NOTES AND CORRESPONDENCE

Contributions of Convectively Coupled Equatorial Rossby Waves and Kelvin Waves to the Real-Time Multivariate MJO Indices

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ABSTRACT

The real-time multivariate (RMM) Madden–Julian oscillation (MJO) indices have been widely applied to diagnose and track the progression of the MJO. Although it has been well demonstrated that the MJO contributes to the leading signals in these indices, the RMM indices vary erratically from day to day. These variations are associated with noise in the outgoing longwave radiation (OLR) and wind data used to generate the indices. This note demonstrates that some of this “noise” evolves systematically and is associated with other types of propagating modes that project onto the RMM eigenmodes. OLR and zonal wind data are filtered in the wavenumber–frequency domain for the MJO, convectively coupled equatorial Rossby (ER) waves, and convectively coupled Kelvin waves. The filtered data are then projected onto the RMM modes. An example phase space associated with these projections is presented. Linear regression is then applied to isolate the wave signals from random variations in the same bands of the wavenumber–frequency domain, and the regressed data are projected onto the RMM EOFs. Results demonstrate the magnitudes of the contributions of the systematically evolving signals associated with these waves to variations in the RMM principal components, and how these contributions vary with the longitude of the active moist deep convection coupled to the waves.

1. Introduction

In a widely acclaimed recent article, Wheeler and Hendon (2004, hereafter WH04) applied combined EOF analysis of outgoing longwave radiation (OLR) and wind anomalies at 850 and 200 hPa to extract signals of the Madden–Julian oscillation (MJO; e.g., Madden and Julian 1994; Zhang 2005). They labeled the first two principal components as the real-time multivariate (RMM) MJO indices. They showed that the first two eigenmodes have horizontal and vertical structures consistent with the known structure of the MJO. These two eigenmodes are in quadrature in longitude, and their principal component (PC) time series are frequently in temporal quadrature. WH04 used these relationships to demonstrate that the pattern associated with the combination of these two modes usually propagates eastward. They demonstrated that the MJO dominates the RMM PCs. However, they also noted that noise (i.e., signals unrelated to the MJO) results in day-to-day erratic variations in the two PCs. The purpose of this work is to analyze the nature of these noisy patterns and to determine to what extent they might be associated with convectively coupled equatorial waves.

To simplify this demonstration, we focus on three modes of organized tropical convection: the MJO, convectively coupled equatorial Rossby (ER) waves, and convectively coupled Kelvin waves. These modes are each associated with patterns of alternating zonal wind on the equator. However, each evolves differently with time. The MJO and the Kelvin waves both propagate eastward, but their phase speeds differ substantially, with the MJO moving at roughly 5–8 m s⁻¹ and the Kelvin waves moving at 10–17 m s⁻¹ (e.g., Yang et al. 2007; Roundy 2008). Convective anomalies associated with Kelvin waves tend to be a few thousand kilometers wide, whereas those directly associated with the MJO are roughly an order of magnitude larger. Wind anomalies associated with Kelvin waves extend across broader
spatial scales than do convective anomalies associated with Kelvin waves. The ER wave propagates westward at roughly 5–7 m s\(^{-1}\) (e.g., Roundy and Frank 2004a; Yang et al. 2007). A quick comparison of the zonal structures of each of these modes suggests that ER and Kelvin wave signals would project onto the RMM eigenmodes (see the horizontal structures of each mode plotted by Matsuno 1966; Hendon and Salby 1994; Wheeler et al. 2000; and Roundy 2008.). WH04 suggest that the deep baroclinic vertical structure of the MJO distinguishes it from convectively coupled ER waves. However, ER waves do occasionally develop deep baroclinic circulations similar to those of the MJO, especially as they propagate over the Eastern Hemisphere warm pool (Wheeler et al. 2000; Yang et al. 2003; Kiladis et al. 2008).

2. Development of the RMM eigenmodes

Daily interpolated OLR data on a 2.5° grid were obtained from the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory Web site for June 1974–2006 (Liebmann and Smith 1996). Daily zonal winds at 850 and 200 hPa on a 2.5° grid were obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis for the same period (e.g., Kalnay et al. 1996). The long-term mean and primary three harmonics of the seasonal cycle were then subtracted from the OLR and wind data. Then, the spatial patterns of the RMM eigenmodes were calculated. This was done following WH04.

1) The longer time-scale components were removed: The 120-day mean of the previous 120 days was subtracted daily from each grid point. We found that this subtraction produced eigenmodes that are essentially identical to those of WH04, so no further removal of the El Niño–Southern Oscillation (ENSO) was deemed necessary for the applications in this note.

2) Meridional averaging: The resulting OLR and wind anomalies are averaged over all latitudes from 15°N to 15°S. These averages are then normalized by dividing by the zonal mean temporal standard deviation. As WH04 suggest, this step is required so that the results are not biased toward the OLR or wind data.

3) EOF analysis: The time series of the normalized OLR and wind anomalies are placed as columns in a matrix \(\mathbf{D}\). The covariance matrix of \(\mathbf{D}\) is calculated, and the RMM EOFs are the leading two eigenvectors of the result. As demonstrated by WH04, these are consistent with the horizontal and vertical structure of the MJO. The eigenvectors calculated here are indistinguishable from those shown in Fig. 1 of WH04. The RMM index PCs are obtained by projecting the anomalies calculated in step 2 onto these EOF patterns. Although ENSO was not deemed to contribute to the EOFs, some ENSO signal may remain in the PCs, but it does not influence the conclusions of this work.

3. Projections of wave-filtered data onto the RMM eigenmodes

To diagnose the relevance of modes other than the MJO to the RMM PCs, it is useful to filter the OLR and wind data for bands of the wavenumber–frequency domain that are consistent with these other modes and then to project the filtered data onto the EOF patterns derived above. Many authors have applied filtering in the wavenumber–frequency domain to isolate the signals of the MJO and convectively coupled equatorial waves (e.g., Wheeler and Kiladis 1999; Roundy and Frank 2004a; Roundy 2008). We filtered OLR and wind data for the MJO and for these waves by using the filter bands shown in Fig. 1. The filtered data were obtained by calculating the Fourier transform in longitude, followed by another transform in time, and then performing the inverse transform by integrating only over the region of the spectrum defined by the filter. We then developed analogs to the RMM principal components related to those selected wavenumber–frequency bands by projecting the filtered data onto the same RMM eigenmodes based on the unfiltered data. It is important to point out here that although this filtering algorithm increases the concentration of signals associated with the waves relative to other signals when compared with unfiltered data, random variations still contribute substantially to the filtered data. Linear regression is applied below to further isolate the wave signal from more random events.

Figure 2 shows the RMM PCs developed from projections of filtered data for the period 25 May 2002–12 August 2002. This analysis yields similar conclusions almost regardless of what period is chosen, although the relative amplitudes of each mode will vary. Figure 2a shows the RMM index based on unfiltered data. Although the pattern clearly demonstrates counterclockwise rotation consistent with gradual eastward progression, the signal varies erratically. This result would vary slightly from that of WH04 for the same period because we did not remove ENSO. Figure 2b shows the result based on projection of MJO-filtered
OLR and wind data onto the same EOF patterns used in Fig. 2a. In contrast to Fig. 2a, the pattern varies smoothly in time and space (as would be expected from projection of bandpass-filtered data that removes high frequencies). The basic overall pattern in Fig. 2a including counterclockwise rotation and most of the amplitude is retained in the MJO-filtered data (Fig. 2b), supporting the assertion of WH04 that the MJO usually contributes the leading signal to the RMM phase space.

Figure 2c shows the result for data filtered for the ER band and Fig. 2d shows the result for the Kelvin band. Although the projections of Kelvin and ER band data are smaller in amplitude than the MJO projection shown in Fig. 2b, these patterns would contribute substantially to the variations in Fig. 2a. The curve in Fig. 2c rotates clockwise instead of counterclockwise, consistent with the westward movement of anomalies filtered for this band. Furthermore, the ER band pattern revolves around the origin more times than the MJO signal does in Fig. 2b, consistent with the higher frequencies and higher phase speeds characteristic of the ER band. Figure 2d shows that the Kelvin band curve progresses counterclockwise around the origin (similar to the MJO), but it makes more than twice as many revolutions, consistent with phase speeds of anomalies in the Kelvin band. Comparison of the ER- and Kelvin-filtered data (Figs. 2c,d) shows that during this particular period of time, the amplitude of the signal in the Kelvin band projecting onto the RMM EOFs is greater than the corresponding projection of data filtered for the ER band.

To determine the effects of the combined signals of these bands on the RMM indices, we add the ER and Kelvin band signals iteratively to those of the MJO band, project the result onto the RMM EOFs, and compare the results with the standard RMM indices (Fig. 2a). Figure 2e shows the result of projecting the sum of MJO- and ER-filtered data onto the same spatial patterns, and Fig. 2f shows the result after adding the Kelvin band. Figure 2e demonstrates that the combination of the MJO and ER bands results in sharper changes in the direction of progression across the phase space than are seen with the MJO band alone (i.e., the curve associated with the combined signal follows nearly straight lines punctuated by rapid turns in the phase space). These changes make the combined signal more consistent with the unfiltered data shown in Fig. 2a. Figure 2f demonstrates that addition of the Kelvin band further helps to develop the pattern of lobes seen in Fig. 2a.

Comparison of the unfiltered projection (Fig. 2a), MJO-filtered projection (Fig. 2b), and the sum of the
filtered projections (Fig. 2f) demonstrates that the sum (Fig. 2f, which includes the MJO signal together with the ER and Kelvin band signals) is more similar to the unfiltered projection (Fig. 2a) than is Fig. 2b (which includes only the signal consistent with the commonly accepted spectral characteristics of the MJO). Although Fig. 2f is similar to Fig. 2a, it is not an exact match, suggesting that patterns in other bands (e.g.,

Fig. 2. (a) Example RMM phase space for the period 25 May–12 Aug 2002, made by projecting anomalies from the seasonal cycle and the recent 120-day mean onto the spatial patterns of the RMM EOFs. (b) As in (a), but for projections of MJO band OLR and winds onto the same spatial patterns. (c) As in (a), but based on ER filtered OLR and winds. (d) As in (a), but for Kelvin-filtered OLR and winds. (e) The sum of projections based on MJO-filtered OLR and winds and ER-filtered OLR and winds. (f) The projections of the sum of MJO-, ER-, and Kelvin-filtered OLR and winds onto the same spatial patterns. The most recent 20 days of the curves are highlighted gray to distinguish the ends from the beginnings. The circle near the center of the phase portraits represents the one SD level for the combination of the first and second PCs.
ENSO) also project onto the RMM eigenmodes besides the two analyzed here.

4. Regression analysis

a. Regression method

Projection of wave-filtered data onto the RMM EOFs demonstrates only that rapid variations in the RMM indices are associated with signals found in the filter bands. Although the filtering increases the fraction of variance associated with the target waves relative to other signals, it does not guarantee that the projected signals are associated with convectively coupled waves. Random noise in the same bands might generate substantial projections as well. Further analysis is required to estimate to what extent the observed fluctuations associated with the different filter bands can be attributed to the waves themselves. Any projections of specific types of waves onto the RMM EOFs may vary with the geographical location of active convection coupled to the waves, and multiple waves of the same type coupled to distinct convective anomalies would complicate the problem.

To estimate the contributions of the waves themselves to the RMM PCs and to diagnose how these contributions change with the longitude of the most enhanced convection in the waves, we performed simple linear regression analyses of ER and Kelvin waves based at each longitude around the global grid, then projected each “composite” pattern onto the RMM EOFs. Such statistical composites largely exclude random noise (e.g., Wheeler et al. 2000; Kiladis et al. 2008, and references therein), leaving the patterns associated with systematically evolving waves. The following algorithm was applied to develop the regression models:

1) Average wave-filtered OLR data over 7.5°S–7.5°N. This band reduces the contributions of extratropical waves to the averaged data, which are present at higher latitudes (e.g., Straub and Kiladis 2003).
2) Select a longitude base from which to obtain a time series \( X \) from the filtered data averaged over latitude in step 1.
3) Solve the linear regression model \( Y = XA \) for the vector of regression coefficients \( A \). The columns of \( Y \) are the unfiltered anomalies of OLR, 850-hPa zonal winds, and 200-hPa zonal winds averaged over 15°N–15°S at each longitude grid point around the globe. Since ER waves are occasionally correlated with the MJO, we performed the same analysis again for ER waves with the MJO band subtracted from the columns of \( Y \). We also generated regression coefficients for time lags between \( X \) and \( Y \) at each grid point to diagnose the temporal progression of the regressed waves.
4) Substitute a single value into the regression equation for \( X \) to get a field of OLR and wind anomalies associated with a wave. We used −2 standard deviations (SD), consistent with Wheeler et al. (2000).
5) Normalize the regressed OLR and wind data by dividing by the respective zonal mean SD of the unfiltered anomalies. Project the normalized regressed wave patterns onto the RMM EOFs. It is important to point out that the results scale linearly with the amplitude assumed in step 4 (e.g., if a one SD wave were projected onto the RMM EOFs, then the result would be half that of the two SD wave).
6) Calculate the absolute amplitude of the projections \( \sqrt{PC1^2 + PC2^2} \).
7) Apply a bootstrap resampling test to estimate the 95% confidence interval of the projection amplitudes. This test was applied by randomly resampling a new set of dates from the original set, with replacement, such that each new sample is the same length as the original sample, but individual dates could be included any number of times in each sample. After all 1000 iterations, the resulting list of amplitudes was sorted in ascending order. The 95% confidence interval begins at the 25th value and ends at the 975th. This test is robust to the number of degrees of freedom in the data, since its application at coarser temporal resolution consistent with the decorrelation time scales of the wave signals yields similar results (not shown).

b. Projections of regressed waves at lag = 0 days

Each of the above steps was applied at every longitude grid point around the globe. This global analysis is appropriate since the MJO, ER waves, and Kelvin waves have been shown to influence the entire equatorial zone (e.g., Roundy and Frank 2004a). Resulting amplitudes in the RMM PCs at time lag = 0 days are plotted with respect to longitude in Fig. 3 for the regressed Kelvin wave (heavy solid curve) and for the regressed ER wave (heavy dashed gray curve includes the MJO band in the columns of \( Y \) and the heavy dashed black curve excludes it). Amplitude is reported in terms of SDs of the RMM PCs as calculated from June 1974 to December 2006 (based on projections of unfiltered data). The confidence intervals for the Kelvin wave and for the ER wave excluding the MJO are outlined by thin curves of the same formats. Two SD Kelvin waves project as little as 0.17–0.27 SDs to as much as 0.31–0.42 SDs. Two SD ER waves excluding the related part of the MJO project less, ranging from
near 0–0.05 SDs to as much as 0.11–0.16 SDs. These results imply that a single wave event would be associated with a peak-to-peak range in the RMM PCs of twice the noted amplitude over its full cycle (suggesting that a single 2 SD Kelvin wave over South America would be associated with a 0.5–0.7 SD adjustment in the RMM PC amplitude over a full wave cycle). A single ER wave might be associated directly with a maximum swing of 0.2–0.3 SDs. Figure 3 also suggests that a wave moving from a region of relatively low projections toward a region of higher projections would influence the RMM PCs progressively more until it reaches the longitude of maximum projections, after which its contribution would decline.

Results of the regression analysis for the ER wave without excluding the MJO band from the columns of Y yield much higher projections (up to 0.44 SDs near 120°E, as indicated by the heavy, dashed gray curve on Fig. 3). This result implies that part of the MJO is correlated with the signal in the ER band, and that the MJO itself is responsible for these projections. Roundy and Frank (2004b) demonstrated that the MJO and ER waves are occasionally correlated in time, and that the MJO and related ER waves sometimes combine to produce standing patterns in OLR, water vapor, and winds. The RMM PC orbits based on the ER composites without subtracting the MJO thus revolve counterclockwise about the origin like the MJO (in spite of the westward movement of ER waves). However, they do not revolve as smoothly about the origin as composites based directly on the MJO (not shown). Instead, the orbits progress along roughly straight lines punctuated by more abrupt curves, as in Fig. 2e. These results together suggest that the MJO itself might behave differently when ER waves are active. If so, then the relationship between the MJO and ER waves might be relevant to interpretation of the RMM PCs when ER waves are active, even though the ER waves themselves project little onto the RMM EOFs. In any case, it is apparent that ER waves do not directly influence the RMM PCs as much as Kelvin waves, and it seems that the indirect influence of ER waves may actually be associated with the MJO itself. Further work is necessary to fully understand the relationship between the MJO and ER waves and its influence on the behavior of the RMM PCs.

![Figure 3](image-url)
c. Impact of a full life cycle of a Kelvin wave on the RMM PCs

To determine the combined effects on the RMM PCs of a single Kelvin wave event occurring at the same time as a moderate MJO, we generated longitude–time lag composites for the MJO and for Kelvin waves separately following steps 1–6. We then projected the individual composites and their sum onto the RMM EOFs. The longitude time lag composite at 87.5°E for the Kelvin wave OLR and 850-hPa zonal wind anomaly is shown in Fig. 4a for time lags from −15 through 15 days. The location of maximum projections of Kelvin waves onto the RMM PCs (i.e., 87.5°E) is indicated by Fig. 3. The projections of the composites are shown in Fig. 4b, for time lags from −30 to +30 days. The MJO composite assumes that a two SD MJO-band OLR minimum is located at 80°E at lag = 0 days. It is interesting that this composite MJO event reaches two SDs in the local OLR index, but it only attains roughly one SD in the RMM PCs. The lower amplitude in the RMM PCs suggests that a regression model based on high-amplitude-filtered OLR anomalies at a single longitude is not sufficient to ensure high amplitude in the broad spatial structure of the MJO simultaneously in OLR and the 850- and 200-hPa zonal winds. This result also suggests the possibility that projections of individual wave events onto the PCs may be higher than those suggested above, because far-field patterns that are relevant to the amplitudes of the projections might be smaller in the composites than in individual events of the same amplitude in OLR at the base point. However, since we assumed two SD local OLR anomalies in the regression models, our results represent conservative estimates of the influence of high-amplitude wave events, with the caveat that many wave events do not attain amplitudes that high.

Figure 4b shows that the Kelvin wave composite contributes close to 0.3 SDs at lag = 0 (thin gray curve near the center of the diagram). The black curve shows the sum of the MJO and Kelvin wave composite patterns. When compared with the composite MJO alone (gray curve with filled circular markers), the contribution of the Kelvin wave becomes evident as a shift in the center of the orbit. Furthermore, variations in the widths of the spaces between individual time steps (marked by small heavy circles along the orbits) change after inclusion of the Kelvin wave (i.e., the Kelvin wave causes the day-to-day revolution to speed up and slow down with time around different parts of the orbit depending on the location of the active convection coupled to the Kelvin wave relative to that of the MJO).

This compositing method might not represent all of the impacts on the RMM PCs of some individual Kelvin wave events. For example, some waves propagate more than once all the way around the world (e.g., Kiladis et al. 2008, manuscript submitted to Rev. Geophys.). Such events might exhibit high amplitude in their projections throughout the lives of the waves, varying according to the geographical pattern seen in Fig. 3. Such waves would not show the same attenuation seen in the composite at long leads. Loss of amplitude at long lead times suggests that these composite results would provide conservative estimates for the contributions of individual high-amplitude Kelvin waves to the RMM PCs. Individual events would not likely vary as smoothly in their contributions to the PCs as the composite event. Roundy (2008) demonstrated rapid variations associated with Kelvin waves moving from over the ocean to over land or from the active convective phase of the MJO into the suppressed phase. Since the
unfiltered data normally projected onto the RMM EOFs includes these rapid variations, they would be expressed in the RMM PCs as more abrupt fluctuations superimposed on the underlying MJO signal.

d. Impact of two distinct Kelvin waves on the RMM PCs

Multiple distinct active convective anomalies associated with the same type of wave can occur around the globe at the same time, and each of these would contribute to the RMM PCs. Multiple Kelvin waves can occur in rapid succession over the Indian and west Pacific Oceans during the active convective phase of the MJO (e.g., Nakazawa 1988; Roundy 2008). The signals of the different waves would interfere, and the interference pattern would project onto the RMM EOFs in varying amounts depending on whether the interference is constructive or destructive. This interference might result in the signals of two distinct active convective phases of Kelvin waves centered at different longitudes combining to contribute nothing to the RMM PCs, but if located elsewhere, the two waves might contribute nearly double the contribution of a single wave. To estimate the contribution of such interference between two waves present at the same time, we developed two regression models for Kelvin waves. The two are assumed to be independent from each other. One of these composites was held fixed at 60°E, while another composite was calculated multiple times at other base points around the globe. We then projected the sum of the two composites onto the RMM EOFs. This method presents a first guess of the actual impacts of two waves occurring at the same time. We did not account for nonlinear interactions between the convective anomalies of the two waves, which might modify wave structures and propagation characteristics. Nonlinear advective effects are likely to be small since Kelvin wave phase speeds are more than 10–15 times their associated wind speeds (e.g., Wheeler et al. 2000; Roundy 2008). Figure 5 shows the resulting projections plotted as a function of the longitude of the active convective anomaly of the second wave in terms of RMM SDs. Results are not plotted near 80°E, where the two composite waves combined to enhance the negative OLR anomaly of the wave at 80°E. This result illustrates that a pair of one SD Kelvin waves located over the Indian Ocean or West Pacific within 30°–45° longitude of each other can together produce a 0.25 SD contribution to the RMM PCs (or a 0.5 SD adjustment in the PCs over the lifetimes of the two waves). Such events in close proximity occasionally occur during the active convective phase of the MJO over the Indian Ocean and west Pacific. In contrast, if one Kelvin wave is located over

5. Conclusions

Wheeler and Hendon (2004) clearly demonstrated that the RMM PCs are dominated by signals associated with the MJO, but that they evolve erratically in time in response to signals other than the MJO. By projecting data filtered in the wavenumber–frequency domain for ER waves and Kelvin waves onto the RMM EOFs, we have demonstrated that anomalies in these bands contribute to the RMM PCs. However, signals unrelated to Kelvin and ER waves also occur in these filter bands. By projecting simple linear regression models of these waves, we showed that the wave signals are in fact responsible for some of the variations in the RMM PCs.
Our results suggest that the convectively coupled Kelvin wave provides a nonnegligible contribution to the RMM PCs, but that ER wave contributions are relatively small unless the part of the MJO associated with the ER wave signal is included (Roundy and Frank 2004b).

A wavenumber–frequency spectrum analysis of OLR data reconstructed from the RMM PCs is shown in Fig. 11a of WH04. That spectrum clearly demonstrates the dominance of the MJO in the RMM PCs, but it also shows power extending into the ER and Kelvin bands, consistent with our results. Their spectrum suggests very strong contrast between power in the ER and Kelvin bands and power in the MJO band, and no distinct spectral peaks remain in either the ER or Kelvin bands. However, since power in the spectrum goes with the square of wave amplitude, the square root of the power plotted in their figure would be proportional to amplitudes in the RMM indices associated with the different modes. The square root of the maximum power in the ER band exceeds 30% of the square root of the peak power in the MJO band. This result is consistent with comparison of the relative amplitudes of the projections of the MJO and ER bands onto these eigen-modes shown in Fig. 2. Although projection onto the RMM EOFs removes the peaks associated with ER and Kelvin waves, such removal does not necessarily imply that the modes are entirely removed unless the organization of the phases in those portions of the spectrum can be deemed to be random. The composites shown here demonstrate clearly that systematically evolving wave signals in the Kelvin and ER bands remain in the RMM PCs even though their spectral peaks are removed by the projection process. This result raises questions about conclusions drawn by many authors based on the locations of peaks in power spectra: power in a given range of wavenumbers and frequencies does not necessarily need to extend above that at neighboring wavenumbers and frequencies in order to be associated with systematically evolving patterns. The above composite analysis demonstrates that significant wave signals are in fact retained in the RMM PCs, even though the MJO signal usually dominates.

Our results suggest that projections of observational and model data onto these EOFs should be interpreted carefully in terms of the different modes that contribute to the total signal if the purpose of the analysis requires that the MJO be considered in isolation from ER and Kelvin waves. It is clear that the leading signal in observed data projecting onto these EOFs is contributed by the MJO, but this might not be true for some numerical weather models. For example, a model that produces high-amplitude Kelvin waves but lacks a robust MJO might still produce significant projections onto the RMM modes. Such projections would revolve around the origin more quickly than does the observed MJO. The projections characteristic of the Kelvin wave should therefore be considered while applying the RMM PCs when Kelvin waves are present. In many applications, the wave signals might detract little from interpretation of the RMM PCs. In other applications, the contributions of convectively coupled Kelvin waves might lead to misinterpretation of the actual status of the MJO. We therefore recommend that a method be devised to diagnose the locations and amplitudes of Kelvin waves around the world. Then, their estimated contributions to the RMM PCs could be subtracted. A similar method could also be applied to remove the contributions of ER waves, but since these waves tend to have smaller direct projections onto the RMM PCs, the benefit of such removal would not be as great.

The authors are presently developing an algorithm for tracking the MJO in real time that applies time-extended EOFs of OLR anomalies, and preliminary results suggest that a phase space developed from this method does not include significant contributions from ER waves and Kelvin waves. This new method is promising since its indices vary more smoothly from day to day, but the principal benefit of the RMM method to real-time analysis is its relative simplicity in calculation. Although other methods may provide clearer results, such enhanced clarity comes with a cost of requiring more complicated statistics.

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