Characteristics of 3–4- and 6–8-Day Period Disturbances Observed over the Tropical Indian Ocean

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ABSTRACT

A field observational campaign [i.e., the Mirai Indian Ocean cruise for the Study of the MJO-convection Onset (MISMO)] was conducted over the central equatorial Indian Ocean in October–December 2006. During MISMO, large-scale organized convection associated with a weak Madden-Julian oscillation (MJO) broke out, and some other notable variations were observed.

Water vapor and precipitation data show a prominent 3–4-day-period cycle associated with meridional wind variations. Filtered $v$ anomalies at midlevels in reanalysis data [i.e., the Japan Meteorological Agency (JMA) Climate Data Assimilation System (JCDAS)] show westward phase velocities, and the structure is consistent with mixed Rossby–gravity waves. Estimated equivalent depths are a few tens of meters, typical of convectively coupled waves. In the more rainy part of MISMO (16–26 November), the 3–4-day waves were coherent through the lower and midtroposphere, while in the less active early November period midlevel $v$ fluctuations appear less connected to those at the surface.

SST diurnal variations were enhanced in light-wind and clear conditions. These coincided with westerly anomalies in prominent 6–8-day zonal wind variations with a deep nearly barotropic structure through the troposphere. Westward propagation and structure of time-filtered winds suggest $n=1$ equatorial Rossby waves, but with estimated equivalent depth greater than is common for convectively coupled waves, although sheared background flow complicates the estimation somewhat.

An ensemble reanalysis [i.e., the AGCM for the Earth Simulator (AFES) Local Ensemble Transform Kalman Filter (LETKF) Experimental Reanalysis (ALEREA)] shows enhanced spread among the ensemble members in the zonal confluence phase of these deep Rossby waves, suggesting that assimilating them excites rapidly growing differences among ensemble members.

1. Introduction

Temporal variations in tropical convection occur on various scales ranging from hours to seasons and beyond. The Madden–Julian oscillation (MJO; Madden and Julian 1971, 1972) is one of the most prominent phenomena regulating the tropical convection. Now, many features of the MJO are well described: its 30–60-day period, eastward propagation with a phase speed of 5 m s$^{-1}$ in the Eastern Hemisphere, zonal wavenumbers 1–6, frequent initiation of convection in the Indian Ocean and termination over relatively low sea surface temperature (SST) in the central Pacific Ocean, and others [see review paper by Zhang (2005)]. However, several fundamental issues still remain unexplained, including the initiation process over the Indian Ocean, slow propagation speed, and scale selection of the cloud envelope.

With regards to the initiation process of the MJO convection over the Indian Ocean, many hypotheses have been proposed. However, the triggering mechanism still...
remains a matter of controversy. The mechanisms may be classified into two types: tropical and extratropical triggering. The former includes the initiation by equatorial waves (e.g., Kikuchi and Takayabu 2003; Matthews 2000, 2008; Seo and Kim 2003), and local moisture buildup (e.g., Kemball-Cook and Weare 2001; Maloney and Hartmann 1998). The latter contains extratropical Rossby wave propagation and energy dispersion from midlatitude baroclinic eddies (e.g., Hsu et al. 1990; Ray et al. 2009), although the extratropical flow is deeply affected by the (tropical) MJO convection (e.g., Kiladis and Weickmann 1992; Matthews and Kiladis 1999; Moore et al. 2010). Whichever triggering factor is more critical than the others, atmospheric moisture and temperature fields (and oceanic heat storage) over the Indian Ocean play crucial roles in all hypotheses, because convection cannot organize without sufficient moisture and heat storage. Unfortunately, there are few observations of the detailed variations of these variables over the Indian Ocean, compared with those over the western Pacific, where an extensive field experiment was conducted during November 1992–February 1993 [i.e., the Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE)].

To meet these scientific needs, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) conducted a field experiment in October–December 2006 on board the R/V Mirai, focusing on the initiation of convection in the MJO in the central equatorial Indian Ocean. This project was named the Mirai Indian Ocean cruise for the Study of the MJO-convection Onset (MISMO; Yoneyama et al. 2008b). One of the concrete objectives of MISMO was to describe local (or meso-scale) moisture variations and air–sea interaction in the onset of a MJO over the Indian Ocean. MISMO encountered the initiation of a weak MJO (as described in section 3) and also observed some noteworthy variations emphasized here: 3–4-day period cycles in water vapor, precipitation, and meridional wind; and enhancements of the diurnal variations in SST every 6–8 days.

Disturbances corresponding to theoretical equatorial waves (Matsuno 1966) have been reported over the past few decades. In particular, comprehensive investigations by Takayabu (1994) and Wheeler and Kiladis (1999) show a clear correspondence between the frequency–wavenumber spectra of the cloud field and the dispersion relationships of linear equatorial waves. It is commonly accepted that equatorial waves play important roles in modulating tropical weather. Therefore, it is reasonable to consider the regular variations observed during MISMO in terms of equatorial wave modes, although many questions remain, such as the generation mechanisms of each wave mode, preferred mode types and wavenumbers and frequencies, relationships with oceanic processes, and so on. Detailed observations like those in MISMO are useful for raising these questions, especially over the Indian Ocean where lack of in situ data makes such studies rare.

The atmospheric and oceanic variations highlighted here occurred in the transition period from the MJO inactive phase to the active one, and might have some relevance to MJO initiation. But of course, MISMO had only one intraseasonal event. Furthermore, the weak “MJO” signal of the MISMO experiment might differ in many respects from stronger bona fide MJO events. So generalizations will require more data.

The remainder of the paper is organized as follows. In section 2, a brief description of the instruments and data are presented. Meteorological conditions during MISMO are overviewed in section 3. The 3–4- and 6–8-day period variations are focused on in sections 4 and 5, respectively.
The main results of the present study are summarized in section 6.

2. Data obtained during MISMO

The data used for this study were obtained from the R/V Mirai stationed in the Indian Ocean at (0°, 80.5°E) from 23 October 2006 to 25 November 2006 (34 days), during the MISMO field campaign. Several measurements were collected in addition to standard surface meteorological observations. We will briefly overview the observations conducted during MISMO in this section. More details of platforms and measurement systems are found in Yoneyama et al. (2008b).

A weather radar (C band) was operated to obtain the spatial and temporal distribution of rainfall within a 160-km range every 10 min. Radiosonde measurements were launched every 3 h (0200, 0500, 0800, 1100, 1400,
The radiosonde humidity sensor we employed suffers from dry bias, so the vapor mixing ratio data were corrected, making use of the Meteolabor Snow White chilled-mirror dew/frost-point hygrometers (Yoneyama et al. 2008a). One novelty was a GPS receiver installed on the R/V Mirai, giving precipitable water (PW) with high accuracy every 1 min through the calculation using the zenith total delay (Fujita et al. 2008). Thousands of ground-based GPS sites have been established all over the world, and the accuracy and usefulness of PW derived from the ground-based GPS is commonly accepted. Shipborne GPS is also recently confirmed to be accurate and useful to estimate PW, regardless of the motions of the platform (Rocken et al. 2005). An infrared sea surface temperature autonomous radiometer (ISAR) instrument was mounted on top of the ship’s foremast to measure sea skin, sky, and two internal blackbody temperatures using a narrow field-of-view IR radiometer (Donlon et al. 2008). Individual samples of ISAR were taken every 2–3 s; an entire sweep required about 3 min. Samples were processed at a standard 10-min averaging time.
3. Meteorological conditions during MISMO

Figure 1 shows a time–longitude plot of outgoing long-wave radiation (OLR) anomalies in the global tropical belt (15°S–15°N). These total anomalies were defined by a temporal Lanczos high-pass filter (Duchon 1979) with a cutoff period of 120 days. Further space–time filtering, following Wheeler et al. (2000), defined the overlaid contours of OLR anomalies associated with the MJO and convectively coupled Kelvin and \( n = 1 \) equatorial Rossby wave (ER\( n = 1 \)) waves.

Four intraseasonal enhancements of convection occurred over the Indian Ocean (west of 90°E): early September, late October, late November (the MISMO period), and late December. Two of these intraseasonal organized convective areas slowly propagated from the Indian Ocean to the central Pacific (in September and December), and these are diagnosed as strong MJO events. Westward propagation of convective areas associated with ER\( n = 1 \) is found in October and November. The negative OLR anomalies in November are identified as a weak MJO signal, although those in late October are too modest. The MISMO campaign period (23 October–25 November) corresponds to the transition period from the inactive to the active phase of this weak (or rather, merely short lived and thus weak in the filtered data) MJO.

In a normal year, zonal winds in the lower and upper levels are westerly and easterly, respectively, in the eastern equatorial Indian Ocean (not shown). However, 2006 was an Indian Ocean dipole event (the equatorial eastern Indian Ocean was cooler than the west; Saji et al. 1999), and zonal wind averaged for MISMO was easterly in the whole troposphere (Fig. 2a). Still, the mean meridional wind was weak southerly (Fig. 3a), as is seen in a normal year. It is also noteworthy that westerly wind prevailed around the tropopause (150-hPa level) in the first half of the MISMO and drastically changed to easterly on 16 November when the negative OLR areas associated with an ER\( n = 1 \) wave extended over the R/V Mirai and the weak MJO broke out (Fig. 1).

Both wind components show regular variations, although the period of zonal wind variations was a little longer than that of meridional wind variations. Power spectra of winds, calculated by a simple FFT method, are plotted in Figs. 4a,b. Zonal wind had a distinct 6–8-day peak in almost the whole troposphere, while meridional wind had a clear 3–4-day peak near the surface and in the midtroposphere (500–400-hPa level). These peaks at 6–8- and 3–4-day periods are also seen in the zonal and meridional winds at the surface, respectively (Fig. 4c).

GPS-derived PW remained about 60 mm in the late October, then drastically decreased at the beginning of November (Fig. 5b). The decrease reflects the intrusion of dry air in the 900–600-hPa layer (Fig. 5a), where relative humidity dropped to as low as 10% on 3 November (not shown). After the minimum, PW steadily increased and attained 60 mm again on 16 November, when convection associated with a MJO became active in the vicinity of the R/V Mirai (Fig. 1). Power spectra show that mixing ratio in the lower troposphere and PW had a prominent 3–4-day period peak (Fig. 6). On the other hand, temperature had no prominent spectral peak (not shown).
Figure 7a shows variations in the coverage of C-band radar echo for reflectivity factors larger than 15 dBZ at 3 km within a radius of 160 km. Radar echo is classified as either convective or stratiform, following the method used by Steiner et al. (1995). In Fig. 7b, time series of the precipitating system number are shown. A precipitation system is identified using convective or total precipitation grids (>15 dBZ at 3 km) connecting with each other in north–south or east–west directions.

In the beginning of MISMO, precipitation echoes showed regular variations with a period of about 2 days, which would be associated with the westward propagation of convective areas in the vicinity of the R/V Mirai (Fig. 1). In November, westerly wind prevails in the upper level, and the westerly wind phase corresponds to the convectively suppressed period. In this period, large areas of precipitation were not observed except on 10 November. We call this period (MJO) the “inactive period.” After the dramatic change of westerly into easterly around the 150-hPa level on 16 November, precipitation systems cover a large area around the R/V Mirai and stratiform coverage is enhanced. We call the period after
16 November (MJO) the “active period.” The regular 3–4-day variations in the number of precipitating systems are remarkable during both the inactive and active periods in November, and the power spectra have a clear 3–4-day peak throughout this period (not shown). Therefore, the 3–4-day period variation is not just a dynamical (and adiabatic) phenomenon, but is also accompanied by diabatic processes. This 3–4-day period variation will be focused on in section 4.

SST remained above 28.5°C during almost the whole period of MISMO after a minimum of about 28.2°C in late October (Fig. 8a) and exceeded 29°C on 2, 8, 14, and 23 November. In these warmer periods, undisturbed (mainly clear) and light-wind conditions are observed and SST diurnal variations are prominent. The variations of surface wind strength are negatively correlated with those of SST (Figs. 8a,b), and the power spectra of surface wind strength have a significant 6–8-day peak as does zonal wind (Fig. 4c). Radar echo coverage and precipitation system number (and PW) do not show the 6–8-day-period variations, so it appears to be more of a dry dynamical phenomenon unlike the 3–4-day period variations. However, heat storage in the undisturbed conditions would be favorable to the MJO development. This 6–8-day-period variation is further examined in section 5.
4. 3–4-day period variations

Time filtering is used to isolate the vertical structure of the 3–4-day variations in the radiosonde-derived meridional wind (Fig. 3c), based on a Lanczos bandpass filter having cutoff periods of 2.5 and 5 days and a filter length of 21 days (Duchon 1979). The largest amplitude is seen in the 500–400-hPa level and there are two nodes in the upper and lower troposphere. The level of the lower node varies with time, while the upper node is constantly located around the 350-hPa level. The lower node is seen at around the 600-hPa level in late October and decreases to the 800-hPa level in the middle of November. The lower node disappears and an in-phase vertical structure is found in the lower troposphere after the onset of the MJO active convection (16 November), while the 3–4-day period component of the vapor mixing ratio shows tilting near the surface (Fig. 5c).

The horizontal structure of the 3–4-day period component is examined in the 500–400-hPa level where the amplitude is the largest in Figs. 3c and 4b. We used re-analysis data offered by the Japan Meteorological Agency (JMA) known as the JMA Climate Data Assimilation System (JCDAS) a continuation using the same system as the Japanese 25-yr Re-Analysis (JRA-25; Onogi et al. 2007). The radiosonde observations conducted during MISMO were shared through the Global Telecommunication System (GTS), and assimilated wind variations show similar patterns to the radiosonde observations except near the surface (not shown).

Figure 9 shows time–longitude variations of the 3–4-day period component of the meridional wind. Around 80°E, a westward-propagating signal is prominent, although the propagation speed is not constant. The propagation is about 15°–90° day^{-1} (=19–116 m s^{-1}) in the inactive period, and the propagation speed shifts to slower range (8°–18° day^{-1} = 10–23 m s^{-1}) in the active period. The corresponding zonal wavelengths are estimated to be about 6100 km (=55°) and 3300–7800 km (=30°–70°) in the inactive and active periods, respectively. Figure 10 shows latitude–time sections of the 3–4-day period component of the zonal and meridional winds along 80°E. Antisymmetric patterns across the equator are found in the zonal wind variations, while patterns are symmetric in the meridional wind variations (Figs. 10a,b), indicative of vortex centers located over the equator (Fig. 10c), consistent with mixed Rossby–gravity (MRG) waves, although the structure of the circulation is significantly distorted by the convection in the MJO active period (Fig. 10c). Taking into the account the Doppler shift by the environmental wind, calculated equivalent depths are about 24 and 1.5–22 m in the inactive and
active periods, respectively [environmental wind in the 500–400-hPa level is assumed to be \(2.7 \text{ m/s}\) from the reanalysis data (JCDAS)]. The corresponding deformation radiuses are 7.3 and 3.7–7.2. The deeper equivalent depth in the inactive period may imply that coupling with convection is less significant than in the active period. The change in the phase speed of equatorial waves from the active convective to suppressed convective phases of the MJO is consistent with Roundy (2008) for Kelvin waves embedded in the MJO.

Disturbances associated with MRG waves over the western Pacific have been reported by several previous papers. Hendon and Liebmann (1991) pointed out that the disturbances corresponding to the theoretical MRG wave are dominant in the central and western tropical Pacific in the 3–6-day period range. Takayabu and Nitta (1993) also detected 3–5-day period variations from satellite data and global objective analysis data and classified them in two types of disturbances (MRG and TD). Numaguti et al. (1995) reported a significant 4–5-day period variation in surface and atmospheric data obtained at the equatorial western Pacific during TOGA COARE, and clarified that the 4–5-day period variation can be explained by westward-propagating MRG wave disturbances. The equivalent depth of the inactive period estimated in the present study (24 m) overlaps the range estimated over the western Pacific (30–50 m; Takayabu and Nitta 1993), although the equivalent depth in the active period (1.5–22 m) is a little shallower.

Composites of time-filtered data (Figs. 11–12) serve to clarify the vertical structures of the MRG waves observed during the MJO inactive and active periods. In each period, we selected 3 samples, using the northerly (negative) peak of the 3–4-day period meridional wind component averaged over the 1000–900-hPa level as an indicator (0900 UTC 5 November, 0900 UTC 9 November, and 1500 UTC 12 November in the inactive period, and 0000 UTC 16 November, 0600 UTC 19 November, and 0300 UTC 23 November in the active period). The composite center (northerly wind peak near the surface) corresponds to 1200 UTC on day 2 in Figs. 11 and 12.

In the inactive period, meridional variations have two nodes at the 350- and 800-hPa levels and three maxima around the 200-, 500-, and 900-hPa levels (Fig. 11a). The phase below the 800-hPa level is opposite that in the midlevel, although the phase above the 350-hPa level is delayed by about 90°. Vapor mixing ratio in the lower level (below the 700-hPa level) increases in the northern wind phase near the surface, while that in the upper level lags and peaks in the transition from the southern to northern wind phase (Fig. 11b). The PW also peaks in the transition phase (Fig. 11c), and variations in the stratiform-type radar echo coverage show a peak around the PW maximum (Fig. 11d). Convective-type radar echo coverage predates the PW variations by several hours and the precipitation system number peaks 12 h prior to the PW maximum.

In the active period, meridional wind variations have only one node around the 350-hPa level, although three maxima are located around the 200-, 500-, and 900-hPa levels (Fig. 12a). In-phase (or slightly eastward tilt) structure is found in the lower and midtroposphere (between the 1000- and 350-hPa levels), while the variations below and above the 350-hPa level are out of phase. A lower-level maximum of amplitude (around 950-hPa level) is seen, different from the inactive period of Fig. 11. On the other hand, the upper-level peaks (around the 500- and 200-hPa levels) are weaker in Fig. 12 than in Fig. 11.

Vapor mixing ratio profiles show eastward tilt with height, but peaks are found in the northerly (negative) wind phase in the lower troposphere (Fig. 12b). Reflecting these vapor variations, PW also peaks in the northerly wind phase (Fig. 12c). The precipitation system number predates the PW variations like in the inactive period (Fig. 12d). However, the peak of convective-type radar
The maximum of stratiform-type radar echo coverage lags the PW peak by about a half day, and corresponds to the transition phase from the northerly to southerly wind phase in the lower troposphere.

The vertical structures including the moisture buildup from the lower to upper troposphere display a wide range of similarity on the life cycle of convectively coupled equatorial waves [see the review paper by Kiladis et al. (2009)]. On the other hand, these different phase
Fig. 11. Composite 3–4-day period variations in (a) radiosonde-derived meridional wind, (b) vapor mixing ratio, (c) GPS-derived PW, and (d) precipitation system number (solid line; left axis) and radar echo coverage (dashed and dotted lines; right axis) in the inactive period. The contour interval is 0.7 m s$^{-1}$ and 0.2 g kg$^{-1}$ in (a) and (b), respectively, and the positive area is shaded. In (d), convective- and stratiform-type echo coverage is indicated by dashed and dotted lines, respectively (km$^2$). The Lanczos bandpass filter having cutoff periods of 2.5 and 5 days and a filter length of 21 days is applied to the all variations. The composite center (northern wind peak of the 3–4-day period meridional wind component averaged over the 1000–900-hPa level) corresponds to 1200 UTC on day 2.
relationships and characteristics between in the inactive and active periods might result from different degrees of coupling with convection and vertical shear of the zonal wind might influence the coupling (e.g., Wang and Xie 1996). However, three samples is too weak a basis for drawing any robust conclusions.

To check the generality of MRG activity in MISMO’s MJO active period, Fig. 13 shows 5-month time–longitude sections of symmetric and antisymmetric components of the meridional wind anomaly with respect to the equator. Here a simple 30-day running mean is subtracted to define the high-frequency anomalies. Westward-propagating waves whose packet migrates to the east are prominent in the symmetric component during the convectively active period, while these features are obscure in the antisymmetric component. Different latitude band

FIG. 12. As in Fig. 11, but for the composite variations in the active period.
selections do not affect these results much. Despite the broad high-pass filter, the periods do not exceed 8 days. From these characteristics and the analysis in the present investigation, it would be reasonable to consider that these waves are associated with the MRG wave (e.g., Yang et al. 2003).

Nasuno et al. (2007) also point out the dominance of westward-propagating disturbances with cross-equatorial flow, associated with MRG waves, in the organized convection envelope of a MJO in global numerical experiments with explicit moist physics. Furthermore, Miura et al. (2009) conducted a numerical experiment during the MISON period with the same model as Nasuno et al. (2007), and MRG wave disturbances were again dominant in the simulation. These results suggest that disturbances associated with the MRG wave type are one of the important components of MJO-related convection.

5. 6–8-day period variations

The vertical structure of the 6–8-day-period variations in radiosonde-derived zonal wind was shown above (Fig. 2c) based on a Lanczos bandpass filter having cutoff periods of 5 and 10 days and a filter length of 31 days. The largest amplitude of the 6–8-day variations is seen around 400–300 hPa. However, the peak shifts to the lower levels (900–800 hPa) during the active period. Nearly barotropic vertical structure is found in the troposphere during the entire period.

The horizontal structure of this 6–8-day period component is examined in the 400–300-hPa level where the amplitude is the largest in Figs. 2c and 4a. Reanalysis data products (JCDAS) are used again and the same Lanczos bandpass filter is applied. Around 80°E, westward-propagating signals are prominent, with propagation...
speed estimated to be about 14 m s\(^{-1}\) with a zonal wavelength of 80° (Fig. 14). Figure 15 shows latitude–time sections of the 6–8-day period component of the zonal and meridional winds along 80°E. Symmetric patterns over the equator are found in the zonal wind variations, while patterns are antisymmetric in the meridional wind variations, quite contrary to the 3–4-day period variations. These imply antisymmetric twin vortexes across the equator with a node at the equator (Fig. 15c), although the structure of the circulation is significantly distorted by the convection in the active period. These characteristics are consistent with \(n = 1\) equatorial Rossby waves (ER\(n_1\)).

Taking into the account the Doppler shift by the environmental wind at this level, the calculated equivalent depth is about 66 m [environmental wind in the 400–300-hPa level is assumed to be \(2.7\) m s\(^{-1}\) from the reanalysis data (JCDAS)], but Doppler shifting by a weaker layer-averaged wind gives a substantially larger value (>100 m), closer to dry rather than moist wave equivalent depths, and this may be more relevant for a deep wave structure. The estimated deformation radius is consistent with the latitude of the vortex centers, although this is only a weak confirmation of the wave interpretation.

Several previous papers have pointed out that ER\(n_1\) waves (they are frequently associated with midlatitude Rossby trains) may play some role in MJO amplitude and timing (e.g., Matthews 2000, 2008; Meehl et al. 2001; Roundy and Frank 2004; Seo and Kim 2003). During the MISMO period, a drastic change in the upper-level zonal wind associated with ER\(n_1\) wave is also observed around the onset of a weak MJO (Fig. 2, around 16 November), and negative OLR anomalies diagnosed as ER\(n_1\), which partly compose the MJO convection, develop at the western Indian Ocean (Fig. 1). Therefore, we will examine the fidelity of the ER\(n_1\) waves in reanalysis data, making use of the AGCM for the Earth Simulator (AFES) Local Ensemble Transform Kalman Filter (LETKF) Experimental Reanalysis (ALER; Miyoshi et al. 2007). ALERA is an experimental ensemble reanalysis dataset produced by the 4D-LETKF (Hunt et al. 2007; Miyoshi and Yamane 2007) with AFES (Ohfuchi et al. 2004). It is independent of the JCDAS, although a lot of observational data are shared through the GTS and analyzed fields are very similar to each other (not shown). The main advantage of the ALERA dataset is that the spread of atmospheric variables among the ensemble members is provided, which can be used to estimate the reliability of the analyzed field.

Figure 16 shows a time–longitude plot of the anomaly of a vertically averaged ensemble spread of zonal winds. (We focus on the vertical average due to the barotropic structure of the 6–8-day period variations in Figs. 2 and 4.) Clear westward-propagating signals are found, coinciding with the speed of the ER\(n_1\) wave identified in Fig. 14 (as annotated here by solid and dashed lines). Positive anomalies are located between in the positive and negative peaks of the 6–8-day period variations. In the theoretical horizontal structure of the ER\(n_1\) wave, this is where zonal confluence occurs along the equator and wind convergence peaks in symmetric off-equatorial patches. It should be noted that no specific mode filter is applied to get the anomaly of the spread. Therefore, we can say that the ER\(n_1\) wave makes a distinct contribution to the uncertainty in the analyzed zonal wind field during the MISMO period. Possible interpretation is that the assimilated wave structure in this confluent part of the wave phase especially excites the model’s convection scheme in some way that leads to rapid growth of differences among ensemble members. Further investigations of the analysis ensemble spread will be useful to understand whether these points to predictability limits that may affect the ability to capture and simulate such ER\(n_1\) waves and the MJO onset process.

6. Summary and conclusions

JAMSTEC conducted a field experiment in October–December 2006 aboard the R/V Mirai, focusing on the initiation of convection in the MJO in the central equatorial Indian Ocean (MISMO). During MISMO, large-scale organized convection was found over the Indian Ocean, and it was diagnosed as a weak MJO that did not go on to propagate into the western and central Pacific.
Zonal and meridional wind components have prominent 6–8- and 3–4-day period variations, respectively. GPS-derived PW, radiosonde-derived vapor mixing ratio, and precipitation system number identified by radar echoes also show a clear 3–4-day cycle. SST diurnal variations are enhanced every 6–8 days in the undisturbed (mainly clear) light-wind conditions, and this surface wind fluctuation seems to be part of a deep barotropic zonal wind structure.

The largest amplitude of the 3–4-day period variations in the radiosonde-derived meridional wind is found in the 500–400-hPa level. At this level, meridional wind anomalies in the reanalysis data (JCDAS) propagate westward, and the horizontal wind structures suggest

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**Fig. 15.** As in Fig. 10, but for the 6–8-day period component of reanalyzed wind (JCDAS). To get the 6–8-day period component, the Lanczos bandpass filter is applied, having cutoff periods of 5 and 10 days and a filter length of 31 days.
that the 3–4-day period variations are associated with the MRG wave with equivalent depths estimated to be 24 and 1.5–22 m in the MJO inactive (1–16 November) and active (16–26 November) periods, respectively. The former equivalent depths overlap the range estimated by Takayabu and Nitta (1993) (30–50 m), although the latter is a little shallower.

Composites of 3 samples in the inactive and active periods reveal that meridional wind variations in the middle (500–400 hPa) and upper (200 hPa) levels are more prominent in the inactive period than in the active period, while those in the lower troposphere (around 900 hPa) are more pronounced in the active period. Stratiform-type radar echo coverage was synchronized to the PW variations in the inactive period, while convective-type radar echo coverage and precipitation system number lead (predate) the vapor signal. In the active period, the convective echo number still leads PW, but convective-type radar echo coverage was almost synchronous with PW while stratiform-type radar echo coverage lags PW by about 12 h.

The dominance of the MRG wave is also found in other intraseasonal convective outbreaks over the Indian Ocean from September to December in 2006. A recent paper using a numerical model points out importance of the MRG wave disturbances in a MJO (Nasuno et al. 2007), so further investigation on the role of the MRG wave in the MJO is needed.

The 6–8-day period variations in the radiosonde-derived zonal wind are most prominent in the 400–300-hPa level, although the peak shifts to the lower level (900–800 hPa) in the active period. At the 400–300-hPa level, zonal wind anomalies propagated westward with horizontal wind structures suggesting an ERn1 wave with much greater equivalent depth than is typical of convectively coupled waves. This wave poses a special challenge to data assimilation, as seen in the spread in ensemble analysis system members, indicating the analyzed zonal wind field has larger uncertainties associated with the ERn1 wave. Further investigations for the reasons of this enhanced analysis ensemble spread at the MJO developing stage might give new insights into the ER wave, the MJO onset mechanism, and the analysis model’s challenges of capturing these phenomena.

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