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The effects of equatorial Kelvin waves and mixed-Rossby gravity waves on the mesoscale structure of tropical oceanic convection

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1 Introduction

Large-scale tropical deep convection is associated with several types of synoptic disturbances. Kelvin and mixed-Rossby gravity (MRG) waves are convectively coupled equatorial waves with distinct signatures in the outgoing longwave radiation (OLR) frequency-wavenumber spectrum. This study investigates whether these synoptic differences result in differences in radar-observed mesoscale precipitation structures.

Sobel et al. (2004) (hereafter S04) used an OLR anomaly technique from Wheeler and Kiladis (1999) to link Kelvin and MRG waves to major storm events in the western tropical Pacific during the Tropical Rainfall Measuring Mission Kwajalein Experiment (KWAJEX), centered on Kwajalein Atoll in the Republic of the Marshall Islands (Yuter et al., 2005, hereafter Y05).

Swann et al. (2006) (hereafter S06) also used the Wheeler and Kiladis (1999) OLR method to examine storms associated with Kelvin and MRG waves affecting Kwajalein during the rainy seasons of 1999-2002. By constructing composites of radar data for each type, S06 looked for differences in statistical distributions of reflectivity between the two wave types. S06 identified 26 separate Kelvin wave precipitation events totaling 59 days and 18 MRG cases totaling 38 days.

The lengths of the individual events found in S06 varied from 0.5 to five days. There was no real difference in length distribution between wave types. Contoured frequency-by-altitude diagrams (CFADs - Yuter and Houze, 1995) of radar reflectivity were similar between accumulated Kelvin radar volumes and those of MRG (Fig. 1a and d). Overall, the Kelvin distribution mode was shifted toward slightly lower reflectivities. A lower reflectivity mode suggests more stratiform precipitation, indicating more mesoscale organization for Kelvin-related storms since mesoscale circulations are needed to sustain large stratiform areas (S06).

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In this study, the data set from S06 is used to address several questions regarding the two wave types: (1) Is one wave type 'rainier' than the other? (2) Do three-dimensional (3D) convective and stratiform components vary? (3) Do relationships among convective, stratiform, and total areas vary?

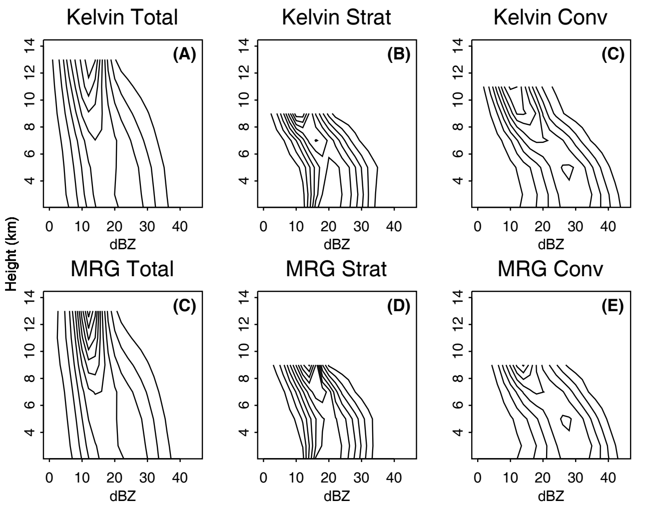

Fig. 1. Contoured frequency-by-altitude diagrams of radar reflectivity for precipitation-type subsets of Kelvin and MRG events. All radar volumes for Kelvin and for MRG are merged into respective ensembles and interpolated to 1 km horizontally and vertically, with contour intervals of 0.125% data dBZ^{-1} km^{-1}. Convective and stratiform precipitation are separated following Y05.

2 Data

The operational S-band Kwajalein radar obtains volume scans every 10-12 minutes. The radar data used here are the same as for S06, with quality control, interpolation, and tabulation described in Y05. Radar data are also separated into convective and stratiform precipitation components following Y05.

3 Results

At 0.5 km height, the area frequency distribution among the Kelvin and MRG radar volumes is logarithmic, with MRG volumes more skewed toward smaller areas than Kelvin volumes (Fig. 2). Fig. 3 indicates the fractions of Kelvin and MRG volumes in area bins every 10,000 km^2 for total and stratiform area and every 2,000 km^2 for convective area. The area frequency distributions all show a trend of fewer smaller areas and larger median and maximum areas in Kelvin radar volumes compared to MRG. These trends are replicated in the 3D volume distributions as well.

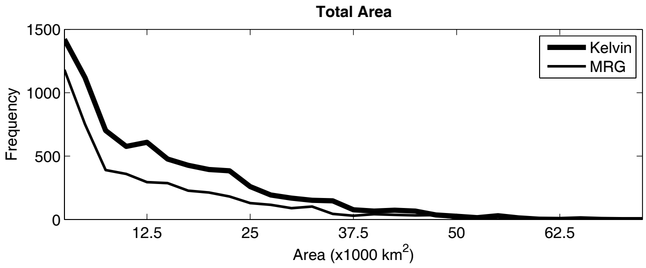

Fig. 2. Frequency distribution of areas for Kelvin and MRG radar data at 0.5 km height. Frequencies are not normalized to account for more Kelvin volumes than MRG.

Four separate Kelvin events reach larger total precipitation area than that of any MRG event. The distribution of event-summed precipitation coverage (not shown) indicates a higher frequency of larger coverage in Kelvin events than MRG. Specifically, 51% of total Kelvin areas and 59% of MRG areas are less than 10,000 km^2, while 10% of Kelvin areas and 7% of MRG areas are greater than 30,000 km^2. Using a mean rain rate of 2.1 mm h^{-1} found during KWAJEX (Y05) and an approximate convective:stratiform rainrate ratio of 3:1, the normalized frequency distributions of event-summed precipitation totals are very similar to the area frequency distribution. This similarity suggests that precipitation area for event totals is a good proxy for rainfall accumulation at Kwajalein, and Kelvin events have a higher frequency of larger rainfall totals than MRG.

The similarities between wave types noted in S06 for the 3D vertical reflectivity distribution ensembles are also present in convective and stratiform precipitation components (Fig. 1b,c,e,f). The ensemble convective CFADs, however, indicate that MRG storms may have lower maximum radar echo top heights than Kelvin. This will be examined in future research.

At 0.5 km height, total precipitation area in the scan volume is tightly coupled with stratiform area for both wave types (not shown). Correlation values are near 1, and Kelvin and MRG have nearly identical linear regression equations: $S=0.84T-790$ for Kelvin and $S=0.86T-860$ for MRG, where S is stratiform precipitation area in km^2 and T is total area.

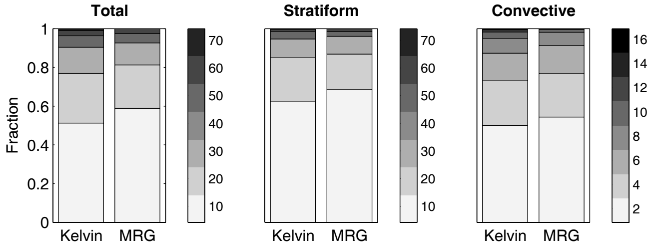

Fig. 3. Fraction of Kelvin and MRG volumes corresponding to different area size categories indicated by shadings (x1000 km^2). Note scales for convective area differ from those for total and stratiform.

Fractions of stratiform area per unit total area are also examined following Yuter and Houze (1998) (hereafter Y98). There is a definite range of stratiform fractions and associated total areas that did not occur in the events examined, similar to Y98 results from the west Pacific warm pool (Fig. 4). For total areas greater than about 10,000 km^2 there is an observed minimum amount of stratiform fraction per total area, and above about 20,000 km^2 this minimum is generally larger for MRG than Kelvin for a given total area. A line is drawn for MRG in Fig. 4 to mark the approximate minimum stratiform fraction per total area. This line is superimposed onto Kelvin to highlight the larger minimum stratiform fractions per total area for MRG. As total area increases, the minimum stratiform fraction increases toward 1.0 (more steeply for Kelvin because of larger observed Kelvin areas).

Unlike stratiform area, the amount of scatter in the convective-to-total area relationship prevents prediction of convective area from total area (Fig. 5). Convective areas vary in size for a given total area but appear to have a size limit as a function of total area. We define maximum potential area as the maximum observed convective area associated with a given total area. Convective areas larger than this maximum are not observed. The maximum potential convective area increases with increasing total area to a certain threshold of total area and then decreases. An approximate line following this maximum is shown in Fig. 5 for Kelvin and reproduced for MRG for total areas through 20,000 km^2.

The peak in maximum convective area (at ~42,000 km^2 total area for Kelvin, ~28,000 km^2 for MRG) is about 1,000 km^2 larger for Kelvin events than MRG. This peak value suggests a maximum amount of sustainable convective precipitation and the total precipitation size at which it occurs. The 14,000 km^2 difference between Kelvin and MRG in total size at peak convective size suggests that above a total area of about 28,000 km^2, Kelvin events can support more convective precipitation than MRG. This difference is roughly proportional to the difference between the two waves in the range of observed total area values.

Stratiform area shows a rather weak positive correlation with convective area for both wave types (0.55 Kelvin, 0.53 MRG). Preliminary analysis suggests a lagged relationship between the two precipitation types, with convective:stratiform area correlations increasing through a 2-hour lag and then decreasing. A lagged relationship is consistent with conceptual models of stratiform precipitation occurring in older convection regions (Houze (1997)), but the apparent lag length of 2 hours is surprising and warrants further investigation.

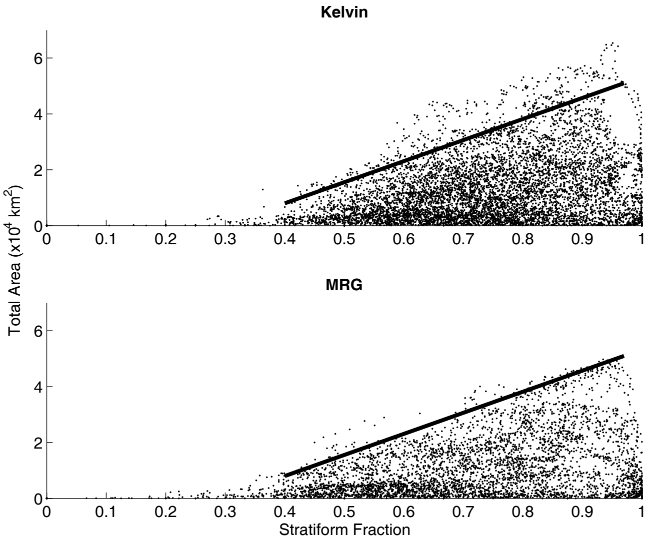

Fig. 4. Scatter plot of total precipitation area and corresponding stratiform precipitation fraction. A line is fit approximately to the boundary of minimum stratiform fraction per total area for MRG and superimposed onto Kelvin.

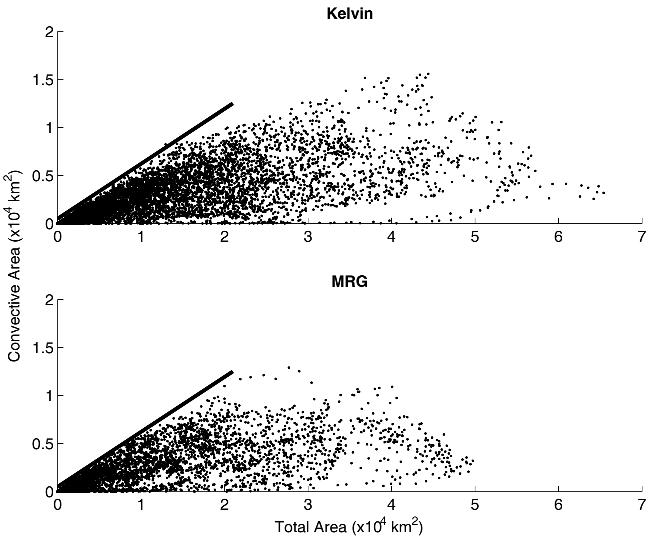

Fig. 5. Scatter plot of areas of convective and total precipitation for the radar volumes from Kelvin and MRG events. The line on each graph is the same and roughly indicates the maximum observed convective area for a subset of total areas.

4 Conclusions

The S-band radar on Kwajalein Atoll in the tropical western Pacific is used to investigate potential differences in precipitation structure for two types of convectively coupled equatorial waves. Twenty-six Kelvin wave events consisting of 7451 radar volumes and 18 mixed-Rossby gravity (MRG) events consisting of 4558 radar volumes across the 1999-2002 rainy seasons are examined, excluding precipitation not associated with either Kelvin or MRG wave events. The radar observes a domain of $7x10^4$ km^2, which is usually smaller than the size of the larger precipitation events. The synoptic differences in Kelvin and MRG waves manifest as differences in mesoscale precipitation structures, especially for the subset of larger storms and in the frequency distribution of storm areas. Because the radar volumes are dominated by small precipitation areas, the similarities between CFADs suggests that smaller area storms are very similar between the two wave types. That smaller Kelvin and MRG storms have similar strictures is further supported by similarities in frequency contours of smaller areas and nearly identical linear fits for convective- and stratiform-to-total areas.

Similar to previous studies, the distribution of precipitation areas is logarithmic for both wave types. Kelvin events exhibit a higher frequency of larger precipitation areas and MRG a higher frequency of smaller areas. Using the radar-derived KWAJEX mean rainrate (Y05) and a 3:1 convective:stratiform rainrate ratio, event-summed precipitation totals are roughly proportional to event-summed precipitation areas, indicating that Kelvin events are more often 'rainier' than MRG events.

The 3D reflectivity distributions for the ensembles of the Kelvin and MRG events are nearly identical between wave types within the convective and stratiform precipitation categories. However, these statistics are heavily weighted by the more frequently occurring smaller storms. The next step in the analysis will subdivide the CFADs by total storm area.

Stratiform areas increase linearly with total precipitation areas for both wave types. Correlations are near 1 and the equation of the least squares regression fit is nearly identical for both types. In contrast, there is a large scatter between convective and total precipitation areas. The maximum observed convective area for a given precipitation area increases to a certain threshold and then sharply decreases. The existence of this threshold implies that there is a maximum amount of convective precipitation that a storm event can sustain and this corresponds to a particular total storm area. For the subset of storms larger than 28,000 km^2 (11% of Kelvin volumes, 9% of MRG volumes), Kelvin storms can sustain more convective precipitation than MRG storms.

While stratiform area can be well predicted from total precipitation area, the stratiform area fraction (stratiform area percentage of total area) shows considerably more scatter. There is a distinct minimum stratiform area fraction as a function of total area for both wave types, similar to results from Y98 for the western Pacific warm pool. For smaller total areas (< 10,000 km^2) the stratiform area fraction can be any value. For total areas greater than 10,000 km^2, the minimum stratiform fraction increases towards 1.0 with increasing total area more steeply for Kelvin than for

MRG. As such, for total areas larger than about 20,000 km^2, Kelvin stratiform fractions are generally smaller than MRG for a given total area. The non-occurrence of observed stratiform fractions below this minimum as a function of total area could be used as an evaluation criterion for numerical model output.

Whereas S06 and this study examined the full set of Kelvin and MRG cases, further analysis will partition the data set by total area size since the larger precipitation areas appear to exhibit more differences in precipitation structure between Kelvin and MRG wave types than smaller areas. Future work will investigate the differences in echo top heights suggested by the Kelvin and MRG ensemble CFADs. The intriguing 2-hour lag correlation between convective and stratiform precipitation will be explored. The upper-air sounding analysis from S04 will be extended to include regional operational soundings for the 1999-2002 rainy season periods corresponding to the Kelvin and MRG events. This larger data set will be used to calculate composite soundings before, during, and after the events to determine differences in the environment associated with Kelvin and MRG waves.

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