13D.6 MODULATION OF THE MJO PV BUDGET BY ATMOSPHERIC CONVECTIVELY COUPLED KELVIN WAVES

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1. INTRODUCTION

Convectively coupled atmospheric Kelvin waves (hereafter "Kelvin waves") form a substantial part of the subscale anatomy of the Madden Julian oscillation (MJO, Madden and Julian 1994). The MJO modulates the background state of the atmosphere through which Kelvin waves travel, thereby allowing it to influence their structures and propagation. Within the local active convective phase of the MJO (hereafter just "active MJO"), Kelvin waves tend to propagate more slowly, occur more frequently, and attain higher amplitude than in other background states (e.g. Roundy 2008). These waves have been associated with the eastward moving "super cloud clusters" embedded within the MJO noted by Nakazawa (1988), who suggested that these clusters account for most of the rainfall within the active MJO. Most of the rainfall within these super clusters occurs in smaller convective elements that move mostly westward.

Roundy (2008) demonstrated that bands of cyclonic vorticity develop in the lower troposphere on the poleward sides of anomalies of convection coupled to Kelvin waves. These bands extend poleward and westward behind the convection. Ertel's potential vorticity (PV) is a convenient tool with which to track such development.

We hypothesize that diabatic signals associated with Kelvin waves might more effectively generate PV than destroy it. In that case, PV would increase across Kelvin wave convection but not decline substantially for an extended period afterward. This study analyzes generation of Ertel's PV by convection coincident with Kelvin waves, and its relevance to the MJO. The work presented here is a summary of that found in MacRitchie and Roundy (2012).

2. DATA AND METHODS

PV data on the 315K isentropic surface from the ECMWF interim reanalysis were used. These data span 1 January 1989 through 31 December 2010.

All PV data used in this study are anomalies with the time mean and the seasonal cycle removed. The PV data are given in potential vorticity units (PVU), which are defined as 10^{-6} m^2 s^{-1} K kg^{-1}.

NOAA interpolated outgoing longwave radiation (OLR) data were used to identify Kelvin wave events. These data were filtered for the Kelvin band in the manner of Straub and Kiladis (2003). Rainfall was estimated using Tropical Rainfall Measuring Mission (TRMM) 3B42 data. These data span 1 January 1998 through 31 December 2008.

This study employs a simple lag composite approach to diagnose the portions of PV signals that develop in association with Kelvin waves propagating through the active phase of the MJO. Three types of lag composites are created: one centered on the MJO, one centered on Kelvin waves, and another centered on Kelvin waves within the active MJO.

A time series of Kelvin filtered OLR averaged between 5°N to 5°S was obtained every 2.5° from 65°E to 115°E (for a total of 21 points). Active Kelvin wave events were defined as normalized OLR minima that exceeded -0.75σ and had no other qualifying minima within ±3 days. All events included occurred during the Northern Hemisphere cold season, defined as October through March. A composite Kelvin wave was made at each of the 21 longitudes by averaging unfiltered PV and OLR anomaly data over the dates of the active Kelvin waves (lag zero) and every day from 15 days prior to 15 days after. We also apply composite MJO-filtered OLR, which includes wave numbers 0-9 eastward and periods of 30-100 days.

MJO events were selected by using a modified version of the Real-time Multivariate MJO (RMM) indices (Wheeler and Hendon 2004; hereafter WH04), calculated following WH04 except from OLR and 850 and 200 hPa wind anomaly data pre-filtered for the MJO band to reduce noise and other signals. This pre-filtering

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removes Kelvin wave signals and other noise, which contribute significantly to the standard RMM PCs in a manner that would invalidate the composite analysis because it might specify some of the Kelvin wave signal. The principal components (PCs) were created by using data from 1979 through 2008. We divided the phase space spanned by the first two PCs into 8 phases as by WH04.

Figure 1 shows a comparison of our MJO PCs to the corresponding WH04 RMM PCs during an arbitrarily chosen 31-day period beginning 13 July 2002. The dark curve represents our version and the lighter curve represents the WH04 version. Our result is smoother, but otherwise comparable. We identified MJO events of a given phase on the dates when the amplitude (defined as the absolute value of the normalized PCs) was greater than 0.75σ.

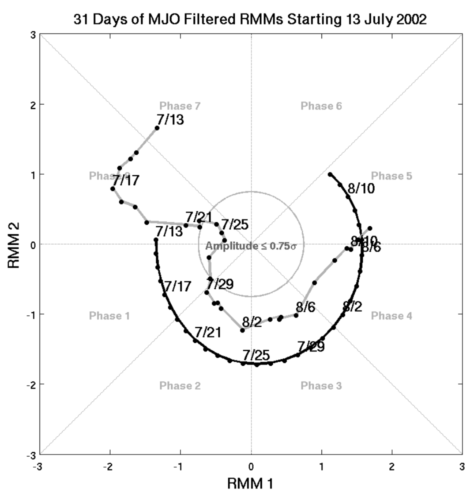

Figure 1: Comparison of filtered MJO phase space to WH04.

3. RESULTS

Composite Kelvin waves in phase 4 were created at each of the twenty-one longitudes described in Section 2. Composites based on Kelvin waves alone at the arbitrarily chosen longitudes of 70°E, 90°E and 110°E are shown in Fig. 2.

It is evident from this figure that the increase in PV across a Kelvin Wave, with no information about the state of the MJO, is very small. Figure 3 shows composites of Kelvin waves at the same longitudes in Fig. 2, but restricted to the subset of events that occurred when the MJO was in phase 4. Note that the color scales are identical between Figs. 2 and 3.

Figure 3 shows that Kelvin waves during the same MJO phase but at different longitudes still show pronounced increases in PV across the waves, with little gradual change in PV on the timescale of the MJO independent of the Kelvin waves.

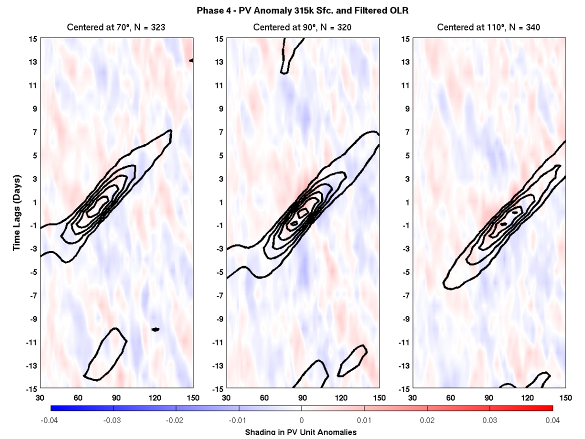

Figure 2: PV anomalies are shaded in PVU, with blue representing negative anomalies and red positive, averaged from 3°N-6°N. Solid black contours represent negative Kelvin-filtered OLR anomalies on the equator. Longitude is shown on the x-axis with time lags on y-axis.

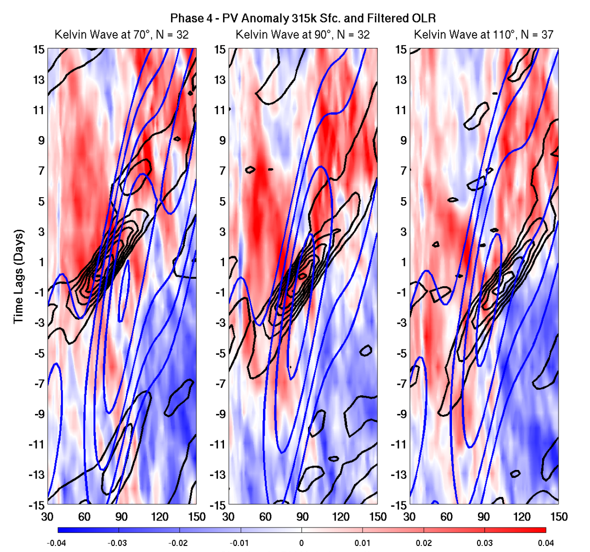

Figure 3: Solid blue contours represent negative MJO-filtered OLR anomalies contoured every -4 W/m2. The rest of the figure is plotted as in Fig. 2.

Similar plots at all other Kelvin base longitudes through the domain show clear migration of rapid PV increases with Kelvin waves. Keep in mind that each MJO event might have 1-4 Kelvin wave events, which could not each be specified in these composites. Nevertheless, this relationship suggests that the convection coincident with the Kelvin waves is a principal source of low-level PV in the active MJO.

Composites at all twenty-one longitudes, including those shown in Fig. 3, were shifted to be centered on the same longitude and averaged together to form a Kelvin wave-centric composite of the composites, to reduce terrain-influence. This result is compared to a composite centered only on days when the MJO is in phase 4, and the two are shown in Fig. 4. The black dotted areas represent results that are not statistically significantly different from zero at the 95% level using a 1000-iteration bootstrap test (e.g. Wilks 2005).

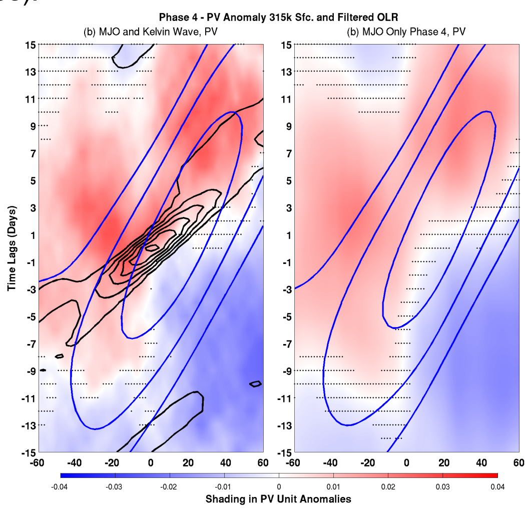

Figure 4: (a) Composite of Kelvin waves and (b) Composite of MJO events in Phase 4. Plotted as in Fig. 3 except that black dots represent statistically insignificant values of PV.

The transition between negative PV anomalies during earlier time lags and positive PV anomalies during later time lags occurs gradually on the same timescale as the MJO OLR anomalies. The gradual increase in PV in this composite does not necessarily imply that PV increases as gradually in individual events.

A simple analysis of unfiltered TRMM rainfall data and MJO and Kelvin-filtered OLR anomalies is helpful to understand why rapid changes in low-level PV occur across Kelvin waves. This analysis includes only the period of the TRMM data specified in Section 2.

First, we found the dates and grid points of all MJO-filtered negative OLR anomalies between 65°E and 65°W and from 10°N to 10°S using the same methodology described above to identify active MJO and Kelvin wave events. From that set of dates and locations, we found the subset in which the Kelvin band OLR anomalies were less than zero, and which also enclosed a minimum Kelvin band OLR anomaly of less than –0.75σ in space and time. The sum in time and space of rainfall in this subregion divided by the sum of rainfall throughout the entire MJO active region reveals that 62% of the total rainfall, within the active MJO, occurs within Kelvin waves.

Furthermore, the active Kelvin wave region accounts for 46% of the area of the active MJO region. Therefore, the rain rate per unit area within the active Kelvin wave is 135% of the rain rate per unit area within the active MJO region. Rain rates per unit area in the active MJO within the negative OLR anomalies of the Kelvin waves are 60% higher than those averaged across the entire negative OLR region of the active MJO and 88% higher per unit area than in the active MJO area outside of the Kelvin waves.

Thus most of the latent heat released within the active MJO occurs within the region occupied by the negative OLR anomalies of the Kelvin wavenumber frequency band. If most rainfall in the MJO occurs within these eastward waves, then most of the PV generated within the active MJO must occur following these waves. Analysis of phases 2-7 yields similar results.

4. CONCLUSIONS

Our results paint PV aspects of the MJO in a new light. Figures 2-4 suggest that low-latitude low-level PV increases rapidly within the active MJO across Kelvin waves. Our TRMM rainfall analysis shows that nearly 1.9x more rainfall occurs, per unit area, within the active convective phases of Kelvin waves than outside of them.

This analysis supports the hypothesis that most low-level PV increases in the MJO occur largely as a response to diabatic heating in convection coincident with the Kelvin waves. That convection is most directly associated with smaller scale disturbances moving westward through the Kelvin waves.

Recently, Zhang and Ling (2012; ZL12) concluded that PV associated with the MJO is not attributable to Kelvin waves. While their results contrast ours, differences in the analysis methods explain the discrepancies. In our result, PV increases rapidly across Kelvin waves, then remains relatively flat after the Kelvin wave passes. Linear regression of PV against Kelvin-filtered OLR anomalies as applied by ZL12 requires that the resultant regressed PV must be correlated with the Kelvin band OLR signal—that is, their result would indicate only the portion of PV that increases and then decreases directly with the amplification and subsequent weakening of the

Kelvin OLR anomaly. In short, our result demonstrates that the PV generated by convection coincident with Kelvin waves does not stay in the wave number frequency band of the Kelvin waves. Instead, it remains in the environment as part of the MJO.

The rapid adjustment of PV across Kelvin waves embedded within the active MJO suggests that these waves actively influence MJO dynamics. However, analysis of PV accounts for only one facet of the anatomy of the MJO. MJO events are also associated with substantial divergent circulations that would interact and evolve with the rotational patterns diagnosed by PV. Roundy (2008) showed substantial meridional divergence from Kelvin wave convection embedded in the active phase of the MJO, but little similar divergence associated with Kelvin waves propagating through the local suppressed MJO, suggesting that Kelvin waves might contribute both to divergent and rotational flow in the MJO. This study represents the first step in a more extensive analysis of the associations between rotational and divergent circulations associated with Kelvin waves and the MJO including interactions with extratropical waves.

Acknowledgements: Funding was provided by NSF from grant 0850642 to Paul Roundy. OLR data were obtained from the Earth System Research Laboratory/Physical Science Division. PV data were obtained from the European Centre for Medium Range Weather Forecasting. This work benefitted greatly from discussions with Chidong Zhang and George Kiladis.

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