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AIRCRAFT OBSERVATIONS OF DRY AIR, ITCZ, CONVECTIVE CLOUD SYSTEMS AND COLD POOLS IN MJO DURING DYNAMO

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Abstract

One of the most challenging problems in predicting the Madden-Julian Oscillation (MJO) is the initiation of large-scale convective activity associated with the MJO over the tropical Indian Ocean. The lack of observations is a major obstacle. The Dynamics of MJO (DYNAMO) field campaign collected unprecedented observations from airborne, land and ship based platforms from October 2011-February 2012. Here we provide an overview of the aircraft observations in DYNAMO, which captured an MJO initiation event from November-December 2011. The NOAA WP-3D aircraft was stationed at Diego Garcia and the French Falcon-20 aircraft on Gan Island in the Maldives. Observations from the two aircraft provide a unique data set of three-dimensional structure of convective cloud systems and their environment from the flight level, airborne Doppler radar, microphysics probes, ocean surface imaging, GPS dropsonde and Airborne eXpendable BathyThermographs (AXBT) data. The aircraft observations revealed interactions among dry air, ITCZ, convective cloud systems, and air-sea interaction induced by convective cold pools, which may play important roles in the multiscale processes of MJO initiation. This overview focuses on some key aspects of the aircraft observations that contribute directly to better understanding of the interactions among convective cloud systems, environmental moisture, and the upper ocean during the MJO initiation over the tropical Indian Ocean. Special emphasis is on distinct characteristics of convective cloud systems, environmental moisture and winds, air-sea fluxes, and convective cold pools during the convectively suppressed, transition/onset, and active phases of the MJO.
**INTRODUCTION.** The Madden-Julian Oscillation (MJO; Madden and Julian 1971, 1972) is known to have a major impact on global weather systems such as heat waves, tropical cyclones, and winter storms (e.g., Maloney and Hartmann 2000, Zhou et al. 2012). The intraseasonal/planetary time and spatial scales of the MJO makes it a critical link between the global weather and climate systems (Zhang 2013). However, current global weather and climate models have little skill in predicting the MJO. The convective initiation of the MJO over the Indian Ocean, typically consisted of suppressed, onset, and active phases of the large-scale equatorial convection (Stephens et al. 2004; Yoneyama et al. 2013), is one of the most challenging problems in prediction of the MJO (e.g., Benedict and Randall 2009). A major international field campaign supported by DYNAMO/the Cooperative Indian Ocean Experiment on Intraseasonal Variability (CINDY)/the ARM MJO Investigation Experiment (AMIE)/the Littoral Air–Sea Process (LASP) programs took place over the Indian Ocean with an Intensive Observing Period (IOP) from 1 October 2011–15 January 2012 (Yoneyama et al. 2013). Three MJO events were observed during the IOP of the field program (hereafter DYNAMO). A detailed description of the MJO events during DYNAMO can be found in Gottschalck et al. (2013). Here we focus on key observations from aircraft measurements collected during the MJO initiation over the tropical Indian Ocean from November-December 2011.

**SCIENCE OBJECTIVES AND MEASUREMENTS OF THE AIRCRAFT MISSIONS IN DYNAMO.** The aircraft missions aimed to address three main science objectives of DYNAMO: to better understand 1) multiscale convection-environment interactions, 2) water vapor variability and three-dimensional (3-D) dynamical and microphysical structure in convective cloud systems, and 3) air-sea fluxes and boundary layer structure in MJO initiation over the Indian Ocean. The
flights were designed to sample the MJO initiation processes including convective cloud systems and their atmospheric and oceanic environment during all MJO phases from the convectively suppressed phase to the active phase. This sampling strategy allowed us to address one of the most challenging problems in MJO initiation: the multiscale interaction among convective cloud systems, their large-scale environment, and the upper ocean on time scales from hours to weeks. Summaries of the NOAA WP-3D and French Falcon-20 aircraft flights, specific objectives, and key measurements of each mission are given in Tables ES1 and ES2 in the electronic supplement, respectively.

The two aircraft provided fine-scale, dynamic, mobile measurements to sample the gaps between the stationary ground and ship sites that formed the DYNAMO arrays (Fig. 1). The WP-3D actively pursued the largest convective systems in the DYNAMO domain during the convective missions using primarily its vertically-scanning Doppler radar (Jorgensen et al. 1996, 1997). The flight strategies contained various aircraft tracks, including one allowed the analysis of mesoscale convective systems (MCSs) during each roughly hour-long portion from the Doppler radar reflectivity and velocity (Guy and Jorgensen 2014) and microphysics probes (Guy et al. 2015, personal communication). Other WP-3D flight tracks focused on the large-scale environmental conditions including water vapor, temperature, and winds from transects between the island and ship sites (Kerns and Chen 2014a), the coupled atmosphere-ocean boundary layers, convectively generated cold pools, and air-sea fluxes using the GPS dropsondes, the Airborne eXpendable BathyThermographs (AXBTs), and the downward-looking IR imaging spectrometer called Jade (Table ES1). The French Falcon-20 operated by SAFIRE (Service des Avions Français Instrumentés pour la Recherche en Environnement) was equipped with a mm-wave Doppler cloud radar and a set of microphysics in-situ probes along with the usual environmental...
measurements (e.g., temperature, relative humidity and winds; Table ES2). The Falcon-20 aircraft flew mostly near Gan Island (Fig. 1b) and focused on the upper troposphere ice cloud properties in MCSs. Collectively the two aircraft provided the most comprehensive suite of observations of combined Doppler radar reflectivity and velocity from the lower to upper troposphere, microphysical properties, convective cold pools and air-sea fluxes from the GPS dropsondes and AXBTs in tropical oceanic MCSs to date.

**LARGE-SCALE CONTEXT OF THE AIRCRAFT OBSERVATIONS.** A strong MJO initiation event was observed from 10 November-15 December 2011 (Yoneyama et al. 2013). An objective cloud cluster tracking analysis using hourly Meteosat-7 IR data (based a method described in Chen et al. 1996, 1997a and b), along with the TRMM 3B42 rain rate (Huffman et al. 2007), satellite AMSR-E sea surface temperature (SST), and the NOAA SeaWinds surface wind data (Zhang et al. 2006), and the DYNAMO in-situ observations provide a four-dimensional description of the multiscale variability of convective cloud systems and the air-sea fluxes in relation to MJO initiation over the Indian Ocean. Figure 2 shows the eastward propagation of the large-scale envelope of TRMM precipitation and convective cloud clusters (IR cloud top temperature < 208 K), changes in SST and surface winds during the MJO. The cloud clusters became more numerous and increase in size as each MJO event developed. Prior to the onset of convectively active phase of the MJO in late November 2011, the DYNAMO array is characterized by relatively warm SST and easterly winds (Figs. 2b and c). Significant SST cooling and strong near surface westerly winds occurred during and after the convectively active phase from 25 November to early December. The convective cloud systems are highly correlated with features in the surface winds from meso- and synoptic to intraseasonal time scales as seen in the NOAA
SeaWinds zonal wind (Fig. 2c), including a complex mix of both local and remote large-scale conditions and impacts of these systems.

The eastward propagating large-scale convection had two maxima (Fig. 2a). The first one represents the leading edge of the large convective envelope of the MJO (see Fig. 9 in Johnson and Ciesielski 2013). It has been described as associated with a convectively coupled Kelvin wave in Gottschalck et al. (2013). The second maximum consisted of mostly westward-propagating large precipitating cloud clusters that may be associated with the equatorial Rossby waves and mixed Rossby-gravity waves (Kiladis et al. 2009). One of the largest westward propagating systems occurred on 28 November over the DYNAMO array, which was described in detail by Judt and Chen (2014). The distinct rainfall minimum between the two maxima (Fig. 2a) is due to dry air advection into the equatorial region by Rossby wave gyres that were continually generated as part of the large-scale convective complex of the MJO (Kerns and Chen 2014a; b).

Another interesting feature is the transition of the large-scale convective activity from the ITCZ to the equator during MJO initiation (Fig. 3a). Prior to the onset of the equatorial convective activity, deep convection was concentrated within the ITCZ near 8-10°S (Fig. 3a). The convection shifted toward the equator in mid-November. An abrupt northward jump from the ITCZ to the equator occurred on 22 November when a strong dry air intrusion from the subtropical region south of the DYNAMO array intruded north to 5°S of the equator (Fig. 3b). The dry air surge (minimum Total Precipitable Water [TPW] between 5-10°S) is associated with a maximum in the southerly (equatorward) wind from 15-5°S on 21-23 November (Fig. 3c). The group of long-lasting, northward propagating clusters and the associated anomalous northerlies-southerlies couplet (meridional confluence zone) north of the equator from 24-27 November (Fig.
These features mark a Rossby gyre developed in the active phase of the MJO, which later become Tropical Cyclone 5 (Moum et al. 2014). Another southerly dry air intrusion occurred from 8-15 December (Figs. 3b and c), but apparently with less favorable equatorial environment for widespread deep convection in that case.

The WP-3D aircraft sampled all phases of the MJO as well as the ITCZ from 11 November-13 December, while the Falcon-20 observations captured the convectively active and suppressed phases from 22 November-14 December near Gan Island as shown in Figs. 1-3. Examples of the aircraft observations from various large-scale conditions during MJO initiation are presented in the follow sections.

**CONVective CLOUD SYSTEMS IN SUPPRESSED, Transition, AND Active Phases of MJO.**

Tropospheric moisture is a major parameter affecting convection during MJO initiation (Kerns and Chen 2014a). Satellite and rawinsonde observations suggest that synoptic scale dry air advection plays an important role in convective suppression in the tropics (Yoneyama and Parsons 1999, Kerns and Chen 2014a). The synoptic scale variability in the wind and the atmospheric moisture fields is a key feature distinct the different global model forecasts of the late November MJO initiation event during DYNAMO (Kerns and Chen 2014b). Moreover, the interactive processes between convective cloud systems and their large-scale environmental moisture on various scales, e.g., equatorial waves, are not well understood. Here we use the WP-3D Doppler radar and the GPS dropsonde data together with the cloud cluster tracking analysis using hourly Meteosat-7 IR data and satellite observed TPW to provide a four-dimensional description of the multiscale variability of environmental moisture and convective cloud systems during this MJO initiation. Observations from four WP-3D aircraft missions are shown covering
the entire MJO initiation from the convectively suppressed phase on 13 November (Fig. 4a), the transition/onset phase on 22 November (Figs. 4b), the active phase on 24 November (Fig. 4c), and the return to suppressed phase on 8 December (Fig. 4d). The following three subsections describe the aircraft observations from the transition/onset, active, and suppressed phases of the MJO.

**Dry air, ITCZ, and transition from convectively suppressed to active phase of MJO.** To address the question of convective organization and its interaction with the large-scale environment during MJO initiation, observations of convective cloud systems and their immediate surrounding environmental moisture were measured by the airborne Doppler radar, the GPS dropsondes, and flight-level measurements on board of the WP-3D aircraft. During the onset of equatorial convection at the early stage of the MJO event from 20-23 November, dry air intrusion from the extratropical regions may be instrumental in disrupting the southern ITCZ and forcing convection toward the equator (Kerns and Chen 2014a). Figure 5 shows an example of the dry air and a strong relative humidity (RH) gradient observed by the GPS dropsondes on 22 November when the convection moved toward the equatorial region in response to the dry air intrusion from the south. The WP-3D flew through the dry air mass on its way to sample the convective cloud systems near the equator (Fig. 4b). The extreme low values of RH < 10% were observed in the low-mid troposphere near 4-5°S (Fig. 5a). Prior to 22 November, the convection in the southern ITCZ was active near 10°S (Fig. 3). This dry air intrusion was found to be responsible for “pushing” convective activity from the southern ITCZ to the equator during the transition/onset of the MJO convective phase (Kerns and Chen 2014a). The GPS dropsondes deployed from WP-3D provided *in-situ* observations of the large-scale environmental moisture
and winds as well as the atmosphere boundary layer structure. The depth of the atmosphere boundary layer (defined by the mixed layer using 0.5 K virtual potential temperature gradient) is higher in the dry air region (600-800 km) and lower in the moist region from 5ºS to the equator (below 400-500 km) as shown by the white dots in Fig. 5a. The lower tropospheric wind is easterlies in the southern portion of the DYNAMO array with a relative strong southeasterly component observed by the dropsonde near 7ºS-75ºE (Fig. 5a) corresponding with the dry air intrusion (Fig. 4b). The winds changed to low-mid tropospheric westerlies from about 4ºS to the equator with a transition zone from 6-4ºS where relatively weak mid-level westerly was observed in between the lower and upper tropospheric easterlies (Fig. 5a).

The distinct vertical moisture and wind profiles from the extremely dry air environment to the nearly saturated region close to the equator as well as the transition zone are shown clearly by skew-T diagrams from the WP-3D transect on 22 November (Fig. 5). The dry air region was dominated by a relatively strong, deep layer of easterlies, with RH as low as ~10% above 800 hPa (Fig. 5b), whereas the equatorial region had low-mid level westerlies and upper-level easterlies with RH greater than 90% through a deep layer (Fig. 5d). The sounding collected in the transition zone between the dry and moist areas displayed an interesting “onion” shaped temperature and dewpoint temperature profile (indicative of subsidence) between 600-700 hPa below a nearly saturated melting layer as well as a mid-level westerly wind (Fig. 5c), which displayed a somewhat similar property to those observed in the stratiform rain region of MCSs (e.g., Zipser 1977).

**Convective cloud systems and enhanced surface winds in the active phase.** Organized MCSs can interact with their large-scale environment through vertical transport of heat, moisture, and
momentum. Previous observations and modeling studies have shown that tropical MCSs can enhance surface westerlies in the MJO during TOGA COARE (e.g., Houze et al. 2000, Mechem et al. 2005). Midlevel inflow jets developed in the large MCSs can enhance the surface westerlies through melting and evaporative cooling driven downward motion and momentum transport in the active phase of the MJO (Jorgensen et al. 1997). During DYNAMO, the onset of the active phase of the MJO and its enhanced westerly winds on 24 November were observed by the in situ GPS dropsonde and Doppler radar measurements from the WP-3D aircraft near the equator (Figs. 4c and 6). A strong westerly jet was associated with the large complex system with multiple MCSs (Fig. 6a), descending from the mid-upper troposphere to the surface (Figs. 6b and c). The descending jet coincided with the large areas of the stratiform precipitation as observed by the WP-3D Doppler radar reflectivity and downward velocity as shown in Fig. 6b. Although the type of rear inflow associated with organized MCSs has been observed by Zipser (1977) and Smull and Houze (1987), the very large spatial scale of the descending jet observed by the dropsonde data from 72-79°E (> 700 km, Fig. 6c) in this case has not been documented prior to DYNAMO. It is interesting to note that, from the Doppler radar reflectivity and velocity data, multiple MCSs were observed along the WP-3D transect from R/V Revelle to Gan Island (Fig. 6b). The radar reflectivity shows bright bands along the long transect and multiple descending jets including one from 1-9 km layer between 400-500 km markers and another 1-5 km layer between 250-350 km (Fig. 6b).

The large multi-MCS complex produced a strong and deep cold pool (> 4 K in potential temperature depression) extending from the ocean surface up to the 1000 m level (Fig. 6c). Both the enhanced surface westerly wind and the convective cold pools were also captured by the observations at the R/V Revelle (Moum et al. 2014). These observations indicate that the MCSs
may enhance the surface westerlies during the active phase of the MJO (e.g., Houze et al. 2000),
prolong the surface temperature recovery via convective cold pools and enhancing wind-induced
upper ocean mixing (Moum et al. 2014). Thus, these convective upscaling effects of the MCSs
may play an important role in MJO initiation over the tropical Indian Ocean.

Dual aircraft observations of three-dimensional structure of a convective cloud system during
the suppressed phase. The WP-3D and Falcon-20 aircraft flew a coordinated mission on 8
December 2011 (Fig. 4d). An example of the dual aircraft measurements in a convective cloud
system near Gan Island is presented here (Fig. 7). The mission was designed to characterize the
3-D structure of convective cloud systems including the dynamic, thermodynamic, and
microphysical properties. This is a unique data set for cloud-resolving model evaluation and
verification. Figure 8 shows a cross-section along the coincident flight paths that was extracted
from the 3-D gridded WP-3D X-band (3.22 cm) tail Doppler radar data by projecting the WP-3D
data onto the Falcon-20 W-band (3.19 mm) Doppler radar data grid using a bilinear interpolation
scheme. Due to the increased sensitivity of the Falcon-20 measurements for smaller
precipitation particles, observations where reflectivity was less than 15 dBZ were removed for
the WP-3D reflectivity and wind fields. For the preliminary view presented here, the fields were
simply overlaid. While wind field magnitudes are very close, it can be seen that minor
directional discrepancies exist where the two fields merge. This is not surprising given that each
instrument has an ideal performance window that becomes increasingly reliable at this
intersection. To improve the analysis going forward, a weighted averaging technique using the
magnitudes of reflectivity (or perhaps uncertainties) at each individual point and surrounding
eight adjacent neighboring points will be employed to smooth the data at this interface.
The combined vertical cross section of wind shows vertical wind shear within the MCS observed on 8 December (Fig. 8c). This feature is consistent with the observation from the DYNAMO sounding array, which showed strong easterlies in the upper troposphere and moderate westerlies during this time (Johnson and Ciesielski 2013). Understanding how the vertical motion in convective cloud systems interacts with the large-scale horizontal winds in the different phases of the MJO initiation requires synthesis of multiple observational platforms and data sources like in this case.

**Distinct convective structure and microphysics in three MJO phases.** Sampling from all phases of MJO initiation allowed us to compare the convective structure and microphysical properties of MCSs in different large-scale conditions. The WP-3D Doppler radar reflectivity data were processed from Radar Convective Element (RCE) modules as described in Guy and Jorgensen (2014). Distributions of the height of radar echo tops and the level of maximum reflectivity from the transition/onset phase on 22 November, the convectively active phase on 24 November, and the convectively suppressed phase on 8 December are shown in Fig. 9. It includes a total of six RCEs with two from each of the three days. Although some echo tops reached 13-14 km height in all cases, echo tops was mainly below 5-6 km during the suppressed phase on 8 December (Fig. 9c), but higher than 10 km in the transition/onset and active period from 22-24 November (Figs. 9a-b). A pronounced maximum in peak reflectivity near the melting level (4.5-5.5 km) indicating stratiform precipitation in convective onset and active cases (Figs. 9d-e), which is in strong contrast to that of suppressed case (Fig. 9f). The highest echo tops and largest stratiform region were observed during the active phase on 24 November (Fig. 9b), in agreement with the ground-based observation of Zuluaga and Houze (2013). The dry
environment in the suppressed phase (Fig. 4d) may have contributed to the relatively shallower
convective cells and lack of stratiform precipitation in the MCSs of 8 December. Similar
relationship between the environmental moisture and depth of convection was observed during
TOGA COARE (Brown and Zhang 1997).

In-situ measurements of water droplets were obtained using a combination of optical
spectrometers mounted under the left wing of the WP-3D aircraft. The Cloud Imaging Probe
(CIP) and Precipitation Imaging Probe (PIP) measured particle size and shape between 25 µm –
1.55 mm and 100 µm – 6.2 mm, respectively. Data were collected during each flight shown in
Fig. 1a, with the exception of 11 November due to system errors. These data were largely
collected at flight levels typically from 1500-3000 m. Raindrop size distributions (RSDs,
Jackson and McFarquhar 2014) were produced for each flight. A three-parameter gamma
distribution model was used to fit the RSD data. Analysis was performed using a normalized
RSD to reduce the impact of mathematical artifacts possible from the highly correlated nature of
the parameters of the gamma distribution fit model and removal of a priori shape constraints.
The observed droplet sizes tended to be larger on 22 and 24 November during the onset
and active phases than the suppressed periods on 16 November and 8 December (Fig. 10a). This
is consistent with the corresponding convective organization on 22-24 November and 8
December shown in Fig. 9. The onset-active phase was characterized by MCSs with broad
stratiform regions and embedded deep convective cells (Guy and Jorgensen 2014). This resulted
in an enhanced dependence on ice-phase hydrometeor growth, leading to larger D_m of melted
drops and broadening the distribution. Warm rain microphysics dominated during this regime.
The 16 November case was sampled in MCSs from 8-10^oS within the ITCZ during the
suppressed phase and exhibited behavior in between the extremes in contrasting MJO phases.
The generalized intercept parameter ($N_w$), probability distributions in Fig. 10b indicated the general similarity of systems observed during DYNAMO, namely an embedded MCS archetype that tends toward the “transition” state between the classically defined convective and stratiform rain regimes. The 8 December case exhibited slightly greater probabilities of higher $N_w$, though all were within previous maritime measurement variability. The secondary peak on 8 December corresponds to small particles measured by the CIP.

These data can also be used to calculate reflectivity (Z) and rainfall rate (R) using moments of the RSD spectrum. Calculations of Z-R power law relationships were found to be similar to those found in previous tropical ocean experiments (e.g. TOGA COARE). The imaging probe dataset also allowed a unique look at the vertical structure of RSDs, which has been sparsely studied. Further work is underway to develop a full understanding of the RSD variations during DYNAMO measured by aircraft (Guy et al. 2015, personal communication).

**Coupled Observations of Convectively Induced Air-Sea Interaction.** It has been hypothesized that air-sea interaction is one of the important factors affecting the equatorial convective cloud systems and the MJO. Chen and Houze (1997b) identified a bi-diurnal cycle of large MCSs, referred to as “diurnal dancing,” during the MJO active phases over the West Pacific warm pool during TOGA COARE. They speculated that the convective cold pools and large cloud shields have contributed to slow recovery (>24 h) of the SST and atmospheric boundary layer after a major convective event. Using satellite-derived SST, wind, and rainfall data, Li and Carbone (2012) showed coherent mesoscale patterns in these fields suggesting that air-sea coupling plays an important role in the observed rainfall and SST variability over the tropics. However, there are no *in-situ* observations to address the physical processes through
which the convection interacts with the ocean and how the air-sea interaction processes vary in
different phases of the MJO until DYNAMO. Here we use the aircraft data to examine the
coherent variability of the air-sea fluxes and convection during the suppressed and active phases
of the MJO over the Indian Ocean. More than 200 co-located GPS dropsondes and AXBTs pairs
were deployed from the WP-3D aircraft from 11 November-13 December 2011, which covers
the convectively suppressed, transition and active phases of the MJO.

Convectively induced SST variability. Convective downdrafts and freshwater pools from the
rain induce a large spatial and temporal variability in the sea surface temperature (SST), which in
turn affect the development of convective cloud systems and air-sea fluxes. During the
suppressed phase of the MJO, cool water pools were observed from the infrared camera onboard
the WP-3D. An example from the WP-3D mission targeting the convective cool pools near Gan
Island on 16 November is shown in Fig. 11. The flight track is overlaid on the S-PolKa radar
reflectivity image showing isolated small convective cloud systems that the WP-3D was
sampling (Fig. 11a). A detailed description of the convective rain cells and associated cold pool
signals observed by S-PolKa on 16 November 2011 can be found in a science report by Houze et
al. (2011, DYNAMO Field Catalog). Figures 11b-c show a mosaic and spatial series of SST
variation along the flight leg marked in red, across a gust front-like feature near convective cells
(> 40 dBz, Fig. 11a). The cross-track scale was roughly 1.4 km, and this flight leg spanned
roughly 15 km (Figs. 11b-c). The small convective systems generated a significant cold pool
possibly related to the gust front. Note two specific features that appear as a pool of cool water
and a sharp frontal feature from warm to colder water. The sharp front was detected around 8.5
km in to the flight leg. Both of these features may be due to recent rain from the convective cells
in the region as seen in the S-PolKa radar reflectivity (Fig. 11a). Although it is difficult to obtain absolute SST\textsubscript{skin} without ambient measurements, the temperature gradient of nearly 1°C across the flight leg is a robust signal with the effects of window and atmosphere having been removed. Within the cold pool on the ocean surface, the small-scale temperature variability is about 0.1 °C m\textsuperscript{-1}. During the active phase of the MJO, the SST (not shown) is more complex with multiscale variability that may be due to both the convectively induced local winds from downdrafts and rain and is under further investigation.

**Upper ocean and atmospheric boundary layer temperatures, and air-sea fluxes.** One of the sampling strategies of the WP-3D aircraft missions was to observe the atmosphere and ocean environments during both the convectively suppressed and active phases of the MJO. The lower-level atmospheric and upper ocean temperature were observed by the GPS dropsondes and AXBTs deployed concurrently from the WP-3D aircraft from SW-NE transects between Diego Garcia and the R/V Revelle during the convectively suppressed period on 13 November (Fig. 12a) and the active phase on 26 November (Fig. 12b). Three main features are noteworthy. First, the upper ocean temperature is 2-3 °C warmer during the suppressed phase with weaker winds than the active phase, whereas the atmosphere surface and boundary layer temperatures remained similar. Second, the height of the atmosphere boundary layer (based on the definition of mixed layer using virtual potential temperature < 0.5 K) was higher during the suppressed phase (600-700 m) than in the active phase (500-600 m). Third, there were isolated, deep convective clouds along the WP-3D transects on both days, as shown by Meteosat-7 IR temperatures < 225 K on 13 November (Fig. 12a) and < 215 K on 26 November (Fig. 12c), respectively. However, the convective cold pools were stronger during the suppressed phase (> 3 °C depression, Fig. 12b)
than the active phase (<1.5 °C, Fig. 12d). The dryer mid-upper level environmental moisture may be a contributing factor to the stronger cold pools during the suppressed phase (Saravin et al. 2014).

The air-sea sensible and latent heat fluxes are computed from the GPS dropsonde and AXBT measurements using the COARE bulk flux algorithm (Fairall et al. 2003). The sensible heat flux is larger during the suppressed phase on 13 November than the active phase on 26 November over the regions without influence of convection (from 100-750 km, Figs. 12 and 13a). The large surface temperature difference between the air and sea (2-3 °C) and relative low wind speed (<5 m s\(^{-1}\)) are the main reasons for the higher sensible heat flux during the suppressed phase (Fig. 13b). While the difference in the air-sea mixing ratio was larger on 13 November (suppressed conditions), the latent heat flux was larger on 26 November (active phase) due to the higher wind speed (Figs. 13c and d).

Convective cold pools and boundary layer recovery. Convectively generated cold pools can suppress convection by cooling and/or drying the surface and boundary layers. Future development of convective cloud systems depends on the recovery of the surface and boundary layers, which is a function of the sunlight and air-sea fluxes. To better understand the air-sea interaction and its impact on convection, we use the aircraft data to investigate both the convectively generated cold pool depth and strength and boundary layer recovery time during convectively active and suppressed phases of MJO. The WP-3D Doppler radar data was used to identify the convective cloud and precipitation structures that produced the cold pools. The GPS dropsonde data were used to compute the depth and strength of the cold pools, i.e., the depth and intensity of negative buoyancy similar to that described in Bryan (2005). The air-sea fluxes are
computed from the GPS dropsonde and AXBT data. To assess the accuracy of the bulk fluxes, we compared with the turbulence sensible and latent heat flux data from R/V Revelle that overlapped in time with the WP-3D observations in November-December 2011 (C. Fairall and J. Edson, personal communication). The two air-sea flux data sets matched remarkably well. The boundary layer recovery time is then calculated based on the method used in TOGA COARE (Jorgensen et al. 1997), which is the time for the boundary layer properties to recover to the environmental conditions.

In general, the boundary layer recovery times are positively correlated with the surface wind speed and air-sea fluxes (Figs. 14a, c, and d). Stronger winds and increased air-sea fluxes reduce the recovery time during the convectively active phase, which indicates a positive feedback between the convection and air-sea fluxes. However, the recovery times are longer (5-24 h) during the suppressed phase on 8 December than the 22-24 November cases (1-13 h, Fig. 14a). The slower recovery time is related to the environmental lower troposphere water vapor (700-500 hPa layer mean RH, Fig. 14b). The depth of the cold pools varies from less than 100 m to over 2000 m. The deepest and strongest cold pools were observed in convective cloud systems during the suppressed phase on 8 December (Savarin et al. 2014), which is consistent with the example shown in Fig. 12. The drier the environment the stronger and deeper the cold pools, which is not unexpected given that dry air entrainment by convection can enhance evaporation and convective downdraft. These results may have important implications for the timing of the post-convection surface/boundary layer recovery during an MJO event.

**Concluding Remarks.** The DYNAMO field campaign collected unprecedented aircraft observations over the tropical Indian Ocean during November-December 2011. The mobility of
the aircraft proves to be vital in capturing some key features, such as the spatial distribution of
the large-scale water vapor and the small-scale SST variations associated with convective cold
pools, filling a gap from the ship- and land-based station observations. These observations, in
combination with other DYNAMO land-based, shipborne, and satellite data, have provided
invaluable new insights into MJO initiation over the tropical Indian Ocean. A number of
emerging science topics are highlighted here:

- Dry air intrusions from subtropics may suppress convection in the ITCZ, which is
  favorable for the onset of the equatorial convection during MJO initiation (Figs. 3-5),
- Distinct characteristics in convective structure and microphysical properties of MCSs
during the suppressed, transition/onset, and active phases of the MJO (Figs. 9-10),
- Convective cold pools are deeper and stronger in MCSs surrounded by the low-mid level
dry air (Figs. 6, 8, and 14) in the suppressed phase, which prolong the atmosphere
  boundary layer recovery time, and
- The atmospheric boundary layer depth and upper ocean temperature are higher during the
  suppressed phase than during the active phase, and the air-sea temperature difference and
  sensible fluxes (Figs. 12-13) are larger during the suppressed of the MJO.

These topics deserve further investigation. Collectively they highlight the importance of the
atmospheric water vapor variability and its impact on organizations and structure of convective
cloud systems, as well as their interaction with the ocean through air-sea fluxes on MJO
initiation over the tropical Indian Ocean. The aircraft sampling strategy allowed for coherent
observations of MCS structure and microphysics using the Doppler radar and microphysics
probes and the large-scale atmospheric and ocean environment using the GPS dropsonde and
AXBT measurements, which were not available in TOGA COARE. The dual aircraft
measurements by the WP-3D and Falcon-20 Doppler radars provided a first 3-D reflectivity and 
velocity observations from the 0.5-15.0 km height. The results shown here will help us improve 
and evaluate high-resolution, cloud-resolving and coupled atmosphere-ocean models for better 
prediction of MJO initiation processes in the future. The aircraft data has been organized into an 
easily accessible form made available (http://data.eol.ucar.edu/master_list/?project=DYNAMO).

It is hoped that they will be used by others in studies for better understanding and predicting the 
MJO and numerical model evaluation and verification.

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the Py-ART and AWOT software packages courtesy of the Department of Energy ARM Climate 
Research facility and NOAA National Severe Storms Laboratory, respectively. Comments and 
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Rain, cold pools, and sea states during the suppressed and active phases of the MJO.

Rain-induced freshwater pools on the ocean surface and the atmospheric cold pools from convective downdraft driven by evaporation of precipitation can modulate air-sea fluxes and the atmospheric stability that in turn affect convective variability. During the suppressed phase of the MJO, convective rain showers produce cool freshwater lenses over the ocean surface in low-wind conditions (Fig. SBa). The sea surface temperature (SST) variability in the vicinity of the rain cell shown in Fig. SBa was captured by the WP-3D aircraft during the DYNAMO field campaign on 16 November 2011 (Fig. 11). Although it is well known that convective rain cells such as the one shown in Fig. SBa are numerous, the spatial and temporal scales of the cool freshwater pools and how they may affect the SST and air-sea fluxes are difficult to quantify. In contrast, during the active phase of the MJO, large convective mesoscale systems produced extensive and deep layer of cold pools from the ocean surface to the atmospheric surface and boundary layers (or above in some cases). Strong winds induced surface waves and white caps (Fig. SBb) produce strong mixing in the upper ocean and enhanced air-sea fluxes during the active phase of the MJO. The contrasting air-sea interaction processes in the suppressed and active phases of the MJO and their impact on the evolution of MJO initiation need to be further investigated.
REFERENCES


Fig. 1. (a) The NOAA WP-3D aircraft (stationed at Diego Garcia-DGAR) flight tracks of the 12 missions from 11 November-13 December 2011 during DYNAMO. The black dots and open circles indicate air-deployed GPS dropsonde and AXBT locations, respectively. (b) The French Falcon-20 aircraft (stationed at Gan Island) flight tracks of the 15 missions from 22 November-16 December 2011 over the region near Gan as marked by the inset square in (a). The aircraft missions are color coded by dates.

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Fig. 3. Time-latitude diagrams of (a) the TRMM 3B42 rain rate (mm day$^{-1}$), (b) Total Precipitable Water (TPW, mm), and (c) NOAA SeaWind meridional component (m s$^{-1}$) averaged over the DYNAMO array longitude 72-80°E from 10 November–15 December 2011. The black circles are the IR (<208 K) cloud clusters. The size of circles is proportional to the size of the cloud clusters. The WP-3D aircraft tracks are marked in red in (a) and white in (b)-(c). The Falcon-20 flight tracks are shown in black lines in (a).
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Fig. 11. (a) S-PolKa radar reflectivity at 1100 UTC 16 November 2011 (from 0.5-degree elevation scan) overlaid with the WP-3D flight track (black). The segment of track in red corresponds to the time of 11:08:05-11:10:00 for the SST\textsubscript{skin} data shown in (b) and (c). A zoomed region near the Jade IR SST measurement is shown in (a). The radial range rings are every 50 km. (b) Mosaic and (c) spatial series of SST\textsubscript{skin} variation measured from the Jade IR camera on the WP-3D near Gan Island. (Note the large region of cold pool in the mosaic of SST\textsubscript{skin}.)

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Fig. 14. The WP-3D aircraft observed convective cold pool recovery time varies with wind speed (a) and the 700-500 hPa environment RH averaged over a circular area of 200-500 km
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varying with wind speed, for individual convective modules from 22 November (blue),
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transition/onset and convectively active and suppressed phases, respectively. The error
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Fig. SB. (a) Clouds, rain, and calm sea surface during the WP-3D flight near Gan Island on 16
November when surface wind speeds < 5 m s⁻¹. (b) Sea surface waves and white caps
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speeds > 15-20 m s⁻¹ during the DYNAMO field campaign over the equatorial Indian
Ocean. (The photos were taken by Shuyi S. Chen).
Table ES1. NOAA WP-3D flight summary and main measurements including the C-band tail Doppler and Lower Fuselage (FL) radar, the GPS dropsonde, Airborne eXpendable BathyThermographs (AXBT), the Jade IR camera, the Raindrop size distribution (RSD), the Cloud Imaging Probe (CIP) and the Precipitation Imaging Probe (PIP) measuring particle size and shape between 25 µm–1.55 mm and 100 µm–6.2 mm, respectively.

<table>
<thead>
<tr>
<th>Date (time)</th>
<th>Mission objective</th>
<th>Measurements</th>
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<tbody>
<tr>
<td>11 Nov (0703–1034 UTC)</td>
<td>Instrument and operations test at northwest of Diego Garcia</td>
<td>X-band Doppler and C-band LF radar, GPS dropsonde</td>
</tr>
<tr>
<td>13 Nov (0312–1234 UTC)</td>
<td>Large-scale moisture variability between Diego Garcia, Mirai, and Revelle; air–sea interaction near Revelle</td>
<td>C-band Doppler and LF radar, GPS dropsonde, AXBT, IR camera, RSD, CIP, PIP</td>
</tr>
<tr>
<td>16 Nov (0406–1302 UTC)</td>
<td>Convection and surface flux in the ITCZ south of Diego Garcia; large-scale variability across the ITCZ and from Diego Garcia to the center of the south array; freshwater pool and vertical moisture layers near Addu Atoll</td>
<td>X-band Doppler and C-band LF radar, GPS dropsonde, AXBT, IR camera, RSD, CIP, PIP</td>
</tr>
<tr>
<td>19 Nov (0343–1229 UTC)</td>
<td>Shallow cumulus boundary layers and air–sea processes in an MJO suppressed phase; large-scale variability between Diego Garcia and the center of the south array</td>
<td>X-band Doppler and C-band LF radar, GPS dropsonde, AXBT</td>
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<tr>
<td>22 Nov (0206–1208 UTC)</td>
<td>Large-scale variability from Diego Garcia to Revelle and in the north–south direction near the center of the south array; deep convection and surface flux from suppressed to disturbed conditions west of Revelle</td>
<td>X-band Doppler and C-band LF radar, GPS dropsonde, AXBT, IR camera, RSD, CIP, PIP</td>
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<tr>
<td>24 Nov (0128–1117 UTC)</td>
<td>Convection upwind (west) of Revelle under disturbed conditions; large-scale variability in wind and moisture from Diego Garcia to Revelle and from Addu Atoll to Revelle</td>
<td>X-band Doppler and C-band LF radar, GPS dropsonde, AXBT, IR camera, RSD, CIP, PIP</td>
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<tr>
<td>26 Nov (0315–1253 UTC)</td>
<td>Boundary layer and air–sea interaction near Revelle; large-scale variability between Diego Garcia and Revelle in the morning and afternoon</td>
<td>X-band Doppler and C-band LF radar, GPS dropsonde, AXBT</td>
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<tr>
<td>28 Nov (0207–1122 UTC)</td>
<td>Boundary layer variability and air–sea interaction under disturbed conditions during an active phase of MJO east and southeast of Diego Garcia</td>
<td>X-band Doppler and C-band LF radar, GPS dropsonde, AXBT</td>
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<tr>
<td>30 Nov (0136–1133 UTC)</td>
<td>Convection and cold pool south of Diego Garcia</td>
<td>X-band Doppler and C-band LF radar, GPS dropsonde, AXBT, IR camera, RSD, CIP, PIP</td>
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<tr>
<td>4 Dec (0202–1207 UTC)</td>
<td>Boundary layer variability and air–sea interaction near convective bands east of Diego Garcia; Diego Garcia island effect</td>
<td>X-band Doppler and C-band LF radar, GPS dropsonde, AXBT</td>
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<tr>
<td>8 Dec (0427–1211 UTC)</td>
<td>Convection and microphysics near Addu Atoll in coordination with Falcon and in comparison with S-PolKa</td>
<td>X-band Doppler and C-band LF radar, GPS dropsonde, AXBT, IR camera, RSD, CIP, PIP</td>
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<td>13 Dec (0306–0737 UTC)</td>
<td>Instrument calibration and intercomparison</td>
<td>GPS dropsonde</td>
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<td>near Diego Garcia</td>
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Table ES2. French Falcon-20 flight summary and main measurements including the W-band Doppler radar, the Forward Scattering Spectrometer Probe (FSSP) by *Particle Measuring Systems* Inc. cover 2 to 47 mm range, the Cloud Imaging Probe (CIP) by *Droplet Measurement Technologies* cover the 25 to 1600 mm range of particles diameter with a 25 mm resolution, the 2D stereo probe (2D-S) from *Stratton Park Engineering Company Inc.* record images of particles from 10 to 1280 mm with 10 mm resolution, and the Precipitation Imaging Probe (PIP) from *Droplet Measurement Technologies* provided images in the 100 to 6200 mm range with a 100 mm resolution.

<table>
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<tr>
<th>Date (time)</th>
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</tr>
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<tbody>
<tr>
<td>22 Nov (1205–1432 UTC)</td>
<td>Decaying stratiform east of Gan</td>
<td>W-band Doppler radar, FSSP, CIP, 2D-S, PIP</td>
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<tr>
<td>23 Nov (0814–1124 UTC)</td>
<td>Stratiform associated with scattered convection north of Gan</td>
<td>W-band Doppler radar, FSSP, CIP, 2D-S, PIP</td>
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<tr>
<td>25 Nov (0911–1024 UTC)</td>
<td>Microphysical probes testing</td>
<td>W-band Doppler radar, FSSP, CIP, 2D-S, PIP</td>
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<td>27 Nov (0533–0851 UTC)</td>
<td>Two stratiform systems with embedded convection, north and northwest of Gan</td>
<td>W-band Doppler radar, FSSP, CIP, 2D-S, PIP</td>
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<td>27 Nov (1519–1822 UTC)</td>
<td>A stratiform area east-southeast of Gan</td>
<td>W-band Doppler radar, FSSP, CIP, 2D-S, PIP</td>
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<td>2 Dec (0454–0548 UTC)</td>
<td>Instrument calibration in clear sky west of Gan</td>
<td>W-band Doppler radar, FSSP, CIP, 2D-S, PIP</td>
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<tr>
<td>3 Dec (0722–1034 UTC)</td>
<td>Small punctual convective outbreaks from south-southwest to east-northeast of Gan</td>
<td>W-band Doppler radar, FSSP, CIP, 2D-S, PIP</td>
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<tr>
<td>6 Dec (1325–1536 UTC)</td>
<td>Microphysics instrument test</td>
<td>W-band Doppler radar, FSSP, CIP, 2D-S, PIP</td>
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<tr>
<td>8 Dec (0604–0857 UTC)</td>
<td>Initiation of convective cells, coordination with WP-3D for simultaneous sampling at different levels</td>
<td>W-band Doppler radar, FSSP, CIP, 2D-S, PIP</td>
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<tr>
<td>8 Dec (1309–1609 UTC)</td>
<td>Deep convection (17 km) north of Gan</td>
<td>W-band Doppler radar, FSSP, CIP, 2D-S, PIP</td>
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<tr>
<td>12 Dec (1146–1352 UTC)</td>
<td>Convection east of Gan</td>
<td>W-band Doppler radar, FSSP, CIP, 2D-S, PIP</td>
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<tr>
<td>13 Dec (0840–1116 UTC)</td>
<td>Convection north of Gan</td>
<td>W-band Doppler radar, FSSP</td>
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<tr>
<td>14 Dec (0732–1126 UTC)</td>
<td>Isolated convection northwest and north of Gan</td>
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