Modulation of the Extratropical Circulation by Combined Activity of the Madden–Julian Oscillation and Equatorial Rossby Waves during Boreal Winter

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ABSTRACT

Time indices of the Madden–Julian oscillation (MJO) are often used to generate empirical forecasts of the global atmospheric circulation. Moist deep convection associated with the MJO initiates eastward-propagating Rossby waves that disperse into the midlatitudes. The background circulation then guides extratropical waves back into the tropics of the eastern Pacific Ocean. Previous works have shown that equatorial Rossby (ER) waves occur following intrusion of extratropical Rossby waves into the tropics. Westward-propagating ER waves and the MJO modulate the total convection. This convection modulates the zonal wind, which influences the location and existence of westerly wind ducts. These wind ducts, in turn, guide extratropical waves into the tropics. This paper demonstrates through a simple composite analysis that a simultaneous assessment of MJO and ER waves yields more information about the extratropical circulation during boreal winter than can be obtained based on either type of disturbance alone, or from a sum of the signals associated with the MJO and ER waves composited separately. This analysis, together with previous results, suggests a feedback loop between the MJO, these waves, and the extratropical circulation. Thus, assessment of the ER wave state during a particular phase of the MJO might yield better empirical prediction of the global atmospheric circulation that follows.

1. Introduction

The Madden–Julian oscillation (MJO) is an eastward-propagating large-scale coupling of atmospheric circulation and deep moist tropical convection. Active convection associated with the MJO is most commonly observed over the Indian Ocean, the Maritime Continent and Southeast Asia, and the tropical western Pacific Ocean. While the structure of the MJO has been widely observed since the 1970s, its internal dynamics and mechanisms for onset and decay remain elusive. One characteristic of the MJO that is well documented is its interactions with convectively coupled equatorial Rossby (ER) waves and extratropical waves in particular geographical regions (e.g., Sardeshmukh and Hoskins 1988; Kiladis and Weickmann 1992; Roundy and Frank 2004; Masunaga 2007; Moore et al. 2010).

Extratropical waves interact with and respond to the MJO. Mass divergence in the upper troposphere associated with organized deep convection in the tropics causes Rossby waves to disperse into the extratropics (e.g., Sardeshmukh and Hoskins 1988; Kiladis and Weickmann 1992; Moore et al. 2010). Meehl et al. (1996), Kiladis (1998), and Matthews and Kiladis (1999) showed that equatorward-propagating extratropical Rossby waves, steered by the background circulation, perturb the equatorial waveguide and initiate eastward-moving regions of active convection on the time scale of the MJO as well as ER waves upon intruding into the tropics of the eastern Pacific basin. That background circulation includes the circulation associated with the MJO, implying that the MJO must modulate the formation of ER waves through this mechanism. Funatsu and Waugh (2008) linked the perturbation of the equatorial waveguide to positive potential vorticity (PV) anomalies accompanying the intrusion of extratropical upper-level troughs into the tropics. Masunaga (2007) demonstrated associations between ER waves and convectively coupled Kelvin waves (hereafter Kelvin waves) that suggest that

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these modes might modulate MJO convection. He observed a peak in off-equatorial surface convergence and convection associated with the superposition of Kelvin waves and ER waves within the MJO convective envelope.

This paper addresses these associations between the MJO, extratropical Rossby waves, and ER waves. We assess whether considering the phasing of ER waves relative to the MJO might provide additional information about the extratropical circulation. Further, by analyzing the simultaneous combination of the MJO and ER waves, we assess feedbacks between the tropics and extratropics, with the MJO and ER waves both forcing and being forced by the extratropical circulation.

2. Data and methodology

a. Data and compositing technique

The National Oceanic and Atmospheric Administration (NOAA) interpolated outgoing longwave radiation (OLR) data (Liebmann and Smith 1996) and the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis 300-hPa geopotential height and wind data (1974–2009) were obtained from the Earth System Research Laboratory (ESRL; Kalnay et al. 1996). Anomalies were generated by subtracting the annual cycle and its first four harmonics. These anomalies were then averaged over selected dates to composite MJO, ER wave, or simultaneous combinations of MJO and ER wave events following Roundy et al. (2010). All composite anomalies were tested for statistical significance from zero using the Student’s *t* test. The dates of MJO events in selected phases were obtained by using a smoothed version of the Real-time Multivariate MJO (RMM) indices described by Wheeler and Hendon (2004). The OLR and 850- and 200-hPa zonal wind data used to calculate these indices were first filtered for the MJO band including wavenumbers 0–9 eastward and periods of 30–100 days (MacRitchie and Roundy 2012). The result is a pair of indices that exclude signals linearly correlated with interannual variability, Kelvin waves, ER waves, and weather noise that Roundy et al. (2009) showed project onto the standard RMM indices. Dates of OLR minima associated with ER wave events—filtered for wavenumbers 1–12 westward and periods of 10–100 days—were obtained by finding time local minima less than $-1$ standard deviation (SD) at each longitude around the globe in these data averaged from 7.5°N to 7.5°S. The number of such minima at each longitude was tabulated.

The first set of composites was constructed based on averaging over all of the dates of OLR minima in the ER wave band less than $-1$ SD during boreal winter. To prepare composites comparable with those made later for simultaneous MJO and ER wave activity, we first selected one ER wave base longitude during a specified RMM phase for detailed study, followed by several different base longitudes to demonstrate sensitivities of the composite patterns to ER wave signals at other points. However, this first set of composites only accounts for ER wave events at that location without considering the phase of the MJO at the time. The second set of composites was calculated by averaging OLR and reanalysis data anomalies over all dates and corresponding time lags during a selected phase in the smoothed RMM indices during boreal winter. Included events had RMM amplitudes exceeding 0.75 SDs. The third set of composites is based on the intersection of these two sets of dates. For both composite sets 2 and 3, each day from 2 days before to 2 days after the ER wave crest was included in the composite to average out synoptic noise.

b. Monte Carlo test

Any difference between the extratropical circulation pattern associated with the composite MJO and the composite MJO and ER wave acting in concert might result from random chance. The composites based on combined activity of the MJO and ER waves are averaged over a smaller sample of dates than the composites based on the MJO alone. Since synoptic disturbances have high amplitudes, averaging over a smaller set of events would increase the relative contributions of high-amplitude random synoptic patterns to the composites, increasing the net amplitude of the composite anomaly fields. A Monte Carlo significance test was employed to determine the statistical significance of the difference between composite anomaly amplitude fields associated with the MJO alone and the simultaneous composites, correcting for the reduced number of degrees of freedom in the combined composite. We assumed the null hypothesis that the composite geopotential height anomaly fields for both MJO-only and simultaneous MJO and ER wave composites were not statistically distinguishable.

To perform the Monte Carlo test, “pseudo” ER wave events equal to the number of combined events identified in the simultaneous composites were drawn at random from the set of dates included in the composites based on the MJO alone. Each of these events was padded with two days on each side of day zero as in the original composite combined events. Thus, the number of degrees of freedom in each of these pseudocombined composites is identical to that in the combined composites. If the range of amplitudes in the composite based on the random draws is statistically smaller than the range of amplitudes achieved by the composite based on the actual ER wave timing, then the ER wave
signals contribute more information about the global circulation when taken together with the MJO than a subset of events taken from the MJO can explain by random chance. The random drawing of events was repeated 1000 times, and composites were generated for each of the 1000 iterations.

3. Results

The composites are presented here in the form of plan view maps and longitude–time-lag composites for RMM phase 4 (RMM4). RMM4 was selected to provide a general view of the results, but similar conclusions with respect to the amplitude of composite extratropical patterns are associated with the other seven RMM phases. The base longitude for ER wave signals during RMM4 is 157.5°E.

a. Composite plan view maps based on ER wave signals alone

Composites based only on ER wave signals (Fig. 1) show a low amplitude but statistically significant extratropical circulation pattern associated with ER waves. OLR and 300-hPa geopotential height and wind anomalies retain low amplitudes through each panel. Composite geopotential height anomaly amplitudes only exceed 20 m in Figs. 1d,e, but the composite wind anomaly field over the eastern North Pacific and western North America in Figs. 1d–e suggests a weak but statistically significant extratropical Rossby wave response to ER wave convection in the central and western tropical Pacific.

Twelve days prior to the arrival of the composite ER wave OLR anomaly at its base longitude, a 300-hPa easterly wind anomaly occurs between a ridge anomaly over the central North Pacific and a subtropical trough anomaly to the south of the ridge anomaly. This pattern includes the characteristic backward S pattern in the wind anomalies suggestive of the residual of anticyclonic wave breaking (e.g., Thorncroft et al. 1993; Postel and Hitchman 1999; Moore et al. 2010), and it is consistent with a reduction in the amplitude of the subtropical jet. Figures 1e–g suggest that at later lags, the easterly anomalies become more westerly as the jet extends eastward simultaneous with the westward movement of the ER wave.

The presence of the residual signals of anticyclonic wave breaking suggests that synoptic extratropical waves break in these regions. This finding is not new. Moore et al. (2010) noted a split subtropical jet pattern and associated synoptic life cycle 1 (LC1; anticyclonic; following Thorncroft et al. 1993) wave breaking over the central North Pacific during RMM4. Postel and Hitchman (1999) developed a climatology of Rossby wave breaks for both hemispheres and noted a maximum in wave break frequency over the central North Pacific collocated with a weakness in the meridional PV gradient. Breaking of synoptic extratropical Rossby waves over the North Pacific can be accompanied by the intrusion of upper-level troughs associated with PV maxima into the tropics. Kiladis (1998), Matthews and Kiladis (1999), and Funatsu and Waugh (2008) suggested that these extratropical trough intrusions could project signals onto the equatorial waveguide and generate circulations associated with ER waves.

b. Composites based on MJO signals alone

Composites of OLR, geopotential height, and total wind anomalies corresponding to RMM4 show the widely known circulation pattern associated with MJO convection in the Northern Hemisphere extratropics (Fig. 2). An extratropical Rossby wave pattern, suggested by a sequence of positive and negative 300-hPa height anomalies, extends from the North Pacific eastward to the North Atlantic.

The composite wind anomaly field in the first three panels of Fig. 2 includes easterly wind anomalies over the western subtropical Pacific. An amplifying ridge anomaly, suggested by positive geopotential height anomalies, is present over the North Pacific, with a trough anomaly equatorward of this location.

Figure 3a overlays the 300-hPa total wind field on top of the composite 300-hPa geopotential height anomalies reproduced from Fig. 2d to illustrate the response of the subtropical jet to the MJO in the region of these ridge and trough anomalies. For reference, red contours in the tropics highlight the location of MJO active and suppressed convection following the algorithm of Roundy (2012). Figure 3b shows the corresponding pattern during RMM8 for comparison. An elongation of the jet from Figs. 3a to 3b is consistent with the eastward propagation of MJO convection and the sign reversals of the two central North Pacific geopotential height anomalies.

While the specific origins of the tropical central Pacific trough anomaly during RMM4 remain to be investigated, this ridge–trough pattern carries the characteristic backward S pattern residual of synoptic extratropical Rossby waves breaking into the tropics (this breaking is the well-known mechanism of the generation of cut off cyclones known as tropical upper-tropospheric troughs (e.g., Postel and Hitchman 1999; Waugh and Polvani 2000; Funatsu and Waugh 2008). This trough anomaly appears in most composite MJO events as the Northern Hemisphere upper-level cyclone associated with the suppressed convective phase of the MJO. The similarity
of this pattern with the expected residual of anticyclonic wave breaking in a location where anticyclonic wave breaking is known to be frequent during this RMM phase suggests the possibility that this gyre may originate from anticyclonic wave breaking. Although such a mechanism can explain the origins of these troughs, upper-level trough anomalies associated with the suppressed convective phase of the MJO might be generated or reinforced by base-state latent heat release not achieved because of the presence of suppressed convection associated with the MJO, which likely shows up better at higher atmospheric levels. The suppressed convection and the extratropical wave intrusions are not mutually exclusive and might even be related, since wave intrusion can modulate convection and convection influences the upper-level circulation that can then guide

FIG. 1. (a)–(h) Composite OLR (shaded, W m$^{-2}$; dark blue shading suggests convection associated with composite ER wave events) and 300-hPa wind anomalies (vectors; m s$^{-1}$). Geopotential height anomalies do not exceed the 20-m contour amplitude required for consistency with other figures except in (d) and (e). Hatches represent statistically significant geopotential height anomalies at the 95% level. The base longitude for composite ER wave events is 157.5°E; n represents the number of events included in the composites.
waves into the tropics. Such troughs are associated with upper-level mass convergence on their western sides, such that they would maintain a signal of suppressed moist deep convection concomitant with the phase of the MJO in which they occur.

c. Composites based on simultaneous MJO and ER wave signals

Figure 4 provides a composite based on the simultaneous combination of MJO events in RMM4 and ER band OLR minima at 157.5°E. These simultaneous composites reveal a high-amplitude extratropical Rossby wave pattern across the North Pacific and North America. Although there is no clear presence of 300-hPa westerly wind anomalies over East Asia, a mean subtropical jet is present in the total wind field in which the mean and seasonal cycle are retained (Fig. 3). The absence of westerly wind anomalies in the vicinity of the western Pacific subtropical jet might be attributed to large-scale suppressed convection east of the organized MJO convective
envelope (Figs. 4e,f), which does not appear in the corresponding diagrams for the MJO only (Figs. 2e,f). This comparison shows that MJO events with ER waves crossing the base longitude at 157.5°E are associated with different patterns of divergence in meridional wind than during MJO events when ER waves are not considered. This result suggests that ER waves might modify the patterns of Rossby wave dispersion into the extratropics induced by MJO convection. To the east, an amplifying ridge anomaly is present over the North Pacific with an amplifying trough on its equatorward side, which demonstrates the characteristic backward S pattern of the residual of anticyclonic wave breaking (e.g., Thorncroft et al. 1993; Postel and Hitchman 1999).

In addition to the trough in the subtropics of the central Pacific basin, a similar central Atlantic trough is evident in Figs. 4e–g. The pattern over the central Atlantic appears to evolve simultaneously with an amplifying trough over eastern North America and the western North Atlantic. This result suggests a possible extratropical Rossby wave intrusion into the central tropical Atlantic on MJO time scales. Unlike the central Pacific trough, the amplifying trough over the central Atlantic is not located poleward of a region of suppressed convection, suggesting that it could not have also evolved as a consequence of anomalously suppressed convection near the equator like the similar signals farther west.

The magnitudes of many of the composite OLR, wind, and geopotential height anomalies in Fig. 4 are nearly twice the magnitudes of composite anomalies in Figs. 1 and 2 when the MJO and ER wave signals are considered separately. This amplitude difference is robust at the 99% level in the Monte Carlo tests explained in section 2, so that the likelihood that these differences could be explained by the smaller sample size and reduced degrees of freedom is exceedingly small. The selection of 157.5°E as the crossing longitude for ER waves during RMM4 happens to highlight the same basic pattern observed in the composite based on the MJO alone (Fig. 2), but different base longitudes yield dramatically different outcomes.

Figure 5 compares the result for the ER wave base longitude at 157.5°E (Fig. 5a, as in Fig. 4d) during RMM4 with the corresponding result for the ER wave base longitude at 117.5°W (Fig. 5b) and 42.5°W (Fig. 5c). Selection of 117.5°W yields similar height and wind anomaly patterns to 157.5°E, but subtle phase shifts are evident between the two composites. For example, the

![Figure 3](image-url)
significant trough anomaly over western Russia in Fig. 5a is replaced by a lower-amplitude trough anomaly in Fig. 5b. Additionally, the ridge anomaly over Hudson Bay in Fig. 5a is displaced equatorward and eastward in Fig. 5b, and it extends eastward across the North Atlantic. Selection of 42.5°W yields a much greater change in the height and wind anomaly patterns compared to the patterns in Figs. 5a,b. A large ridge anomaly is visible over far eastern Siberia, the northwest Pacific ridge anomaly in Figs. 5a,b is shifted eastward closer to the West Coast of the United States, and the North Atlantic trough anomaly is shifted southward and amplified by a factor of 4. Further analysis demonstrates a wide range of other outcomes related to ER wave base longitudes during RMM4 (not shown). The number of ER wave crests simultaneous with all eight RMM phases at each longitude around the globe is detailed in Fig. 6.

d. Comparison in the longitude–time-lag domain

Figure 7 provides a comparison of each of the aforementioned sets of composites in the longitude–time domain, averaged from 40° to 50°N. Regions of statistically significant anomalies are highlighted on the corresponding plan view maps in Figs. 1–3. Figures 7a,b show

![Fig. 4. As in Fig. 2, but for events corresponding to RMM4 simultaneous with ER wave crests at 157.5°E.](image-url)
extratropical circulation patterns associated with composite ER wave and MJO events, respectively, comparable with Figs. 1 and 2 (respectively). Figure 7c provides the sum of Figs. 7a,b to illustrate the expected outcome of linear interaction between the MJO and ER waves. Figure 7d shows the composite of simultaneous interaction between the MJO and ER waves, comparable with Fig. 4.

Comparison of Figs. 7c,d shows that although the results contain similar OLR and geopotential height anomaly structure, the geopotential height anomalies in these panels are characterized by much lower amplitudes than the simultaneous composites of MJO and ER wave events. The statistical significance of the amplitude differences between the MJO only and simultaneous MJO and ER wave composites was tested using the bootstrap sampling test described in section 2, demonstrating that assessment of ER wave and MJO events relative to one another yields more information about the extratropical circulation signals than can be obtained by assessing the signals associated with the two modes separately. As discussed above, this test result is robust to the sample size and the number of degrees of freedom included. Although the composite geopotential height patterns show some structural similarities to the composites based on RMM4 only, this outcome is not true for composites based on different ER wave base longitudes.
4. Conclusions and future work

Composite results demonstrate high-amplitude extratropical circulation patterns associated with the simultaneous assessment of MJO and ER wave events. These results were shown to be statistically significantly different at the 99% level from the composite based on MJO signals alone, implying that the amplitudes in the composite anomaly fields associated with these composites are unlikely to be explained by random chance or by a smaller number of degrees of freedom in the combined composites. In contrast, taking a sum of MJO and ER wave events yields little additional information about the extratropical circulation pattern than assessing the MJO separately. These results suggest that assessing ER waves relative to the MJO yields more information about the extratropical circulation than can be obtained from either mode alone or from a sum of the signals associated with the two modes separately.

The presence of upper-level westerly winds associated with the base state and the MJO, together with the climatological location of the mean subtropical jet suggest favorable conditions for intrusion of extratropical waves into the tropics (e.g., Webster and Holton 1982; Kiladis 1998; Matthews and Kiladis 1999). These patterns allow extratropical Rossby waves to project signals onto the ER wave band in the equatorial waveguide (e.g., Meehl et al. 1996; Kiladis 1998; Slingo 1998; Matthews and Kiladis 1999; Funatsu and Waugh 2008). The MJO thus modulates the locations of ER wave formation. Since the MJO and ER waves both act to organize convection as they intersect farther west, the interaction between the active convective phases of the resulting ER waves and the MJO would help to specify new locations of extratropical Rossby wave dispersion events into the midlatitudes from the tropics. Such Rossby wave dispersion depends on the locations of concentrated release of latent heat in the tropics (e.g., Sardeshmukh and Hoskins 1988), and since the ER waves concentrate heating in specific regions of the active convective envelope of the MJO while reducing heating in other regions, the maxima in upper-level mass divergence associated with the two modes combined would determine some of the source locations of Rossby wave dispersion into the midlatitudes. Thus, interactions between the MJO, ER waves, and extratropical Rossby waves can form a feedback loop that might yield better empirical prediction of the global atmospheric circulation.

Much work remains to be done to determine more specifically how ER waves and the MJO influence one another. The simultaneous composites revealed an expansion of the MJO convective envelope as ER waves neared the eastern flank of MJO convection a few days prior to lag zero. The approach of the ER wave from the east might moisten the atmosphere, preconditioning it
for local MJO development. However, the dynamics of this phenomenon are unknown. Additionally, little is known about the specific mechanisms whereby extratropical Rossby wave intrusion into the tropics forces equatorial Rossby waves. Analyzing synoptic extratropical Rossby wave activity over the central and eastern Pacific and the central and western Atlantic will likely yield a better understanding of the evolution of high-amplitude wave trains over these regions. Additional insight into the association of the observed central Pacific and Atlantic troughs with the observed amplifying central North Pacific and western North Atlantic ridges is also sought in these future analyses.

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