early June, an area of sea surface temperature (SST) often exceeding 29^oC is found within the southeast portion of the Arabian Sea. This has come to be known as the Arabian Sea mini warm pool (Rao & Sivakumar, 1999). Moist convection is also frequently observed over the Arabian Sea. This convection can occur in localized areas such as the mini-warm pool (Vinayachandran et al., 2007) as well as in association with the northward movement of the monsoon convergence zone (Geen et al., 2020). The mini warm pool likely plays a role in the organization of convection in the incipient MOV. However, the underlying mechanism has not been elucidated in past studies. Moreover, since the MOV does not form each year, the factors that modulate the genesis of the MOV are also not clear.

The Madden–Julian Oscillation (MJO) is a key source of intraseasonal modulation of convection over the tropics, including the Arabian Sea (Madden & Julian, 1994, 1972). The MJO has been found to influence tropical cyclone activity over different ocean basins (e.g. Klotzbach (2010); Kim et al. (2008); Hall et al. (2001)). Krishnamohan et al. (2012)

found that nearly 82% of all pre-and post-monsoon tropical cyclones in the north Indian Ocean formed during the convectively active phase of the MJO. Evidently, the MJO is a major factor in the modulation of tropical cyclone activity over the north Indian Ocean. However, the role of the MJO in the formation of MOVs has not been examined before.

The objective of this paper is to examine whether the MJO modulates the formation of the MOV. We hypothesize that similar to tropical cyclones, the convective phase of the MJO promotes the formation of MOVs, while the suppressed phase inhibits their formation. To investigate the physical mechanism underlying the hypothesized relationship, we examine the genesis potential index, a composite measure of the environmental factors that are known to affect the formation of tropical cyclones (e.g., Emanuel and Nolan (2004)). Previous studies have shown that the impact of the MJO on tropical cyclone activity can be partially explained by variations in the genesis potential associated with different phases of the MJO (Camargo et al., 2009; Tsuboi & Takemi, 2014; Zhao & Li, 2019; Rahul et al., 2022). However, the applicability of this genesis potential index in the formation of MOVs has not been examined before. Therefore, a secondary objective of our study is to evaluate whether the genesis potential index, originally developed for tropical cyclones, is a useful metric to account for the formation of MOVs.

2 Data and Method

2.1 MOV identification

At present there is no established definition of MOVs in the literature. Deepa and Oh (2014) presented a list of past MOVs from 1982–2011, but their rationale for identification was not clear. Recently, Sasanka et al. (2023) classified cyclonic synoptic systems over the Arabian Sea within -10 days to +20 days of the monsoon onset over Kerala as MOVs. It is important that the definition of the MOV includes only those vortices which are associated with the onset and advance of the monsoon over the Arabian Sea and not the pre-monsoon or seasonal monsoonal disturbances. In this paper, we defined MOVs as synoptic-scale vortices with a minimum strength equivalent to a tropical depression (wind speed $\geq$ 17 knots) that form within 10 days of the Indian summer monsoon onset over the state of Kerala or until the northern limit of the monsoon has covered 20°N latitude over the Arabian Sea. We obtained the monsoon onset dates from the India Meteorological Department (IMD), following the new criteria for monsoon onset defined by Pai and Nair (2009).

For the majority of cases, the MOV formation was deemed to be the first instance of the report of the best track of a low by the Joint Typhoon Warning Center (JTWC), wherein the windspeed was $\geq$ 17 knots. The JTWC best track data does not include the systems which remained a tropical depression. We use the IMD best-track data for such MOV cases (non-cyclones) to ascertain the date of MOV formation. We considered all MOVs that were identified during the years 1982–2021. We chose 1982 as the starting year because satellite remote sensing observations had become routine by then. Additionally, detailed records of tropical systems are available from the India Meteorological Department's (IMD) best track data archive from 1982.

Based on the aforementioned criteria, a MOV was identified during the following years: 1983–1985, 1987–1989, 1992, 1994, 1996, 1998, 1999, 2001, 2004, 2007–2011, 2014, 2015, and 2018–2020. Thus, over the period 1982–2021, the MOV formed in $\sim$58% of the years.

2.2 MJO

The daily state of the MJO is obtained from the Bureau of Meteorology, Australia. It is represented by a real-time multivariate (RMM) index as described in Wheeler and Hendon (2004). The RMM index is based on the first two empirical orthogonal functions (EOFs) of the combined wind (850 hPa and 200 hPa) and the outgoing longwave radiation fields averaged along the equator. The RMM index consists of a phase and amplitude. The index allows the regional MJO signal to be categorized into 8 phases. Typically, the MJO is considered to be active when the magnitude of RMM $\geq$ 1 (Wheeler & Hendon, 2004). In our study, we have added a phase 0 (RMM index $<$ 1), which implies that the MJO was not active, or too weak to influence the tropics.

We categorized each day within the monsoon onset period (May 10–June 15) for the years 1982–2021 into one of the 9 groups based on the MJO phase (0-8). This time frame covers the climatological onset phase of the Indian summer monsoon till it has advanced up to 20°N latitude over the Arabian Sea.

2.3 Genesis Potential

We use the genesis potential index (GPI) developed Emanuel and Nolan (2004).

$$GPI = \left|10^5\eta\right|^{3/2}\left(\frac{RH}{50}\right)^3\left(\frac{V_{pot}}{70}\right)^3(1+0.1V_{shear})^{-2} \quad (1)$$

where η is the absolute vorticity at 850 hPa (in s^{-1}), RH is the relative humidity at 700 hPa, V_{pot} is the potential intensity in ms^{-1}, and V_{shear} is the magnitude of the vertical wind shear (in ms^{-1}) between 850 hPa and 200 hPa.

2.4 Data

All atmospheric fields and SST data were obtained from The European Centre for Medium-Range Weather Forecasts reanalysis (ERA5; Hersbach et al. (2020)). These data are available hourly on a $0.25^o \times 0.25^o$ grid spacing.

3 Results

We begin by examining the climatological characteristics of the Madden-Julian Oscillation (MJO) during the monsoon onset period (May 10–June 15). To describe MJO activity, we used the variance of outgoing longwave radiation (OLR) after applying a filter in the wavenumber-frequency domain based on the spectral properties of the MJO. The filter parameters were identical to those used by Wheeler and Kiladis (1999).

Figure 1 illustrates MJO activity in three different ways. The contours in Figure 1a show the climatological MJO activity during the onset period. Two maxima are noted in this field. One maximum is situated over the mini-warm pool region over the Arabian Sea, off the southwestern coast of India, while the other is located over the equatorial Indian Ocean. The shading in Figure 1a represents the difference in the MJO-filtered OLR variance calculated for two periods: May 10–June 15 and May 1–September 30. Therefore, the shaded field shows the anomalous MJO activity during the monsoon onset period relative to the seasonal MJO activity. The anomalous MJO activity is broadly enhanced over the entire Arabian Sea during the monsoon onset period.

Past studies have suggested that the onset of the Indian summer monsoon over the state of Kerala is linked to the convectively active phase of the MJO (Bhatla et al., 2017; Taraphdar et al., 2018; P. Baburaj et al., 2022). In particular, Taraphdar et al. (2018) reported that 82% of monsoon onsets during 1979–2016 occurred corresponding to RMM phases 1–3. They referred to these RMM phases as the wet phase of the MJO. However, the RMM magnitude exceeded 1 for only 53% of these years during the monsoon onset. Importantly, none of these studies have explicitly considered the impact of the MJO on the MOV.

How is the MJO activity different during the years when a MOV forms compared to the years when it does not form? To answer this question, we show the mean difference in the OLR variance between MOV and non-MOV years in Figure 1b. The filled circles mark the MOV genesis locations. A clear dipole in MJO activity is observed. The MJO activity is enhanced over the Arabian Sea and suppressed over the equatorial Indian Ocean during the MOV years as compared to the non-MOV years. Although it may be argued that the presence of the MOV itself could influence the results owing to the artifact of spectral filtering, Aiyyer et al. (2012) found that, compared to the synoptic-scale equatorial wave modes, the MJO-filtered OLR is less sensitive to coherent convective features such as tropical cyclones.

3.1 MOV and MJO Phase

Figure 1 indicates that, on average, the amplitude of the MJO signal over the south-eastern Arabian Sea is stronger during MOV years compared to non-MOV years. However, this figure does not provide any information regarding the phase of the MJO signal. That is addressed in this section.

Previous studies have typically regarded MJO phases 1-3 as convectively active over the tropical Indian Ocean (Taraphdar et al., 2018; P. Baburaj et al., 2022). However, since most of the MOVs form north of 8°N, the RMM phases commonly used for the Indian Ocean may not be suitable for the Arabian Sea, particularly during monsoon onset. For instance, anomalously low OLR values over the Arabian Sea can be seen in Wheeler and Hendon (2004) even in MJO phase 4 during May-June. Therefore, we first established the appropriate RMM phases that correspond to different MJO states within the Arabian Sea as follows. We calculated the long-term daily climatology of the OLR averaged over the Arabian Sea (7.5–22.5°N, 57.5–75°E) for each day between May 10 and June 15. This time series was then smoothed by applying a running mean of 5 days. Next, daily anomalies were calculated relative to the long-term climatology for that day. Finally, the daily anomalies for all years were grouped based on the RMM phase.

The distributions of grouped OLR anomalies for different RMM phases are displayed in Figure 2a. The box encloses the middle 50% of the distribution, with the bottom and top whiskers extending to 1.5 times the interquartile range from the lower and upper quartile, respectively. Black dots indicate data outside these bounds. To provide further clarity, Figure 2b displays the median and mean of each distribution. Based on these distributions, we classified the RMM phases as follows: The convectively active phase of the MJO (phases 2–4); the convectively suppressed phase of the MJO (phases 6–8); and the transition phase of the MJO (phases 1,5). The weak phase of the MJO (phase 0) is treated independently.

Figure 2c shows the number of MOVs associated with each MJO phase, with the percentages above each bar representing the proportion of total MOVs that occurred during that phase of the MJO. The key observations from this figure are: Nearly 39% of all MOVs formed during the convectively active phases of the MJO, while only 9% formed during the convectively suppressed phases of the MJO. Importantly, no MOV formed during the peak of the suppressed phase (phases 6,7). Around 26% of past MOVs formed during the transition between active and suppressed phases of the MJO, and the remaining 26% formed during the weak phase of the MJO.

The relative dearth of MOVs during MJO phases 6-8 is noteworthy, indicating that the convectively suppressed MJO likely generates an unfavorable environment for MOV formation over the Arabian Sea. However, taken together, more MOVs form during the transition and weak MJO phases than the convectively active phase of the MJO. This indicates that a convectively active MJO is not necessarily a prerequisite for MOV formation.

3.2 Anomaly composites of the tropical cyclone Genesis Potential Index

We now examine the modulation of the environment over the Arabian Sea by the MJO during the onset phase of the Indian summer monsoon. As noted earlier, past studies have found that genesis potential indices are useful in discerning the impact of the MJO on developing tropical cyclones. Here, we attempt to extend the use of the genesis potential indices to the MOV. Figure 3 shows the composite anomaly of the GPI for different MJO phases. The anomaly fields were calculated in the same way as the OLR anomalies, as described in section 3.1. However, for the GPI, we did not spatially average the individual parameters.

When the MJO is in its convectively active phase over the Arabian Sea, the GPI is anomalously high over most of the basin (Figure 3a). The MOVs during this MJO phase have formed in the regions of anomalously high GPI. When the MJO is in its convectively suppressed phase, the GPI is anomalously low over most of the Arabian Sea (Figure 3b). Importantly, only 2 MOVs have been observed to form during periods of suppressed MJO. During the transition phase of the MJO, the GPI is anomalously high mainly over the southern, southeastern, and east-central parts of the Arabian Sea (Figure 3c), corresponding to most of the observed MOV formation locations in these regions of the Arabian Sea. When the MJO signal is weak (phase 0), the GPI anomalies are mostly negative over parts of the southeastern and east-central Arabian Sea (Figure 3d). Interestingly, MOVs in phase 0 have formed in these regions with weak or near-zero GPI anomalies, where the actual values are close to climatology. We also note that most of these MOVs have formed in the southeastern part of the Arabian Sea, which corresponds to the mini-warm pool region (Vinayachandran et al., 2007) and is likely to have a high climatological GPI. These results are consistent when we use another tropical cyclone genesis index – the genesis potential parameter developed by Kotal et al. (2009) for the north Indian Ocean (not shown).

3.3 MJO during non-MOV years

Although the MOV is a common feature of the monsoon onset, it does not form every year. Figure 4 shows the cloud distribution during the monsoon onset, as seen in the infrared images from INSAT 3D. In 2015, we see cloud bands around a developing MOV, which later intensified into cyclone 'Ashobaa'. In 2016, there was no MOV during monsoon onset. Here, we see the cloud bands covering a larger area over the southeastern part of the Arabian Sea and spreading into the Bay of Bengal.

As noted earlier, only two MOVs formed when the MJO was in the convectively suppressed phase. In fact, during the peak of the suppressed phase (phase=6, 7; Figure 2c), no MOV has formed in the past. This leads to the question: What is the disposition of the MJO during the non-MOV years? Is it predominantly in the suppressed phase? To answer this question, we examined the MJO phases during each day of the monsoon onset period for non-MOV years and calculated the percentage of days associated with different MJO phases.

During the monsoon onset period for all the non-MOV years, the MJO was in convectively active phases for 22% of the days, in transition phases for 16% of the days, and in phase 0 (weak) for 33% of the days. In contrast, the MJO was in a convectively suppressed phase only for 29% of the days. Thus, the answer to the question raised earlier in this section is that the MJO is not necessarily in a predominantly convectively suppressed phase during the non-MOV years. Importantly, this means that despite the MJO being in convectively active or transition phases during these years, the MOV did not form. This suggests that the presence of the MJO in the convectively active phase at any time during the monsoon onset is not a sufficient condition for MOV formation.

4 Discussion

Unlike other monsoon-related disturbances such as monsoon depressions, the MOV has received significantly less attention in the existing literature. Routine observations show that the MOV develops within a region of widespread moist convection over the Arabian Sea. Nevertheless, past studies have not investigated the role of moist convection or its modulation by intraseasonal oscillations in the origin of the MOV.

To explore the relationship between the MJO and the MOV, we first ascertained the RMM index values that correspond to the different states of the MJO over the Arabian Sea. We found that the convectively active and suppressed phases correspond respectively to RMM=2–4 and 6–8. We classified RMM=1, 5 as the transition phase and instances of RMM amplitude < 1 as phase 0, to denote weak MJO. The results suggest the following:

1. The MJO activity over the southeastern Arabian Sea is enhanced during the onset period of the Indian monsoon as compared to the entire season (May–September). Furthermore, the MJO is also found to be more active over this region during MOV years as compared to non-MOV years.
2. A convectively active MJO is not a necessary condition for the MOV formation. While 39% of all past MOVs have formed in the convectively active MJO phase, 52% formed either in the transition phase or when the MJO signal was weak over the Arabian Sea. The fewest number of MOVs (9%) occur during the convectively

suppressed MJO phase. In particular, no MOVs have formed the peak convectively suppressed MJO corresponding to phases 6 and 7. The MOV's response to the MJO phases is therefore non-linear. Additionally, the presence of the MJO in convectively active phases during the monsoon onset does not always result in the formation of the MOV. In the years without a MOV, on average, 22% of the days during the monsoon onset phase was characterized by convectively active MJO. While it is not clear why the MOV did not form in these years, it is evident that the convectively active MJO is also not a sufficient condition for MOV to form.

3. Over most of the Arabian Sea, around the monsoon onset period, the GPI is anomalously low during the convectively suppressed phase of the MJO and high during the convectively active phase of the MJO. It is also high over the eastern Arabian Sea during the transition phase, and nearly zero (i.e. the same as climatology) when the MJO is weak. In general, the MOV formation locations correspond to GPI being at or above climatological values, indicating that it is a useful bulk metric for identifying the favorable regions for MOV. However, taken together with the previous point, the likelihood of MOV formation is not substantially higher during the convectively active phase of the MJO as compared to the same when the transition and weak phases are combined. On the other hand, the hindering effect of the convectively suppressed phase of the MJO seen via the broad negative GPI anomalies is more robust since very few MOVs form during this phase.

Returning to our hypothesis outlined in the introduction, we find that the convectively active phase of the MJO is not necessarily favorable for MOV formation. On the other hand, the convectively suppressed phase of the MJO inhibits MOV formation more robustly. The results suggest that local monsoon dynamics over the Arabian Sea likely play a significant role. Possible factors include the Arabian Sea mini-warm pool (Vinayachandran et al., 2007; Shenoi et al., 1999) or the strength and positioning of the Somali Jet. For instance, Deepa et al. (2007) observed that the MOV formed in 2001 when the shear zone at 850 hPa developed north of the Somali jet over the mini-warm pool, while this factor was absent in non-MOV years. However, this finding was based on a limited sample size of years (2000–2006).

These results raise several other questions, such as whether the MOV is a result of convective aggregation in the northward shifting convergence zone over the Arabian

Sea, whether the timing of the monsoon onset relative to its climatological onset date determines the probability of its formation, and why the MOV does not form in certain years. The observed non-linear response of the MOV towards the MJO phases may inform the predictability of MOV. If the forecasts indicate a convectively suppressed MJO over the Arabian Sea during the monsoon onset phase, the likelihood of MOV formation during that period could potentially be very low. Additional work is needed to account for the formation and dynamics of the MOV.

5 Conclusion

In this study, we investigated the role of the MJO in the formation of the MOV over the Arabian Sea during the monsoon onset phase. The novel aspect of this study is that it is an initial step towards understanding the importance of large-scale processes in the MOV formation, which itself is a unique subset of cyclonic disturbances in the tropics. We infer that a convectively active MJO is neither a necessary nor a sufficient condition for MOV formation. On the other hand, the convectively suppressed MJO phase inhibits MOV formation more robustly. We speculate that during the monsoon onset, the Arabian Sea is in a close (but favorable) critical state that is conducive for MOV formation. Thus the inhibitory effect of the convectively suppressed MJO phase is more effective than the favorable effect of the convectively active MJO phase. Additional work is needed to better understand the mechanism of MOV formation.

324 ## 6 Figures

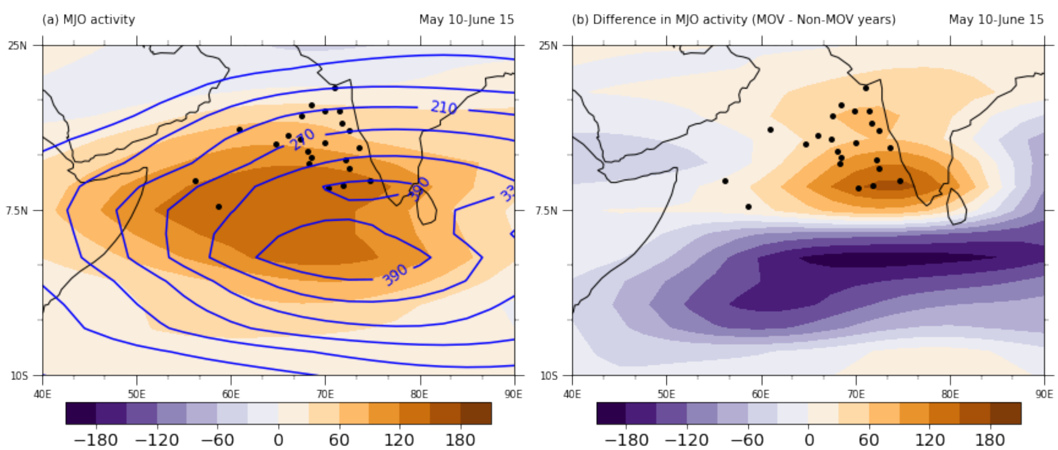

Figure 1. (a) MJO filtered OLR variance (contours) during May 10–June 15, the difference in the MJO filtered OLR variance between May 10–June 15 and May 1–September 30 (shaded), (b) Difference in the MJO filtered OLR variance between the MOV and non-MOV years. Black dots denote the locations of MOVs since 1982.

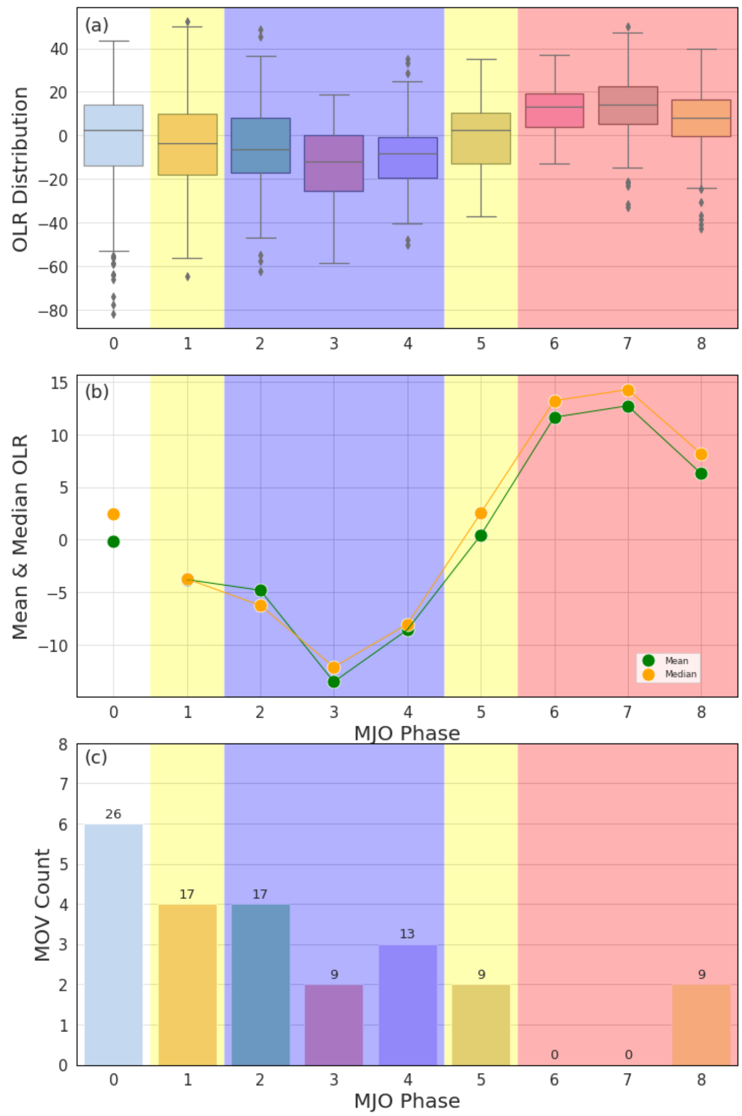

Figure 2. (a) Box and whisker plots of OLR anomaly composites averaged over the Arabian Sea during May 10–June 15 for different MJO phases. The box encloses the middle 50% of the distribution. The horizontal line in the box denotes the median of OLR anomaly while the whiskers extend to 1.5 times the interquartile range, (b) The mean and median of OLR anomaly composites for different MJO phases, and (c) A histogram denoting the distribution of MOVs across different MJO phases. The numbers on top of the bars denote the percentage of total MOVs (rounded up to the nearest integer) for the respective MJO phases. The phases shaded in blue, red, and yellow denote the convectively active (2–4), convectively suppressed (6–8), and transitional (1,5) MJO phases respectively for the Arabian Sea during May 10–June 15.

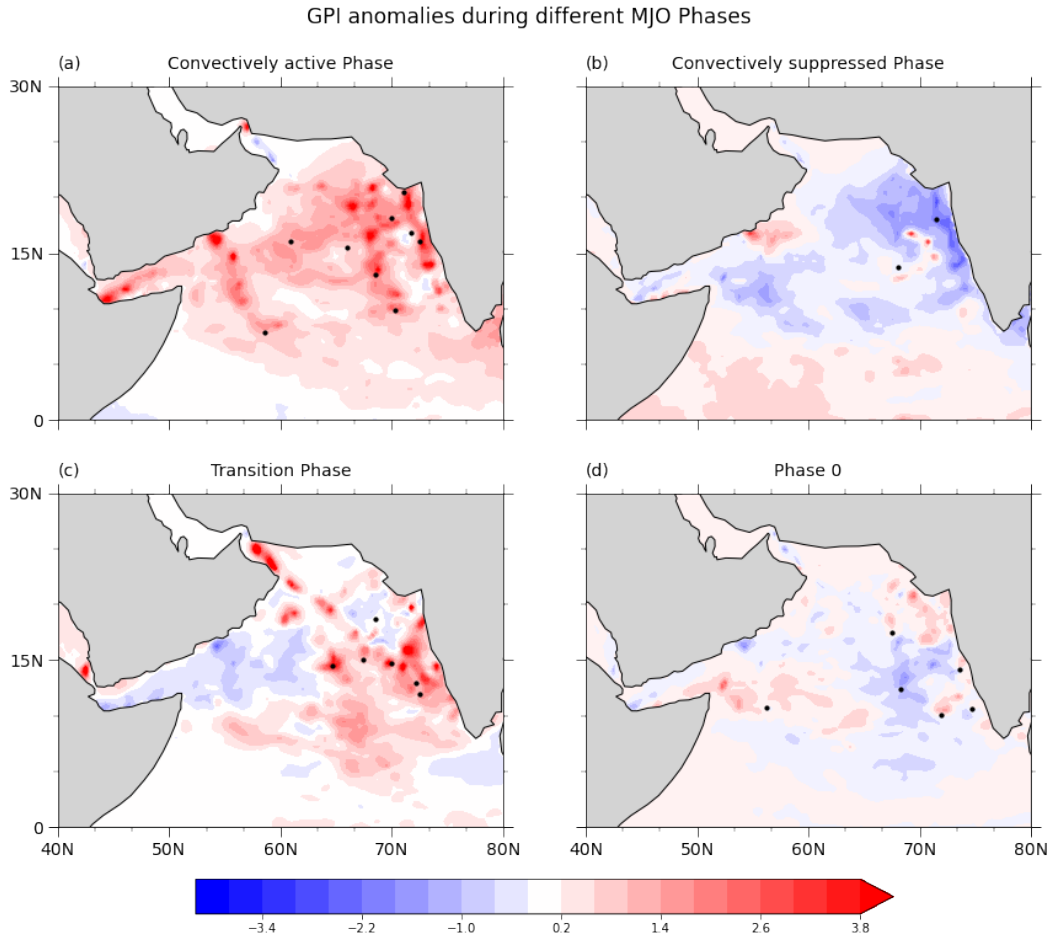

Figure 3. GPI anomalies during different MJO Phases. The black dots denote the locations of MOVs since 1982.

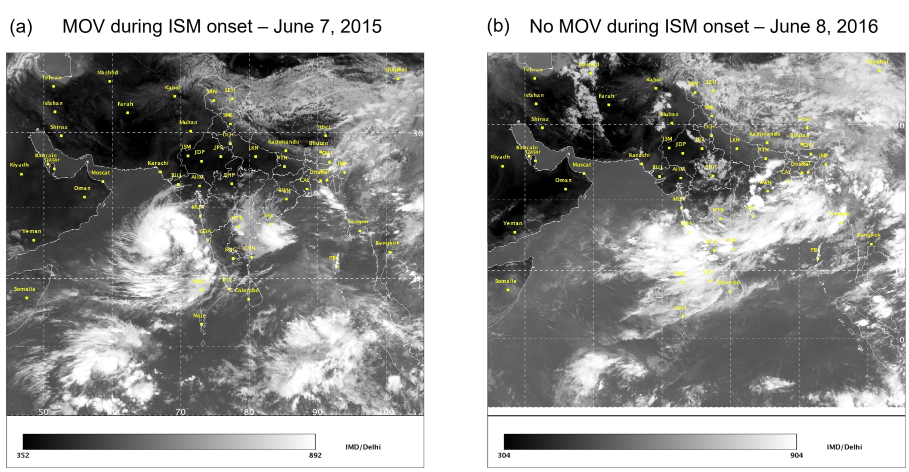

Figure 4. Infrared images from INSAT 3D (credits: India Meteorological Department)

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7 Open Research

7.1 Data Availability Statement

The data of daily MJO phase can be found at `http://www.bom.gov.au/climate/mjo/`. ERA5 reanalysis data can be found at `https://climate.copernicus.eu/climate-reanalysis`. The Joint Typhoon Warning Center Best Track Data for north Indian Ocean can be found at `https://www.metoc.navy.mil/jtwc/jtwc.html?north-indian-ocean`. The India Meteorological Department's Best Track Data for tropical cyclones and tropical depressions can be accessed at `https://rsmcnewdelhi.imd.gov.in/report.php?internal_menu=MzM=`

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Figure 1.

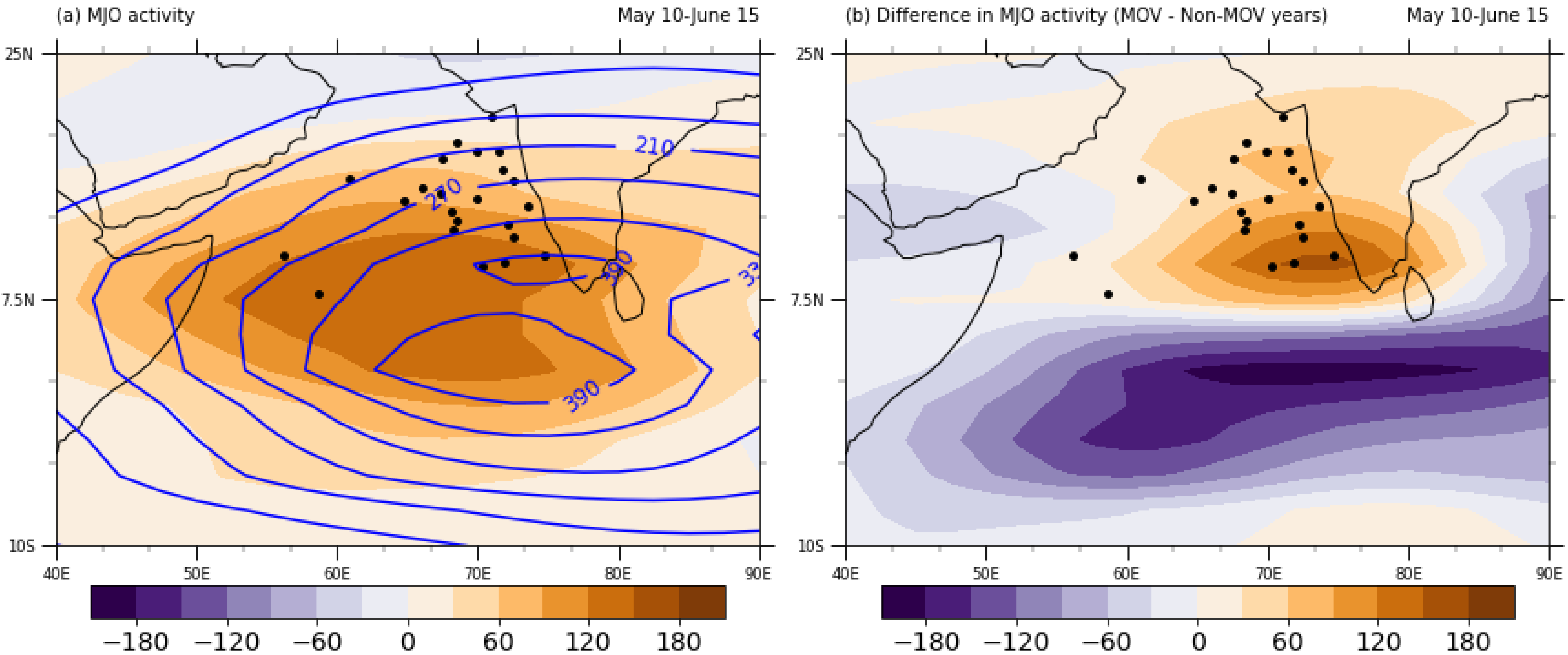
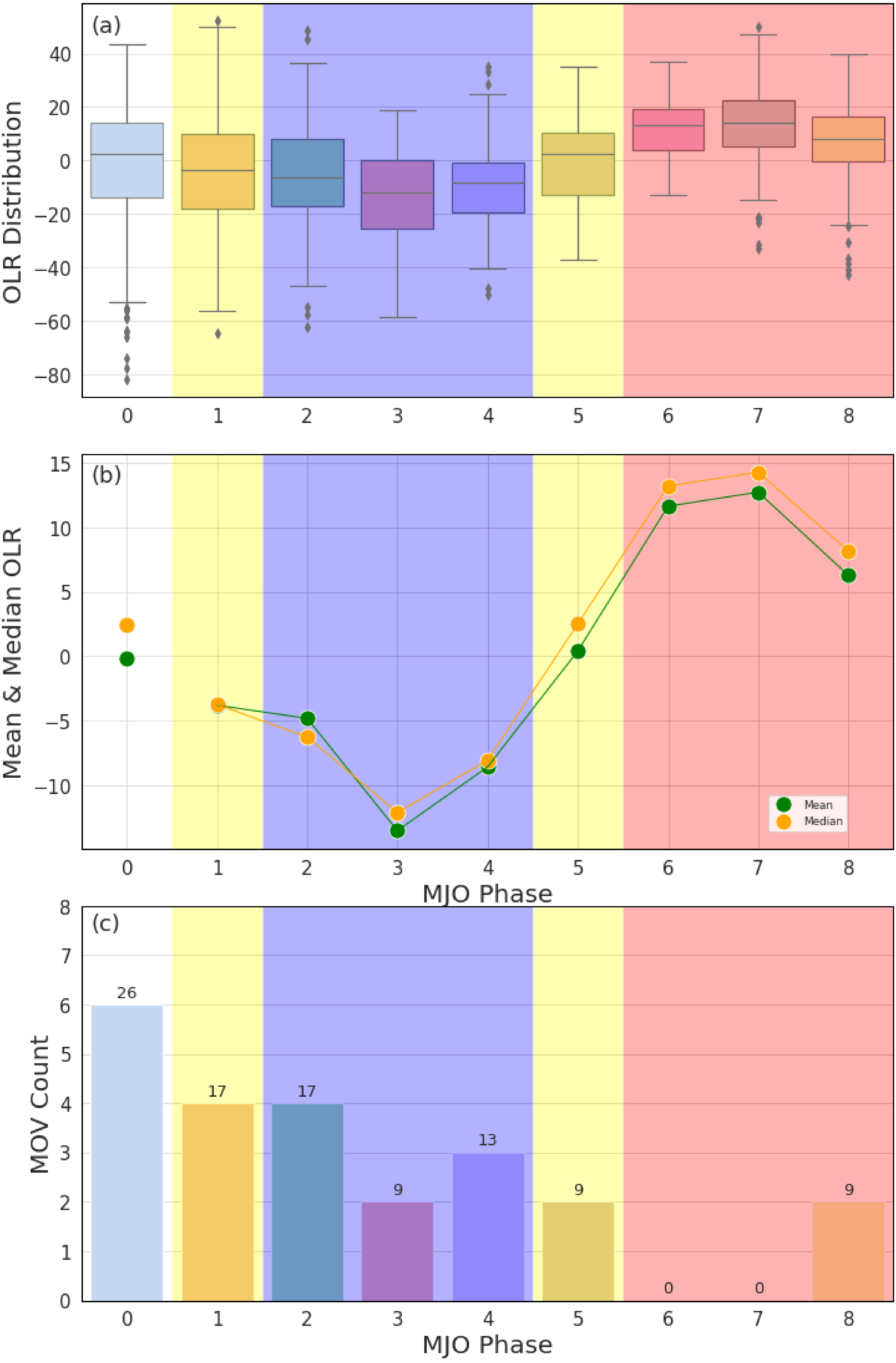
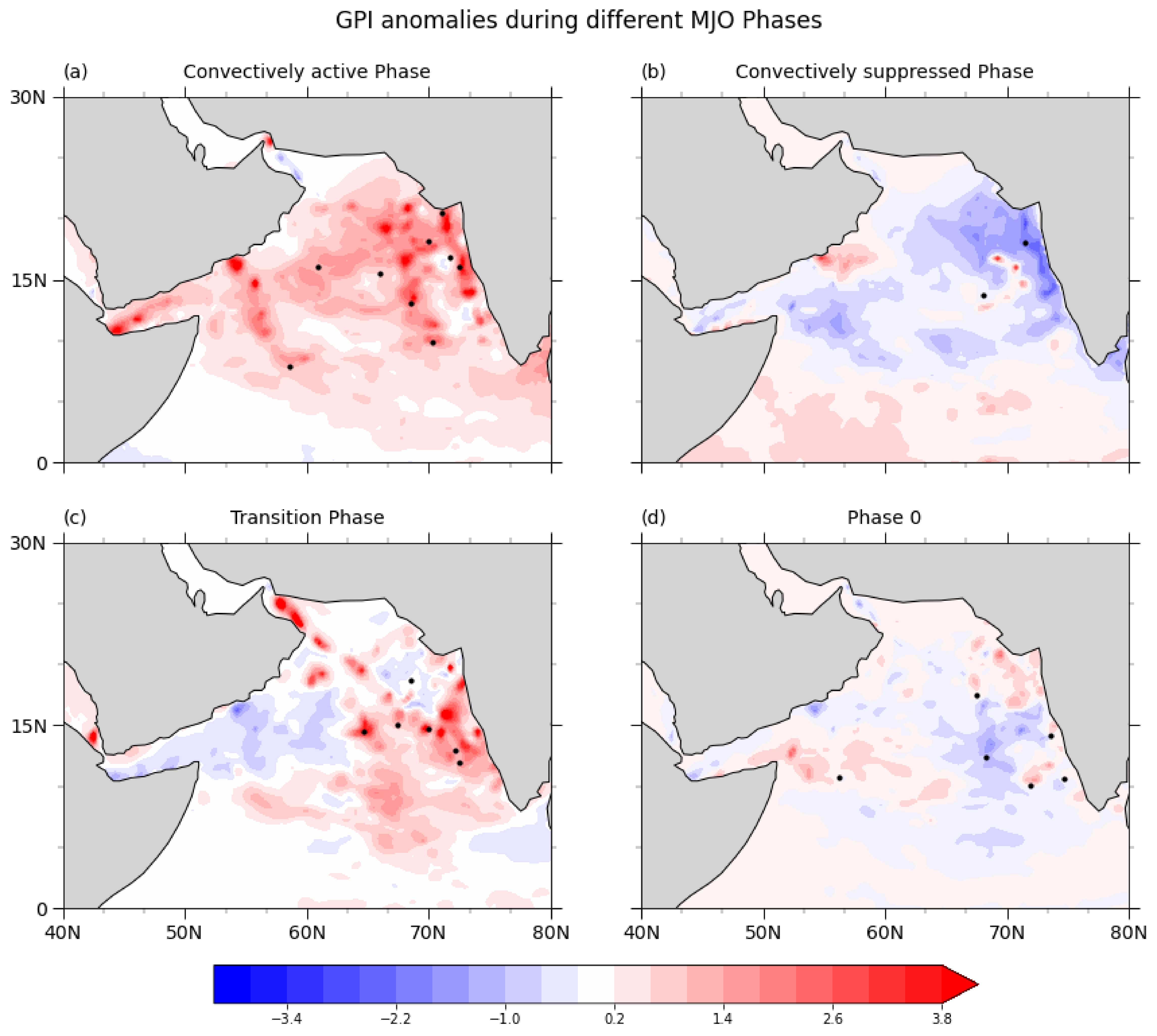

(a) MJO activity
May 10-June 15
210
270
390
390
25N
7.5N
10S
40E
50E
60E
70E
80E
90E
−180
−120
−60
0
60
120
180
(b) Difference in MJO activity (MOV - Non-MOV years)
May 10-June 15
25N
7.5N
10S
40E
50E
60E
70E
80E
90E
−180
−120
−60
0
60
120
180

Figure 2.



(a)
OLR Distribution
40
20
0
−20
−40
−60
−80
0 1 2 3 4 5 6 7 8
(b)
Mean & Median OLR
15
10
5
0
−5
−10
Mean
Median
0 1 2 3 4 5 6 7 8
MJO Phase
(c)
MOV Count
8
7
6
5
4
3
2
1
0
26
17
17
9
13
9
0
0
9
0 1 2 3 4 5 6 7 8
MJO Phase

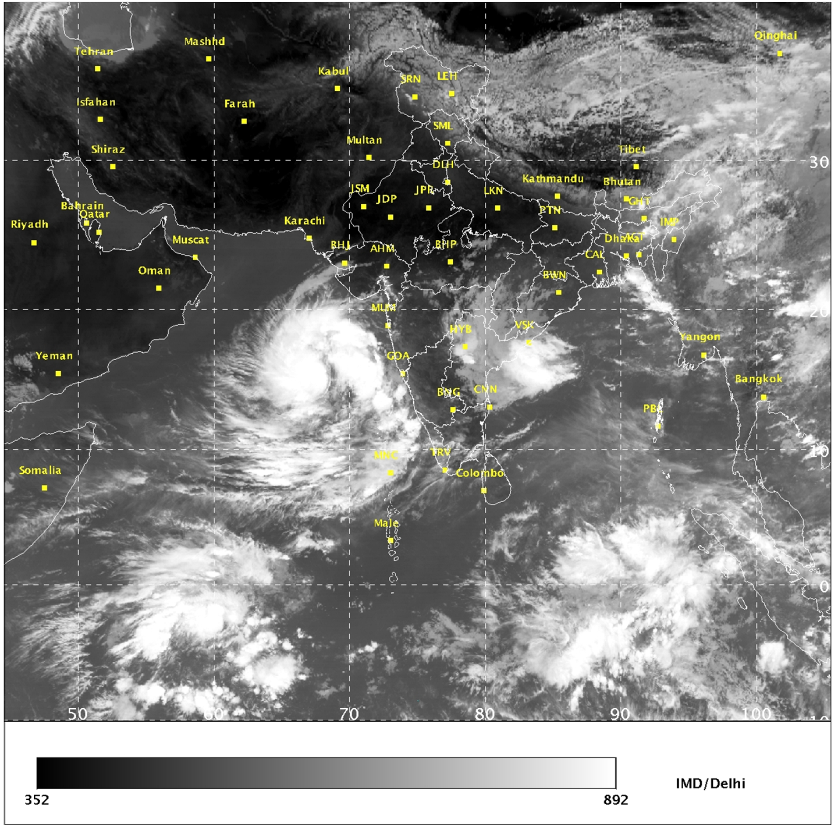
Figure 3.



GPI anomalies during different MJO Phases
(a)
Convectively active Phase
(b)
Convectively suppressed Phase
(c)
Transition Phase
(d)
Phase 0
30N
15N
0
40N
50N
60N
70N
80N
−3.4
−2.2
−1.0
0.2
1.4
2.6
3.8

Figure 4.

(a) MOV during ISM onset – June 7, 2015



(b) No MOV during ISM onset – June 8, 2016