DOE/SC-ARM-16-039

Atmospheric Radiation Measurement Madden-Julian Oscillation Investigation Experiment Field Campaign Report

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Executive Summary

Every 30–90 days during the Northern Hemisphere winter, the equatorial tropical atmosphere experiences pulses of extraordinarily strong deep convection and rainfall. This phenomenon is referred to as the Madden–Julian Oscillation, or MJO, named after the scientists who identified this cycle. The MJO significantly affects weather and rainfall patterns around the world (Zhang 2013).

To improve predictions of the MJO—especially about how it forms and evolves throughout its lifecycle—an international group of scientists collected an unprecedented set of observations from the Indian Ocean and western Pacific region from October 2011 through March 2012 through several coordinated efforts. The coordinated field campaigns captured six distinct MJO cycles in the Indian Ocean.

The rich set of observations capturing several MJO events from these efforts will be used for many years to study the physics of the MJO. Here we highlight early research results using data from the Atmospheric Radiation Measurement (ARM) Madden-Julian Oscillation Investigation Experiment (AMIE), sponsored by the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility.

Acronyms and Abbreviations

AMIE	ARM–MJO Investigation Experiment
ARM	Atmospheric Radiation Measurement Climate Research Facility
C	celsius
CINDY2011	Cooperative Indian Ocean Experiment on Intraseasonal Variability in the Year 2011
DOE	U.S. Department of Energy
DYNAMO	Dynamics of the Madden–Julian Oscillation
ECMWF	European Centre for Medium-Range Weather Forecasts
GTS	Global Telecommunication System
HARIMAU	Hydrometeorological Array for Intraseasonal Variability-Monsoon Automonitoring
HSRL	High Spectral Resolution Lidar
IOP	intensive operational period
ITCZ	Intertropical convergence zone
k	kilometer
KAZR	Ka-band ARM Zenith Radar
LASP	Littoral Air-Sea Process
m	meter
MJO	Madden-Julian Oscillation
NOAA	National Oceanic and Atmospheric Administration
OLR	outgoing longwave radiation
RMM	Real-time multivariate MJO
s	second
SMART-R	Shared Mobile Atmospheric Research and Teaching Radar
Sop	standard operating procedure
S-Pol	Ka S-band and Ka-band polarization Doppler radar
SST	sea surface temperature
TWP	Tropical Western Pacific

Contents

Figures

1.0 Background

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 (O[1,000 km]) region of abnormal deep convective cloud and rainfall propagating eastward at on 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 the viewpoints of observations, numerical modeling, and theories (Zhang 2005, Lau and Waliser 2011). 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), significant unmet challenges remain. 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.

To improve predictions of the MJO—especially about how it forms and evolves throughout its life cycle—an international group of scientists collected an unprecedented set of observations from the Indian Ocean and western Pacific region from October 2011 through March 2012 through the following coordinated efforts:

- AMIE (Atmospheric Radiation Measurement [ARM] MJO Investigation Experiment) on the Addu Atoll (Maldives) and the ARM Facility's Manus Island site (Papua New Guinea);
- CINDY2011 (Cooperative Indian Ocean Experiment on Intraseasonal Variability in the Year 2011);
- DYNAMO (Dynamics of the MJO); and LASP (Littoral Air-Sea Process), in the Indian Ocean area; and
- HARIMAU (Hydrometeorological Array for Intraseasonal Variability-Monsoon Automonitoring), throughout the maritime continent.

Figure 1 shows the various sites involved in the coordinated campaign. The rich set of observations from these efforts will be used for many years to study the physics of the MJO. One hypothesis is that heating and moistening provided by the distribution of cloud types (cirrus, stratocumulus, etc.)—or cloud populations—at different stages of the MJO is essential to its initiation and evolution. Therefore, one major thrust of the campaign was to document the cloud populations and their properties as a function of MJO onset, as well as the pre- and post-onset periods of the MJO in the Indian Ocean. To date, several teams of researchers have gleaned results from the various radar observations during the campaign.

Radar data have been used for documenting the cloud populations (Powell and Houze 2013) and the evolution of precipitating systems (Zuluaga and Houze 2014) by MJO state—pre-onset, onset, and post-onset. These three MJO states are illustrated in Figure 2. Rowe and Houze (2014) used data from the scanning precipitation radars to determine microphysical characteristics of precipitating convection. Feng et al (2014) have produced combined radar products, leading to profiles of macrophysics and radiative heating rate profiles submitted as PI Products to the ARM Archive. Hagos et al. (2014) are using the combined radar product with sonde data and a cloud permitting model to test hypotheses related to the processes of mid-level moistening on MJO scales for initiation.

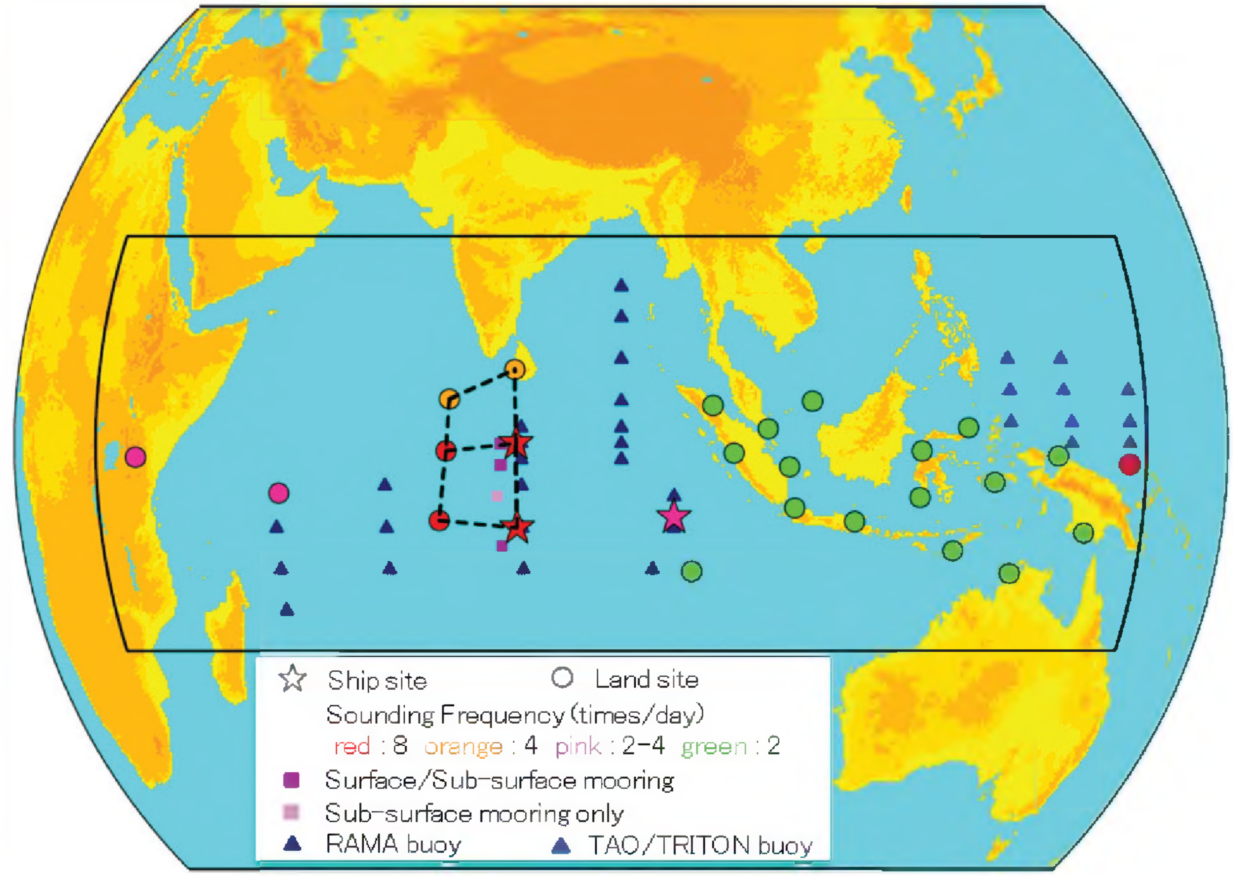

Figure 1. Observation network for the international field campaign. Dashed lines indicate the intensive southern/northern sounding arrays, which consist of Addu Atoll and Male, Maldives; Diego Garcia Island; Colombo, Sri Lanka; and two ship sites at 0°, 80.5°E and 8°S, 80.5°E. Shapes (diamond, circle, square, and triangle) indicate platform types, while radiosonde sounding frequencies during standard operating procedure (SOP) are expressed with different colors. In addition to these sounding sites, routine sounding data, which were sent via Global Telecommunications System (GTS), and data taken by other collaborative campaigns such as HARIMAU2011, are also incorporated into the campaign (not plotted).

Additional researchers have developed novel new retrievals using the ARM zenith radar data to classify convective or stratiform rain and estimate rain rate (Deng et al. 2014, Chandra et al. 2014). Others are using the zenith radar data to investigate shallow convection at Manus Island (Zermeno et al. 2014) and adding cloud-resolving models to study the relationship of clouds to heat and moisture budgets (Janiga et al. 2014).

One potent observational data set of which AMIE data form a key element is the atmospheric profiles from the many sonde sites (Ciesielski et al. 2014, Hungjui et al. 2014). These sounding array data have been used to illustrate the large-scale atmospheric conditions during the observed MJO cycles and to study specific processes related to MJO initiation. Johnson and Ciesielski (2013) find the rainfall maximum is characterized by east-west bands north and south of the Equator during the inactive phase of the MJO, switching to a single rainfall maximum on the Equator during the active phases.

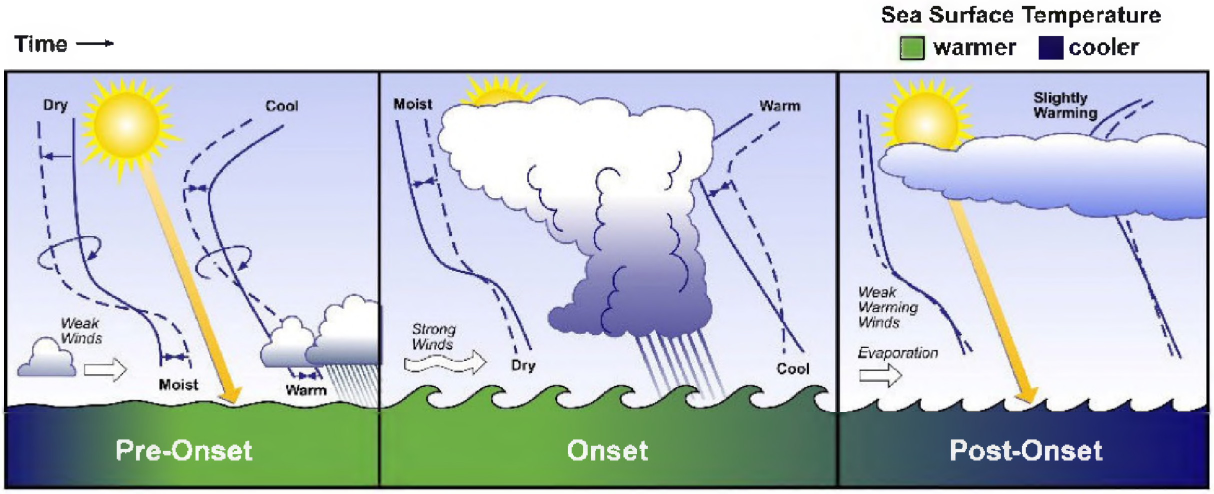

Figure 2. As shown in this illustration, the MJO lifecycle includes (A) pre-onset, (B) onset, and (C) post-onset phases, with warming sea-surface temperature (SST) during the onset period, and cooling SST in the post-onset phase.

Judt and Chen (2014) investigated an unusually large, explosive, mesoscale convective cloud system observed over the equatorial Indian Ocean during the initiation of a strong MJO event; Kerns and Chen (2014) found that a synoptic-scale dry-air intrusion played a key role in the evolution of this MJO occurrence. Powell and Houze (2014) are studying the relationship between upper tropospheric wind and temperature anomalies and MJO convective onset, again using the sounding data.

Most results to date naturally tend to be based on analyses of observations gathered during the campaign. But like the Hagos et al. (2014) efforts noted above, the testing and improvement of model representation of the MJO is gaining momentum. Already Ling et al. (2014) are using the data to test the forecast skill of the European Centre for Medium-Range Weather Forecasts (ECMWF) model. The observational data now available are a unique and powerful record that will increase our understanding of this phenomenon and improve the ability of computer models to realistically simulate the observed MJO initiation and propagation characteristics.

2.0 Notable Events or Highlights

The coordinated field campaigns captured six distinct MJO cycles in the Indian Ocean (Yoneymaya et al. 2013). Three of the MJO cycles were observed during the 3.5 month intensive operational period (IOP) at the start of the campaign, which combined measurements from research ships in the Indian Ocean, a sounding array, a radar supersite on Addu Atoll, and the Manus Island fixed-site observations. The first four identified MJO events are depicted in Figure 3 in both time-longitude diagram of infrared radiation brightness temperature and Wheeler and Hendon (2004) MJO index in the inset. A La Niña event took place in the Pacific, reaching its peak during November 2011-February 2012, with Nino 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 Figure 3 of Gottschalck et al. 2013) suggest that conditions in the central equatorial Indian Ocean were favorable for convective development during the IOP.

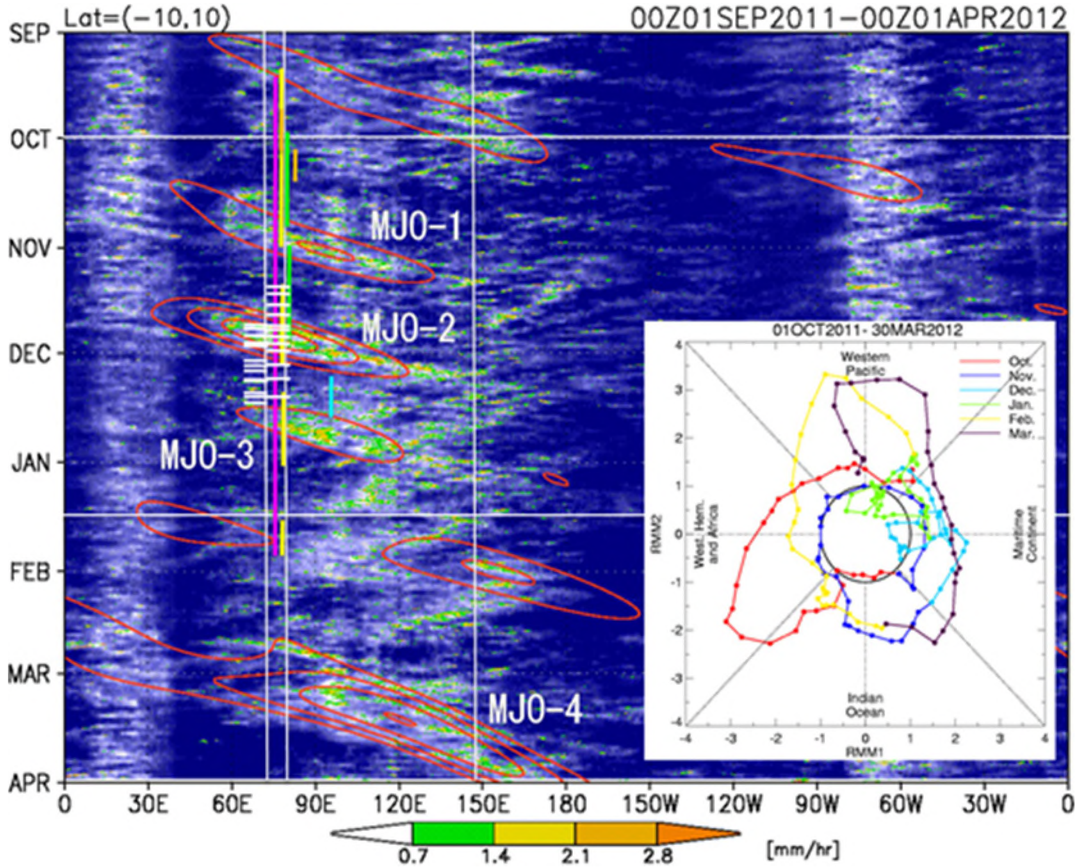

Figure 3. Time-longitude diagram of infrared radiation brightness temperature (white shading) and precipitation (color shading) along the Equator averaged over 10°S-10°N. Red contours indicate convective MJO signals based on the Wheeler and Weickmann (2001) method applied to OLR, with only negative contours plotted (interval 10 Wm-2). Vertical lines indicate the time of observations by ships (yellow for Revelle, orange for Sagar Kanya, green for Mirai, and blue for Baruna Jaya) and moorings (pink); horizontal white bars indicate the time of aircraft observations (left for Falcon-20, right for WP-3D). The Wheeler and Hendon (2004) MJO index is shown in the inset for the period of 1 October 2011-30 March 2012, with dots and color indicating days and months, respectively.

These MJO events spanned a range of larger-scale atmospheric and oceanic conditions, allowing investigation of several scientific issues pertaining to scientific understanding of the MJO, or lack thereof. These issues include the roles of planetary waves in MJO convective initiation, decoupling of convection-circulation on the MJO scale, applications of different methods for identifying and filtering the MJO signal in observations and model simulations, and ocean-atmosphere coupling (Gottschalck et al. 2013). While these convective events unambiguously moved from the Indian Ocean 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 counter-clockwise (red and dark blue lines in the inset of Figure 3), or MJO spectral filtering (Wheeler and Weickmann 2001) applied to outgoing longwave radiation (OLR; Figure 3).

Relative humidity profiles at Manus Island 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 fourth MJO event migration into the western Pacific (Figure 3).

A radar "super site" was established on the Addu Atoll, along with the ARM Mobile facility as shown in Figure 4. An example of the observations from the super radar site at Addu Atoll is shown in Figure 5. The same cloud system was observed simultaneously by the three radars on November 27, 2011. The Ka-band ARM Zenith Radar (KAZR) recorded the evolution of shallow cloud bracketed by deep and anvil clouds through the day.

The Shared Mobile Atmospheric Research and Teaching Radar (SMART-R) and Ka S-band and Ka-band polarization Doppler radar (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 deep cloud.

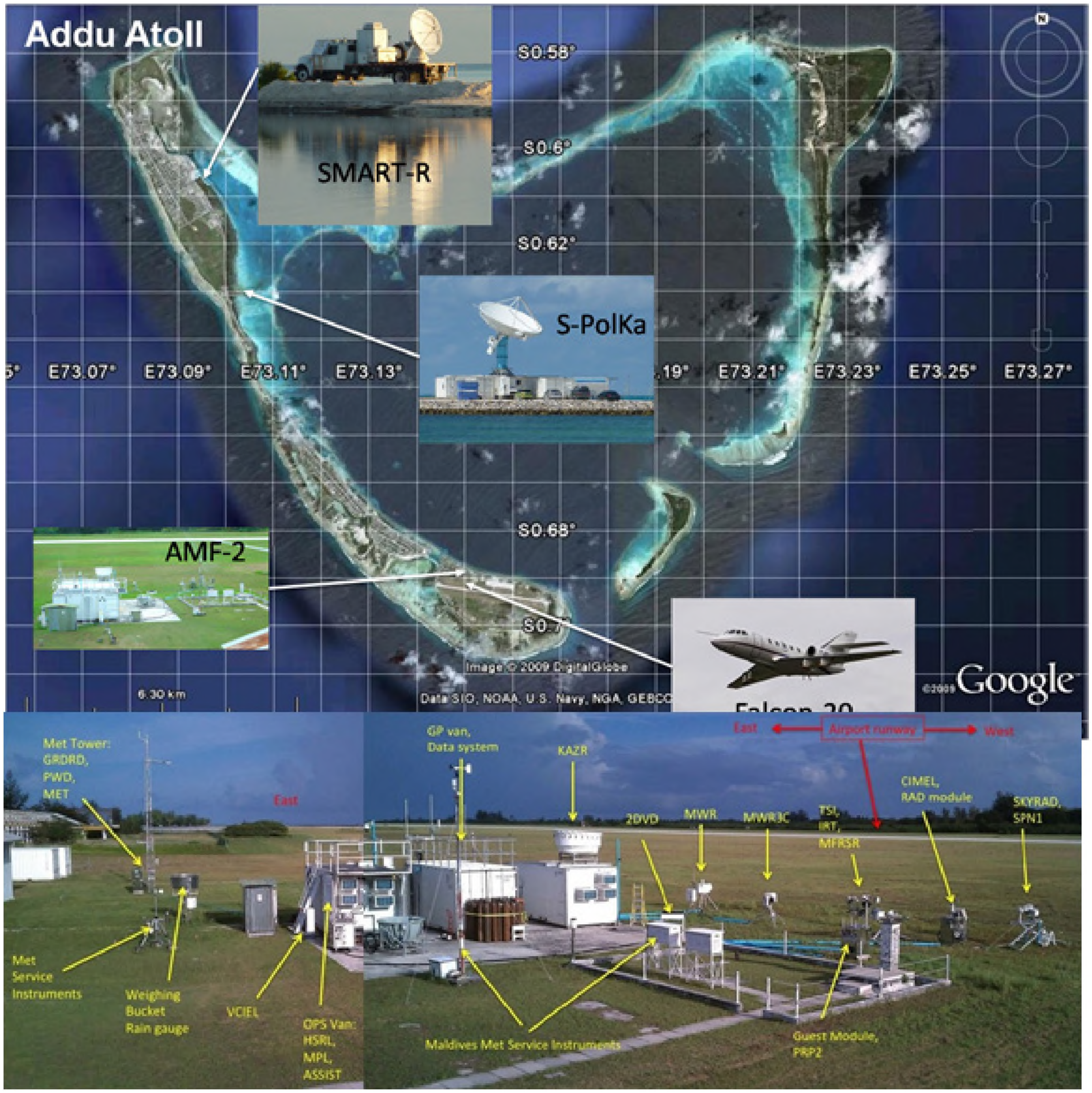

Figure 4. A super radar site was established on Addu Atoll, Maldives. (top) Locations of three radar sites and an aircraft base. (bottom) AMF-2 deployed at the Gan airport.

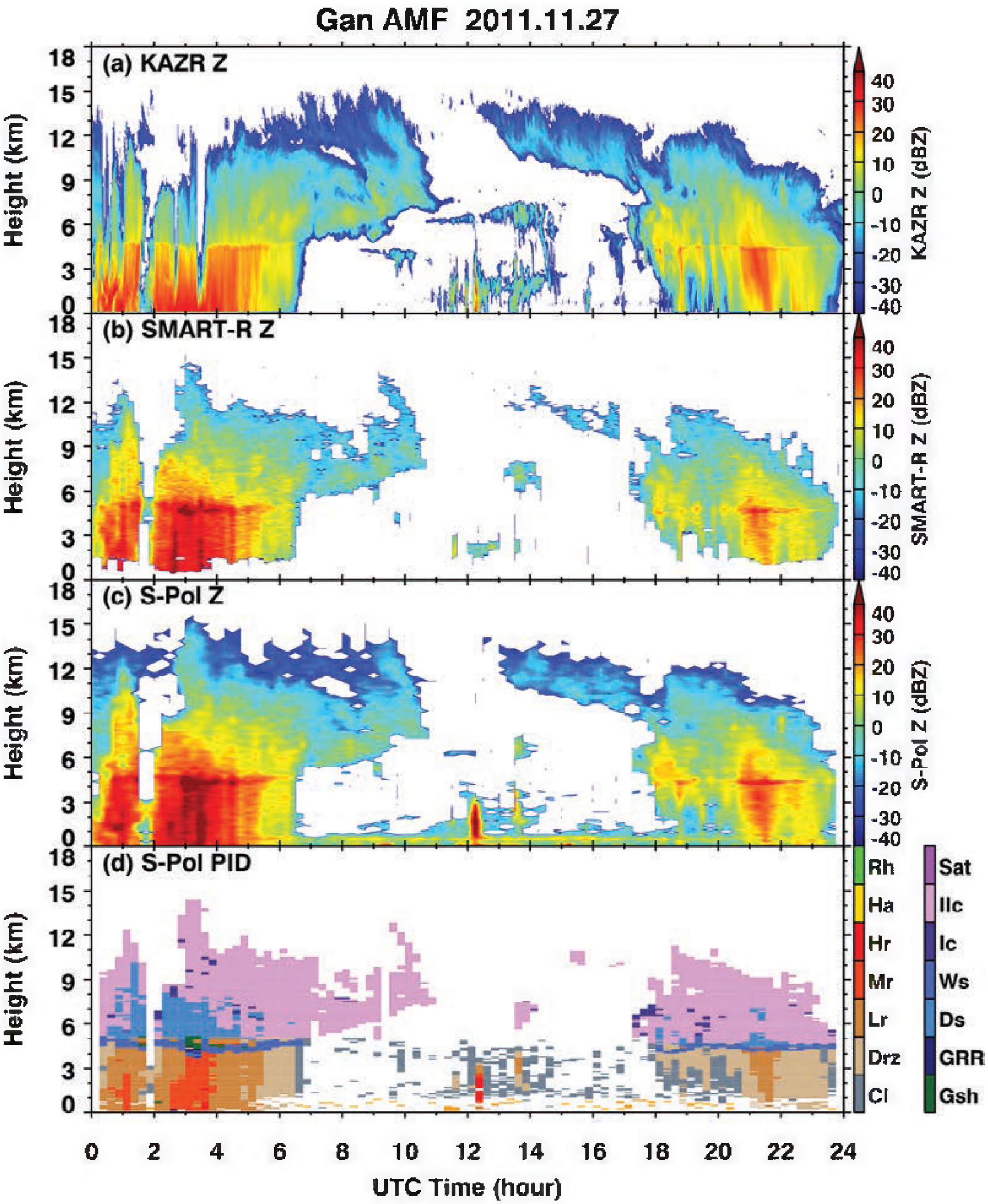

Figure 5. Time series of vertical profiles of (a) reflectivity of KAZR; RHI reflectivity of (b) SMART - R and (c) S-PolKa over KAZR; and (d) RHI hydrometeor identification of S-PolKa over KAZR on 27 November, 2011. (Courtesy of Zhe Feng. Pacific Northwest National Laboratory.)

One of the most notable events impacting the campaign had nothing to do with atmospheric science or the MJO, but rather with local politics. Due to sudden unrest in the Maldives in early February, operations of the ARM Mobile Facility on Gan Island were suspended on February 9, 2012, and all instruments were secured and powered down. The sometimes volatile unrest eventually led to the resignation of the President in disputed circumstances. The AMF team enjoyed excellent relationships with the community on Gan and did not experience any negative treatment during their stay. Unfortunately, the unrest endured long enough that we decided to end the campaign early and bring the equipment out.

3.0 Lessons Learned

Several overarching issues were experienced for the campaign. First, great appreciation and thanks are due to both the Manus and Gan sonde launching teams. Launching 8 sondes per day around the clock, one every 4 hours, is a grueling schedule for even a short-term, 1-month campaign. But the ambitious schedule of doing so for the entire 6 months of the campaign is exceptionally difficult and taxing. The Gan crew ended their activities after 4 months due to the civil unrest, but the Manus crew accomplished the entire 6 months with almost a 95% success rate with no relaunches. The Gan crew, with relaunches when needed, achieved an even higher success rate. This is simply an incredible accomplishment, by both crews.

One disappointing issue involved important, and in some cases critical, instrumentation arriving and/or becoming operational late or not at all. One example is the vertical wind profiler, a significant addition to characterizing the boundary-layer wind flows and their relationship to convection. Another instrument that suffered a late start was the High Spectral Resolution Lidar (HSRL), which arrived with the optics knocked out of alignment An instrument engineer arrived and eventually got it operational again.

Several critical instruments never did produce much, if any, usable data. One was the marine AERI version that was deployed. Some consider the data seriously questionable and likely not usable. These data were depended upon to run various AERI-type retrievals for water vapor, cloud properties, and the like. But the most critical loss was in relation to the scanning X and Ka band radars. The primary purpose for the "radar super site" on Addu Atoll was to document the cloud populations. While the C-band SMART-R and the S-band S-PolKa radar did manage to detect a significant portion of the clouds, and the vertically pointing ARM KAZR worked very well, the loss of the Ka-SACR and X-SACR radars severely handicapped what the campaign could have accomplished.

Nevertheless, this field campaign did produce many papers and studies, a sampling of which are listed below. These would not have been possible without significant successful observations. Hopefully the "lessons learned" from this maiden foreign deployment of the AMF2 will help to ensure more success in the future.

4.0 Results

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 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 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 Indian Ocean with continuous time series of atmospheric and upper-ocean profiles. It is the first time the entire cloud population ranging from shallow non-precipitating 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 intertropical convergence zone [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 post-field-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.

5.0 Public Outreach

Campaign web address: http://campaign.arm.gov/amie/

Campaign ARM press releases and links to media coverage: http://campaign.arm.gov/amie/news.php

6.0 AMIE-Gan Publications

6.1 Journal Articles/Manuscripts

6.1.1 Published

Barnes, HC, and RA Houze. 2013. “The precipitating cloud population of the Madden-Julian Oscillation over the Indian and west Pacific Oceans.” *Journal of Geophysical Research–Atmospheres* 118(13): 6996-7023, doi:10.1002/jgrd.50375.

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6.1.2 Submitted or in Preparation

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6.3 Meeting Abstracts/Presentations/Posters

Sessions at several conferences have been held with their attendant oral and poster presentations, and online access to abstracts. These sessions include:

2012 AGU Fall Meeting–Atmospheric and Oceanic Variability Associated With the MJO in the Tropical Indian and Western Pacific Oceans

2012 AMS 30th Conference on Hurricanes and Tropical Meteorology–Dynamo/CINDY2011

2013 AGU Fall Meeting–The Madden-Julian Oscillation: Its Initiation, Identification, and Structure

2014 AGU Fall Meeting–Madden-Julian Oscillation: Observations, Modeling, and Prediction

2014 AMS 31st Conference on Hurricanes and Tropical Meteorology–Dynamo/CINDY2011

2014 Asia Oceania Geosciences Society (AOGS) 11th Annual Meeting–Diurnal-to-intraseasonal variability over the tropical Indian Ocean and adjacent regions

2014 Asia Oceania Geosciences Society (AOGS) 11th Annual Meeting–Climate and weather over the Maritime Continent

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