14D.3 MODULATION OF THE EXTRATROPICAL CIRCULATION BY COMBINED ACTIVITY OF THE MADDEN−JULIAN OSCILLATION AND EQUATORIAL ROSSBY WAVES

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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 in Southeast Asia, and the tropical Western Pacific Ocean.

Kiladis (1998) and Kiladis and Matthews (1999) addressed the role of equatorward-propagating extratropical Rossby waves, steered by the background circulation, in initiating equatorially trapped Rossby (ER) waves upon intruding into the tropics. Other studies by Roundy and Frank (2004b) and Masunaga (2007) have demonstrated associations between the circulation and convection associated with the MJO and ER waves.

This paper will address the associations between the MJO and ER waves, and suggest the potential for ER wave generation associated with extratropical Rossby wave intrusion into the tropics. ER waves will be assessed relative to the MJO during phase 4 in a smoothed version of the Real-time Multivariate MJO (RMM) indices of Wheeler and Hendon (2004). These assessments will demonstrate the importance of assessing ER waves relative to the MJO to additional information about the extratropical circulation.

Further, by assessing a simultaneous combination of the MJO and ER waves, a feedback loop between the tropics and extratropics is demonstrated, with the MJO, extratropical Rossby waves, and ER waves comprising the three modes of this feedback process.

2. DATA AND METHODOLOGY

NOAA interpolated outgoing longwave radiation (OLR) data and NCEP—NCAR reanalysis 300-hPa geopotential height and wind data were obtained from the Earth System Research Laboratory (ESRL). Anomalies were generated by subtracting the annual cycle and its first 4 harmonics. These data were averaged into four sets of composite MJO, ER wave, or simultaneous combinations of MJO and ER wave events following Roundy et al. (2010).

The first set of composites was calculated by averaging OLR and reanalysis data over all dates and corresponding time lags during NH winter, and phase 4 in the smoothed RMM indices with an amplitude exceeding ±0.75 standard deviations. The next three sets of composites were constructed based on OLR signals in the ER wave band, or based on these ER wave signals simultaneous with RMM phase 4.

The number of ER wave events exceeding 1 standard deviation crossing each 2.5-degree longitude grid point was counted for RMM phase 4. The grid point with the largest number of ER wave cresting events was selected as the ER wave base longitude for the composites. One set of composites was based on the dates of all ER wave cresting events at the identified base longitude, and another set was generated based only on the ER wave events identified during RMM phase 4.

3. RESULTS

The composites are presented here in the form of plan view maps and four sets of OLR Hovmöller diagrams. The Hovmöller diagrams show composite OLR anomalies averaged from 7.5°S to 7.5°N, and composite 300-hPa geopotential height anomalies averaged from 40°N to 50°N.

The first set of Hovmöller diagrams is based on averaging over periods of RMM phase 4 that exceeded 0.75 standard deviations. The second, third, and fourth sets of Hovmöller diagrams correspond to ER wave events, a linear combination of MJO and ER wave events, and the total OLR and geopotential height anomaly signals associated with a simultaneous

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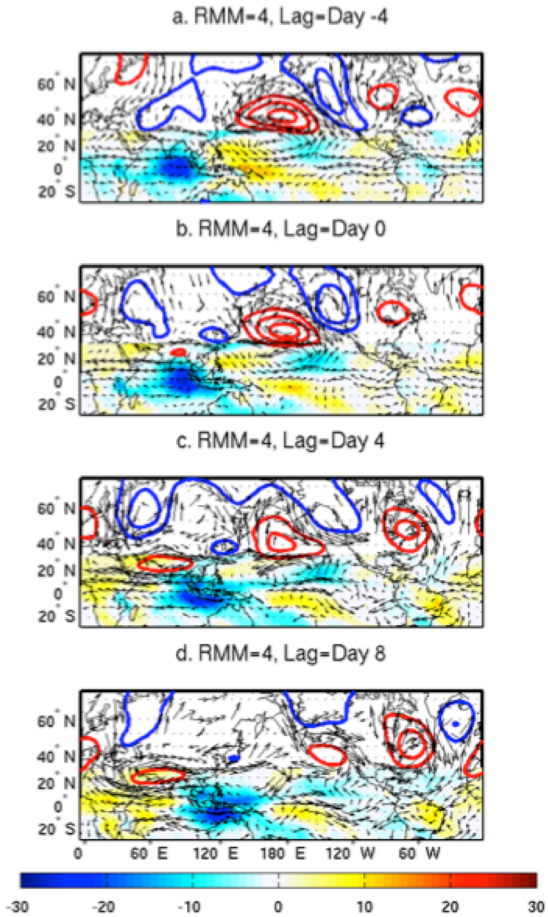

Fig. 1. Composite OLR (shaded from 30°N to 30°S according to scale) and 300-hPa geopotential height and total wind anomalies. Geopotential height contours are drawn every 20 m, with red contours corresponding to positive height anomalies beginning at +20 m, and blue contours corresponding to negative height anomalies beginning at -20 m.

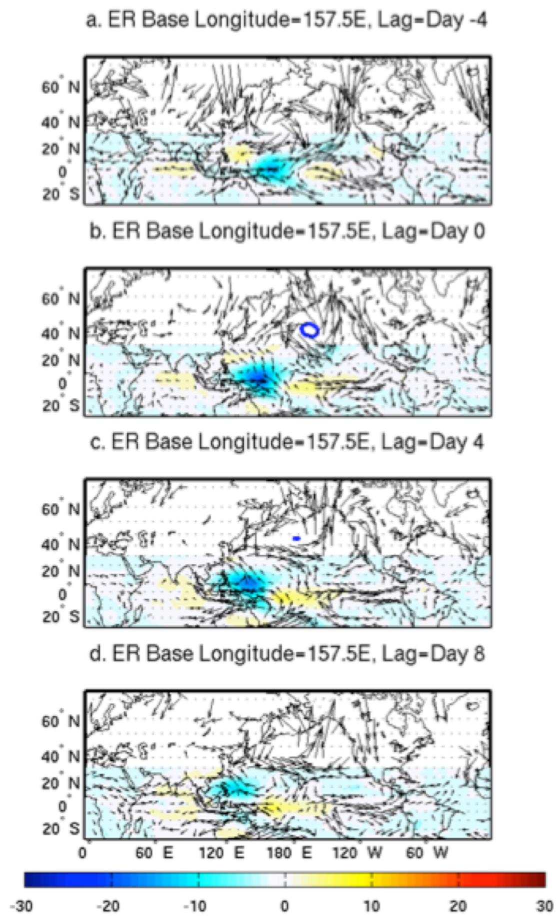

Fig. 2. As in Fig. 1, but for ER wave events.

assessment of MJO and ER wave events, respectively.

3.1 Composites Based on the MJO Alone

Composites of OLR, geopotential height, and total wind anomalies corresponding to RMM phase 4 show the widely known high amplitude response to MJO convection in the extratropics of the Northern Hemisphere (Fig. 1). A high-amplitude extratropical Rossby wave pattern with height anomalies ranging from +60 m to −40 m extends from the North Pacific, eastward to the North Atlantic.

The composite total wind anomaly field in the first three panels is consistent with a retracted subtropical jet over East Asia, with easterly wind anomalies providing evidence for an anomalously weak jet east of Japan.

An amplifying ridge, suggested by positive geopotential height anomalies, is present over the North Pacific, with a trough equatorward of this location. The origins of the tropical central Pacific trough remain to be investigated, but its presence suggests an interaction between the tropics and extratropics, possibly associated with an intrusion of extratropical Rossby waves into the tropics.

Work has been done to demonstrate associations between the intrusion of extratropical Rossby waves into the tropics and the generation of ER waves. Kiladis (1998) and Matthews and Kiladis (1999) demonstrated that extratropical Rossby waves, guided by the background circulation into the tropics, could project signals onto the ER wave mode in the equatorial waveguide, increasing the likelihood of the generation of ER waves.

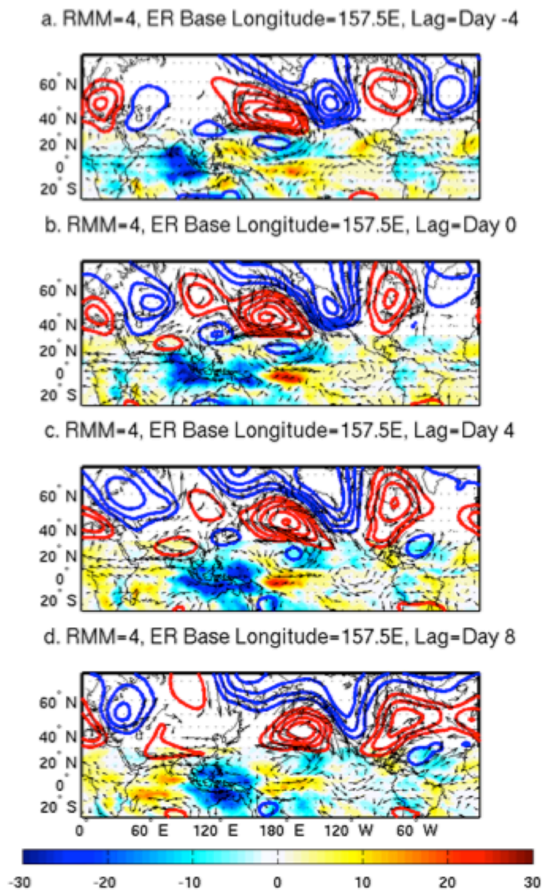

Fig. 3. As in Fig. 2, but for a simultaneous assessment of MJO and ER wave events.

3.2 Composites Based on ER Signals Alone

Composites based only on ER wave signals (Fig. 2) show lower amplitude geopotential height and OLR anomalies than the corresponding MJO composites shown in figure 1. Geopotential height anomaly amplitudes almost never exceed a 20 m threshold for contouring on each of the four panels, suggesting that, although the composite anomaly fields are statistically significant, assessing ER waves separately from the MJO yields less information about the extratropical circulation than assessing these events relative to the MJO.

Similar to the MJO composites, the composite wind anomaly field suggests an elongated subtropical jet across the central North Pacific on lag days 4 and 8 (Fig. 2c, d), with an amplifying ridge (evidenced by the 300 hPa wind anomalies) present over western North America.

3.3 Simultaneous Composites: ER Waves and MJO

Figure 3 provides the composite analysis based on the simultaneous combination of MJO and ER wave events. The magnitudes of both the OLR and geopotential height composite anomalies exceed the magnitudes of OLR, geopotential height, and total wind composite anomalies corresponding to separate assessments of the MJO and ER waves. This result provides additional evidence that supports assessing ER wave events relative to the MJO to gain the most information about the extratropical circulation.

Composite anomalies show double the amplitude of the MJO-only composites in some regions of the world, and this difference is robust in Monte Carlo tests in which an equal number of random pseudo "Rossby wave" dates are extracted from RMM phase 4 to generate new composites. Such composites generate anomaly amplitudes that are smaller than those associated with the true ER wave events identified for the simultaneous composites at the 99% confidence level.

The simultaneous composites demonstrate a high-amplitude extratropical Rossby wave pattern across the North Pacific and North America. Although there is no clear westerly wind anomaly present at 300-hPa over East Asia, a mean subtropical jet is present in the total wind field. To the east, an amplifying ridge is present over the North Pacific, with an amplifying trough equatorward of this location.

3.4 Comparison of Composites

Figure 4 provides a comparison of each of the aforementioned composites, as well as the addition of a linear combination of MJO and ER wave events using Hovmöller diagrams. The diagrams demonstrate a clear difference between the separate MJO and ER wave composites, the simultaneous composites, and the composites corresponding to the sum of MJO and ER wave events.

Diagrams corresponding to the MJO and the sum of MJO and ER wave events contain similar OLR and geopotential height anomaly structure. The geopotential height anomalies possess much lower amplitudes than the simultaneous composites of MJO and ER wave events. This

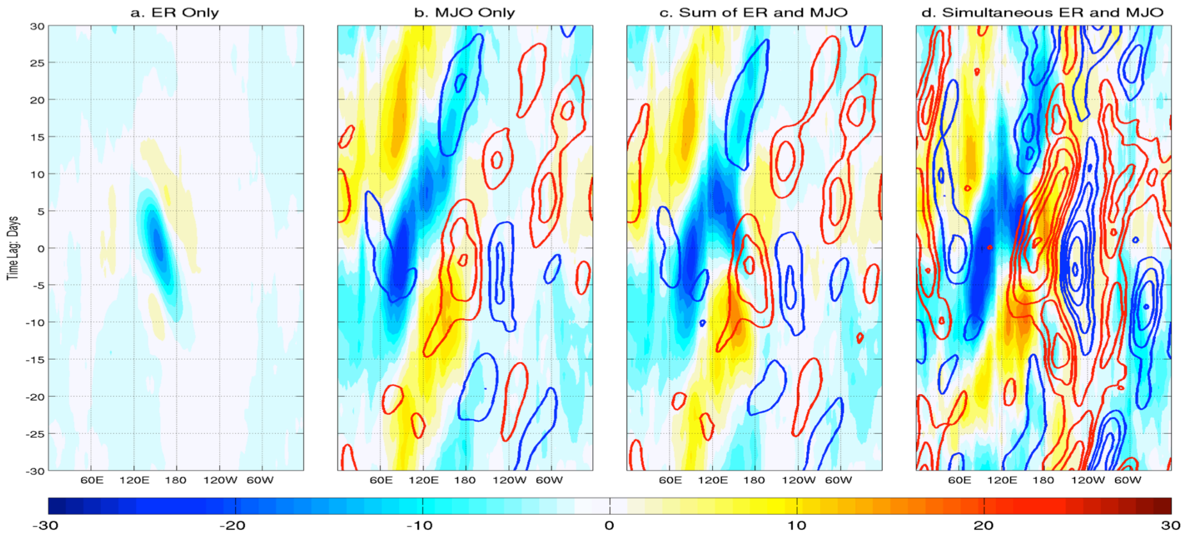

Fig. 4. Composite OLR (shaded in W m^{-2}) and 300-hPa geopotential height anomalies. MJO composites correspond to RMM phase 4. ER wave base longitude corresponds to 157.5°E. Geopotential height contours (red and blue) are averaged between 40°N and 50°N, and are drawn every 20 m. Red contours correspond to positive height anomalies beginning at +20 m, and blue contours correspond to negative height anomalies beginning at −20 m.

amplitude difference further demonstrates the importance of assessing ER wave events relative to the MJO events, as opposed to treating the two types of events separately.

4. CONCLUSION

Composite results have demonstrated that taking a linear combination of MJO and ER wave events yields little additional information about the extratropical circulation than assessing the MJO separately. These results suggest that assessing ER waves relative to the MJO yields far more information about the extratropical circulation than can be obtained from either mode alone or from a linear combination of the signals associated with the two modes separately.

Each set of composites suggests circulation patterns favorable for extratropical wave intrusion into the tropics. These patterns can allow extratropical Rossby waves to project signals onto the ER wave mode in the equatorial waveguide. The interaction between the active convective phases of the resulting ER waves and the MJO helps to specify new locations of extratropical Rossby wave dispersion events into the midlatitudes from the tropics. 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.

5. REFERENCES

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