A field campaign in the Indian Ocean region collected unprecedented observations during October 2011–March 2012 to help advance knowledge of physical processes of the MJO—especially its convective initiation—and improve its prediction.

From time to time, the tropical atmosphere feels the pulses of extraordinary strong deep convection and rainfall that repeat every 30–90 days. They come from the Madden–Julian oscillation (MJO; Madden and Julian 1971, 1972). The MJO is identified as a large-scale [\(1,000 \text{ km}\)] region of abnormal deep convective cloud and rainfall propagating eastward at an average 5 m s\(^{-1}\) together with its associated fields of wind, humidity, and temperature. Its cloud and rainfall signature is prominent usually from the Indian to the western Pacific Oceans. Its wind signals may move circumequatorially. During its life cycle, the MJO influences global weather and climate (Zhang 2013). This has motivated growing interest in its real-time monitoring (Wheeler and Hendon 2004) and forecasts (Gottschalck et al. 2010). Tremendous efforts have been made to improve our knowledge of the MJO from viewpoints of observations, numerical modeling, and theories (Zhang 2005; Lau and Waliser 2012). While there has been progress in MJO prediction (Bechtold et al. 2008; Vitart and Molteni 2010) and simulation (Miura et al. 2007; Benedict and Randall 2009), they are still significant unmet challenges. The inability of many state-of-the-art global models to produce...
The MJO (Hung et al. 2013) degrades their seasonal to interannual prediction, lessens our confidence in their ability to project future climate, and manifests our lack of full understanding of the MJO.

Our global climate prediction and projection will rely on models with parameterized convection in the foreseeable future. Improved simulations of the MJO will continue to serve as a benchmark of the advancement and development of model cumulus parameterizations. Development of physical parameterizations in numerical models has been a long, painstaking endeavor. It has greatly benefited from observations of past field campaigns in the tropics (e.g., GATE, TOGA COARE; see appendix for acronym expansions). The stunning lack of in situ observations in the region of the tropical Indian Ocean (IO), where convective initiation of the MJO often takes place, has impeded progress on understanding atmospheric and oceanic processes related to weather and climate there. What we learned from the other tropical oceans may not completely apply to the IO because of its unique setting (see sidebar on the uniqueness of the Indian Ocean). A field campaign in the tropical IO region was urgently needed (ICTP 2006).

An internationally cooperative field campaign was operated in 2011–12 (see sidebar on participating programs) to investigate physical processes of the MJO in the central equatorial IO, with components in the tropical western Pacific and intervening Maritime Continent area. With advanced observing technology, this field campaign tracked the intraseasonal pulses of the MJO at its infant and mature stages. This article summarizes the scientific rationale, hypotheses, objectives, experimental design and operation, and preliminary results of this field campaign.

**SCIENTIFIC RATIONALE, HYPOTHESES, AND OBJECTIVES.** Convective initiation of the MJO (referred to here as MJO initiation) over the IO conceptually consists of three stages (Stephens et al. 2004). The first is a pre-onset stage. Atmospheric deep convection is generally suppressed in a large area except in the ITCZ when it is present south of the equator. There can be precipitating and nonprecipitating shallow clouds and occasionally isolated deep convective cloud. SST is relatively high and surface wind weak. The second is an onset stage. Deep convection gradually becomes more active and widespread in a basin-scale area. A convective envelope of the MJO is thus formed. Its eastward movement signifies the commencement of a new MJO event. The final one is a post-onset stage. After deep convections move eastward, convectively suppressed condition returns and prevails again over a large area. Strong westerly wind reigns at the surface and low levels, and SST reaches its minimum. This
post-onset stage eventually turns into another pre-onset stage as surface westerlies give way to easterlies and SST gradually increases. There are many mysteries in convective initiation of the MJO. What determines the time scales of the post- and pre-onset stages, which make the MJO episodic? What are the key factors for the transition from the pre-onset to onset stages? What makes the large-scale convective envelope move eastward and thus inaugurates a new MJO event?

To efficiently address these and other questions regarding MJO initiation using field observations, three hypotheses were proposed which focused on processes local to the tropical IO:

- Hypothesis I: Deep convection can be organized into an MJO convective envelope only when the lower-tropospheric moist layer has become sufficiently deep over a region of the MJO scale; the pace at which this moistening occurs determines the duration of the pre-onset stage.
- Hypothesis II: Specific convective populations at different stages are essential for MJO initiation.
- Hypothesis III: The barrier layer, wind- and shear-driven mixing, shallow thermocline, and mixing layer entrainment all play essential roles in MJO initiation over the IO by controlling the upper-ocean heat content and sea surface temperature and thereby surface flux feedback.

Hypothesis I is built upon the abundant literature on the sensitivity of convection to environmental moisture (Brown and Zhang 1997; Raymond 2001; Kuang and Bretherton 2006; Peters and Neelin 2006). The importance of lower-tropospheric moisture to the MJO has been suggested by its increases prior to convectively active phases in observations and reanalysis data (Johnson et al. 1999; Kemball-Cook and Weare 2001) and in model simulations (Thayer-Calder and Randall 2009). This increase in low-level moisture in numerical models is mainly due to transport of the atmospheric circulation (Benedict and Randall 2009; Maloney 2009) or surface evaporation (Maloney and Sobel 2004; Sobel et al. 2008). Direct or indirect evidence for the commonly assumed moistening by shallow and congestus clouds has been, however, very limited (Benedict and Randall 2007).

Hypothesis II advances the conventional thinking of convection versus no convection or shallow versus deep convection during MJO initiation to a holistic view of cloud population evolution, including precipitating and nonprecipitating clouds of all sizes, depths, and degrees of organization. The MJO life cycle features a rich variability of different types of clouds (Lau and Wu 2010; Riley et al. 2011; Del Genio et al. 2012). Shallow and congestus clouds, in addition to their possible role of moistening the lower troposphere as discussed earlier, provide low-level heating, when they precipitate, that induces low-level large-scale moisture convergence (Zhang and Hagos 2009), which helps maintain small or negative gross moist stability (Neelin and Held 1987; Raymond et al. 2009) and thereby convective development of the MJO. The essential role of low-level heating in the MJO has been suggested in theoretical studies (Wu 2003; Khouider and Majda 2006) and demonstrated in numerical simulations (Li et al. 2009). Upper-level heating due to

### Participating Programs

The 2011–12 MJO field campaign was initiated and organized internationally under the Cooperative Indian Ocean Experiment on Intraseasonal Variability in the Year 2011 (CINDY2011). Researchers, including roughly 100 students from more than 60 institutes of Australia, France, India, Indonesia, Japan, Kenya, Korea, Maldives, Papua New Guinea, Poland, Seychelles, Singapore, Sri Lanka, Taiwan, the United Kingdom, and the United States, participated in this campaign. The U.S. participation consisted of three projects. Dynamics of the MJO (DYNAMO) has worked with CINDY2011 in experimental design, organized the U.S. participation, and represented the U.S. participation at the international level. CLIVAR endorsed CINDY2011/DYNAMO in 2009. The ARM MJO Investigation Experiment (AMIE; Long et al. 2010; 2011) provided observational facilities at two sites (Manus and Gan Island) for the extended observing period (1 October 2011–31 March 2012). Littoral Air–Sea Process (LASP) emphasized observations of multiscale air–sea interaction processes in the Indian Ocean. The different stages of MJO initiation provide ideal contrasting large-scale background for studies of detailed multiscale air–sea interaction processes in the Indian Ocean. The 2011–12 MJO field campaign was designed to embrace complementary research interests.
stratiform precipitation may generate instabilities that help trigger new convection through interaction with equatorial waves (Mapes 2000; Kuang 2008) and thus may help maintain MJO convectively active phases (Seo and Wang 2010). Stratiform heating, on the other hand, may help terminate MJO convectively active phases through inducing midlevel inflows (Zhang and Hagos 2009) that drain moist static energy (Peters and Bretherton 2006). It is paramount to understanding the respective roles of different types of clouds in each stage of MJO initiation.

Hypothesis III targets some of the unique features of the IO (see sidebar on the uniqueness of the Indian Ocean). Large intraseasonal fluctuations in SST (Vialard et al. 2008) can be generated through complex processes over the thermocline ridge region. Their feedback to the MJO is expected but unsubstantiated (Duvel and Vialard 2007). Intraseasonal surface westerlies enhance the Wyrtki jets and their eastward transport of heat and salinity (Han et al. 2004). Their roles in the SST feedback to the MJO are completely unknown.

These hypotheses were proposed to be tested using field observations. Many other possible mechanisms for MJO initiation that cannot be effectively addressed by field observation were not included in these hypotheses. A combination of observations collected during the field campaign and large-scale data (e.g., global reanalyses, satellite data) is needed to investigate all aspects of MJO initiation.

The overarching goal of the 2011–12 MJO field campaign was to expedite our understanding of the MJO, especially its initiation processes, and our efforts to improve simulation and prediction of the MJO. Its specific objectives were to

- collect observations that are urgently needed to advance our understanding of the processes key to MJO initiation and propagation;
- identify critical deficiencies in numerical models that are responsible for their low prediction skill and poor simulations of the MJO;
- provide unprecedented observations to assist the broad community effort toward improving model parameterizations; and
- provide guiding information to enhance MJO monitoring and prediction capacities for delivering better climate prediction and assessment products on intraseasonal time scales for risk management and decision making over the global tropics.

The field campaign was integrated with modeling, data analysis, and real-time forecast to help accomplish these objectives.

**DESIGN AND OPERATION OF THE CAMPAIGN.** Based on the pilot studies (see sidebar on pilot studies), the 2011–12 MJO field campaign was designed to ensure a sufficient length to capture the

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**PILOT STUDIES**

In the boreal fall of 2006, the field campaign MISMO was conducted to observe the atmosphere and ocean of the central equatorial Indian Ocean (Yoneyama et al. 2008). During 1½ months of this field campaign, its triangle observing array formed by two islands and a ship captured a transition period from convectively inactive to active phase of tropical intraseasonal variability. Its observational data reveal that eastward-propagating mesoscale cloud systems played an important role in moistening the middle and upper troposphere to assist the onset of large-scale convection (Katsumata et al. 2009), as suggested by theories and numerical simulations (e.g., Raymond and Fuchs 2009; Maloney 2009; Sugiyama 2009). MISMO has also led to other lessons. A quadrilateral sounding array is needed to reduce observational errors in estimates of atmospheric heating and moisture budgets (Katsumata et al. 2011). In particular, it is important to evaluate the influence of meridional advection associated with large-scale disturbances (Yasunaga et al. 2010). A longer duration is necessary to capture a full cycle of convective initiation of the MJO. These lessons paved the road to the design of the 2011–12 MJO field campaign in the Indian Ocean region.

In January–February 2007, another field campaign, Vasco–Cirene, took place in the Indian Ocean to study the role of air–sea interaction in initiation and evolution of deep convection of the MJO in the thermocline ridge region (Vialard et al. 2009). It consisted of an island site and a research vessel with measurements of the atmospheric and oceanic profiles. Active scale interaction was observed among the IOD, MJO, tropical cyclones, diurnal cycle, and turbulent mixing. No anticipated surface cooling related to the MJO was observed because of an abnormally deep thermocline that resulted from the strong 2006 IOD.

Data collected at the ARM Manus site demonstrated the utility of single point measurement in detecting various aspects of the MJO (Wang et al. 2010) and motivated a tropical western Pacific MJO campaign at the Manus Island site (AMIE-Manus). It was desired to have a twin site of ARM in the Indian Ocean to monitor the same MJO events from their infant to mature stages as they were initialized over the Indian Ocean and propagated into the western Pacific. Both AMIE-Manus and AMIE-Gan were held in partnership coinciding with the larger international campaign.
full initiation cycle of at least one MJO event by the following observing components (Fig. 1):

(i) two quadrilateral sounding arrays for adequate atmospheric budget estimates, embedded in a broad sounding network from East Africa to the Maritime Continent within 20°S and 20°N;
(ii) multiple radars of different wavelength to sample the full spectrum of cloud population during all stages of MJO initiation;
(iii) simultaneous and continuous observations of atmospheric and upper-ocean profiles to measure coherent and coupled air–sea variability at time scales from turbulence to the MJO;
(iv) identical twin sites in the IO (Addu Atoll) and western Pacific (Manus Island) to sample the same MJO event at its initiation and mature stages; and
(v) an aircraft operation to sample the atmospheric and oceanic boundary layers and large-scale variability between atoll and ship sites.

Studies on the MJO mean seasonal cycle (Zhang and Dong 2004; Matthews 2008) indicated that main MJO initiation activity takes place in the central IO from October to March, with the highest occurrence probability near the equator in October–January. Accordingly, the field campaign covered three nested periods (Fig. 2):

- special observing period (SOP), 1 October–28 November 2011;
- intensive observing period (IOP), 1 October 2011–15 January 2012; and
- extended observing period (EOP), 1 October 2011–31 March 2012

The SOP was designed to obtain high-resolution data to capture the diurnal cycle of convective activity with the maximum observing capacity. All instruments deployed during the field campaign operated during the SOP. The transition from a quadrilateral to triangle array south of the equator because of the departure of a ship and the completion of the aircraft operation marked the end of the SOP. All other instruments continued to operate after the SOP until the end of the IOP. Beyond the IOP, almost identical instruments at the IO site of Addu Atoll and the western Pacific site of Manus Island were planned to continue taking observations until the end of the EOP. However, a political regime change...
in the Maldives and subsequent civil unrest led to an early termination of the campaign at Addu Atoll on 9 February 2012. Observations at Manus Island continued as planned until the end of the EOP.

More detailed descriptions of each campaign component are given below. Detailed information on the measurement systems is given in Tables ES1–ES5 in the electronic supplement.

**Soundings.** Central to the campaign were two quadrilateral sounding arrays over the central equatorial IO (outlined by dashed lines in Fig. 1). Their main mission was to observe the evolution of atmospheric vertical structures in wind, temperature, humidity, energy, and moisture budgets using radiosondes. The southern array was formed by two islands at Gan Island of Addu Atoll (0.7°S, 73.2°E) and Diego Garcia (7.3°S, 72.4°E), marked as red dots in Fig. 1, and two ship sites, one at 0°, 80.5°E (NE) and one at 8°S, 80.5°E (SE), marked as red stars in Fig. 1. The northern array was formed by NE and three land sites at Gan Island, Hulhule Island of Male Atoll (4.2°N, 73.5°E), and Colombo (6.9°N, 79.8°E), marked as yellow dots in Fig. 1 and Gan Island.

Surrounding the two quadrilateral sounding arrays is a broad sounding network that includes sites over East Africa (Nairobi) to the western Pacific (Manus Island) (Fig. 1). This sounding network monitored atmospheric state from MJO initiation stages over the western/central IO, its modulation by the Maritime Continent, to its mature stages over the western Pacific. Additional dropsondes were launched from an airplane during the SOP. The launch success rate was 98% for the two sounding arrays and 99.8% for the aircraft dropsondes. In total, near 20,000 radiosondes and 5,000 pibals were launched during the campaign, including nearly 13,000 high-resolution soundings. The mean termination level is 60 hPa (20 km). The radiosonde and surface meteorological data were immediately sent to the NWP centers via the GTS during the campaign with a 95% success rate to assist real-time numerical weather prediction.

**Radars.** Accompanying the sounding arrays and equally essential to the field campaign was a radar network. It included three radar sites in the IO (Addu Atoll, NE, and SE) and one in the western Pacific (Manus Island). Radars with multiple wavelengths were deployed at all these sites to observe the broad spectrum of cloud population.

Addu Atoll, which occupied the vertex of both the northern and southern arrays, was selected as a “radar supersite” where a unique radar triad consisting of the S-PolKa, SMART-R, and KAZR was deployed (Fig. 3).

The KAZR is a profiling Doppler radar that operates at a Ka band (8.6-mm wavelength). Located at the Gan Island airport (0.69°S, 73.15°E) as part of the DOE AMF2. It determines the first three radar moments (reflectivity, mean Doppler velocity, and spectrum width) with a range resolution of 30 m from near the ground to nearly 20 km in altitude.

The S-PolKa is an advanced dual-polarimetric, dual-wavelength (10 cm for S band and 0.8 cm for Ka band) radar. It was located near the wharf of Hithadhoo Island (0.63°S, 73.10°E), 8.62 km from the KAZR. It determines the first three radar moments (reflectivity, mean Doppler velocity, and spectrum width) with a range resolution of 30 m from near the ground to nearly 20 km in altitude.
identification of hydrometeor types and humidity-gradient layers, cold pools, and detailed structure and evolution of precipitating deep convection. The dual-wavelength capability allows some detection of boundary layer humidity profiles and cloud liquid water content estimates that are independent of drop size distribution. The scanning plan of S-PolKa (see sidebar on radar scanning strategy) was designed to collect 3D distributions of clouds with special vertical profiles of cloud at the location of the KAZR.

The SMART-R is a scanning Doppler system that operates at C band (5-cm wavelength). It was located on Hithadhoo Island (0.61°S, 73.09°E), 9.28 km from the KAZR. Both S-PolKa and SMART-R observations allow a separation of precipitation into its convective and stratiform components and estimates of vertical latent heating profiles. The SMART-R scanning strategy also included special vertical profiles of cloud at the location of the KAZR.

This radar triad at Addu Atoll provided unprecedented observations of the entire tropical cloud population, including precipitating and nonprecipitating shallow cumulus clouds, midlayer altostratus and altocumulus, convective congestus, isolated deep convective clouds, upper-level anvil and cirrus clouds, mesoscale convective systems, and hydrometer types. The regular horizontal PPI scans of S-PolKa and SMART-R provided a mesoscale context for the KAZR data collection. The RHI scans of the S-PolKa and SMART-R radars over the KAZR extended vertical profiles of reflectivity measured by the KAZR into altitudes above precipitation where the KAZR signal is attenuated, yielding vertical profiles of reflectivity over the KAZR site for both raining and nonraining clouds. These three radars in combination covered both nonprecipitating and (lightly and heavily) precipitating clouds, thus producing a merged cloud–precipitation product specifically tailored for model evaluation (Feng et al. 2009).

The other two radar sites were onboard R/V Mirai at SE and Revelle at NE, where C-band scanning Doppler radars and vertically pointing W-band (3.2-mm wavelength) Doppler radars were deployed. Radar observations from Revelle and Mirai captured cloud population during contrasting large-scale convective conditions (see “general conditions during the campaign” section).

At Addu Atoll, a multichannel scanning microwave radiometer was deployed next to the S-PolKa for humidity and liquid water retrievals during the IOP. Microwave radiometers of two and three channels operating in vertically pointing mode were deployed.

**RADAR SCANNING STRATEGY**

S-PolKa performed a combination of full horizontal scans (PPI) and vertical cross-sectional scans (RHI) as illustrated in the figure. The scanning strategy included 8 PPI elevation angles (from 0.5° to 11°) and 55 RHIs with scan angles of 0°–45°. Of the 55 RHIs, 39 were toward the north to the east and 16 were toward the AMF2 site. Two special vertical scans over the KAZR had a wider range of scan angles 0°–60° (represented by the transparent vertical cross section in the figure). The pattern repeated on a 15-min cycle. The maximum range for the PPI and RHI scans was 150 km for the S band.

The SMART-R performed full volume scans of 25 elevation angles (from 0.5 to 33°) every 10 min, interspersed with a long-range, low-level PRF surveillance scan and an RHI scan over the KAZR. The maximum range for the PPI and RHI scans was 150 km and was extended to 300 km for the long-range surveillance.

Within each 10-min cycle, the C-band radars onboard R/V Revelle and Mirai performed a combination of full horizontal volume scans of about 8–9 min and vertical RHI scans of about 1–2 min to a range of 150 km. Every 30 min a 0.5° elevation low-level PRF surveillance scan to a range of 300 km was added to the RHI scan. The RHI scans targeted a specific cloud system at the scene. The horizontal scans of the Revelle C-band radar were in either deep (22 elevations from 0.8° to 21.5°) or shallow (22 elevations from 0.8° to 35.9°) modes, depending on whether deep or shallow clouds are present. The Mirai C-band radar kept the same 21 elevations from 0.5° to 40° in its horizontal scans regardless of the cloud type at the scene.

Fig. SB1. Illustration of S-Polka scanning. Colors are S-band reflectivity at the top PPI and RHIs. (Courtesy of Scott Ellis)
at the airport site near the KAZR to retrieve column water vapor and liquid water. At Diego Garcia, the southwestern corner of the southern intensive array, a 915-MHz wind profiler, a ceilometer, a surface meteorological station, and a whole-sky camera were deployed in addition to radiosondes.

In addition, X-band (3.22-cm wavelength) and C-band radars were deployed onboard one research airplane and W-band radars were onboard another airplane.

Ships, moorings, and floats. Four research vessels were deployed during the field campaign: R/V Roger Revelle (United States), R/V Mirai (Japan), ORV Sagar Kanya (India), and R/V Baruna Jaya-III (Indonesia) and cruise tracks and major observation sites for (e) Revelle legs 1 and 5; (f) Revelle legs 2, 3, and 4; and (g) Mirai, Sagar Kanya, and Baruna Jaya-III. Solid thick lines in (e) and (g) indicate the cross sections where CTD/XCTD/XBT measurements were performed. Dates indicate the period for port or on station.

Several additional and special observations were made onboard R/V Revelle. A thermistor chain was deployed during her legs 2 and 3 to measure detailed temperature structure and evolution in the upper 10 m with a 0.25-m vertical resolution and extremely high frequency (10 Hz). Vertically profiling wire walkers (Pinkel et al. 2011), each equipped with temperature–pressure or CTD sensors, were deployed during leg 4 to measure the upper-ocean structure without ship effects in the top 20 m every 5 min and in the top 200 m every 20 min.

Surface and subsurface moorings (Fig. 5) were deployed along 78.5°E. Surface and subsurface moorings were deployed at 9.75°S, 1.5°S, and 0° during the IOP by R/V Revelle, while a subsurface mooring was deployed at 5°S, 78.1°E during the SOP by R/V Mirai. The location of 9.75°S was chosen because of a peak of the thermocline ridge in September based on the XBT measurement by R/V Revelle. Since both Revelle and Mirai occupied a stationary site at 7°S, 95°E for 10 days.

Time series of upper-ocean structures were measured by CTD profiler and shipboard ADCP from R/Vs Roger Revelle, Mirai, and Sagar Kanya. Water sampling for biogeochemical analyses (e.g., nutrients, chlorophyll a) were also collected (1–4 times per day). To understand the detailed features of ocean surface flux, microstructure (turbulent) profilers were frequently casted down to 200–300 m during on-station times both at the Revelle and Mirai. In addition, Mirai made a meridional XCTD/ADCP survey in late November, and Revelle made an XBT/ADCP survey on 8 November, a CTD/ADCP survey along the equator on 2 December, followed by another XBT/ADCP survey. In total nearly 750 CTD/XCTD/XBTs and over 8,000 turbulent profilers were deployed. The tracks of these surveys are shown in Fig. 4.
and *Mirai* occupied locations near RAMA moorings that have been deployed along 80.5°E (McPhaden et al. 2009), it is possible to evaluate the accuracy of long-term moored buoy data by comparing with the CTD and surface meteorological data. Moreover, such sustained monitoring systems deployed in the IO (Meyers and Boscolo 2006) provide invaluable information regarding how representative the field campaign period is.

An Argo float was released at 5°S, 78.1°S from R/V *Mirai* with its parking depth at 500 m and daily ascent. A sea glider was deployed from R/V *Revelle* to measure temperature and salinity along 80°E between two RAMA moorings at 1.5° and 4°S during 14 September 2011 through 23 January 2012. Surface temperature and salinity along 78.5°E were measured by a sea soar deployed from R/V *Revelle* during her leg 5.

**Aircraft measurements.** The aircraft measurements featured a unique standalone suite of instruments and the capability of extending the observations from the fixed locations of ships and atolls to a wider coverage in the vicinity of the field campaign domain. Two research airplanes participated in the campaign. One was the NOAA WP-3D, based on Diego Garcia. It flew 12 missions from 11 November to 13 December 13 (Table ES4a in the electric supplement), sampling processes involved in the atmospheric boundary layer, air–sea interaction, atmospheric convection, and the large-scale gradient in atmospheric and oceanic dynamical and thermodynamical fields. Atmospheric and oceanic vertical profiles were measured by dropsondes, AXBTs, and AXCTDs, and convective cloud was measured by X-/C-band Doppler radars. A total of 468 profiles of wind, temperature, and humidity; 395 profiles of upper-ocean temperature; and 106 profiles of upper-ocean salinity were collected. The WP-3D flight tracks with the locations of dropsondes, AXBTs, and AXCTDs are summarized in Fig. 6a, and the details of flight-level data and instruments are provided in Table ES5.

The other airplane was the SAFIRE Falcon-20, operated from Gan Island, Addu Atoll during 22 November–14 December (Table ES4b). The Falcon participated in the field campaign as part of an algorithm development/validation project of the French–Indian satellite Megha-Tropiques, which was launched on 12 October 2011. Its missions focused on the characterization of ice particles in the upper part of the clouds. The Falcon was equipped with a series of microphysics in situ probes and vertically (both upward and downward) pointing W-band Doppler radars to document the variability of the ice particle properties in various parts of the cloud. The Falcon’s flight tracks are given in Fig. 6b.

**ARM Mobile Facility.** The second ARM Mobile Facility (AMF2) was deployed on Gan Island, Addu Atoll (AMIE-Gan) (see the bottom of Fig. 3) serving two primary purposes: (i) to form the radar super site in
combination with the S-PolKa and SMART-R during the IOP and (ii) to form a twin observing site with the experiment at Manus Island (AMIE-Manus) in the western Pacific to document the evolution in the surface, atmosphere, cloud, and aerosol optical properties for MJO events at their initiation and propagation stages during the EOP using an almost identical suite of instruments. The instruments deployed at Gan and Manus sites include 3-hourly radiosondes, vertically pointing Ka-band radar, micropulse lidar, high-spectral-resolution lidar, wind profiler, dual and three-channel microwave radiometers, ceilometer, rain gauges, total-sky imager, surface meteorology instruments, and a suite of upwelling and downwelling radiation instruments.

At the Manus site, a scanning C-band Doppler radar was added, thanks to Recovery Act funds, prior to the field campaign, which paired up with SMART-R at Addu Atoll. This C-band radar at Manus is critical for the production of model forcing datasets where a network of radiosonde sites is not feasible (Xie et al. 2010).

Logistic and forecast support. During the field campaign, logistic supports were provided by the DYNAMO Project Office at the NCAR Earth Observing Laboratory (EOL). EOL maintained the field catalog on the Internet. It includes all necessary information for the field operation and in-field data analysis, such as field reports from all observation sites that summarized instrument conditions, status of data collection and transmission, operational products such as satellite images and numerical forecasts, preliminary data analysis, and update of the operational schedule. Through this catalog, all participants had the same information of the field operation. Glitches (e.g., tardy transmission of radiosonde data to NWP centers via GTS) were quickly identified and addressed.

Real-time forecast support was provided to the field campaign by various operations and research centers, including NCEP, ECMWF, NRL, Meteo-France, JMA, and IMD. In addition, JAMSTEC provided experimental forecast by a high-resolution Nonhydrostatic Icosahedral Atmospheric Model (NICAM) with a regionally stretched grid system technique (Tomita 2008). These and other forecast products were delivered to and archived by the DYNAMO field catalog and available to the field operation in real time. Based on dynamical and statistical forecast products, an international MJO forecast team, led by NCEP CPC, conducted weekly teleconference briefings to field participants on past and current large-scale atmospheric conditions including MJO activities and outlook of potential MJO development in the coming 1- and 2-week time ranges. It was evident from this weekly briefing that the current dynamical and statistical models did not outperform human experience in MJO prediction. Several times models predicted aborted MJO initiation with its amplitude plunging quickly. Forecasters nevertheless maintained their confidence that the initiation process would continue. They were proven right. At the weekly briefing, scientists at different sites also provided their weekly updates of their instrumentation status and observations. This weekly exchange of information proved extremely fruitful in helping scientists in the field to connect their point measurements to each other, put their observations in a large-scale context, and exchange new scientific ideas.

Related projects. In addition to routine soundings over the Indonesia Maritime Continent region, a 1-month intensive observation (HARIMAU2011) was conducted by Japanese and Indonesian research groups over the...
western Indonesia area in December 2011. Two X-band Doppler radars were operated near Tabing, Sumatra Island, and higher-frequency radiosondes were launched at Sumatra and the Kalimantan Islands. Collaboration has been established for data exchange with the MJO field campaign.

The U.S. DOE ARM facility in Darwin, Australia, operated during the MJO field campaign. Data were collected at the Darwin site, instrumented similar to the Gan and Manus sites, from twice-daily radiosondes, scanning and vertical pointing radars, lidars, radiation and surface meteorology measurements, and a C-band radar operated by the Australian BoM. The Darwin site experiences a monsoon climate, and thus these data will afford the study of the interaction of MJO influences on the monsoonal convection regime.

**GENERAL CONDITIONS DURING THE CAMPAIGN.** The general atmospheric and oceanic conditions during the field campaign are briefly summarized in this section. Their more detailed descriptions can be found in Gottschalck et al. (2013). A La Niña event took place in the Pacific, reaching its peak during November 2011–February 2012, with Niño-3.4 SST anomalies of about –1°C. Meanwhile, a weak positive Indian Ocean dipole mode started in mid-2011, peaked in September, and became negligible by November and after. Monthly mean SST distributions (see Fig. 3 of Gottschalck et al. 2013) suggest that conditions in the central equatorial IO were favorable for convective development during the IOP.

Four intraseasonal and eastward-propagating large-scale convective events occurred over the tropical IO in late October, late November, late December, and March, respectively (Fig. 7). While these convective events unambiguously moved from the IO over the Maritime Continent, the October and November events barely reached the Pacific, partially because of the La Niña condition there. Nonetheless, they were undoubtedly part of the MJO, judged by either the real-time multivariate MJO (RMM) index (Wheeler and Hendon 2004) with its amplitude greater than one and rotating counterclockwise (red and dark blue lines in the inlet of Fig. 7) or MJO spectral filtering (Wheeler and Weickmann 2001) applied to OLR (Fig. 7). We refer to these two events as MJO1 and MJO2, respectively. The December event can be identified as a weak MJO event by the spectral filtering of OLR alone (single red contour in Fig. 7). However, the RMM index does not recognize it as an independent MJO event for its lack of a clear counterclockwise rotation in the phase diagram (cyan in the inlet of Fig. 7). The cloud system related to MJO2 appeared to stagnate after it had passed over the Maritime Continent and then retreated westward. For the convenience of narration, this December intraseasonal event is referred to as MJO3. This event is very telling
and suggestive for future research; it requires a reassessment of the conventional MJO index. The March event was again unambiguously an MJO event (MJO4) and the strongest one among the four. Its cloud signals propagated eastward the farthest, passing the Manus site and reaching the date line.

An intriguing feature of the first three MJO events is their short intervals (~30 days), which is on the high-frequency end of intraseasonal oscillation (30–90 days). One possible reason is the fast circumnavigating propagation of the dynamic field (mostly at 200 hPa; see Gottschalck et al. 2013). The RMM phase diagram suggests that the short interval between MJO2 and MJO3 came from a hiccup of MJO2, and MJO3 was really a continuation of MJO2 after that. Another possible reason is that high-frequency MJO events tend to occur near the equator and their signals are strong after a positive IOD phase (such as in October–December 2011) due to their coupling with the ocean surface (Izumo et al. 2010). There was an MJO event in September that might have served as the predecessor of MJO1. There is no obvious sign that suggests MJO4 is directly related to MJO3. If so, MJO4 could be categorized as “primary,” meaning initiated without help from any previous MJO event (Matthews 2008).

Figure 8 shows the time–latitudinal cross section of the infrared radiation brightness temperature averaged over the IO intensive array (70°–80°E). The convective center tended to move from the Northern Hemisphere in the early part of the field campaign to the Southern Hemisphere during the latter part of the campaign as indicated by a dashed arrow. This matches well the climatological seasonal migration in latitude of the ITCZ (Zhang 2001) and MJO activities (Zhang and Dong 2004) over the IO. Meanwhile, there were intraseasonal fluctuations in the latitudinal positions of convective centers. Prior to the convective peaks of MJO1 and MJO2, there was a northward shift of convective signals toward the equator as indicated by solid arrows from roughly 10°S, the usual latitude of the ITCZ in the IO. The commonly defined convectively suppressed periods near and north of the equator prior to convective initiation of the two MJO events were actually periods of active convection in the ITCZ. Convective initiation of the two MJO events coincided with the northward shift of the ITCZ.

### Preliminary Results

**Sounding observations.** Time series of vertical profiles of relative humidity (RH) at the southern intensive array and Manus Island are shown in Fig. 9. The first three MJO events were well captured by the sounding observations at Gan and Revelle as high RH penetrating upward from the boundary layer into the upper troposphere (Figs. 9a,b), presumably resulted from upward moisture transport by deep convection. The local convective initiation of these MJO events were preceded by a gradual increase of the depth of the moisture layer (RH > 70%), as stated in hypothesis I. Near the end of each active convective (high upper-tropospheric RH) period, the entire...
tropospheric column seemed to abruptly become very dry. The local intraseasonal variability in RH was therefore asymmetric with respect to the peak of local convection. This asymmetry in moisture variability associated with the MJO has been documented before (Kiladis et al. 2005). Intraseasonal fluctuations in RH at Mirai appeared to be out of phase with those at Revelle, with vertical penetration of high RH into the upper troposphere, representing the existence of deep convection, which occurred in early October and mid-November prior to convective initiation of MJO1 and MJO2 at Revelle. At Diego Garcia west of Mirai, a similar situation is found, with variability in RH profiles out of phase compared to those at Gan. Deep convection events, however, were more frequent than at Mirai, though they did not last as long as at the equatorial sites. As convective initiation of MJO1 and MJO2 started at Revelle, convection at Mirai became very suppressed, with the middle to upper troposphere extremely dry (RH < 10%). This contrast in the RH profiles between Revelle and Mirai came from the latitudinal shift of the ITCZ before and during convective initiation near the equator (Fig. 8). After MJO3, the troposphere became very dry in general at Gan until the beginning of February.

RH profiles at Manus from October to early February were dominated by synoptic-scale variability. The convective centers of the three MJO events before March did not reach Manus. The only obvious intraseasonal signal during this time was a dry period coinciding with the convective initiation of MJO1 over Gan and Revelle during mid to late October. A similar pattern occurred again with a dry period in late February preceding a distinct moistening associated with the MJO4 migration into the western Pacific (not shown).

The zonal wind (u) profiles (Fig. 10) near the equator (Gan, Revelle, and Manus) generally exhibit a typical gravest baroclinic structure with u of the opposite signs in the upper and lower troposphere, subject to variability on various time scales. Off the equator at Mirai and Diego Garcia, however, the u profiles were mostly barotropic and dominated by easterlies, with deep westerlies occasionally punctuating through the troposphere during October–November. The expected
low-level westerlies during convective initiation of the MJO at Gan were deeper and stronger for MJO2 and MJO3 than MJO1. While the westerlies occurred after the passage of convective peak for MJO1, both occurred at the almost same time for MJO3. There were tendencies of descending easterlies from the upper to middle troposphere prior to the three MJO events at Gan and Revelle, which is equivalent to decreases in the depth of low-level westerlies. Very strong and persistent surface westerlies were observed at both Gan and Revelle at the beginning of MJO2. About one week later an abrupt change from low-level/midlevel easterlies to westerlies can also be found at Diego Garcia. There was a sharp transition in the vertical structure of u at Manus near the end of 2011 from upper-level westerlies and low-level easterlies to the opposite. Since there was a possibility that the abrupt change of wind pattern over the Manus site may have been related to the Australian monsoon onset, these data might be used for studying the relationship between the MJO and the Australian monsoon.

**Oceanic observations.** The oceanic variability through the first two MJO events is exemplified by the time series of surface and subsurface measurement during legs 2 and 3 of Revelle (Fig. 11). Prior to their convective initiation of MJO1 and MJO2, surface stress was weak. Under such calm surface conditions, diurnal heating of the ocean surface was large. Large diurnal cycle in the mixed layer depth (thick black lines) occurred only in October, which was accompanied by strong diurnal turbulent mixing in the upper 50 m of the ocean. In mid to late November, however, the mixed layer remained very shallow without any significant diurnal cycle, despite strong diurnal heating at the surface (about 1°–2°C) and diurnal mixing at the 50–80-m depth. The eastward strong surface current (Wyrtki jet) was maintained through most of October. It almost disappeared in mid-November, but quickly re-amplified into an extraordinarily strong one by the abrupt onset of surface westerlies on 24 November as MJO2 started at Revelle. This jet was able to maintain its strength (~1 m s⁻¹) even when surface wind quieted down (beginning of December) and lasted through a large portion of December. Shear-induced mixing was not confined to the mixed layer. There were multiple layers of turbulent mixing throughout both legs. In addition to
generation of turbulent mixing through shear, another substantial effect of the Wyrtki jet is zonal advection of surface salinity. Fresh surface water in October was replaced by an incursion of saline water from the Arabian Sea in November. The Wyrtki jet is commonly regarded as a semiannual phenomenon associated with the monsoon transition in boreal spring and fall. MJO influences on the Wyrtki jets have been well documented (e.g., Han et al. 2004). However, westerly wind bursts associated with the MJO may generate “off season” Wyrtki jets. It may provoke discussion on the definition of the Wyrtki jet itself. In addition, further studies are needed to explore dynamical impacts of the Wyrtki jet on subsequent MJO events.

On 24 November, the WP-3D aircraft flew from Gan to Revelle and captured the large-scale vertical cross section between the two using dropsondes (Fig. 12). There was an evident west–east westerly momentum transport downward from the middle to lower troposphere that was partially responsible for the sudden onset of surface wind stress experienced at Revelle. Accompanying this was an onset of a cold pool at Revelle. The sudden appearance of atmospheric forcing associated with MJO2 and the abrupt oceanic response on this day and after are apparent in Fig. 11.

Radar observations. The C-band radars onboard Revelle and Mirai sampled cloud
populations in two distinct climate regimes (Fig. 13), because of the latitudinal shift of the ITCZ and seasonal position of the MJO (Fig. 8). During the pre-onset stages of both MJO1 and MJO2, the Revelle radar recorded a cloud population dominated by shallow and isolated deep convection under a generally suppressed condition of deep convection, and the Mirai radar captured a cloud population dominated by many deep convective clouds in the ITCZ. The cloud populations sampled by the two radars switched when MJO convection had been initiated and became active at Revelle.

Figure 13 also shows plenty of radar echoes during the periods that led to the convective initiation of the two MJO events when cloud-top IR temperature was relatively high (>280 K). This suggests the abundance of shallow, precipitating clouds in those periods. An example of the observations from the radar super site at Addu Atoll is shown in Fig. 14. The same cloud system was observed simultaneously by the three radars on 27 November 2011. The KAZR recorded the evolution of shallow cloud bracketed by deep and anvil clouds through the day. The SMART-R and S-Pol confirmed that some shallow clouds were precipitating, others were not. Most of the anvil clouds recorded by the KAZR were not precipitating. In addition, the S-PolKa helped identify various types of hydrometeors within both shallow and deep clouds.

Concluding Remarks. The 2011–12 MJO field campaign conducted in and around the tropical Indian Ocean sampled atmospheric and oceanic variability from turbulent to intraseasonal time scales using its land-based, sea-borne, and airborne instruments. The success of this field campaign was an outgrowth of collaboration and coordination among several programs (see sidebar on participating programs), participation by scientists and supporting personnel from 16 countries, and some cooperation suggested by measurements from Revelle (September, January) and Mirai (November). Frequent convective cold pools were observed over the ocean during all stages of MJO initiation. Extremely large horizontal moisture gradients (transitions from 10% to 90% relative humidity within 100 km) in the troposphere were observed by aircraft dropsondes. Near-inertial waves and Langmuir cells in the upper ocean were repeatedly detected. There was a rich spectrum of high-frequency (convective, diurnal, 2–4 day, synoptic) fluctuations in rainfall within the

DATA POLICY AND ARCHIVE. CINDY2011 and DYNAMO data policies require timely release of field observations for public use no later than April 2013. The ARM program has a policy of free and immediate release of measurement data to the community at near–real time, with higher-level data products (e.g., value added products) released for distribution when they are generated from field measurements. There are three data centers that archive the field data: the CINDY2011 data archive at JAMSTEC (www.jamstec.go.jp/iorgc/cindy/), the DYNAMO data archive at NCAR EOL (www.eol.ucar.edu/projects/dynamo/), and the AMIE data available at the ARM archive (http://archive.arm.gov/). Links between them allow for one-stop data searching.
from nature. Four major intraseasonal events were covered, with three of them clearly belonging to the MJO. Two of the three MJO events (in October and November 2011) were captured by most instruments. The November event was sampled by all instruments in the field. It is an ideal case for observational and numerical studies. It is thus desirable to include this event as a targeted case in coordinated model intercomparison, including global and regional models of both coarse and cloud-system permitting resolutions [one such model intercomparison effort is the “Vertical Structure and Diabatic Processes of the MJO” project under the framework of the Year of Tropical Convection (YOTC) MJO Task Force and the Global Energy and Water Exchanges (GEWEX) Global Atmospheric System Studies: www.ucar.edu/yotc/mjodiab.html]. One of the contentious issues might be the December case, which poses a challenge to our conventional definition of the MJO and motivates further studies on convection–circulation coupling of the MJO.

The 2011–12 MJO field campaign provided observations that are unique in several aspects in comparison to previous tropical field campaigns that aimed at interactions between atmospheric convection and its large-scale environment and between the atmosphere and ocean. It is the only one in the tropical IO with continuous time series of atmospheric and upper-ocean profiles. It is the first time the entire cloud population ranging from shallow nonprecipitating and precipitating clouds to deep convection with anvils were simultaneously sampled by modern radars of different wavelengths over a tropical open ocean. It is also the first time observations were collected by identical instruments for two tropical climate regimes (the ITCZ and MJO) and from two oceans (the Indian and western Pacific Oceans). The instruments used in this field campaign are far superior to any previous campaigns of similar scope.

Data collected by this field campaign will benefit the study of the MJO and tropical atmospheric and oceanic processes in general for many years to come. It is very meritorious that the modeling community has been actively involved with the field campaign, from its planning to operation and postfield data analysis and applications. A close collaboration between experts of field data collection and modeling is the foundation for the legacy of this field campaign: using the observations in hypothesis testing and model development and improvement.

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APPENDIX: LIST OF ACRONYMS AND ABBREVIATIONS.

AAMP  Asian–Australian Monsoon Panel
ADCP  Acoustic Doppler current profiler
AMF2  The second ARM Mobile Facility
AMIE  ARM–MJO Investigation Experiment
ARM  Atmospheric Radiation Measurement
ASR  Atmospheric System Research
AXBT  Airborne expendable bathythermograph
AXCTD  Airborne expendable CTD
BMKG  Badan Meteorologi, Klimatologi, dan Geofisika (Meteorological Climatological and Geophysical Agency)
BoM  Bureau of Meteorology
BPPT  Badan Pengkajian dan Penerapan Teknologi (Agency for the Accessment and Application of Technology)
CINDY2011  Cooperative Indian Ocean Experiment on Intraseasonal Variability in the Year 2011
CLIVAR  Climate Variability and Predictability
CNES  Centre National d’Etudes Spatiales, France
CNRS  Centre National de la Recherche Scientifique, France
CPC  Climate Prediction Center
CSIR  Council of Scientific and Industrial Research, India
CTD  Conductivity–temperature–depth
DOE  Department of Energy
DYNAMO  Dynamics of the Madden–Julian Oscillation
ECMWF  European Centre for Medium-Range Weather Forecasts
EOL  Earth Observing Laboratory
GATE  Global Atmospheric Research Program Atlantic Tropical Experiment
GOOS  Global Ocean Observing System
GPS  Global Positioning System
GTS  Global Telecommunication System
HARIMAU  Hydrometeorological Array for Intraseasonal Variability-Monsoon Automonitoring
ICPO  International CLIVAR Project Office
IMD  Indian Meteorological Department
IOC  Intergovernmental Oceanographic Commission
IOD  Indian Ocean Dipole
ISS  Integrated Sounding System
ITTCZ  Intertropical convergence zone
JAMSTEC  Japan Agency for Marine-Earth Science and Technology
JMA  Japan Meteorological Agency
KAZR  Ka-band ARM Zenith Radar
LASP  Littoral Air–Sea Process
MISMO  Mirai Indian Ocean Cruise for the Study of the MJO-Convection Onset
MJO  Madden–Julian oscillation
REFERENCES


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