Potential Vorticity Accumulation Following Atmospheric Kelvin Waves in the Active Convective Region of the MJO

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ABSTRACT

Previous works have shown that most of the rainfall embedded within the Madden–Julian oscillation (MJO) occurs in large eastward-moving envelopes of enhanced convection known as super cloud clusters. Many of these superclusters have been identified as convectively coupled Kelvin waves. In this work, a simple composite-averaging technique diagnoses the linear and nonlinear contributions to MJO potential vorticity (PV) structure by convection collocated with Kelvin waves. Results demonstrate that PV is generated coincident with active convection in Kelvin waves, but that this PV remains in the environment after Kelvin wave passage and becomes part of the structure of the MJO. Analysis of the Tropical Rainfall Measuring Mission (TRMM) rainfall suggests that 62% of the total rainfall within the MJO occurs within the active convective phases of the Kelvin waves (88% higher than the rain rate that occurs outside of the Kelvin waves), supporting the hypothesis that diabatic heating in cloud clusters embedded within the Kelvin waves generates this PV.

1. Introduction

Convectively coupled atmospheric Kelvin waves (hereafter “Kelvin waves”) form a substantial part of the subscale anatomy of the Madden–Julian oscillation (MJO; Zhang 2005; 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., Dunkerton and Crum 1995; Roundy 2008). These waves are associated with eastward-moving “super cloud clusters” embedded within the MJO (Nakazawa 1988). Nakazawa (1988) suggested that these clusters account for most of the rainfall within the MJO. Rainfall in these superclusters in turn 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. Schreck and Molinari (2011) demonstrated accumulation of positive low-level PV poleward of Kelvin wave convection over the western North Pacific Ocean. Schubert and Masarik (2006) analyzed PV generation in the MJO. They demonstrated that cyclonic PV accumulates at the low levels within the active MJO. More recently, Zhang and Ling (2012, hereafter ZL12) analyzed the variation of PV with the MJO. They provide a thorough overview of analysis of PV in the MJO and equatorial waves. They demonstrated that most PV generated within the active MJO develops from processes of different temporal and spatial scales than the MJO. Through linear regression they further demonstrated significant PV anomalies in Kelvin waves, contrary to the expectations of linear wave theories. The PV generation on isentropic surfaces can be attributed to diabatic heating (e.g., Hoskins et al. 1985), so it is not surprising that convection coupled to Kelvin waves generates PV. ZL12 further suggest that PV generated by Kelvin waves contributes little to total PV within the MJO. However, their approach might be insufficient to diagnose the impacts of rainfall coincident with Kelvin waves, because diabatic signals associated with Kelvin waves might more effectively generate PV than destroy it. In that case, PV would increase across

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Kelvin wave convection but not decline substantially for an extended period afterward. PV generated by rainfall within Kelvin waves would thus not occur in the Kelvin band, but at lower frequencies. Linear statistics combined with filtering in the wavenumber frequency domain for Kelvin waves as by ZL12 would not diagnose such signals. This paper analyzes the generation of ErTEL’s PV by convection coincident with Kelvin waves and its relevance to the MJO.

2. Data and methodology

PV and wind data on the 315-K isentropic surface were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis. This surface was chosen because it is representative of the lower troposphere in the tropics. These data span 1 January 1989–31 December 2010. Anomalies are calculated by removing the time mean, the annual cycle, and the first three harmonics of the seasonal cycle. The PV data are given in customary potential vorticity units (PVU), defined as $10^{-6}$ m$^2$ s$^{-1}$ K kg$^{-1}$ (e.g., Hoskins et al. 1985).

The National Oceanic and Atmospheric Administration (NOAA) interpolated outgoing longwave radiation (OLR; Liebmann and Smith 1996) data were applied to identify Kelvin wave events. These data were filtered for the Kelvin band in the manner of Straub and Kiladis (2003). We also apply composite MJO-filtered OLR, which includes wavenumbers 0–9 eastward and periods of 30–100 days. Rainfall was estimated using the Tropical Rainfall Measuring Mission (TRMM; Huffman et al. 2007) 3B42 data, which span 1 January 1998–31 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 MJO. Wheeler et al. (2000) and others have shown that Kelvin band filtering, when combined with regression or composite analysis based on filtered data near the equator, reveals well the coherent signals that largely relate to Kelvin waves without more complicated analysis. 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 and 5°S was obtained every 2.5° from 65°E to 115°E (for a total of 21 points). Active Kelvin wave events were identified as normalized OLR minima that exceeded $-0.75\sigma$ (where $\sigma$ represents one standard deviation) with no other qualifying minima within ±3 days. All events included occurred during October–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 0) and every day from 15 days prior to 15 days afterward.

MJO events were selected using a modified version of the Real-time Multivariate MJO (RMM) indices (Wheeler and Hendon 2004, hereafter WH04), calculated following WH04 except that OLR and 850- and 200-hPa wind anomaly data were prefiltered for the MJO band as in Wheeler and Kiladis (1999) to reduce noise and other signals. The wind data were obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996). This prefiltering removes Kelvin wave signals, 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 (Roundy et al. 2009). The principal components (PCs) were created using data from 1979 through 2008. We divided the phase space spanned by the first two PCs into eight phases as by WH04.

Figure 1 compares our MJO PCs to the corresponding WH04 RMM PCs during an arbitrary 31-day period beginning 13 July 2002. Our result is smoother, but otherwise comparable. Events were included when the amplitude (defined as the absolute value of the normalized PCs) was greater than 0.75$\sigma$.

3. Results

The remainder of this paper focuses on phase 4 for brevity. Although not shown, with the exceptions of
phases 1 and 8, the results for phase 4 are similar except for zonal translation. Phases 1 and 8 represent active convection across the Western Hemisphere and Africa, where MJO deep convection normally propagates eastward much more quickly and occurs over narrow meridional bands. The distinction of these phases is therefore not surprising.

Composite Kelvin waves in phase 4 were created at each of the 21 longitudes described in section 2. Composites based on the Kelvin wave alone are not shown but are similar to those shown by ZL12 except with some elevated PV remaining after Kelvin wave passage. Each of these composites was 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. The result is shown in Fig. 2a. The PV anomalies are shaded (PVU), with blue representing negative anomalies and red positive, averaged from 3° to 6°N. Solid contours represent negative PV anomalies, both on the equator. Longitude is shown on the x axis with time lags on the y axis. The black-dotted areas represent results that are not statistically significant at the 95% level using a 1000-iteration bootstrap test (e.g., Wilks 2006). This test was applied to the composites at each individual base longitude.

Figure 2b shows the composite based on the MJO without respect to Kelvin waves, plotted as in Fig. 2a. The transition between negative PV anomalies during earlier time lags and positive PV anomalies during later time lags occurs gradually on the same time scale 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.

Figure 3 shows composite maps of the same events used to generate Fig. 2a. Figure 3a represents lag −2 days, Fig. 3b shows lag 0 days, and Fig. 3c shows lag +2 days. The shading is as in Fig. 2. Vectors represent 850-hPa wind anomalies. Solid contours represent negative Kelvin-filtered OLR anomalies, both on the equator. Longitude is shown on the x axis with time lags on the y axis. 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 2006). This test was applied to the composites at each individual base longitude.
(active) MJO-filtered OLR and dashed contours represent negative Kelvin-filtered OLR. Both sets of contours begin at $-4 \text{ W m}^{-2}$ with a contour interval of $-4 \text{ W m}^{-2}$. A positive PV anomaly is seen near the center of the Kelvin wave convection. As the Kelvin wave moves eastward, the PV generation continues with the old PV staying behind within the MJO, resulting in a strip of positive PV. The alternating PV anomalies shown in these maps are consistent with the cyclonic and anticyclonic gyres often associated with the MJO (Zhang 2005).

Figures 4a–c shows some of the 21 aforementioned composites at 70°, 90°, and 110°E, respectively, plotted as in Fig. 2a. These results show 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 time scale of the MJO independent of the Kelvin waves. 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
from one to four Kelvin wave events, which could not be individually specified in these composites (the timing between individual Kelvin waves varies between events, so that their signals average out). Nevertheless, this relationship suggests that the convection coincident with the Kelvin waves is a principal source of low-level PV in the active MJO.

Although Figs. 2a, 3, and 4a–c are based on the same MJO events that were included in Fig. 2b, the transition from negative to positive PV anomalies in the active phase is much more abrupt because they are fixed on the timing of the Kelvin waves. Kelvin waves also occur in each of the MJO events included in Fig. 2b, but their specific timings vary between events, leading to a smoother composite. Our hypothesis is that this PV generation is caused by diabatic heating coincident with the passage of the Kelvin wave and that the PV remains in the environment as part of the MJO as the Kelvin wave moves east.

A simple analysis of unfiltered TRMM rainfall data (hereafter just “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. 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 that 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

Fig. 4. Hovmöller composites of Kelvin wave events that occur within active MJO phase 4 regions. Longitudes are as in Fig. 3. Colors and shading are as in Figs. 2 and 3.
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 wave-number 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.

We have shown that most of the PV generated within the MJO occurs within the active convective phases of Kelvin waves. However, we did not show whether rainfall and PV within these Kelvin waves differs from any other modes. A similar analysis to that above demonstrates that 17% more rainfall (corresponding to 60% more in Kelvin waves) occurs within the negative OLR anomalies of the equatorial Rossby wave band of Roundy and Frank (2004) than occurs on average across the negative OLR anomaly of the MJO. Obviously each of these quantities is not exclusive, as wave signals overlap. For example, Nakazawa (1988) showed, using cloud brightness temperature data, that westward-moving cloud clusters produce their maximum rainfall within the eastward-moving superclusters, which were later associated with Kelvin waves. Nevertheless, if the composite analysis shown in Fig. 2a is calculated based on unfiltered OLR minima within the MJO instead of Kelvin band OLR minima, the basic structures in Fig. 2a are reproduced, including the Kelvin waves, with little evidence of westward-moving waves. Thus the Kelvin wave signals clearly dominate over all others larger than the mesoscale.

4. Summary and conclusions

Our results paint PV aspects of the MJO in a new light. Figures 2 and 3 suggest that low-latitude low-level PV increases rapidly within the active MJO across Kelvin waves. Nearly 1.9 times more rainfall occurs, per unit area, within the active convective phases of Kelvin waves than outside of them. Equatorial Rossby waves contribute less rainfall, and likely less PV, within the MJO than Kelvin waves. 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 (e.g., Nakazawa 1988).

Recently, 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 wavenumber 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, as discussed by ZL12, 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.

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