Observations of a Super Cloud Cluster Accompanied by Synoptic-Scale Eastward-Propagating Precipitating Systems over the Indian Ocean

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ABSTRACT

The multiscale structure of a super cloud cluster (SCC) over the equatorial Indian Ocean, observed in November and December 2006, was investigated using data from satellite microwave sensors and surface-based radars. The smaller-scale structure of this SCC was marked by a complicated relationship between rainfall systems and upper-tropospheric cloud shields, which moved eastward and westward, respectively, with a cycle of 2–4 days. In the analyses, attention was given to the structure of slow eastward-propagating (5–11 m s⁻¹) precipitating systems and related synoptic-scale (~2000 km) disturbances. A case study of one of the systems revealed that it consisted of several lines of convective cells with a depth that was usually shallower than 10 km unless the cells encountered the westward-moving cloud shields. The environment of the convective lines was characterized by persistent unstable conditions with an increase of the westerly flow in the lower troposphere, suggesting the existence of a synoptic-scale upward motion. Composite analyses revealed that each rainfall system formed in a region of zonal flow convergence near the surface and divergence near 300 hPa. The vertical temperature structure tilted westward with height below this pressure level and eastward aloft, similar to that of a convectively coupled Kelvin wave. These results suggest that a SCC involves a group of synoptic-scale shallow waves propagating eastward. An additional analysis over the western Pacific also showed the predominance of eastward propagation in a SCC, demonstrating the advantage of satellite microwave sensors over infrared ones in monitoring the multiscale structure of tropical convection.

1. Introduction

A super cloud cluster (SCC) is an ensemble of equatorial clouds with a horizontal scale of several thousand kilometers (Nakazawa 1988). Such a cluster propagates eastward with a phase speed of about 10–15 m s⁻¹, similar to the eastward propagation of a large-scale disturbance such as the Madden–Julian oscillation (MJO) (Madden and Julian 1971, 1972, 1994) and a convectively coupled Kelvin wave (e.g., Nakazawa 1988; Wheeler et al. 2000; Straub and Kiladis 2002). It is known that the SCC has a hierarchical structure: it consists of several cloud clusters (CCs) with a scale of several hundred kilometers (e.g., Nakazawa 1988; Sui and Lau 1992), each involving mesoscale convective systems (MCSs) of several tens of kilometers scale (e.g., Mapes and Houze 1993). One of the interesting characteristics of the SCC is the diversity of the direction of movement of clouds within it. Using satellite infrared (IR) imagery, Nakazawa (1988) shows that each CC moves westward and the successive CC formation east of an older one leads to the overall eastward propagation of the SCC. On the other hand, Chen et al. (1996) pointed out that some CCs observed during the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) were stationary and a few moved eastward, although most moved westward. In addition, some studies using Doppler radars during TOGA COARE shows a more complicated nature of the MCS motion: that is, a leading convective line propagates eastward, while overlying cloud tops observed by the satellite move in the opposite direction (westward), under prevailing westerlies in the lower troposphere and easterlies aloft (LeMone et al. 1998; Rickenbach 1999; Halverson et al. 1999). The eastward propagation of convective areas has also been reported in a study using a shipborne Doppler radar over the equatorial western Pacific (Kubota et al. 2006). These studies suggest that the actual behavior and

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propagation of MCSs cannot always be viewed from satellite IR images because they are sometimes masked by upper-tropospheric cloud shields.

On the other hand, both IR and outgoing longwave radiation (OLR) data have been utilized to clarify the participation of waves and oscillations in the equatorial cloud motion. Wheeler and Kiladis (1999) and Wheeler et al. (2000) have demonstrated the utility of wavenumber-frequency spectrum analysis of OLR data for identifying large-scale convectively coupled waves such as Kelvin, equatorial Rossby, mixed Rossby–gravity, and inertio–gravity waves. Because of the spatial and temporal resolution of the OLR data, the application of this analysis is restricted to waves with zonal length larger than 2500 km (or wavenumber \( \geq 14 \)), Wheeler and Kiladis 1999).

Smaller-scale oscillations, such as synoptic-scale waves (i.e., \( \geq 3000 \) km, 2 to 3 day cycle), have been studied using a composite technique of IR data. The relevance of westward-propagating inertio–gravity waves to the westward propagation of CCs has been examined in several studies (Takayabu 1994; Takayabu et al. 1996; Haertel and Kiladis 2004). Clayson et al. (2002) examined bandpass-filtered OLR and IR data in the TOGA COARE region and pointed out that not only westward inertio–gravity waves but also eastward ones influence the 2–3-day variability of equatorial convection.

While these analyses demonstrate the relevance of waves to clouds with tops in the upper troposphere, a numerical study by Numaguti and Hayashi (2000) pointed out that waves are not always accompanied by deep convective activity. The two-dimensional simulations of their study demonstrated that eastward propagating waves can couple with deep convective clouds only after sufficient moistening and cooling in the low and middle troposphere. This study also showed that the eastward propagation is characterized by a slow-moving shallow-mode gravity wave, “chased” by a fast-moving deep-mode one, before the evolution of deep convective clouds due to the coupling of the two waves. The role of gravity waves with different vertical wavelength in triggering deep convective clouds has also been demonstrated by Tulich and Mapes (2008). These studies provide another point of view, namely that there may be a phase without deep convection in equatorial (especially eastward propagating) disturbances within a SCC. Analyses of TOGA COARE data (Johnson et al. 1999) provide evidence of abundant populations of convective clouds with tops between 4.5 and 9.5 km throughout periods including both convectively active and inactive phases. The relevance of disturbances to nondeep convective clouds, however, has not been studied because of the limited ability of IR and OLR data in monitoring clouds of shallow to medium depth, as described above. This suggests the necessity to use other instruments for monitoring the behavior and evolution of clouds so as to understand the mechanism of the multiscale organization of a SCC.

In recent years, a method for retrieving rain rates over the ocean from satellite microwave radiometers has been established (Wentz and Spencer 1998), and the data have been applied to investigations on the climatological characteristics of tropical rainfall, such as diurnal variation (Imaoka and Spencer 2000) and regional variability (Berg et al. 2002). An advantage of the microwave-retrieved data over IR and OLR is the capability to measure intense rainfall from MCSs even if they are covered by upper-tropospheric cloud shields. The application of microwave remote sensing to study the hierarchical structure of a SCC will provide new insight into the behavior and propagation of convective elements. At present, it is possible to obtain a large-scale map of rainfall in the tropical area twice daily by combining several of the existing microwave sensors, such as the Special Sensor Microwave Imager (SSM/I, F13–15), the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), and the Advanced Microwave Scanning Radiometer (AMSR-E).

This means that the propagation of convectively coupled synoptic-scale disturbances within a SCC can be captured using existing microwave products. Cho et al. (2004) demonstrated the utility of the TRMM rainfall measurements to identify large-scale equatorial waves.

Moreover, a field experiment using both shipborne and ground-based Doppler radars was carried out in the equatorial Indian Ocean from October through December 2006. This observational campaign, the Mirai Indian Ocean Cruise for the Study of the Madden–Julian Oscillation-Convection Onset (MISMO), had as its objective to understand the onset mechanism of convection associated with the MJO at the beginning of a boreal winter. Yoneyama et al. (2008) reported that a large-scale deep cloud system developed over the experimental area in late November and moved eastward. The filtered OLR data identify this convective signal as a weak MJO. This observation provides a great opportunity to examine the detailed behavior and propagation of convective elements associated with synoptic-scale disturbances within a SCC using a combination of microwave-retrieved and radar-derived datasets. The purpose of the present study is to obtain the basic knowledge required for understanding the mechanisms governing the propagation of MCSs and synoptic-scale disturbances within a SCC. Special attention will be given to synoptic-scale disturbances associated with the eastward propagation of convective systems. The data used in this study are explained in section 2, while the results of analyses are described in sections 3 and 4. The discussion and summary are in sections 5 and 6, respectively.
2. Data

This study used radar and upper-air sounding data collected during the later period of the MISMO field experiment (21 November to 7 December) in addition to satellite infrared and microwave datasets. A map of the observational area is shown in Fig. 1. A C-band Doppler radar was mounted on the R/V Mirai, and an X-band radar was placed on Gan Island in the Maldives (0.78°S, 73.28°E). Each radar performed a full-volume scan out to 150 km in range every 10 min, in addition to a surveillance scan every 30 min at 0.5° elevation angle with a maximum range of 300 km. Reflectivity data of the volume scan were interpolated to 290 × 290 × 21 grids in longitude/latitude/altitude coordinates, centered at each radar, with grid spacing of 0.01° and 0.01° in the horizontal and 1 km in the vertical. Before interpolation, specific attenuation of the X-band reflectivity by strong rainfall was corrected using a one-way technique described in Yamada and Uyeda (2006). The grid data of reflectivity were used to perform the convective/stratiform classification of radar echoes following the method of Steiner et al. (1995). Upper-air sounding data were also collected on the R/V Mirai and at Gan Island every 6 h during the analysis period. A noteworthy point is that the R/V Mirai moved from 4.0°N, 74.0°E to 5.0°S, 95.0°E during the analysis period.

The satellite datasets used in this study are the rain rate and winds near the ocean surface, the IR brightness temperature of cloud tops ($T_{\text{BB}}$), and the OLR. The original rain rate is provided from the Remote Sensing Systems (RSS), where daily orbital data of a microwave radiometer are mapped to a 0.25° × 0.25° grid and stored in a single binary file. In the MISMO period, data corrected by five microwave instruments (SSM/I F13–15, TMI, and AMSR-E) were available. In the present study, the five daily orbital datasets were averaged to obtain a 12-hourly rain rate distribution with small data gaps between orbits. Any adjustment of the displacement of rain areas within the 12 h, using $T_{\text{BB}}$ data, was not applied. The near-surface winds are also provided from the RSS, where daily orbital data of the QuikSCAT microwave scatterometer are mapped to a 0.25° × 0.25° grid. The $T_{\text{BB}}$ used here is globally merged infrared (Global-IR) data with full resolution (~4 km) every half hour, provided by the National Aeronautics and Space Administration Earth–Sun System Division. For the production of longitude–time diagrams, the $T_{\text{BB}}$ data were smoothed and resampled onto a 0.2° × 0.2° grid. Daily-mean interpolated OLR data, provided from the NOAA Climate Diagnostics Center (CDC), were utilized to obtain the OLR anomaly associated with the MJO using the method of Wheeler and Weickmann (2001).

3. Characteristics of the SCC during MISMO

a. Overall characteristics

To provide a general view of SCCs during the MISMO and later periods, Fig. 2a shows the longitude–time section of cloud-top temperature between November 2006
and January 2007. The OLR anomalies for the MJO-filtered band are superimposed. During the MISMO period, a weak signal of MJO appeared in the Indian Ocean (west of 100°E). In addition, a significant MJO signal appeared in the following December–January period through the Indian Ocean and the western Pacific. The TBB distribution shows that these MJO signals correspond to large-scale cloud envelopes propagating eastward. In the Indian Ocean, it is common for these envelopes to involve smaller-scale streaks of cold cloud shields, which mainly moved westward, like the SCC in previous studies (e.g., Nakazawa 1988). These streaks are hereafter referred to as westward-moving cloud shields (WSs) in this paper.

In contrast, the longitude–time section of the rain rate (Fig. 2b) shows the predominance of eastward components rather than westward ones. These characteristics are prominent among the two cloud envelopes in the eastern side of the ocean (75°–90°E). These components are referred to as eastward-propagating precipitating systems (EPs). As for the SCC during MISMO, the eastward propagation is clearly seen within a longitude–time domain from 55°E through 100°E and from 21 November through 9 December (highlighted by a rectangle). The most prominent one started near 26 November at 70°E and was followed by three systems (described later). These systems persisted over the ocean but did not reach the Maritime Continent (east of 100°E). The characteristics and structure of these EPs are described later in detail. The period of clouds and rainfall during the appearance of these rainfall systems is shown in Fig. 3. The zonal distribution of TBB spectra shows the predominance of a 2–4-day cycle between 60° and 90°E. As shown before, this cycle resulted mainly from the successive development of cloud streaks moving westward. It is noteworthy that the rainfall also shows a 2–4-day cycle between 75° and 87°E, while the rainfall areas mainly propagated eastward. The difference in the predominant zonal direction as well as the similarity in periodicity between clouds and rainfalls has not been described in previous studies on SCCs. Thus, it is necessary to examine the detailed smaller-scale characteristics and structure to understand the mechanism governing the coexistence of EPs and WSs in the SCC.

b. A case study of eastward-propagating rainbands on 6–7 December

Both the Gan and Mirai radars succeeded in monitoring the eastward propagation of radar echoes corresponding to the EPs during the analysis period. Here,
a case on 6–7 December is described in detail, as an example of EPs within the SCC. This case corresponds to one of the following EP events within the SCC. The Doppler radar on the R/V Mirai observed the fine structure and evolution of the EP for 1.5 days within a zonal distance of 800 km as the ship moved southeastward from 1.5°S, 90°E, to 5°S, 95°E. Figure 4 shows the longitude–time diagram of the radar reflectivity at 1 km MSL and the cloud-top temperature. This section clearly shows the predominance of eastward propagating features of echoes in the lower troposphere and that of westward movement of clouds aloft. Their mean zonal speed was 11.3 and −10.8 m s⁻¹, respectively. Above 7 km MSL (not shown), radar echoes showed the prevalence of westward movement over eastward, similar to the upper-level clouds, suggesting that only echoes in the lower troposphere propagated eastward. It is noteworthy that these echoes sustained the eastward propagation even under a situation with the $T_{\text{BB}}$ higher than 0°C. The echoes in this diagram can be separated into several components (labeled a–d), and a group of them corresponds to a streak of an eastward propagating packet of rainfall, as shown in Fig. 2b. These echoes are characterized by variations of reflectivity in association with the westward-moving cloud shields. In other words, the mean reflectivity in this diagram usually exceeds 30 dBZ during which these echoes encountered westward-moving cloud tops colder than −15°C. This point will be examined further in the next section.

The horizontal distributions of cloud tops, rainfall, and radar echoes near 0730 UTC 6 December are shown in Fig. 5. At this time, three alignments of echoes, corresponding to the eastward propagating components a–c shown in the previous diagram (Fig. 4), were observed by a surveillance (300-km range, 0.5° elevation) scan of the Doppler radar (Fig. 5c). These echoes are characterized by their linear leading edge extending from southwest to northeast. Individual convective elements along the leading line moved eastward or southeastward, roughly close to the direction of the ship’s track. The echoes (b) were accompanied by trailing linear echoes extending normal to the leading line. The satellite-derived rainfall distribution (Fig. 5b) provides an outlook in which these line echoes are part of a synoptic-scale rainfall system, extending parallel to these line echoes with a length of about 1000 km between 5°S and 2°N. In contrast, although the cloud top (Fig. 5a) shows a southwest–northeast oriented band structure, the existence of the leading line in the eastern periphery is unclear; rather, cloud tops colder than −60°C in the trailing (western) portion are markedly noticeable. The relationship between the precipitation pattern and cloud features is similar to that of the TOGA COARE squall lines studied by Rickenbach (1999). He showed that a leading convective line can be identified using a Doppler radar, but not always from satellite IR images. In addition, the horizontal rainfall pattern of the present case is similar to that of a squall line with a shear-perpendicular line and trailing shear-parallel secondary bands (LeMone et al. 1998).

The evolution of the eastward-propagating leading line echoes is examined using a series of the zonal–vertical
section of reflectivity (Fig. 6). Since the ship moved roughly in the same direction as the propagation of these echoes, it is possible to examine the mean vertical structure and evolution of the echoes. All of the leading lines (a–d) are marked by their vertical extension not reaching 10 km MSL until 1800 UTC, corresponding to the period before their encounter with westward-moving cloud shields (see Fig. 4). The depth of each leading portion was generally near 5 km MSL, and the echo tops rose to 8 km MSL in the trailing part. Reflectivity was usually stronger in the leading portion than in the rear. These characteristics suggest that convective cells formed in the leading edge and moved to the trailing portion, as they do in a tropical squall line. After 1800 UTC, the echo-top height of line d increased gradually and reached 13 km MSL at 0520 UTC the next day. The horizontal area of reflectivity greater than 30 dBZ was highest at this time.

Changes in the thermodynamic stratification and vertical airflow structure are shown using two soundings (Fig. 7) taken before and after the passage of the four lines (a–d). The position of soundings relative to the line echoes is shown as circles with a dot in Fig. 4. The late profile is marked by an increase of $T_d$ below 300 hPa (9.5 km), suggesting moistening due to cloud development. There is no sign of warming and drying in the lower troposphere [i.e., the so-called “onion” shape of the temperature and dewpoint profiles, Zipser (1977)], which can usually be observed in the trailing portion of a squall line due to the mesoscale descent motion. Compared with the early profile, air temperature $T$ in the late profile hardly changed, except for a fall of 1.5°C within a very shallow layer (~250 m) near the surface, which probably resulted from convective downdrafts. A noteworthy point is the very small change in the temperature profile of the parcel $(T_p)$ lifted above the cold pool. The quasi-steady temperature profiles yield a small change of CAPE (from 1196 to 918 J kg$^{-1}$), with mostly constant levels of free convection (near 1.0 km) and neutral buoyancy (13.8 km). This result indicates that the atmosphere was
hardly stabilized despite the convective development. The profile of wind barbs indicates an increase of the westerly flow in the lower troposphere, with a change of the zonal component from 4.2 to 10.8 m s\(^{-1}\) at 900 hPa. By assuming that this wind shift is a manifestation of low-level convergence and upward motion aloft, it can be inferred that the unstable stratification was maintained by the horizontal and vertical advection. It is

FIG. 5. Horizontal distributions of (a) the cloud-top temperature, (b) the AMSR-E-derived surface rainfall rate, and (c) the radar reflectivity at 0.5\(^\circ\) elevation angle, at and near 0730 UTC 6 December. Note that the reflectivities in the 300-km range are shown here whereas those in the 150-km range were used in Fig. 4. Thin arrows indicate the location of eastward propagating echoes.

FIG. 6. (a)–(d) Zonal–vertical sections of reflectivity on 6–7 December. Reflectivities (within the 150-km range) were averaged meridionally in ±0.25\(^\circ\) from the ship and are drawn using the same grayscale as that used in Fig. 5c. Labels a–d indicate the location of the eastward propagating echoes. A bold line in the center of each panel indicates the location of the ship track.
therefore hypothesized that the EP with convective lines was embedded in an updraft portion of synoptic-scale disturbances (or waves) with a periodicity of 2 to 4 days.

So far, we have seen that the SCC during MISMO was characterized by the coexistence of EPs and WSs. The case study of one of the EPs showed that it consisted of several narrow convective lines extending in the south–north direction and propagating eastward. These convective lines were marked by their shallow-to-medium depth (≤10 km MSL) unless they encountered WSs. The atmospheric conditions were characterized by persistent unstable stratification with an increase of the westerly flow in the lower troposphere, suggesting the participation of a synoptic-scale disturbance. This hypothesis provides motivation to investigate the synoptic-scale fields affecting the evolution of EPs within the SCC.

4. Composite analysis

The characteristics and structure of both EPs and WSs within the super cloud clusters are examined here in order to reveal the existence of synoptic-scale disturbance(s) relating to these systems. Since the density of observation was insufficient to examine the structure of individual cases, composite analyses were applied.

a. Method

The westward and eastward components were identified using longitude–time diagrams of clouds and rainfall (Fig. 8), respectively. For the westward component, first the minimum value of the cloud-top temperature was detected at each longitude and a regression line among the minima was obtained using the least squares method.
Regression lines of eastward propagation were also obtained using the diagram of rainfall in a similar fashion. Lines lasting less than 24 h were excluded, and the four eastward (EP1–EP4) and nine westward (WS1–WS9) components were used for the composite analyses. The eastward and westward components on 6–7 December, described in the previous section, correspond to EP-4 and WS-9.

The composite horizontal fields were obtained by plotting satellite data onto the coordinates with the zonal axis centered at the regressed longitude. To distinguish the characteristics of the EP and WS from those during merger of the two, an additional type (EP1WS) was applied to classify data near an intersection between a westward and eastward component, as shown in Fig. 8c.

The vertical fields were obtained by plotting upper-air and radar reflectivity data onto the zonal–vertical coordinates, in which the horizontal axis indicates the zonal distance of the observational point from the linearly regressed point. The composite data were averaged horizontally with a 750-km moving window to obtain smoothed distributions. Figure 8c also shows the areas within the 150-km range of the radar at GAN and the R/V Mirai. A merit of the linear regression technique is that data collected on the moving ship, as well as data at the fixed position, can be used for the composition. Since the radar and radiosonde data was insufficient to be distinguished into the three types, only two types (i.e., EP and WS) were used for the analysis of the vertical structure. For the same reason, the life stages (i.e., formation, mature, and decaying) were not examined, and statistical significance of the composite features was not considered in this analysis.

### b. General characteristics

Before examining the structure, the characteristics of the westward and eastward components are described briefly. The background wind speed, zonal migration speed, and duration of each component are listed in Table 1. In all cases (except for WS-1), the background zonal winds were westerly or calm in the lower troposphere ($U_{850}$) and moderate to strong easterly aloft ($U_{150}$). This easterly vertical shear is similar to the flow structure during a convectively active phase over the western Pacific (e.g., Chen et al. 1996; Kubota et al. 2006). It is noteworthy that all of the EPs show zonal speed (5–11 m s$^{-1}$) faster than the background flow in the lower troposphere ($U_{850}$). Since the upper troposphere was easterly, this indicates a significant departure from the mean flow and suggests the propagating nature of the EPs. In contrast, the zonal speed of the WSs was roughly close to the upper-level flow ($U_{150}$) and means that the WSs correspond to advected clouds. The lifetime of EPs (4 to 9 days), which is longer than that of WSs (2 to 4 days), suggests that EPs are associated with synoptic-scale to meso-a-scale atmospheric motion. The mean cloud-top temperature and rainfall of EP and WS and their combination are shown in Fig. 9. While the rainfall rate of EP is basically higher than for WS, both rainfall and cloud-top height increase during merger of the two. Increases of the echo-top height and reflectivity during merger were also seen in the case described in the previous section. This suggests that convection was most active when the westward and eastward components merged.

### c. Horizontal structure

The composite anomaly distributions of rainfall and horizontal winds at the sea surface are shown in Fig. 10.

<table>
<thead>
<tr>
<th></th>
<th>$U_{850}$ (m s$^{-1}$)</th>
<th>$U_{150}$ (m s$^{-1}$)</th>
<th>Zonal speed (m s$^{-1}$)</th>
<th>Duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP1</td>
<td>2.7</td>
<td>−11.7</td>
<td>5.4</td>
<td>9.0</td>
</tr>
<tr>
<td>EP2</td>
<td>5.1</td>
<td>−19.3</td>
<td>8.5</td>
<td>4.0</td>
</tr>
<tr>
<td>EP3</td>
<td>3.1</td>
<td>−14.3</td>
<td>9.5</td>
<td>5.5</td>
</tr>
<tr>
<td>EP4</td>
<td>9.5</td>
<td>−11.8</td>
<td>11.3</td>
<td>4.0</td>
</tr>
<tr>
<td>WS1</td>
<td>N/A</td>
<td>N/A</td>
<td>−13.0</td>
<td>1.5</td>
</tr>
<tr>
<td>WS2</td>
<td>0.6</td>
<td>−10.4</td>
<td>−7.0</td>
<td>1.5</td>
</tr>
<tr>
<td>WS3</td>
<td>2.5</td>
<td>−12.2</td>
<td>−8.3</td>
<td>2.0</td>
</tr>
<tr>
<td>WS4</td>
<td>−0.5</td>
<td>−14.9</td>
<td>−12.6</td>
<td>1.5</td>
</tr>
<tr>
<td>WS5</td>
<td>−0.8</td>
<td>−22.3</td>
<td>−9.0</td>
<td>3.5</td>
</tr>
<tr>
<td>WS6</td>
<td>4.4</td>
<td>−17.1</td>
<td>−12.1</td>
<td>2.5</td>
</tr>
<tr>
<td>WS7</td>
<td>1.6</td>
<td>−11.5</td>
<td>−15.8</td>
<td>3.8</td>
</tr>
<tr>
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<td>1.7</td>
<td>−15.5</td>
<td>−17.1</td>
<td>1.8</td>
</tr>
<tr>
<td>WS9</td>
<td>14.0</td>
<td>−4.0</td>
<td>−10.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

**Fig. 9.** Cloud-top temperature and surface rainfall, averaged over the observational points (shown in Fig. 8c).
These anomalies are the deviation from mean values during the period from 21 November through 9 December. The abscissa is represented as the relative zonal distance from the linearly regressed longitude, while the ordinate is fixed in latitude. The relationship between rainfall and low-level convergence is evident in the distribution of the EP type (Fig. 10b). A rainfall area, extending about 1000 km in the south–north direction with a zonal width of 500 km, is formed near the leading edge of westerly anomalies. The peak of the rain rate to the south of the equator (near 4°S) probably reflects the seasonality of the period of analysis (i.e., boreal winter). This rainfall distribution roughly represents characteristics similar to those of the eastward propagating system on 6–7 December, which was oriented from southwest to northeast (see Fig. 5b). On the other hand, the relationship between rain and winds is unclear in the distribution of the WS type (Fig. 10a); there are scattered small areas of a positive rainfall anomaly, with an indistinct relationship with the near-surface flow.

d. Vertical structure

The zonal–vertical distribution of the echo occurrence frequency associated with the EP type is shown in Fig. 11a. This distribution is marked by an area of frequency higher than 30% ahead of the linearly regressed point in the lower troposphere (≤4 km MSL). The zonal distribution of the convective-echo fraction (Fig. 11b) shows a large value (≥10%) in the forward part of the regressed point. These facts indicate a high frequency of the occurrence of shallow convective echoes in the forward part of the eastward component. The echoes with a shallow to medium depth (≥10 km MSL), shown in the case study (see Fig. 6), correspond to suchforeside convection of the eastward propagating system. The zonal–vertical anomaly distributions of the zonal wind, relative humidity, and temperature are shown in Fig. 12. These distributions are tilted westward with height. The zonal wind distribution indicates that the forward portion (near 300 km east of the regressed point) corresponds to an area of zonal convergence in the lower troposphere with a zonal divergence near 300 hPa. Since the horizontal flow distribution

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**Fig. 10.** Composite horizontal distributions of the rainfall rate and near-surface horizontal winds associated with (a) WS-only and (b) EP-only categories.

**Fig. 11.** (a) Composite zonal–vertical distribution of the fraction of the radar-echo appearance accompanying the EP. Echoes greater than 10 dBZ were used for the calculation. (b) Zonal distribution of the convective-echo fraction.
(Fig. 10b) does not show the prevalence of a meridional divergence ahead of the rainfall area, the pair of convergence near the surface and divergence aloft represents the existence of upward motion. The height of the convergence between the westerly and easterly anomalies increases toward the rear side. The temperature anomaly shows the existence of warm deviation, which also tilts westward with a height below 250 hPa. The relative humidity shows the formation of a moist layer beneath the deep dry air in the fore side and deepening of this layer rearward. These facts suggest the deepening of convection in the fore side. Another important point is the tilt of temperature anomalies in the opposite direction with a height above 250 hPa, resulting in a vertical temperature structure having a “boomerang” shape. The zonal-wind anomalies also show a similar shape with positive/negative peaks shifting about 800 km (or a half wavelength) from those of the temperature distribution.

This tilted structure, as well as the horizontal distribution with zonal convergence, is similar to the structure of a convectively coupled Kelvin wave (Wheeler et al. 2000; Straub and Kiladis 2002; 2003), although the zonal wavelength in the present case (about 2000 km) is smaller than that in previous studies (≥4000 km). Kiladis et al. (2009) argued that the thermodynamic structure of convectively coupled equatorial waves is similar regardless of scales or direction of propagation. As for the foreside shallow convection, Numaguti and Hayashi (2000) pointed out that an eastward propagating wave is not immediately coupled with deep convective activity because dry air in the middle troposphere prevents convective development. The composite vertical structure with dry air in the forward portion described above is consistent with this idea.

On the other hand, the occurrence of echoes associated with westward components shows quite different features.
The total echo fraction (Fig. 13a) shows a zonally uniform distribution near the regression point with a high value near 4 km MSL. The convective fraction (Fig. 13b) shows a relatively smaller value (≈10%) in this area. This suggests the prevalence of stratiform precipitation with a bright band in the melting layer. The composite of radiosonde data (Fig. 14) shows a considerable moist anomaly in the middle and upper troposphere near the regression point, although variations of zonal winds and temperature are quite small in the lower troposphere. Since the relationship between the zonal–vertical circulation and thermodynamic condition in the lower troposphere is unclear, a plausible interpretation is that the WSs mostly consisted of trailing stratiform clouds advected by upper-tropospheric easterly flow, like a stratiform region of a tropical squall line. It is known that stratiform precipitation of squall lines is maintained by weak vertical upward motion (≈0.5 m s\(^{-1}\)) in the upper troposphere (e.g., Houze 1993). A numerical study by Pandya and Durran (1996) suggests that perturbation of this vertical motion, induced by gravity waves from leading convective lines, is associated with the maintenance of trailing stratiform precipitation. However, the lifetime of a squall line’s stratiform precipitation is usually ~12 h (Houze 1993) and is much shorter than that of WSs (2 to 4 days). It is possible that the WSs were maintained by a disturbance with a weak updraft in the upper troposphere, although its circulation can hardly be identified from Fig. 14. Since it is difficult to examine the finer zonal distribution of the vertical wind component using 6-hourly upper-air sounding data, further analysis of the structure of WSs was not conducted in this study.

Meanwhile, it is worth mentioning that the composite vertical structure of the WSs (Fig. 14) is quite different from the westward-propagating cloud systems within the SCCs during TOGA COARE. Takayabu et al. (1996) showed that these cloud systems have a vertical circulation extending from the surface through 100 hPa, which is associated with a westward-propagating inertio–gravity wave. These systems lasted several days and propagated thousands of kilometers—longer and greater than the WSs in the present study. It is suggested that westward-moving cloud elements within an SCC have a wide variety of characteristics and structure, not all of which are coupled with a specific type of equatorial wave.

5. Discussion

a. Conceptual model

It has been observed that the SCC during the MISMO period was accompanied by four eastward-propagating synoptic-scale precipitating systems. The relationship of the cloud development and disturbances within the SCC can be summarized as schematic diagrams (Fig. 15). The use of satellite IR data provides an ordinary view in which the SCC consists of upper-tropospheric cloud shields moving westward (dashed lines) in the longitude–time section (Fig. 15a). In contrast, satellite microwave data provide a new outlook in which precipitating systems propagate eastward (gray solid lines) with intervals of 2 to 4 days underneath the cloud shields. The vertical structure (Fig. 15b) is marked by the development of eastward-propagating synoptic-scale disturbances with a structure similar to an equatorial Kelvin wave. Convective cells propagate eastward while trailing stratiform clouds in the upper troposphere move westward, according to the background flows with a westerly in the lower troposphere and easterly aloft. The coexistence of eastward and westward components can cause a 2–4-day cycle of cloud tops and rainfall at each longitude. Depth of the convective systems is usually less than 10 km unless the air in the lower and middle troposphere is sufficiently moistened. These convective systems can deepen when they intersect with westward-moving stratiform clouds that provide moisture in middle to upper tropospheric layers. Previous studies have already reported the westward propagation of cloud shields with 2-day cycles in a SCC (e.g., Nakazawa 1988; Takayabu et al. 1996) and the eastward propagation of convection in its leading edge (Numaguti and Hayashi 2000). In contrast, the
present study provides observational evidence that several eastward propagating systems exist in the leading edge and trailing portion. Thus, this study proposes a new aspect, namely that a SCC involves a group of synoptic-scale waves propagating eastward.

b. Deep convection during an intersection

The deepening of a convective system during the intersection with a westward-moving cloud shield is an interesting and important phenomenon for understanding the development of deep convection in a SCC. The role of the westward-moving clouds is discussed here from the viewpoint of thermodynamics. In the case study (section 3), we described sounding profiles with a level of neutral buoyancy (13.8 km). This was higher than the echo-top height (>10 km) and suggests that the buoyancy of air parcels in a convective updraft was reduced by the entrainment of ambient dry air. This evidence is consistent with simulations, conducted by Numaguti and Hayashi (2000), showing that eastward propagating waves can couple with deep convective clouds only after sufficient moistening in the low and middle troposphere. On the other hand, the composite vertical structure of WSs (Fig. 14) shows moist conditions in the middle and upper troposphere. This can provide a suitable condition for eastward propagating convection to avoid dry-air entrainment and deepening in the upper troposphere. Therefore, it can be explained that deep convection at the intersection results from eastward-propagating convective updrafts under the moist environment of westward-moving cloud shields.

c. Maintenance mechanism of the eastward-propagating disturbances

It is necessary to inquire, to some extent, into the maintenance mechanism of eastward propagating disturbances. A wavenumber–frequency spectrum analysis (Wheeler and Kiladis 1999) demonstrated that spectral peaks of the OLR anomaly correspond to the dispersion relations of the equatorially trapped wave modes of the shallow-water theory with equivalent depths \( h \) in the range of 12 to 50 m, where \( h \) is related to the internal
gravity wave speed as \( c = \sqrt{gh} \) (\( g \) is gravity). In the present study, the averaged propagation speed among the four cases (EP1–EP4, Table 1) is 8.7 m s\(^{-1}\), and the equivalent depth is estimated to be 7.7 m. The speed and depth are consistent with the analyzed frequency (2–4 days, Fig. 3b) and zonal wavelength (~2000 km, Fig. 12). In addition, the meridional extension of rainfall area (~1000 km, Fig. 10b) also corresponds to the Rossby radius of deformation \( (R_e = (c/\beta)^{0.5}, \) where \( \beta \) is the parameter for the equatorial beta-plane approximation), estimated to be 5.5°.

The estimated depth suggests that the disturbances studied here were shallower than typical large-scale equatorial waves identified from the OLR data. This idea is supported by the analyzed vertical structure (Fig. 12) with zonal divergence near 300 hPa (~10 km), suggesting an upward motion not reaching the upper troposphere. Numerical simulations conducted by Tulich and Mapes (2008) demonstrated the role of shallow gravity waves in the multiscale organization of tropical clouds. They emphasized the importance of wave packets with phase speed <18 m s\(^{-1}\) and vertical wavelengths comparable to or shorter than the depth of the troposphere, which are excited by stratiform precipitation (Mapes 2000) or a mesoscale cold pool.

It is possible that the eastward propagating disturbances during MISMO correspond to synoptic-scale gravity waves with shallow vertical wavelength. This is supported by evidence that the eastward propagation could be identified from the microwave-derived surface rainfall rather than cloud-top temperature. Although the examination of a vertical heating profile is a good way to prove this hypothesis, this could not be applied for the present study because intense radiosonde observations for the budget analysis were completed on 26 November (Yoneyama et al. 2008). Instead, cloud-resolving numerical simulations of an SCC are necessary for understanding the mechanisms governing the development and maintenance of these waves. Recently, three-dimensional global simulations with explicit cloud processes have yielded a better representation of eastward-propagating cloud systems on an aquaplanet (Nasuno et al. 2007) and the real atmosphere (Miura et al. 2007). Nasuno et al. (2009) outlined the existence of several eastward propagating disturbances in the simulation results of the MJO event between December 2006 and January 2007, corresponding to the case next to the MISMO SCC (see Fig. 2). The detailed examination of these simulation results will be a key to revealing the role of these disturbances in the multiscale cloud organization.

d. Eastward-propagating systems in previous studies

This study and others using Doppler radar(s) report evidence of convection propagating eastward, as noted in section 1. In particular, Halverson et al. (1999) described the successive evolution of eastward-moving MCSs, which resemble the present cases in repeated convective development. In addition, recent observational studies
over the Indonesian Maritime Continent reported the existence of EPs (Shibagaki et al. 2006; Ichikawa and Yasunari 2007), although they attributed the eastward propagation to local circulation over and around major islands. These facts motivated us to discuss the relevance of synoptic-scale disturbances to the convective development in the previous cases as well as the generality of these disturbances in the tropics. Here, a case of convective systems, analyzed in a past study, is reanalyzed in a fashion similar to that in the present study using satellite microwave data. Since many microwave products have become available lately, the case in December 2000 over the western Pacific, studied by Kubota et al. (2006), was selected for the reanalysis. As reported earlier they noted the eastward propagation of MCSs during the active phase of a MJO event.

The longitude–time diagrams (Fig. 16a) show that a large-scale cloud envelope, with a MJO signal, passed the 140°E meridian between 25 November and 6 December. While individual cloud tops generally moved westward within the envelope, the rainfall distribution (Fig. 16b) shows the prevalence of EPs not only at the leading edge but also in the trailing portion, as in the MISMO case.

During this period, the R/V Mirai was placed nearby (2°N, 138°E), and Kubota et al. (2006) examined a case of convective clouds on 3–6 December (highlighted by a rectangle). This corresponds to the passage of one of the EPs in the trailing portion. Figure 16c shows that the center of this system (marked by an arrow) passed the radar observation area on 4 December with a zonal speed of 10.3 m s⁻¹. The longitude–time section of reflectivity shows the prevalence of eastward propagation of radar echoes in the lower troposphere, with intensification of reflectivity near the center of the system. Kubota et al. (2006) reported that many groups of convective echoes moved eastward during this period.

A near-simultaneous view from SSM/I and QuikSCAT was obtained near 0830 UTC the next day when the precipitating system reached eastward to 145°E (Fig. 17). This spatial distribution shows quite similar characteristics to the composite structure of the EP-type systems during MISMO (Fig. 10b), namely rainfall areas extending from south to north, with a strong westerly flow behind. As for the vertical structure, Kubota et al. (2006) described the intensification of the westerly anomaly and deepening of the moist area below 6 km MSL (Fig. 9 in

![Fig. 16. Time–longitude sections during the active phase of a MJO in November and December 2000 over the equatorial western Pacific: (a) cloud-top temperature and MJO-filtered OLR anomaly with the same contour interval as Fig. 2, (b) surface rainfall, and (c) radar reflectivity at 1.0 km MSL. The R/V Mirai was stationed nearby at 2°N, 138°E. Reflectivity data were averaged meridionally between ±0.5°, while T_BB and the rain rate were the average between 5°S and 5°N. In (c), contours of T_BB and shades of the rain rate are superimposed.](http://journals.ametsoc.org/jas/article-pdf/67/5/1456/3515211/2009jas3151_1.pdf)
The period of intensification and deepening (0600 UTC 4 December–0900 UTC 5 December) corresponds to the passage of this system. This evidence suggests the relevance of an eastward propagating disturbance, with a structure such as a Kelvin wave, to the EP within a SCC over the western Pacific. This supports the results of the MISMO study, although the number of cases is insufficient to demonstrate the generality. Recently, Mapes et al. (2006) hypothesized that a MCS may be a small analog or prototype of larger-scale tropical waves. Thus, more studies on the relationship between convection and synoptic-scale waves will be necessary to understand the mechanism of the multiscale structure and eastward propagation of a SCC.

6. Summary

The multiscale structure of a super cloud cluster (SCC) over the equatorial Indian Ocean was investigated mainly using data from satellite microwave sensors and surface-based observations. This SCC developed in a convectively active phase during an intensive field experiment (MISMO) from November through December 2006, which was conducted to learn more about the onset mechanism of convection associated with the MJO (Yoneyama et al. 2008). The smaller-scale structure of the SCC was marked by the complicated relationship between precipitating systems and upper-tropospheric cloud shields, which propagated eastward and moved westward, respectively, with a cycle of 2 to 4 days. Since the eastward propagation was also seen in another SCC associated with a strong MJO event that has not been the focus of previous studies, analytical attention was given to the structure of slow eastward-propagating (5–11 m s\(^{-1}\)) precipitating systems and related synoptic-scale (\(\sim2000\) km) disturbances.

A case study revealed that one of the precipitating systems consisted of several narrow convective lines extending in a south–north direction and propagating eastward. These convective lines were marked by their shallow-to-medium depth (\(\leq10\) km MSL) unless they encountered westward-moving cloud shields. The environment was characterized by persistent unstable conditions with an increase of westerly flow in the lower troposphere, suggesting the existence of upward motion associated with an eastward-propagating synoptic-scale disturbance. Composite analyses of the precipitating systems revealed that each of them formed in a region with convergence of a zonal flow near the surface and divergence near 300 hPa. The vertical temperature structure tilted westward with height below this pressure level and eastward aloft, similar to that of a convectively coupled Kelvin wave. In contrast, the analyses of westward-moving cloud areas could not show the relevance to zonal–vertical circulation in the lower troposphere, suggesting that most of them were trailing stratiform clouds advected by the upper-tropospheric easterly flow.

These results suggest a new aspect of a SCC involving a group of synoptic-scale shallow waves propagating eastward. Additional analyses of a SCC over the western Pacific also showed the predominance of eastward propagation, demonstrating the advantage of satellite microwave sensors over infrared ones in monitoring the multiscale structure of a tropical convection. Although the existence of eastward-propagating precipitating systems and the mean structure of the associated disturbance have been revealed in this study, the mechanisms of the development and decaying of the disturbance are not known. Moreover, the role of these systems, in conjunction with westward-moving cloud shields, in the maintenance of the whole SCC is also unclear. These points remain to be investigated. Continuous observational research over the Indian Ocean and high-resolution numerical studies of SCCs will contribute to the understanding of the multiscale structure of a tropical convection.
REFERENCES


