Interannual variability of the occurrence of MJO at different phases and its association with two ENSO modes

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Abstract

In the present study, we investigate the interannual variability of the occurrence of the Madden Julian Oscillation (MJO) at different Real-time Multivariate MJO (RMM) phase regions (MJO frequency) and its association with the El Niño Southern Oscillation (ENSO). Evaluating the all-season data, we identify the dominant zonal patterns of MJO frequency exhibiting prominent interannual variability. Using Principal Component Analysis Biplot (PCA Biplot) technique, we demonstrate that the MJO frequency has two distinct modes of variability related to RMM1 and RMM2 spatial patterns. The first spatial mode of MJO frequency related to RMM1 is associated with a higher frequency of MJO active days over the Maritime Continent and a lower frequency over the central Pacific Ocean and the western Indian Ocean, or vice versa. The second mode related to RMM2 is associated with a higher frequency of MJO active days over the eastern Indian Ocean and a lower frequency over the western Pacific, or vice versa. We find that these two types of MJO frequency patterns are associated with the central Pacific and eastern Pacific ENSO modes, respectively. These MJO frequency patterns are the lag response of the underlying ocean state.

Introduction

The Madden Julian Oscillation (MJO) and El Niño Southern Oscillation (ENSO) are the two strongest modes in intraseasonal and interannual time scales, and hence of immense importance to the global climate variability. The MJO is evident by the slow eastward propagating tropical convective branch which usually originates over the western Indian Ocean and dies out over the cold sea surface temperature (SST) beyond the dateline. Based on outgoing longwave radiation (OLR) and zonal wind at 850 hPa and 200 hPa, Wheeler and Hendon derived a Real-time Multivariate MJO index (RMM) to track the dynamical and convective signal of the MJO. The eight phases of the RMM index represent the location of active convection of MJO over the tropics. RMM index has been extensively used to explore the role of the MJO in various weather and climate phenomena.

Importantly, the MJO possesses profound seasonal characteristics. MJO is strongest during boreal winter and spring (December-January-February and March-April-May) and weakest during boreal summer and autumn (June-July-August and September-October-November). The number of MJO events also varies according to seasons. Location of the MJO signal shifts southward and northward in boreal winter and summer, respectively.
Despite belonging to widely separated time scales, the MJO and ENSO have profound similarities in large scale convection and circulation patterns. These similarities have led to extensive studies on the connection between the MJO and ENSO in the past few decades\textsuperscript{10-12}. These studies suggest that the overall MJO amplitude or strength of the MJO convection is not appreciably affected by the presence of an El Niño or a La Niña. They suggest that the mature El Niño or La Niña phase only expands the region of MJO activity further eastward or westward\textsuperscript{13}. The inter-annual variation of MJO is therefore observed along the boundaries of the intra-seasonal variability center. Besides this simultaneous connection between the MJO and ENSO, Hendon et al.\textsuperscript{14} observed a lag relationship between the MJO activity in spring (March-April-May) and the state of ENSO in subsequent winter (December-January-February). This explains the role of MJO in the initiation of ENSO events. Pang et al.\textsuperscript{15} examined the effects of two types of ENSO, i.e., canonical and central Pacific warm-cold events on boreal winter MJO. They observed that the MJO strength is generally weaker during the canonical warm period and stronger during the canonical cold period. The case is opposite for central Pacific ENSO events where the MJO strength is generally stronger during warm phases and is weaker during central Pacific cold phases. Overall, these studies are mainly focused on the interannual variation of the strength of MJO convection or the amplitude. Similar to the MJO amplitude, the number of MJO active days (frequency of occurrence) also undergoes through interannual variations which has different characteristics than of the MJO intensity\textsuperscript{16}. The frequency of occurrence in different phase locations in a season is also affected by the two ENSO types\textsuperscript{15}. For example, the frequency of occurrence in phase 2,3 and 4 increases during eastern Pacific and central Pacific El Niño warm phases respectively.

ENSO is known to have global impacts during its extreme phases. The dynamical interaction between tropics and extra-tropics are believed to be the major reason behind the large-scale ENSO-teleconnection pattern. Similar to ENSO, the MJO also has large scale teleconnections in its certain phases (mainly in phase 3 and 7) of its propagation\textsuperscript{13}. Recent studies suggest that the seasonal MJO activity over the Indian Ocean and western Pacific can influence North Atlantic Oscillation (NAO), Pacific North America pattern (PNA) and Atlantic Meridional Oscillation (AMO) through teleconnections\textsuperscript{17}. Seasonal MJO activity, therefore, is an important factor to be understood properly to comprehend the MJO teleconnections.

In most of the earlier studies, the inter-annual variability of MJO and its relation to ENSO were mainly investigated by examining any particular season i.e. boreal winter, spring or summer\textsuperscript{17,18}. ENSO evolution, however, starts from boreal autumn (September-October-November), matures during boreal winter (December-January-February) and decays during the subsequent boreal spring. Therefore, it is important to examine interannual variability of MJO and its relation to ENSO considering all the seasons. Secondly, previous studies majorly focused on the intensity of MJO (variance in intra-seasonal OLR) for
studying the inter-annual variability of the MJO. However, recent studies\textsuperscript{16,19–21} demonstrate that interannual variability of the MJO is more evident in the variation in the number of days MJO convection spent over the certain region (i.e. the frequency of occurrences of MJO phases) rather than its amplitude. The signature of MJO phase occurrence in a season is evident through the seasonal mean convective activity over the respective phase regions. In the present study, we examined the inter-annual variability of the MJO in terms of the frequency of occurrence of the MJO phases, where we consider MJO activity in all four conventional seasons. The major goal of the present study is to find dominant spatial modes of MJO variability. We have employed multivariate Principal Component Analysis (PCA) and PCA Biplot to visualize and interpret our results. Biplot technique to visualize the PCA result is not very common in meteorology. We have tried to implement this method for examining the inter-annual variability of MJO frequency.

**Results**

**Dominant Modes of interannual variability of MJO Frequency anomaly**

Eight phase locations of MJO depict the different sections of the tropics through which the MJO propagates. Phase regions 1 to 3 represent west to central tropical Indian Ocean. Phase regions 4 and 5 depict the eastern Indian Ocean and Maritime Continent. Phases 6 to 8 represent west to central tropical Pacific region.

MJO frequency anomalies at the eight MJO phase locations in a season explain the spatial variation of MJO activity. In this study, we tried to identify the coherent MJO phase locations which undergo a similar interannual variation of MJO. We call this coherent MJO frequency variations in different phase locations as the spatial modes of MJO frequency variation. We identified these spatial modes by employing EOF analysis on MJO frequency anomaly data (Fig. 1a).

Fig. 1b represents the percentage of variance explained by the eight EOFs of MJO frequency anomaly. It is important to note that the first two EOFs explain almost half (48%) of the total variance in MJO frequency anomaly. EOF1 and EOF2 explain about 25.7% and 22.2% of the total variance. The remaining EOFs explain the rest of the variability with nearly equal contributions. The first two EOFs are significantly separated from each other and rest of the EOFs according to North et al.\textsuperscript{22} criteria. The spatial pattern of the first two EOFs is represented in Fig. 1c,d. We find that these structures of the first two EOFs do not change appreciably over time (Supplementary Fig. 3).

EOF1 represents an out of phase pattern of MJO frequency anomaly between the phase regions 1, 2, 8 and 4, 5, 6 (Fig. 1c). This means that a positive MJO frequency anomaly at phase regions 1, 2, and 8 (west to central Indian Ocean) coincide with negative (opposite) MJO frequency anomaly in phase regions 4, 5 and 6 (eastern Indian Ocean to the Maritime Continent to the western Pacific). The MJO frequency anomaly variations at phase 3 (central Indian Ocean) and 7 regions (west-central Pacific) are less in this variation.
pattern. Phase 1 (western Indian Ocean) and 5 (Maritime Continent) MJO frequency variations are most dominant in EOF1. The structure of EOF1 pattern is similar to RMM1 spatial pattern (Fig. 1c). The second EOF also denotes a similar out-of-phase relationship of MJO frequency anomaly between phase regions 2, 3, 4 (central to east Indian Ocean) and 6, 7, 8 (west to central Pacific) (Fig. 1d). In the second EOF structure, MJO frequency anomaly is small over phase regions 1, 5 (western Indian Ocean and Maritime Continent) and are mostly in phase regions 3, 7 (central Indian Ocean and western Pacific). The structure of EOF2 pattern is similar to RMM2 spatial pattern.

MJO frequency variation (interannual variation) at the eight phase locations and their inter-relationship, can be visualized in terms of the two leading EOFs forming a two-dimensional plane through the biplot technique (Fig. 1e,f). We discussed the details of biplot in the method section. MJO frequency anomaly variation at the eight phase locations are represented by the eight arrows in the biplot. Precisely, the length of an arrow represents the variance of MJO frequency at a certain phase location explained by the two leading EOFs (Fig. 1e). An arrow’s direction depends on the correlation of MJO frequency variation at a location with two EOF time series. It tells the extent to which the frequency variation in a certain phase is closely related to either of the spatial modes. As we can see, MJO frequency variation at phase locations 1 and 5 are closely related to EOF1 spatial modes. Similarly, MJO frequency variation at phase regions 3 and 7 are related to EOF2 spatial modes. The MJO frequency variations at these phase locations provide maximum variance to the MJO frequency spatial modes.

The arrows which group together by having the same direction in the two-dimensional plane, represent the positively correlated MJO phase locations having similar MJO frequency variations. The cosine of the angle between two arrows denotes the correlation among MJO frequency variations in the corresponding two-phase locations. From Fig. 1e,f, we observe that the MJO frequency variations at phase locations 1, 2, 7 and 8 are negatively correlated with the variation at phases 5, 6, 3 and 4 respectively (as it also seen in Fig. 1c,d). This in-between relationship among MJO frequency variations at eight phase regions can be also observed in the quadrants of the RMM phase diagram. This means that a positive MJO frequency anomaly in a particular phase region is also associated with the negative MJO frequency anomaly at the opposite phase quadrant in RMM phase diagram.

We obtained correlation coefficients and cosine square, two statistical quantities, to quantify the goodness of representation of the MJO frequency variation through the leading EOFs. The cosine square parameter represents the percentage of the variance of MJO frequency over a location expressed through a certain EOF (Fig. 1e). The sum of cosine square values for all the EOFs is equal to 1. We also measured the correlation coefficient between MJO frequency time series at eight phase locations and the EOF time series to obtain the goodness of representation of MJO frequency data by the two leading EOFs. In Table 1 the correlation coefficient and cosine square values are represented. The significant correlation value for
156 data points at 99% confidence level is 0.21. Considering the cosine square and correlation coefficient, we observed that EOF1 well represents the MJO frequency variation at phase locations 1, 2, 5, and 6 (where correlation values exceeds 0.5). Similarly, EOF2 represents the MJO frequency variation in phase 3, 4, 7 and 8 (Table 1). From correlation coefficients and cosine square values, it becomes reasonable to study the MJO frequency variations in terms of these two spatial EOF modes. MJO frequency in terms of two leading EOF modes also is a dimension reduced form (8 dimensions to 2 dimensions) of MJO frequency anomaly data which is easier to be analyzed than higher dimensional data.

**Frequency modes and its relation with seasonal mean SST anomaly, intraseasonal OLR and precipitation**

To examine the effect of the MJO frequency modes in terms of intraseasonal convection (OLR), we calculated the correlation between seasonal mean filtered OLR (20-100 days filtered) and PC1 and PC2 of MJO frequency. (Fig. 2 a,b). MJO frequency anomaly represents the change in the number of MJO convective days. A change in the number of convective days is generally expected to be evident in seasonal mean OLR rather than the variance of the OLR in a season. The variance of filtered OLR refers to the strength or amplitude of MJO convection whereas a negative mean of filtered OLR expresses the fact that significant part of the signal represented the negative OLR anomaly leading to a higher number of convective days. The filtered OLR patterns correlated with EOF1 and EOF2 is presented in Fig. 2a,b. We obtained the correlated MJO precipitation (space-time filtered) anomaly associated with PC1 and PC2 in Fig. 2c,d. The correlated filtered OLR and precipitation pattern for EOF1 (Fig. 2a,c) shows wet western Indian Ocean and central-east Pacific, when the Maritime Continent and western Pacific regions are dry, and vice versa. The correlated filtered OLR and precipitation pattern for the second mode denotes the wet eastern Indian Ocean when the western Pacific is dry and vice versa (Fig. 2b,d).

To examine the mean state of the tropical ocean associated with the MJO frequency modes, we obtained the correlated seasonal mean SST anomalies of EOF1 and EOF2 time series (Fig. 2e,f). We observed that the first MJO frequency mode (EOF1) is apparently related to central Pacific warm event structure or El Niño Modoki structure (Fig. 2e, Ashok et al.23). The correlation between PC1 (2-8 years filtered) and CP ENSO index is significant at 95% confidence level with a correlation value 0.24 (Fig. 2g; here spatial pattern is related to unfiltered PC1). The associated SST pattern with the second MJO frequency mode (EOF2) shows an EP-type canonical ENSO pattern. The correlation between PC2 (2-8 years filtered) and EP ENSO index is significant at 95% confidence level with correlation value 0.47 (Fig. 2h; here spatial pattern is related to unfiltered PC2). We further examined the lead-lag correlation between PC1 (2-8 years filtered) and CP ENSO index, where we found that the CP ENSO index leads PC1 MJO frequency pattern by one season (3 months) with peak correlation value 0.27. At lag 0 the correlation is approximately 0.24.
From the lead-lag relationship between PC2 time series (2-8 years bandpass filtered) and EP ENSO index, we found that the EP ENSO index leads PC2 timeseries by one season with peak correlation value 0.52 (Fig. 3). At lag 0 the correlation is approximately 0.47 (Fig. 3). Apparently, these MJO frequency patterns fully establish in response to the underlying ocean condition at a 3 months lag. The reason for the weak correlation between PC1 (2-8 years filtered) and CP ENSO index may be due to the sample size in our present study. ENSO is a 2-8 years event and the number of ENSO events during 1979-2018 are few. Generally, the SST variability in the central Pacific is not as large as in the east Pacific, which may also have a bearing on the correlation. The time series of PC1 (2-8 years filtered), CP ENSO index and PC2, EP ENSO index are represented in Fig. 2g,h. These time series plots show significant associations between two MJO frequency modes and two ENSO types.

Since a correlation analysis may not clearly represent the relationship between MJO frequency modes and two ENSO types, we have done composite analysis for CP-type and EP-type El Niño/La Niña years in the next section.

**Composites of MJO frequency during canonical and Central Pacific warm and cold events**

The association between two types of ENSO modes and MJO frequency modes are further examined through a composite analysis. Composites of MJO frequency anomaly during EP-type canonical warm/cold and central Pacific warm/cold seasons are prepared. If the modes are associated with two respective types of ENSO, then composites of frequency anomaly during these ENSO phases should match with the EOF MJO frequency patterns. We observed the MJO frequency composites during warm and cold CP-type ENSO phases and their composite differences resemble EOF1 MJO frequency pattern (Fig. 4a,c,e). Similarly, MJO frequency composites during warm and cold EP-type canonical ENSO events and their differences resemble EOF2 MJO frequency pattern (Fig. 4b,d,f). These composites reveal a possible association between two frequency modes and two types of ENSO events.

**MJO frequency variation through biplot and clusters**

The relation between MJO frequency and ENSO phases are explored from a different perspective using the biplot technique. We represent 156 season’s MJO frequency data in a two-dimensional plane where MJO frequency EOFs are the axes (Fig. 4g,h). In the biplot diagram, MJO frequency in a particular season is represented by a point where its location is estimated by the standardized amplitude of EOF time series. The points in a biplot basically represent a scatterplot in two dimensional EOF plane. MJO frequency points which make a cluster in the biplot space have similar projections on two EOF modes which denotes the fact that seasons had similar MJO frequency anomalies. Distance between two points in biplot space is called Mahalanobis distance$^{24}$, indicating the statistical similarity between the points representing MJO events.
From 1979 to 2018, all seasons are divided into three classes according to CP and EP ENSO index (Supplementary Fig. 1) representing the warm, cold and neutral central Pacific CP-type and canonical EP-type ENSO phases. The points representing a particular class is enclosed by the data ellipse which explains the overall statistics of the points (Fig. 4g,h) in the biplot space. The joint distributions of standardized principal components i.e. PC1 and PC2 for three classes are also represented in Fig. 4g,h. The mean, standard deviation and correlation of PC1 and PC2 for different classes are represented in Table2.

In Fig. 4g, data ellipses represent warm, cold and neutral CP-type ENSO phases. It is observed from the Fig. 4g that from cold to warm CP-type ENSO phases, the center (mean state) of the data ellipse shifts from negative to positive EOF1 axis. This fact is also evident from the probability distribution of EOF1 amplitude during positive, negative and neutral CP-type ENSO phases. It can be seen that the mean of distribution shift from negative EOF1 axis to positive EOF1 axis. This means that positive MJO frequency anomalies are seen at MJO phase regions 1, 2 and 8 (the western Indian Ocean and central Pacific) and negative MJO frequency anomalies are seen at phase regions 5 and 6 (Maritime continent) during warm central Pacific ENSO phases. This MJO frequency anomaly pattern gets reversed during the negative phase of central Pacific ENSO.

Similar to CP-type ENSO phases, three clusters of EP-type ENSO phases are presented in Fig. 4h. In contrast to the case of CP-type ENSO phases, the center of the data ellipse shift from negative EOF2 axis to positive EOF2 axis during canonical EP-type ENSO negative to a positive phase. The shifts in data ellipses centers are associated with the mean MJO frequency pattern changes during cold to warm EP-type ENSO phases. In the case of EP-type ENSO phases, overall MJO frequency changes following the EOF2 axis. This means that positive MJO frequency anomalies are seen at MJO phase regions 3 and 4 (central-east Indian Ocean) and negative MJO frequency anomalies are seen at phase regions 6 and 7 (west to central Pacific) during warm canonical ENSO period. This MJO frequency anomaly pattern gets reversed during the negative EP-type ENSO period. The warm and cold EP-type ENSO data ellipse has directions along with MJO phases 4, 8 and MJO phases 2, 6, respectively. This means that during the canonical warm period, MJO frequencies in phase regions 4 and 8 have the highest variability. Either of the phase region 4 (eastern Indian Ocean) or phase region 8 (central Pacific) may have large MJO frequency anomaly. Similarly, during the canonical La Niña, either of the phase region 2 (central Indian Ocean) or phase region 6 (western Pacific) may have large MJO frequency anomaly.

Therefore, the shift of an ellipse center from cold to warm phases of ENSO modes indicates the basic state change of MJO frequency pattern. These basic state changes in the MJO frequency pattern associated with the ENSO modes are the possible reasons behind the observed correlation between MJO frequency EOFs and two type ENSO indices. It is important to note that time series of two modes of MJO
variability follows normal distribution at a 99% confidence level as evident in D’Agostino and Pearson’s test.

Composite differences between central Pacific and eastern Pacific warm and cold events

The composite differences of SST, filtered OLR, space-time filtered precipitation, vertically integrated MSE, MSE tendency, zonally averaged circulation and specific humidity between the warm and cold phases of the CP-type ENSO are represented in Fig. 5a,c,e,g,l,k. Similarly, composite differences for EP-type ENSO are represented in Fig. 5b,d,f,h,j,l. We derived the composite differences of different parameters between the warm and cold phases of ENSO to investigate the reason for basic state shift of MJO activity following the MJO frequency EOF patterns.

For the CP-type ENSO, the composite differences between warm and cold phases indicate the enhanced intraseasonal precipitation at the western Indian Ocean and central Pacific (RMM phase 1,2 and 8) and suppressed intraseasonal precipitation over the maritime continent (RMM phase 5 and 6) which is similar with the MJO frequency EOF1 pattern (Fig. 5a,c,e). The outcome from the biplot of CP-type ENSO phases also suggest the mean state change following the MJO frequency EOF1 pattern. For the EP-type ENSO, the composite differences between warm and cold phases show the enhanced intraseasonal rainfall near eastern equatorial Indian Ocean and maritime Continent and suppressed intraseasonal rainfall over west-central Pacific Ocean. This is also consistent with the MJO frequency EOF2 pattern and biplot outcome for EP-type ENSO phases (Fig. 5b,d,f).

To investigate the reason for the particular MJO frequency anomaly patterns associated with the two types ENSO phases, we examined the composite differences of vertically integrated intraseasonal MSE anomalies, vertically integrated intraseasonal MSE tendencies, zonally averaged circulation and specific humidity profiles in Fig. 5g–l. For CP-type ENSO phases there are negative intraseasonal MSE anomalies over the maritime continent (RMM phases 5 and 6) and positive MSE anomalies over the west and central Indian Ocean (RMM phases 1and 3) and Central Pacific (RMM phase 8) (Fig. 5g). The negative tendency of intra-seasonal MSE is also observed over the maritime continent (the same region with negative MSE anomalies) decreasing the lifetime of MJO over the maritime continent. The positive MSE tendency is observed over the west-central Indian Ocean and central Pacific enhancing the MJO lifetime over these regions. We find that the mean zonal circulation favors the convection over the western Indian Ocean and the central Pacific Ocean and opposes convection over the Maritime Continent during the CP-type ENSO events (Fig. 5i). During these times, the main descending branch of the Walker circulation is situated over the eastern equatorial Indian Ocean and maritime continent centering at 120° E. The mean moisture distribution (specific humidity) over the maritime continent shows the negative anomalies centered at 120° E following the zonal circulation pattern (Fig. 5k). Therefore, the mean background moisture distribution
is a vital factor determining the intraseasonal MSE tendency. The intraseasonal MSE tendency term generally depends on the advection of mean background moisture by intraseasonal easterly winds. For the CP-type ENSO seasons, negative background moisture anomalies over the Maritime Continent creates negative intraseasonal MSE tendency which restricts the MJO propagation over these regions.

In the case of canonical EP-type ENSO phases, the main descending branch of the Walker circulation is situated over the maritime continent and western Pacific at the east of 120° E (Fig. 5j). The mean moisture distribution (specific humidity) over the maritime continent and west Pacific shows the negative anomalies at the east of 120° E following the zonal circulation pattern (Fig. 5l). Therefore, the intraseasonal MSE tendency term is negative over the maritime continent and west Pacific, restricting the MJO propagation over these regions (Fig. 5h). The intra-seasonal MSE tendency over the eastern Indian ocean is positive due to the moisture contribution from western pacific surface divergence. Vertically integrated intraseasonal MSE anomalies are positive over the central and eastern Indian Ocean and negative at the east of 120°E following the intra-seasonal MSE tendency pattern. Therefore, during the EP-type ENSO phases, positive intraseasonal precipitation anomalies are observed at central and eastern equatorial the Indian Ocean and negative intraseasonal precipitation anomalies are observed over the western and central Pacific.

**MJO propagation during the central Pacific and eastern Pacific warm and cold events**

We further investigated the propagation features of intraseasonal OLR during the warm and cold phases of CP-type and EP-type ENSO events. In Fig. 6, lag-longitude propagations of OLR during CP-type and EP-type warm (shaded anomalies) and cold phases (contoured anomalies) are represented. Here we calculated the lag-propagation of OLR with respect to the central Indian Ocean (80°E-90°E, 15°S-15°N). We also identified location (longitude) of maximum cross-correlation at each time lags. These locations roughly provide an idea about how much time MJO has spent at each of the longitudes. At times when the location of maximum correlation stays at same longitude for consecutive timesteps, it denotes that the MJO convection is spending a longer time over that particular longitude (more MJO frequency over that longitude). For the CP-type negative phases, we find that the MJO spends more time around 120°E (13 days) compared to CP-type positive phases (6 days). Similarly, for the EP-type negative phases, MJO spends more time over the maritime continent and western Pacific between 110°E-150°E (11 days) compared to EP-type positive phases (5 days). During the EP-type positive phases, MJO spends more time at central and eastern equatorial Indian ocean between the 80°E-100°E (16 days) compared to the EP-type negative phases (12 days). This representation approximately provides the differences in the MJO propagations between the warm and cold ENSO phases.
The relationship between the MJO and ENSO has been studied rigorously in the past few decades which comprehended many aspects of their connection. Interannual variability of the MJO can be quantified in terms of the frequency of occurrence of the MJO phases. Interannual variability of MJO frequency at the eight MJO phases (MJO frequency) represent the information on the spatial variability of the MJO. The MJO activity may vary over the warm pool region in a season. Barrier effect is one of the examples of this type of variation where the MJO do not propagate through the Maritime Continent and dissipate over the region. In that case, the number of MJO convective days over the eastern Indian Ocean becomes different from the Western Pacific Ocean due to the lack of MJO propagation beyond the Maritime Continent.

This idea of spatial asymmetry of the MJO activity and its interannual variability leads us to investigate the interannual variability of the MJO frequency over different phase regions. In the present study, we have used an EOF technique on the MJO frequency anomaly data for 156 seasons from 1979-2018. We have used the EOF technique to identify the spatially correlated MJO frequency variability pattern. From the EOF analysis, we find that there are two dominant spatial modes of MJO frequency anomaly present which have significant interannual variation (Fig. 1). These two spatial modes of the MJO frequency explain almost half of the interannual variability of MJO frequency. Interestingly, both of the leading EOFs of MJO frequency have out-of-phase dipole structure that indicates the spatially asymmetric nature of the variability of MJO frequency. The first EOF of the MJO frequency variation shows a reduced number of MJO active days over the maritime continent, with increased MJO active days over the central Pacific Ocean and western Indian Ocean, or vice versa. The second mode of the MJO phase frequency is associated with higher number of MJO active days over the eastern Indian Ocean when the MJO active days over the western Pacific is less than normal or vice versa. The EOFs and their explained variances suggest that interannual variability of MJO frequency is majorly contributed by these two asymmetric MJO frequency pattern. By knowing the amplitudes of the two MJO frequency EOFs in a season, we can assume the MJO frequency anomaly in that season. We regressed seasonal mean OLR on the two MJO frequency EOFs’ time series to observe the EOFs in terms of seasonal mean convection.

Now the question arises, what are the drivers of these two EOFs of MJO frequency? The drivers could be the tropical SST or large-scale circulations, or it could be due to the internal dynamics of the atmosphere. The role of tropical SST on these two modes is investigated further by observing the linear correlation between the time series of the EOF modes and seasonal average tropical SST conditions (Fig. 2). It is observed that the first EOF mode is significantly correlated to CP ENSO state (with correlation value 0.24 significant at 95% confidence level) whereas the second spatial mode is significantly correlated to canonical ENSO state (with correlation value 0.47 significant at 95% confidence level). Further the lead-
lag correlation analysis suggests that these two MJO frequency modes lags the underlying SST condition by one season. Since, the correlation values are not large, so it is not right to jump into the conclusion that the two ENSO modes are responsible for the two respective MJO frequency EOFs. We, therefore, conducted a composite analysis of MJO frequency anomaly during positive and negative phases of central Pacific and eastern Pacific ENSO seasons. A major association of the MJO frequency with these two types of ENSO modes should make the composites of MJO frequency anomaly look like the two MJO frequency EOF patterns. The composites of MJO frequency anomaly during the central Pacific and eastern Pacific ENSO seasons are similar to MJO frequency EOF1 and EOF2 respectively, suggesting that there is a significant relationship between the MJO frequency EOFs and ENSO modes.

Hence, we tried to understand the interannual variability of the MJO frequency in terms of the two leading EOFs of MJO frequency through the biplot technique (Fig. 1,3). Basically, this representation is the scatter plot in two-dimensional leading EOF plane. MJO frequency anomalies for each of the 156 seasons is represented as a position vector in two dimensional EOF plane. The combination of the MJO frequency modes represents the estimate of frequency anomaly in a particular season. We drew data ellipses enclosing the MJO frequency anomaly during central Pacific and canonical ENSO positive and negative states. We find that from the central Pacific cold to warm ENSO state, the mean MJO frequency pattern changes following the EOF1, which means that over phase 4, 5, 6 (Maritime Continent) region, the MJO frequency becomes less and over phase region 1, 7 and 8 (central Pacific and the western Indian Ocean) MJO frequency becomes more. From the canonical eastern Pacific cold to warm ENSO phases, MJO frequency anomaly changes following the EOF2 pattern which is associated with the increased MJO frequency in the phase regions 2, 3, 4 (central and east Indian ocean) and decreased frequency over phase regions 6, 7, 8 (west to the central Pacific Ocean). From a mathematical point of view, it can be stated that MJO frequency EOFs are observed in MJO frequency data due to the basic MJO frequency state change over the eight phase regions during the two types of ENSO.

We conducted the composite analyses of different atmospheric variables during CP and EP-type ENSO phases to identify the reason behind MJO frequency spatial patterns. We find that the mean Walker circulation changes during these two types of ENSO phases alter the mean moisture distribution over the equatorial region. The change in the moisture distribution impacts the intraseasonal moist static energy tendencies which restrict the MJO propagation over the different part of the warm pool introducing the zonal asymmetry in MJO propagation.

Previous studies on the interannual variability of MJO frequency were mostly confined to studying the MJO frequency during boreal or extended boreal winter seasons. On the contrary, the current study investigates the MJO frequency for all seasons and tries to identify dominant spatial patterns of MJO frequency which have prominent interannual variability. RMM index data for MJO is calculated from OLR
and zonal wind by removing the ENSO signal from the data. We show that the intrinsic influences of ENSO are still present in the RMM MJO frequency data that is separated from the ENSO signal.

Methods

ENSO seasons

We computed two type of ENSO indices during the period 1979 to 2018 from Niño 3 and Niño 4 indices following Sullivan et al.\textsuperscript{25}. Sullivan et al.\textsuperscript{25} derived EP and CP index from Niño 3 and Niño 4 indices using the following formulas,

\[ EP = \text{Niño3}_{normalized} - 0.5 * \text{Niño4}_{normalized} \]
\[ CP = \text{Niño4}_{normalized} - 0.5 * \text{Niño3}_{normalized} \]

We prepared a seasonal EP and CP time series from the monthly values for four separated seasons, i.e. boreal winter (December-January-February or DJF), boreal spring (March-April-May or MAM), boreal summer (June-July-August or JJA) and boreal autumn (September-October-November or SON). We chose these four seasons considering the evolution of El Niño. El Niño generally evolves from its initial stage during boreal summer (JJA) to its most active stage during boreal winter (DJF) and decays in following boreal spring (MAM). We identified the warm and cold EP-type ENSO seasons when the seasonal time series of the EP index crossed its positive and negative standard deviation values respectively (Supplementary Fig. 1). Thus from 1979 (DJF) to 2018 (SON), positive, negative and neutral EP-type ENSO seasons were identified. Similarly, as EP-type ENSO seasons, warm, cold and neutral phases of CP-type ENSO (El Niño Modoki) were identified based on CP index (Supplementary Fig. 1 and Supplementary Table 1). We identified two types of ENSO phases to examine their influence on MJO variability.

MJO Frequency

The interannual variability of the MJO is investigated in terms of the frequency of occurrence of the MJO phases in boreal winter by numerous studies\textsuperscript{18,19,26}. We have adopted the same definition for the frequency of occurrence of MJO phases as in the earlier studies. For convenience, we have abbreviated the term “frequency of occurrence of MJO phases” as MJO frequency in this study. MJO frequency represents the number of MJO active days (with RMM amplitude greater than 1.0) over any particular phase locations in a season. RMM amplitude greater than 1.0, conventionally represent the active MJO state\textsuperscript{20}. We calculate MJO frequency at eight RMM phase locations over the time period 1979 to 2018 for DJF, MAM, JJA and SON seasons. From December 1979 to November 2018, MJO frequencies in 156 seasons are considered in this study. For DJF, MAM, JJA and SON, the mean and standard deviation of MJO frequency over the eight phase locations are represented in the Supplementary Fig. 2, where we can see the seasonality in MJO frequency data.
Interannual variation of MJO Frequency

MJO frequency possesses seasonal characteristics which we discussed in the introduction section. We removed the seasonality from the MJO frequency data by standardizing each specific season’s data by that particular season’s climatology (e.g. MJO frequency in SON is standardized by SON climatology of MJO frequency) and thus we obtained normalized MJO frequency anomaly data at each phase location (Fig. 1a).

This normalized MJO frequency anomaly is independent to seasonal characteristics of MJO which are evident through more MJO frequencies in boreal winter and spring than in boreal summer and autumn. The MJO frequency anomaly, therefore, represents the interannual variability of MJO frequency excluding the seasonal cycle of the MJO.

The derived MJO frequency anomaly data is a multivariate dataset which has eight variables representing eight RMM phase regions (m=8) and 156 cases (n=156) representing 156 seasons (Fig. 1a). We performed multivariate Principal Component analysis (PCA) or Empirical Orthogonal Function analysis (EOF) on this data to explore linearly correlated phase regions having similar interannual MJO frequency variation. We obtain the spatial patterns of MJO frequency variation through PCA in terms of spatial EOFs.

We further use the biplot technique to represent the PCA result in the two-dimensional leading principal component plane. Biplot is not commonly used in the field of meteorology. We discussed the details of PCA and the biplot technique in the following section. Each season was represented in biplot plane according to scores (principal components) of the two EOFs. We further use the concept of data ellipse to enclose the ENSO season points and to describe the statistics of MJO frequency during the ENSO phases. The details of data ellipse are also described in the following section.

PCA

The basic idea of PCA is to rotate the reference axis of the variables towards the direction of maximum variability in the data. The leading eigenvectors (Empirical orthogonal Functions-EOFs or loadings or principal axis) point towards directions of maximum variability. Structure of the eigenvectors in terms of variables (EOFs) represents the linear relationship between the variables in the direction of maximum variability. The data represented only by dominant eigenvectors are the dimension reduced version of the data explaining a percentage of total variability. The eigenvalues denote the proportion of variance concerning total variance explained by corresponding eigenvectors. The criteria for degeneracy of eigenvalues are discussed by North et al., 22.
PCA Biplot

In two-dimensional space of two leading principal axes, we used the biplot technique to describe the covariance PCA result. The article Gabriel\textsuperscript{27} is the original foundation of the biplot technique. Jolliffe\textsuperscript{24} discussed the basic concepts of biplot. Using the biplot technique, Takahasi et al.\textsuperscript{28} described two types of ENSO events. Ivanov and Evtimov\textsuperscript{29} used the biplot method on northern hemispheric monthly temperature anomaly data and had explained different attributes of the technique.

Biplot is the most compressed geometrical representation of information from a data matrix, where the attempt is to represent both observation and variables in a two-dimensional space. Covariance biplot describes the covariance PCA outcome in two leading principal component space. Two-dimensional biplot retains first two eigenvectors to give an approximate representation of the data. We will discuss three main basic features of biplot which are its axes, arrows and points. Above mentioned studies explained the detailed theoretical development of these features. The two axes in biplot represent the first two principal axes (EOFs) normalized to unit length by corresponding eigenvalues or variances. The arrow vectors describe the variables in two principal axes space. The length of an arrow represents the standard deviation of the corresponding variable and cosine between two arrows represent the linear correlation between the variables. The position vectors or points denotes the case entry in the centered data matrix. The position vectors are the scoring values (Principal Components-PCs) corresponding to the first two eigenvectors having normalized unit variance. The Euclidean distance between two points denotes the ‘Mahalanobis distance’ between the cases. The ‘Mahalanobis distance’ explains the statistical similarity between the two events. Two cases are statistically similar when they are closer to each other. Therefore, the similar events having less ‘Mahalanobis distance’ form clusters in two-dimensional biplot. The limitations come in biplot when the number of variables is high, and difficulty arises to distinguish between variable vectors. However, biplot allows visual appraisal of the inherent structure of the data, its variance and covariance structures, clustering of the events, extremes and multivariate outliers.

Clusters and Data ellipse

To represent the clusters of events in biplot space we used the data or concentration ellipse\textsuperscript{30}. The data ellipse represents a visual summary of a scatter plot indicating the means, standard deviations, correlation, and the slope of the regression line for two variables\textsuperscript{31}. Friendly et al.\textsuperscript{31} discussed the role of ellipsoids in statistical data analysis and visualizations. For a bivariate normally distributed data $x = (x_1, x_2)$, probability density function $\phi(x)$ is given by

$$\phi(x) = \frac{1}{2\pi|\Sigma|^{-\frac{1}{2}}} \exp\{-\frac{1}{2}(x - \mu)\Sigma^{-1}(x - \mu)\}, \text{ where } \Sigma = (\sigma_{11} \sigma_{12} \sigma_{21} \sigma_{22})$$
Here $\Sigma$ is the covariance matrix of bivariate normal data $x$. The quadratic form in the exponent of the equation is a statistical distance measure, often referred to as Mahalanobis distance. Mahalanobis distance is the squared statistical distance of $x$ from $\mu$ accounting the fact that the variables may be correlated and have different variances. The quadratic form in the exponent follows the $\chi^2$ distribution with two degrees of freedom. Constant density contours of bivariate normally distributed data follow the equation of an ellipse with $e_c = (x - \mu)^\top \Sigma^{-1} (x - \mu) = c^2$, where $c$ is the size of the ellipse. The ellipse is generally referred to as data or concentration ellipse. The data ellipse encloses the points having squared Mahalanobis distance $D^2 \leq c^2 = \chi^2(\alpha)$. One standard deviation data ellipse encloses 68% of the data with $c^2 = \chi^2(\alpha = 0.32) = 2.28$. Where 95% data ellipse has $c^2 = \chi^2(\alpha = 0.05) = 5.99$. The axes of the ellipse are in the direction of the eigenvectors of the covariance matrix $\Sigma$ and the length of the axes are proportional to $\sqrt{\lambda_1}$ and $\sqrt{\lambda_2}$. The orientation of the semi-major axis ($\lambda_1$) of an ellipse with the reference axes depicts the positive or negative correlation between the two normally distributed variables. The area of the data ellipse containing the central $(1 - \alpha) \times 100\%$ of a bivariate normal data is $\pi c^2 \sqrt{\sigma_{11} \sigma_{22} (1 - \rho^2)}$. The eccentricity of a data ellipse is high ($\lambda_1 > \lambda_2$) when there is a large variance in one variable ($\sigma_{11} > \sigma_{22}$ or opposite) or significant covariance existed ($\sigma_{12}$) between two variables. A low eccentricity indicates similar variances ($\sigma_{11} \approx \sigma_{22}$) and less covariance (independent variables with $\sigma_{12} \approx 0$) among the variables. For PCA, biplot and data ellipse, we have used two R library, “FactoMineR” and “factoextra”.

**Intraseasonal parameters**

We applied a 20-100 days band-pass filter on daily OLR (a proxy of convection) to extract the intraseasonal signal of OLR. We compute the seasonal mean of the filtered OLR anomaly for DJF, MAM, JJA, SON seasons from 1979 to 2018. We obtained the space time filtered (1–10 wavenumber and 20–100 days periodicity) CMAP daily precipitation data representing eastward propagating MJO signal\(^{33}\). We also computed the seasonal mean SST, omega ($\omega$), specific humidity ($q$) anomaly from the monthly datasets.

Maloney\(^{34}\) explained that the intra-seasonal moist static energy (MSE) budget could describe the eastward propagation of MJO. The recharge of column integrated MSE at intra-seasonal timescale occurs at the east of the MJO convection center with the help of low-level easterlies and mean background moisture field which helps MJO to propagate eastward. The discharge of column integrated MSE occurs during and after the precipitation occurs at MJO convection along with the lower level westerly anomalies, which stops MJO movement in the westward direction. Therefore, MSE tendency is positive at the east side of MJO convection center and negative at the west side (behind) it. With the help of the moist static energy and its tendency, we tried to explain the result in our study. We computed the moist static energy ($m = C_p^T + Lq + \phi$) from air temperature, specific humidity and geo-potential height dataset. Then, we obtained the
intraseasonal (20–100 days filtered) moist static energy anomaly $(m')$ and moist static energy tendency $<dm'/dt>$.

**Data availability**

The present study is based on 1979 to 2018 period, corresponding to the availability of OLR and the RMM index in the satellite era. RMM index data from 1979 to 2018 is obtained from the Australian Bureau of Meteorology. Monthly Niño 3 and Niño 4 indices are calculated from Extended Reconstructed Sea Surface Temperature version 5 (ERSSTv5) dataset with 2° x 2° resolution. These indices are used to identify the warm and cold Eastern Pacific (EP)-type and central Pacific (CP)-type ENSO phases.

We used daily NOAA interpolated OLR data with 2.5° x 2.5° resolution in our present study. We obtained the 2.5° x 2.5° pentad CPC Merged Analysis of Precipitation (CMAP) data and interpolated the data to daily. We used the zonal wind $(u)$, meridional wind $(v)$, omega $(\omega)$, specific humidity $(q)$, air temperature $(T)$ and geopotential height $(\phi)$ from NCEP/NCAR reanalysis 1 dataset. We also used monthly Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST) to check the consistency of our results.

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Author contributions

P.D. conceived the study, performed the analysis, and prepared the manuscript. R.M.K. provided the idea and supervised the study. R.C. and C.V.N. gave valuable suggestions in manuscript preparation. A.M. provided useful advice in the study.

Competing interests

The authors declare no competing interests.
Figure 1. (a) MJO frequency anomaly (seasonally normalized) at eight RMM MJO phase locations (days), (b) Scree plot denoting the percentage of variance contributed by the eight eigenvectors. The error bars indicate the North et al. criteria for the EOFs. (c) and (d) First two leading spatial EOFs of MJO frequency variability (days). (e) and (f) PCA-Biplot is denoting the relationship among the MJO frequencies at the eight RMM phase locations. The color scale in (e) implies the cos2 (percentage of variance explained through PC space) of the MJO frequency vector. The scatter points in (f) represent each season from 1979 to 2018 over the PC plane.
Figure 2. (a) and (b) MJO frequency EOF1 and EOF2 related 20-100 days filtered seasonal mean OLR (W/m²) anomaly. Similarly, (c) and (d) represent 20-100 days and wavenumber 1-10 space-time filtered precipitation anomaly (mm/day). Only the correlation values exceeding 90% confidence level based on the Student's t test are represented. (e) and (f) represent seasonal mean SST anomalies related to EOF1 and EOF2 (hatched denote the locations having significant correlation with 90% confidence level). (g) represents PC1 timeseries (2–8 years bandpass filtered) (blue line) and CP El Niño index (red line). (h) shows PC2 timeseries (2–8 years bandpass filtered) (black line) and EP El Niño index (red line).
**Figure 3.** Lead-lag relationship between PC1 timeseries (2-8 years bandpass filtered) and CP El Niño index (blue line). It is observed that negative CP El Niño leads PC1 timeseries by one season with correlation value 0.27. At lag 0 correlation is approximately 0.24. Lead-lag relationship between PC2 time series (2-8 years bandpass filtered) and EP El index (blue line). EP El index leads PC2 timeseries by one season with correlation value 0.523. At lag 0 correlation is approximately 0.47.
Figure 4. Composites of MJO frequency anomalies (standardized) at 8 RMM phase regions during (a) Positive CP-type ENSO seasons, (c) Negative CP-type ENSO seasons and their differences (e). Similarly, composites for (b) Positive EP-type ENSO seasons, (d) Negative EP-type ENSO seasons and their differences (f). (g) PCA biplot and clusters of positive (red), negative (blue) and neutral (yellow) CP-type ENSO seasons. Data ellipses represent the statistics of different classes. (h) Similar as Fig. (g) for positive, negative and neutral EP-type ENSO phases.
Figure 5. Composite differences of different fields between positive and negative CP-type and EP-type ENSO phases. (a), (c), (e), (g), (i) and (k) represent the composite differences of SST, 20-100 days filtered OLR, space-time filtered precipitation, 20-100 days filtered vertically integrated moist static energy anomaly \(< m' >\) and moist static energy tendency \(< dm'/dt >\), omega and specific humidity respectively. Similarly, (b), (d), (f), (h), (j) and (l) represent the composite differences of specified fields between positive and negative EP-type ENSO seasons. Hatches represents the 90% confidence level. In (i), (j), (k), (l) only anomalies exceeding 90% confidence level are plotted.
Figure 6. Lag propagation of 20-100 days filtered OLR with respect to central Indian Ocean (80°E-90°E, 15°S-15°N). Left panel shows the MJO propagation during positive and negative CP-type ENSO phases. The shade represents the positive phase and contour denotes the negative CP-type ENSO phase. The dotted lines represent the location (longitude) of maximum correlation at each time lag. The green and violet represent the positive and negative phases. The right panel shows the propagation for EP ENSO positive and negative phases.

Table 1: Correlation coefficients and cos2 of PCs and variables.

| Correlation | PH1 | PH2 | PH3 | PH4 | PH5 | PH6 | PH7 | PH8 |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|
| PC1         | 0.76| 0.50| 0.22| -0.49| -0.68| -0.51| 0.08| 0.42 |
| PC2         | -0.01| 0.43| 0.66| 0.56| 0.06| -0.42| -0.64| -0.47 |
| Cos2        |     |     |     |     |     |     |     |     |
| PC1         | 0.59| 0.24| 0.05| 0.24| 0.46| 0.26| 0.01| 0.18 |
| PC2         | 0.00| 0.18| 0.44| 0.32| 0.00| 0.18| 0.41| 0.22 |
Table 2: Mean, standard deviation of normalized PC1 and PC2 in different ENSO classes

| Variables   | EOF1 (PC1) | EOF2 (PC2) |
|-------------|------------|------------|
|             | mean  | STD  | mean  | STD  |
| EP- El Niño | 0.23  | 1.18 | 0.80  | 0.88 |
| EP- La Niña | 0.15  | 0.96 | -0.40 | 0.92 |
| CP- El Niño | 0.20  | 0.98 | 0.11  | 1.21 |
| CP- La Niña | -0.52 | 1.00 | -0.22 | 0.72 |