Equatorial Dry Air Intrusion and Related Synoptic Variability in MJO Initiation during DYNAMO

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ABSTRACT

Dynamics of the Madden–Julian oscillation (DYNAMO) was conducted over the equatorial Indian Ocean (IO) from October 2011 to March 2012. During mid- to late November, a strong Madden–Julian oscillation (MJO) event, denoted MJO-2, initiated in the western IO and passed through the DYNAMO observation array. Dry air intrusions associated with synoptic variability in the equatorial region played a key role in the evolution of MJO-2. First, a sharp dry air intrusion surging from the subtropics into the equatorial region suppresses convection in the ITCZ south of the equator. This diminishes subsidence on the equator associated with the ITCZ convection, which leads to an equatorward shift of convection. It is viewed as a contributing factor for the onset of equatorial convection in MJO-2. Once the MJO convection is established, a second type of dry air intrusion is related to synoptic gyres within the MJO convective envelope. The westward-propagating gyres draw drier air from the subtropics into the equatorial region on the west side of the MJO-2. This dry air intrusion contributes to a 1–2-day break in the rainfall during the active phase of MJO-2. Furthermore, the dry air intrusion suppresses convection in the westerlies of the MJO in the IO. This favors the abrupt shutdown of MJO convection during transition to the suppressed phase in DYNAMO. The two types of dry air intrusions can redistribute convection from the ITCZ to the equator and favor the eastward propagation of the MJO convection. Further study of multiple MJO events is necessary to determine the generality of these findings.

1. Introduction

The Madden–Julian oscillation (MJO) is the dominant intraseasonal (20–90 day) mode of variability in the tropics (Madden and Julian 1971, 1972, 1994; Zhang 2005). It is most active during boreal winter. Convectively active phases of the MJO are characterized by rainy periods that can last several weeks at a given location. In the Indian Ocean, the MJO can be described as a packet or envelope of convection centered near the equator moving eastward at ~5–10 m s\(^{-1}\). The envelope of convection spans ~2000–4000 km and is often organized into coherent “super cloud clusters,” which can be objectively tracked for several days (Nakazawa 1988; Mapes and Houze 1993; Chen et al. 1996). In addition to convection, the low- (upper-) level winds oscillate between anomalous easterlies (westerlies) and westerlies (easterlies) with the passage of the MJO. Because of its global influence on general circulation patterns, the MJO affects floods (Bond and Vecchi 2003), droughts (Hoell et al. 2012), heat waves, and tropical cyclones (Molinari and Vollaro 2000; Maloney and Hartmann 2001).

The influence of the MJO varies regionally. Rainfall and low-level winds are most affected in regions where deep convection is climatologically favored: the Indian Ocean (IO), Maritime Continent, and western Pacific Ocean. The convection tends to persist longest in the IO and western Pacific (WPAC). The eastward progression of the MJO resembles a “seesaw” between the IO and WPAC (Zhu and Wang 1993; Chen and Houze 1997). The term “MJO event” in this study refers to the initial development of the large-scale convection near the equator in the western/central IO and eastward propagation to the Maritime Continent. This is described as the convective phase in Stephens et al. (2004). The end of the MJO event in the IO is marked by post-MJO suppressed convection throughout the equatorial IO. This is referred to as the restoring phase. The restoring phase
sets up the destablization phase in advance of the next MJO event. Recent work suggests that the triggering of an MJO event may be influenced by the extratropics (Ray and Zhang 2010; Zhao et al. 2013; Ray and Li 2013).

In the tropical IO, the characteristics of convection and wind associated with the MJO differ from the western Pacific. In the western Pacific, Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) provided the most detailed observations of the MJO. The heaviest rain occurred behind the leading edge of the westerlies, in the so-called strong westerly region (Chen et al. 1996; Houze et al. 2000). The overall structure of the MJO was described as a hybrid Kelvin–Rossby wave (Houze et al. 2000). Furthermore, mesoscale descent associated with large (>300 km) cloud clusters reinforced the low-level westerlies. Similarly, Kubota et al. (2006) found that in a WPAC MJO event, the strongest convection was coincident with the strongest westerly winds, which were enhanced by a developing tropical cyclone to the north. In contrast to TOGA COARE, rainfall during an MJO event in the IO during the Mirai Indian Ocean Cruise for the Study of the MJO Onset (MISMO) in October 2006 was concentrated at the leading edge of the westerlies (Yamada et al. 2010). Rainfall was concentrated in eastward-moving bands of rainfall, while bands of cold cloud tops (e.g., cloud shields) tended to move westward. The eastward-propagating precipitation systems were similar to convectively coupled Kelvin waves with rainfall concentrated at the zonal wind confluence. These convectively coupled Kelvin waves move eastward at 12–15 m s⁻¹, much slower than the MJO propagation of 5–10 m s⁻¹ (Kiladis et al. 2009; Yang et al. 2007a,b). In contrast, the westward-propagating systems were mainly mid- and upper-level anvil clouds without much precipitation. A notable feature of the schematic of Yamada et al. (2010) is a 2–3 day “break” in rainfall between the consecutive eastward-propagating precipitation systems within the convectively active phase of MJO.

Equatorial waves play a significant role in modulating tropical convection, including convection within the active MJO envelope (Wheeler and Kiladis 1999; Wheeler and Weickmann 2001; Wheeler et al. 2000; Cho et al. 2004; Kiladis et al. 2009). Equatorial waves have characteristic time scales of 2–15 days and have the highest amplitude near the equator. Kelvin waves are the predominant eastward-propagating mode. Kelvin waves coupled with convection move at 12–15 m s⁻¹, which is much faster than the MJO propagation of 5–10 m s⁻¹. The MJO convection at times resembles a wave packet of convectively coupled Kelvin waves with group velocity slower than the Kelvin wave phase speed (Masanuga 2007; Roundy 2008). However, in some MJO events with the convection concentrated off the equator, the Kelvin mode is not a prominent feature (Chen et al. 1996; Chen and Houze 1997). Westward-propagating equatorial wave modes include the equatorial Rossby (ER) waves, mixed Rossby–gravity (MRG) waves, and westward-moving inertio-gravity waves (Wheeler and Kiladis 1999). ER waves are characterized by symmetric twin gyres on either side of the equator with convection concentrated near the gyre centers. MRG waves are characterized by gyres centered near or on the equator with convection concentrated on the poleward sides of the cross-equatorial flow, which is separate from the circulation center. In nature, ER waves and MRG waves exist as a continuum along with easterly waves and tropical depression type (“TD type”) disturbances which are centered farther off the equator (e.g., 10°–20°) and do not conform to any particular equatorial wave mode (Dunkerton 1993; Takayabu and Nitta 1993; Dunkerton and Baldwin 1995; Kiladis et al. 2009). ER waves and MRG waves can transition to off-equator low pressure systems (e.g., TD-type disturbances), occasionally spawning tropical cyclones (Lau and Lau 1990; Dickinson and Molinari 2002; Frank and Roundy 2006). Because it can be difficult to distinguish between ER waves, MRG waves, and the TD-type disturbances, in this study they are referred to generically as Rossby-like waves. The low-level wind flow associated with Rossby-like waves is generally in the form of synoptic-scale cyclonic gyres, denoted Rossby gyres.

Dynamics of the Madden–Julian oscillation (DYNAMO) was conducted from August 2011 to March 2012, with the intensive observation period (IOP) in October 2011–January 2012 (Yoneyama et al. 2013). In addition to DYNAMO, two concurrent experiments were carried out in the equatorial IO: the Cooperative Indian Ocean Experiment on Intraseasonal Variability (CINDY) and the Atmospheric Radiation Measurement (ARM) MJO Investigation Experiment (AMIE). For brevity, these cooperative field experiments are hereafter referred to simply as “DYNAMO.” One of the major objectives of DYNAMO was to use multiplatform, in situ, and remotely sensed observations to help understand MJO initiation. The three well-defined MJO events that occurred during these field experiments are the most well-observed MJO events over the IO (Gottschalck et al. 2013; Yoneyama et al. 2013). Yoneyama et al. (2013) discussed three hypotheses that motivated the field experiments. In particular, the first one stated that sufficient moistening is necessary over a region of the scale of the MJO, prior to MJO initiation. In this study, it is argued that for the second MJO event in DYNAMO, the intrusion of dry air into this moist equatorial region was a contributing factor in the initiation of equatorial
convection, day-to-day variability within the MJO, and eastward propagation.

This paper is organized as follows. Section 2 describes the data used. Section 3 gives an overview of dry air intrusion during MJO-2. The time–longitude view of MJO-2 is presented in section 4. Vertical structure of dry air intrusion is in section 5. Section 6 discusses the role of the Rossby gyres for dry air intrusion. The topic of section 7 is the possible relationship between an extratropical wave train and the dry air intrusion. Finally, the summary and conclusions are given in section 8.

2. Data

a. DYNAMO field campaign

The DYNAMO field data include an array of six surface stations, four of them on islands and two ships: the R/V Revelle and R/V Mirai (sounding array is drawn in Fig. 1). The stations each had 3-hourly radiosondes during the MJO event considered in this study. This study uses the Southern Hemisphere quadrilateral, also known as the southern array. The sounding data at Gan (0.6°S, 73.1°E), Diego Garcia (7.3°S, 72.4°E), and the RV Revelle (stationed at 0°, 80°E during the period of this study) are level-3 quality controlled data processed by the National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL). See Wang et al. (2012) for details regarding the quality control process used. The RV Mirai (stationed at 8.0°S, 80°E until 28 November) data are level-2 preliminary data from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

In addition, during November–December the National Oceanic and Atmospheric Administration (NOAA) P3 flew 12 science missions and the Centre National d’Etudes Spatiales (CNES) Falcon flew 10 missions. The NOAA P3 was based out of Diego Garcia and the CNES Falcon out of Gan. A total of 468 dropwindsondes were deployed along the P3 flight paths (Chen et al. 2012), which are level-3 quality controlled data from the NCAR EOL (Young et al. 2012). For further details regarding the field experiment objectives, design, and instrumentation see Yoneyama et al. (2013).

This study focuses on the period from 12 November to 5 December, including an MJO event denoted MJO-2 (i.e., the second event of DYNAMO). It includes the pre-MJO-2 convectively suppressed phase (12–23 November), transition to equatorial convection (23–24 November), MJO-2 active convection (24–28 November over the DYNAMO arrays), and the beginning of the post-MJO-2 suppressed phase (29 November into early December). As discussed by Yoneyama et al. (2013) and Gottschalck et al. (2013), two strong, relatively fast, circumnavigating MJO events spaced less than 45 days apart occurred during 17 September–8 December. This second event was MJO-2. The 30-day time scale of these events was relatively short compared with typical MJOs (30–90 days).

b. ECMWF analysis

To document the large-scale flow patterns and moisture distribution, European Centre for Medium-Range Weather Forecasts (ECMWF) operational analysis is used. These data were provided in real time in support of field campaign forecasting efforts. The dataset benefits from 4D variational data assimilation (4DVar), including the DYNAMO field observations. For this study, the 0.25° pressure-level data are used.

c. Infrared satellite data

Infrared (IR) satellite coverage during DYNAMO was provided by Meteorological Satellite-7 (Meteosat-7). For this study, the data were interpolated to a 0.05° grid. The focus is on latitude averages (5°S–5°N), which gives a general indication of convective activity in the equatorial Indian Ocean. Cloud clusters were defined as contiguous areas of <208-K brightness temperatures, and they are tracked in time as time clusters (Chen et al. 1996; Kerns and Chen 2013).

d. TRMM rainfall

Rainfall rate and accumulation are determined using the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA; Huffman et al. 2007). The algorithm uses rainfall rate retrievals from TRMM Precipitation Radar (PR) and Microwave Imager (TMI) as well as the Special Sensor Microwave Imager (SSM/I). Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E), and the Advanced Microwave Sounding Unit-B (AMSU-B). Typically, about 80% of the tropics and subtropics are covered by passive microwave satellite overpasses within a 3-h period. Where there are no passive microwave data available, infrared-based rain estimates are used. The data used here are version 7, which are calibrated using the rainfall rates determined from coincident TRMM PR/microwave overpasses. The data are at 3-h temporal resolution on a 0.25° grid.

e. Total precipitable water

The Cooperative Institute for Meteorological Satellite Studies (CIMSS) morphed satellite total precipitable water (TPW) is described by Wimmers and Velden (2011). The product uses TPW retrievals from the SSM/I and AMSR-E. To fill in the data gaps in between hourly satellite swath data, the latest available
Fig. 1. (a)–(h) CIMSS morphed total precipitable water (color shading) and Meteosat IR brightness temperatures (grayscale) from 20 to 25 Nov 2011. The DYNAMO array is drawn in dark black lines. The equator is indicated with a solid black line. Terrain is indicated by the darker shades of green. The arrows in (b), (c), and (d) denote the approximate leading edge of the dry air surge. Times are in UTC.
previous swath data are advected using low-level winds from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) analysis. The data are provided by CIMSS hourly at 0.25° resolution.

Because the morphed TPW data uses multiple satellites with different calibrations, and the model winds used to advect the TPW fields are subject to errors, there are limitations to the TPW data. Discontinuities of a few millimeters can occasionally be seen at the edges of satellite swaths when the data are updated with new swaths. Also, moderate changes in midlevel moisture with the boundary layer and upper levels remaining moist are not easily distinguished in terms of TPW. For these reasons, the evolution of TPW is most useful at determining strong gradients between moist (>~55 mm) and dry air (<~45 mm) masses, where there are large gradients of moisture through a deep layer of the atmosphere. Fortunately, these sharp moisture gradients are common (Zhang et al. 2003).

3. Moisture, convection, and dry air intrusion in the equatorial region

As shown in Figs. 1 and 2, deep convection (e.g., cold cloud tops <235 K; grayscale), is mainly limited to areas with TPW >50 mm (shaded orange and red). For the Indian Ocean during DYNAMO, this was mainly limited to latitudes from ~10°S to 10°N—referred to here as the equatorial region. Numerous previous studies have noted that moistening of the equatorial region is a necessary prerequisite to MJO initiation [see discussion in Yoneyama et al. (2013)]. Without sufficient moisture there can be no widespread deep convection and no MJO. Nevertheless, even when the equatorial region is sufficiently moist for widespread deep convection, the deep convection does not uniformly encompass the entire moist equatorial region. Instead, it is clustered in mesoscale convective systems [e.g., contiguous gray/white areas with horizontal dimension O(100–500 km) in Figs. 1 and 2], which themselves tend to cluster around large-scale weather systems such as the intertropical convergence zone (ITCZ) and various synoptic disturbances. In particular, an active ITCZ is common during the destabilization phase leading up to MJO initiation (Zhang 2005; Gottschalck et al. 2013; Yoneyama et al. 2013).

When deep convection is concentrated in the ITCZ off the equator, there is likely some large-scale subsidence induced over the equator, which is unfavorable for equatorial convection. Indeed, prior to the onset of MJO-2 convection on the equator, the double ITCZs on both sides were active (Figs. 1a–c). There is a local minimum in TPW (around 50 mm vs >55 mm to the north and south) over the equator on 21–22 November, suggesting some subsidence-induced drying associated with the ITCZs (Figs. 1a–c), which is unfavorable for equatorial convection.

The boundary between the moist equatorial region and the dry subtropics is characterized by a sharp drop off in TPW from >50 to 30–40 mm within a distance of ~100–200 km. This feature is approximated by the yellow shading in Figs. 1 and 2. For example, at 0000 UTC 20 November the sharp moisture boundaries are at around 10°N and 15°S in the western IO (Fig. 1a). Occasionally, the drier air intruded into the equatorial region. This process is referred to as dry air intrusion. For example, a particularly pronounced instance of dry air intrusion began in the eastern IO on 20 November (Fig. 1a) and moved westward into the central IO three days later (Figs. 1b–d; arrows indicate the leading edge of the dry air). As the boundary penetrated deeper into the equatorial region, the deep convection shifted from the ITCZ to the equator (Figs. 1a,d). This particular event is referred to as a “dry air surge” due to the distinct, sharp boundary between the dry and moist air.

During the period of this study, the equatorial Indian Ocean started out on 20 November with a moist (TPW >50 mm) equatorial region with convection concentrated away from the equator, resembling a double ITCZ (Fig. 1a). Although the equatorial region was sufficiently moist, the preferred configuration of convection was not yet favorable for equatorial convection of the MJO. A sharp intrusion of dry air—a dry air surge—penetrated from the southeast IO to within 5° of the equator by 23 November (Fig. 1d). Meanwhile, a companion dry air surge occurred in the Northern Hemisphere, penetrating to 8°N. With the dry air intrusion/surges, convection was no longer favored in the ITCZ. A widespread blowup of convection occurred along the equator, signaling the transition to the convective phase of the MJO (Figs. 1d–h and 2a–f). Note that the surge does not enhance convection. Instead, it shifts the preferred location of the convection such that the new configuration is more favorable for development of the MJO. Even with the dry air surge, most of the equatorial region remained moist, until the end of MJO-2 in the IO. In the wake of MJO-2, the sustained intrusion of moderately dry air (40–50 mm) into the equatorial region suppresses convection throughout the equatorial IO (Figs. 2f–h), leading to the post-MJO-2 suppressed period, referred to as the restoring phase by Yoneyama et al. (2013).

A notable feature of the equatorial region during DYNAMO was the frequent intrusion of drier air (e.g., 40–45 mm) into the moist (>50 mm) equatorial region. This dry air intrusion is particularly persistent from
FIG. 2. (a)–(h) CIMSS morphed total precipitable water (color shading) and Meteosat IR brightness temperatures (grayscale) from 25 Nov to 1 Dec 2011. The DYNAMO array is drawn in dark black lines. The equator is indicated with a solid black line. Terrain is indicated by the darker shades of green. Times are in UTC.
around 28 November into early December (Figs. 2e–h). This was after the MJO convective envelope has moved east of the study region. The intrusion of dry air into the western side of the MJO envelope suppressed convection on the west side, making eastward propagation more favorable. Within the dry air intrusion with TPW < 50 mm, deep convection is nearly nonexistent. Therefore, the dry air intrusion strongly affects the distribution of rainfall, deep convection, and latent heating in the equatorial region of the IO.

4. Time–longitude evolution of MJO-2

The development and eastward propagation of MJO-2 can be clearly seen in time–longitude sections of rainfall (Fig. 3a), clouds (Fig. 3b), and zonal winds (Fig. 4). The rainfall and cold cloud within 5°S–5°N associated with the passage of MJO-2 in the IO were concentrated in two distinct eastward-moving features with a 1–2-day break in between (Figs. 3a,b). The initial development of widespread heavy rain from 55° to 75°E on 22–23 November with subsequent eastward propagation indicates the initiation of MJO-2. The timing corresponds with the penetration of dry air surges close to the equator (Fig. 1d).

Within the DYNAMO observation array, the break period was on 25–26 November. During the peak rainfall maxima, the latitude-averaged rain rates exceeded 5 mm h⁻¹ within the DYNAMO array. During the break period, it was less than 0.5 mm h⁻¹. This break period is similar to Yamada et al. (2010). However, one difference from that study is prominent westward-propagating rain and cold cloud features, especially embedded in the second rain maximum. The westward-moving features had latitude-mean rain rates of >2 mm h⁻¹, while in between them, rain rates were 0–1 mm h⁻¹. Based on the time–longitude variation of the heavier rain rates, the westward-moving features had speeds of 5–10 m s⁻¹. This westward propagation is consistent with the MRGs and ER waves, so they are considered to be related to Rossby-like waves and Rossby gyres.

Corresponding with the leading edge MJO rainfall there was an abrupt shift in low-level winds from easterly to westerly (Fig. 4a) and upper-level winds from
zonal winds of \(<10\, \text{m s}^{-1}\) to strong easterlies of \(>20\, \text{m s}^{-1}\) (Fig. 4b). (The seasonal mean 200-hPa winds during DYNAMO were easterlies of around \(10\, \text{m s}^{-1}\).) Unlike in Houze et al. (2000), but similar to Yamada et al. (2010), the heaviest rainfall coincides with the leading edge of the wind shift. The first rainfall maximum coupled with zonal wind confluence exhibited a predominant eastward motion at \(\sim 6–7\, \text{m s}^{-1}\), slower than the propagation of pure convectively coupled Kelvin waves at \(\sim 10\, \text{m s}^{-1}\). Therefore, the MJO leading edge possessed characteristics of Kelvin waves but was not itself a pure Kelvin wave. At any rate, by helping to shift the convection from the ITCZ to the equator, the dry air surge favors a Kelvin-like response, which tends to move eastward. Also note that the upper-level wind shift signal can be traced back west of the study region, suggesting there may be some influence from the previous circumnavigating MJO event (e.g., MJO-1).

After the passage of the second rainfall maximum on 26–28 November, there was an abrupt decrease in rainfall in the DYNAMO array. This marked the beginning of the suppressed phase of the MJO in the DYNAMO array. Note that at this time the dry air intrusion covered the western equatorial IO and was moving across the DYNAMO arrays in the central IO (Figs. 2f–h). The widespread, persistent intrusion of dry air to the equatorial regions was concurrent with the abrupt transition to suppressed conditions. In order for the next MJO cycle to develop, a buildup or “recharge” of moisture over the equatorial region would be necessary (Blade and Hartmann 1993).

5. Vertical structure of dry air intrusions

a. Dry air “surge”

The first major dry air intrusion event associated with MJO-2 occurred as a sharp surge of dry air. The vertical structure associated with the surge can be seen with the 3-hourly radiosonde data. Generally, Gan (Fig. 5a) and the RV Revelle (Fig. 5b), which were within the moist equatorial region, encountered higher relative humidity throughout the troposphere than Diego Garcia (Fig. 5c) and the RV Mirai (Fig. 5d). Note that the large-scale subsidence drying over the equator induced by the active ITCZ convection was over Gan on 20 November (Fig. 1a), at which time dry air with RH < 50% was seen as low as 650 hPa (Fig. 5a). When the dry air surge
diminished the ITCZ convection during the subsequent days, Gan experienced deepening moist air (e.g., >70% RH up to 700 hPa on 22 November). The sharp boundary of the dry air surge passed directly over the RV Mirai and Diego Garcia on 20–22 November (Figs. 1a–c). This is reflected in the 3-hourly radiosonde data from these stations. At the R/V Mirai, relative humidity above 900 hPa dramatically decreased around 0000 UTC 20 November, associated with the passage of the dry air surge (Fig. 5d). Prior to the surge, the R/V Mirai had recorded RH of ~80% up to 500 hPa. Behind the dry air surge, RH < 30% occurred as far down as 800 hPa. The

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**Fig. 5.** Time–height evolution of relative humidity from radiosondes released at (a) Gan, (b) the R/V Revelle, (c) Diego Garcia, and (d) the R/V Mirai. Date ticks are at 0000 UTC.
dry air remained in place until the R/V Mirai encountered some scattered convection on 25–26 November (e.g., Figs. 1h and 2a,b). Similarly, when the surge passed Diego Garcia late on 21 November, there was a dramatic reduction of RH to $\sim 30\%$ in the low- to midlevels (Fig. 5c).

In addition to the radiosondes, the NOAA P-3 penetrated the boundary of the dry air surge on 22 November as it flew from Diego Garcia, through the southern DYNAMO array, and north to the equator. The vertical cross sections along the first two flight legs suggest that the abrupt drying through most of the troposphere occurred within a distance of 100 km (Fig. 6). Along the leading edge of the surge there was a line of congestus clouds, but not deep convection (F. Judt, 2011, personal communication). The boundary was not simply the boundary between deep convective clouds and dry air (Figs. 1a–d).

b. Equatorial dry air intrusion during the rainfall break

The break period with reduced latitude-averaged rainfall during the active MJO occurred at Gan on 25–26 November and at the R/V Revelle on 26 November (Fig. 3a). Radiosondes released at Gan and the R/V Revelle show drying to $\sim 70\%$ RH at 900–700 hPa during these time periods (Figs. 5a,b). Drying also occurred above 500 hPa, especially at the R/V Revelle. At Gan, this reduction in RH occurred on 25–26 November, with RH $\sim 70\%$ at 800–700 hPa (Fig. 5a). At the R/V Revelle, RH values were $<80\%$ for most of 26 November, between 900 and 700 hPa (Fig. 5b). The low- to midlevel drying is likely not a direct result of mesoscale subsidence within mesoscale convective systems (Zipser et al. 1981), since it persisted over 1 day, and convection was concentrated well away from Gan and the R/V Revelle at this time (e.g., Fig. 2b). It is possible that horizontal midlevel transport associated with inflow into the large convective systems with stratiform rain to the north may play a role (Zhang and Hagos 2009), especially with low TPW air at 5$^\circ$–6$^\circ$S, relatively close to the equator (Figs. 2a–c). In the next section it is shown that the synoptic gyre circulations embedded within the MJO play a major role in this second form of dry air intrusion. Note that this drier air does not show up prominently in TPW (e.g., Fig. 2b) because the integrated tropospheric water vapor content is still relatively high. This form of dry air intrusion is more prominent above the moist boundary layer, at the altitudes where the gyre circulations are strongest. Unlike the dry air surge, this form of dry air intrusion is associated with more diffuse moisture boundaries primarily at the low- to midlevels, which can be difficult to resolve using satellite TPW. It illustrates the importance of in situ observations for detecting equatorial dry air intrusion. At any rate, the relatively dry low- to midlevel air would not be favorable for continued deep convection.

6. The role of synoptic “Rossby” gyres

Much of the heavy rainfall occurring behind the leading edge of MJO-2, on the west side of the convective envelope, was related to synoptic gyre circulations associated with westward-moving Rossby-like waves and Rossby gyres embedded within the MJO. These systems can be identified by cyclonic low-level wind circulations, which are associated with relative maxima in the Northern Hemisphere streamfunction and minima in the Southern Hemisphere (Fig. 7). During the pre-MJO-2 suppressed period, these systems are
relatively weak (Figs. 7a–c, e.g., the gyre centered near 2°N, 87°E in Fig. 7c), but they become more prominent during the active MJO convective phase (Figs. 7d–j, e.g., gyre centered near 2°S, 80°E in Fig. 7h). The Rossby-like waves move westward (Fig. 8) within the eastward-moving MJO-2 envelope (Fig. 3). They are responsible for the westward-moving rainfall features within the active envelope of MJO-2 in the time–longitude perspective, especially during the second MJO-2 rain maximum (Fig. 3). For example, over the DYNAMO array, the second rainfall peak over the DYNAMO array was a direct result of the passage of a Southern Hemisphere
Rossby gyre on 27–28 November (Fig. 8). The westward-moving rain features preferably develop progressively to the east, following the MJO envelope, so that the second MJO-2 rain maximum progresses generally eastward with embedded westward-moving heavy rain features (Fig. 3). Note that this is in contrast to Yamada et al. (2010), in which westward propagation of rainfall was not prominent.

Early in the evolution of MJO-2, the gyres occur as symmetric twin gyres, similar to ER waves, such as along 55°–65°E during 24–26 November (Figs. 7d–f). However, later in the active MJO-2 period, the gyres are asymmetric systems in alternating hemispheres (Figs. 7g–j). These asymmetric systems initiate near the equator with the rainfall concentrated away from the circulation center, similar to MRGs (Figs. 8a,b). Then, as they move off the equator, rainfall becomes more concentrated near the center (Figs. 8d,e), more similar to TD-type disturbances. When the systems move westward and off the equator, the enhanced low-level flow has a significant cross-equatorial component (e.g., Figs. 7f,g,i). This flow can draw in any drier low- to midlevel air that may have penetrated close to the equator. It is a more subtle form of dry air intrusion with more diffuse moisture boundaries than the dry air surge; nevertheless, it can influence rainfall and convection in the equatorial region.

The connection between the dry air intrusion and the Rossby gyres can be seen in the pressure level RH from the ECMWF analysis (Fig. 9). The strong southwesterly, cross-equator flow in between the prominent Northern Hemisphere gyre and developing Southern Hemisphere gyre was drawing in relatively dry air from the western IO (west of 60°E). Higher-latitude drier air, originating >5° poleward of the equator, was also drawn into the west side of the MJO envelope. The subsaturated air associated with the break in rainfall can be seen at 850 and 700 hPa in Fig. 9. In contrast to the MJO-2 leading edge at ~90°E, where the RH was >95%, the RH in the southwest flow associated with dry air intrusion was generally 70%–80%. (At the origins of the dry poleward of the moist equatorial region air the RH was <40%.)

Sustained dry air intrusion in the strong westerlies on the west, back side of the MJO envelope was also strongly affected by the synoptic gyres. As the dry air is caught up in the circulations of the subsequent gyres, it is drawn progressively equatorward into the MJO westerlies, and then eastward along the equator. Also, the MJO westerlies are enhanced in the vicinity of the Rossby gyres (e.g., Figs. 7d–j and 8). Drier air being drawn in to the circulations of the synoptic gyres can be seen by inspection of the TPW maps in Fig. 2. Over the DYNAMO array, this dry air intrusion in the MJO westerlies arrived starting on 29 November (Figs. 2f,g). Radiosonde observations at Gan and the R/V Revelle show the equatorial drying beginning at the low- to midlevels (~850–750 hPa) late on 28 November and early on 29 November and deepening throughout 29 November (Figs. 5a,b). The dry air on the west side of the MJO envelope is not favorable for continued convection in that part of the

Fig. 8. ECMWF 850-hPa wind barbs and TRMM rain rate (shaded, colors as in Fig. 7). Wind barbs and streamfunction contours as in Fig. 7. The portion of the DYNAMO array within the plot area is drawn with dark black lines. Times are in UTC.
envelope. Convection can only continue on the east side of the MJO envelope, where eastward propagation of the Kelvin-like leading edge is also favored.

7. Possible extratropical influences on the initiation of MJO-2

The onset of MJO-2 equatorial convection occurred when dry air intrusion in the form of a dry air surge penetrated close to the equator in the western IO (Figs. 1a–d). Since the surge is apparently connected to the subtropical trade wind region, it could be linked to midlatitude systems, which are known to affect the initiation of Kelvin waves (Straub and Kiladis 2003) and the MJO itself (Ray and Zhang 2010).

As a first step to explore the possible role of extratropical influence, the “W vectors” were calculated using the method of Ray and Zhang (2010) with the ECMWF analysis (Fig. 10). The W vectors are used to quantify the midlatitude Rossby wave activity flux (Takaya and Nakamura 1997); W vectors pointing toward the equator indicate midlatitude Rossby wave energy being directed toward the tropics. Meanwhile, the perturbation streamfunction indicates the overall Rossby wave activity. On 17–18 November, midlatitude Rossby wave activity was weak (Figs. 10a,b). However, on 19 November, a pronounced Rossby wave train began to enter the western south Indian Ocean (Fig. 10c). The wave train remained over the south Indian Ocean through 20–22 November (Figs. 10d–f), which is the period when the dry air surge was penetrating toward the equator (Figs. 1a–c). There were some W vectors pointing toward the equator north of 30°S, indicating wave energy directed toward the tropics at that time. Nevertheless, the wave train (indicated by the perturbation streamfunction) did not penetrate as far to the equator as in the composite of Straub and Kiladis (2003). The connection between the extratropical wave train, the dry air surge, and the initiation of MJO-2 warrants further investigation beyond the scope of this study. The relative roles of the previous circumnavigating MJO (MJO-1; see Yoneyama et al. 2013; Gottschalck et al. 2013), the midlatitude systems, and dry air intrusion/surge cannot be fully determined at this point.

8. Conclusions

MJO-2 occurred in November–December 2011 during CINDY/DYNAMO field campaign. It is the most intensively observed MJO initiation over the Indian Ocean to date. Synoptic weather systems and associated dry air intrusions had a strong influence on the evolution of convection during MJO-2. The heaviest rainfall associated with MJO-2 occurred in two distinct maxima within the eastward-propagating MJO-2 envelope. The rain maxima lasted 2–3 days, with a dry “break” of 1–2 days in between. There were prominent westward-propagating rainfall systems associated with Rossby-like waves within the MJO-2 envelope, which were dominant features of the second rainfall maximum. Rainfall was concentrated in the eastward-propagating MJO leading edge and the westward-propagating waves on the west side of the MJO envelope. The leading edge of MJO-2 was Kelvin wave-like while the west side was dominated by Rossby-like gyres.
Generally, the equatorial IO is favorable for widespread deep convection with TPW > 50 mm. The dry air intrusions, indicated by drier air penetrating into the equatorial region, played an important role in the evolution of MJO-2 initiation. Dry air intrusions do not directly trigger convection. They can only suppress convection. An important factor is that when convection is concentrated off the equator in ITCZ bands, there is subsidence over the equator. Suppressing convection in the ITCZ reduces or eliminates this subsidence, favoring convection over the equator. Similarly, suppressing convection on the west side of the MJO envelope tends to reduce subsidence on the east side, favoring eastward propagation. The three roles of dry air intrusion during

![Figure 10](image-url)

**Fig. 10.** 200-hPa perturbation streamfunction (contours) and \( \mathbf{W} \) vectors. Contours are every \( 5 \times 10^7 \text{ m}^2 \text{s}^{-2} \). Negative contours are both drawn solid, and the zero contour is not drawn. The perturbation streamfunction is based on subtracting the mean of 20 Sep 2011–10 Jan 2012. The scale for \( \mathbf{W} \) vectors is indicated in the top-right corner of each panel; \( \mathbf{W} \) vectors are not drawn for magnitudes less than \( 1000 \text{ m}^2 \text{s}^{-2} \). All plots are for 0000 UTC.

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MJO-2 and associated large-scale weather features are illustrated in Fig. 11. Dry air intrusion affected the MJO-2 initiation in three distinct stages (parentheses refer to the labels in Fig. 11):

1) Initially, convection had been most favored in the ITCZ, not on the equator (stage 1a). Dry air intrusion—in the form of a distinct surge—suppressed convection in the southern ITCZ. This favored the onset of widespread equatorial convection around 23 November (stage 1b).

2) Dry air intrusion on the west and poleward sides of the synoptic Rossby gyres temporarily suppressed convection within the active MJO envelope, leading...
to a 1–2-day break in rainfall within the active convection envelope of MJO-2 (stage 2).

3) Persistent dry air intrusion associated with the westward-propagating gyres helps the shutdown of the equatorial convection in the strong low-level westerlies after 28 November (stage 3). Dry air intrusion suppressed convection on the west side of the MJO envelope, making it more favorable for the envelope of convection to propagate eastward.

The dry surge associated with the initial development of large-scale equatorial convection originated in the eastern IO and progressed to the western IO, penetrating to ~4°S (Fig. 1d). The convection had been previously organized into an ITCZ band at 5°–10°S with little activity on the equator (Figs. 1a–c). After the ITCZ convection was suppressed by the dry air surge, the focus of convection shifted to the equator. This initial burst of equatorial convection spanning ~20° of longitude marked the beginning of the prominent eastward propagation of MJO-2 (Fig. 3). During the suppressed “destabilization” phase convection is often favored in the off-equator ITCZ. By suppressing convection in the ITCZ, dry air intrusions can help determine where subsequent convection is favored to develop (e.g., near the equator). Note, however, that the current study does not directly address how the convection is triggered along the equator. Regarding convective triggering, it is likely that the circumnavigating upper-level signal from MJO-1 played a role, as well as possible midlatitude influences and upper-ocean conditions (e.g., hypothesis 3 of Yoneyama et al. 2013; Stephens et al. 2004).

At the back (west) side of the MJO, Rossby-like waves/synoptic gyres became pronounced enough to draw drier air into their circulations (Fig. 9). This form of dry air intrusion is induced by circulation systems within the MJO envelope, and it is associated with more diffuse moisture gradients than the pre-MJO dry air surge. This drier air was drawn in from higher latitudes and across the zonal moisture gradient in the western equatorial IO. Unlike the western Pacific during TOGA COARE (Houze et al. 2000), the air in the western part of the basin is relatively dry. Finally, when the MJO westerlies weaken, the dry air intrusion would cease, and the restoring phase leading to the next MJO event can begin (e.g., top-right panel of Fig. 11).

Rossby waves and related synoptic gyres have not been a major focus of previous research on the MJO initiation. It can be difficult to distinguish between the various “Rossby” modes. Regarding the nature of the Rossby-like waves during MJO-2, one system originating east of the MJO (in the eastern IO) initially resembled an equatorial Rossby wave, which is symmetric about the equator (Fig. 2c). It transitioned into a “TD type” system (Fig. 7c) and eventually a tropical cyclone in the Arabian Sea. Also, many of the subsequent gyre disturbances initially resembled mixed Rossby–gravity waves, with convection concentrated away from the gyre centers (Figs. 8a,b). Regardless of their original form, the gyres tended to move westward and transition to asymmetric off-equator TD-type systems. Three of them eventually developed into tropical cyclones. The pronounced circulations of these gyres drew the relatively dry subtropical and western IO air into the west side of the MJO envelope. This is viewed as an important factor—though not the only factor—favoring the preferred development of convection on the east side of the MJO envelope. This eastward propagation of the convective envelope near the equator marks the initiation of MJO-2.

More detailed research, including high-resolution modeling, will be beneficial to clarify the physical processes linking dry air intrusion to MJO initiation. It remains to be seen how frequent similar dry air intrusions and synoptic gyres occur in other MJO events in the IO. Also, how common is dry air intrusion into the tropics disrupting the ITCZ convection? Finally, the relevance of the day-to-day synoptic variability, including Rossby-like waves, for MJO dynamics, prediction, and downstream teleconnections, needs to be further explored for multiple MJO events.

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