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ARM MJO Investigation Experiment on Gan Island (AMIE-Gan) Science Plan

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Abstract

The overarching campaign, which includes the ARM Mobile Facility 2 (AMF2) deployment in conjunction with the Dynamics of the Madden-Julian Oscillation (DYNAMO) and the Cooperative Indian Ocean experiment on intraseasonal variability in the Year 2011 (CINDY2011) campaigns, is designed to test several current hypotheses regarding the mechanisms responsible for Madden-Julian Oscillation (MJO) initiation and propagation in the Indian Ocean area. The synergy between the proposed AMF2 deployment with DYNAMO/CINDY2011, and the corresponding funded experiment on Manus, combine for an overarching ARM MJO Investigation Experiment (AMIE) with two components: AMF2 on Gan Island in the Indian Ocean (AMIE-Gan), where the MJO initiates and starts its eastward propagation; and the ARM Manus site (AMIE-Manus), which is in the general area where the MJO usually starts to weaken in climate models. AMIE-Gan will provide measurements of particular interest to Atmospheric System Research (ASR) researchers relevant to improving the representation of MJO initiation in climate models. The framework of DYNAMO/CINDY2011 includes two proposed island-based sites and two ship-based locations forming a square pattern with sonde profiles and scanning precipitation and cloud radars at both island and ship sites. These data will be used to produce a Variational Analysis data set coinciding with the one produced for AMIE-Manus. The synergy between AMIE-Manus and AMIE-Gan will allow studies of the initiation, propagation, and evolution of the convective cloud population within the framework of the MJO. As with AMIE-Manus, AMIE-Gan/DYNAMO also includes a significant modeling component geared toward improving the representation of MJO initiation and propagation in climate and forecast models.

This campaign involves the deployment of the second, marine-capable, AMF; all of the included measurement systems; and especially the scanning and vertically pointing radars. The campaign will include sonde launches at a rate of eight per day for the duration of the deployment. The increased sonde launches for the entire period matches that of the AMIE-Manus campaign and makes possible a far more robust Variational Analysis forcing data set product for the entire campaign, and thus better capabilities for modeling studies and synergistic research using the data from both AMIE sites.

Summary

There is no agreed-upon explanation for the underlying physics that initiate and maintain the MJO. Many climate models do not show well-defined MJO signals, and those that do have problems accurately simulating the initiation, amplitude, propagation speed, and seasonal variations of the MJO signal. Since the MJO is the dominant mode of intraseasonal variability in the tropics, and it interacts with both the monsoon and El Niño, improved simulations are important for climate modeling. Therefore, the MJO is a very important modeling target for the ASR modeling community, geared specifically toward improving climate models. The AMIE-Gan operations period coincides with the timing of the already funded AMIE-Manus campaign. The AMIE-Gan and AMIE-Manus observations will also complement the long-term MJO statistics produced using the ARM Manus and Darwin site data and will allow testing of several of the current hypotheses related to the MJO phenomenon. The unique ARM instrumentation and corresponding deployment for AMIE-Gan and AMIE-Manus will support a systematic analysis of the life cycle of the MJO, which has not been fully understood due to lack of continuous 3D spatially resolved observations.

Several hypotheses regarding the MJO were outlined in the AMIE-Manus proposal, and these are relevant to the AMIE-Gan campaign as well. However in the interests of brevity, we will not repeat them here, but rather concentrate on the additional hypotheses regarding MJO initiation targeted by AMIE-Gan/DYNAMO. AMIE-Gan/DYNAMO hypotheses focus on three key aspects of MJO initiations: (1) interaction between environmental moisture and convection, (2) the dynamic evolution of the cloud population, and (3) air-sea interaction. AMIE-Gan/DYNAMO will particularly target processes deemed critical to MJO initiation but poorly observed and understood: shallow cloud moistening, convective sensitivity to environmental moisture, low-level versus upper-level diabatic heating, cloud microphysics, convective organization, large-scale moisture advection and convergence, surface evaporation, planetary-boundary-layer entrainment, the ocean barrier layer, and upper-ocean mixing and entrainment, among others. Inadequate representations of these processes in numerical models may inhibit accurate simulation and prediction of MJO initiation. A better understanding of these processes is essential for improving their representations in numerical models. Three major hypotheses regarding MJO initiation will be tested as part of AMIE-Gan/DYNAMO:

Hypothesis 1: Deep convection can be organized into an MJO convective envelope only when the 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 state.

Hypothesis 2: Specific convective populations at different stages are essential to MJO initiation.

Hypothesis 3: The barrier layer, wind- and shear-driven mixing, shallow thermocline, and mixing-layer entrainment all play essential roles in MJO initiation in the Indian Ocean by controlling the upper-ocean heat content and sea surface temperature (SST), and thereby surface flux feedback.

The supersite on Gan, of which AMF2 and its variety of instrumentation is the central, critical component (see Section 3.1), will primarily collect data applicable to testing Hypotheses 1 and 2, but will also contribute to testing Hypothesis III. Other funding organizations for DYNAMO/CINDY2011 include:

- Japan Agency for Marine-Earth Science and Technology (JAMSTEC)
- the National Science Foundation (NSF)
- the Office of Naval Research (ONR)
- the National Oceanic and Atmospheric Administration (NOAA)
- the National Aeronautics and Space Administration (NASA)
- Indian National Institute of Oceanography
- the Centre for Australian Weather and Climate Research (CAWCR).

As noted in the AMIE-Manus Science Plan, given the large international effort and required organization involved, a coordinated MJO experiment like AMIE/DYNAMO/CINDY2011 is an opportunity that will likely not reoccur for at least a decade or more.

The AMF2 will be deployed in conjunction with other instruments supplied by numerous international and national research organizations as part of the overarching CINDY2011 and DYNAMO field campaigns. The island site on Gan in the Maldives will be outfitted as a radar "supersite" for the documentation of the entire size range of hydrometeors and convective clouds from small cumulus through precipitating deep convection. This will be accomplished through deploying radars covering a range of frequencies including the AMF2 scanning Ka- and X-band, vertically pointing W-band (and micropulse lidar), the SMART-R scanning C-band, and the S-PolKa scanning S- and Ka-band radars. The objective of the AMIE-Gan/DYNAMO radar observations is to fully characterize the ensemble of convection associated with each stage of MJO initiation, observing the full spectrum of convective clouds, described by as many variables as possible, for example:

- areas and heights of radar echoes
- types and concentrations of hydrometeors
- air motions internal to clouds
- cloud and precipitation element movement
- separation of precipitating and non-precipitating components of clouds
- subdivision of precipitating clouds into convective and stratiform components
- structure and organization of cloud ensembles
- effect of clouds on environmental moisture through detrainment and rain evaporation
- propagation characteristics.

The AMF scanning and vertically pointing cloud radars are critical to comprehensively observing the complete ensemble of cloud types.

Gan Island is well-situated for these observational goals; it is located within the region where the convective population of the MJO initiates. At Gan, precipitation varies by a factor of four from convectively inactive phases of the MJO to convectively active phases. In comparison, at Diego Garcia (south of Gan), the variability of precipitation through the MJO life cycle is much smaller, even though its mean precipitation is larger. Precipitation at Male, to the north of Gan, also varies substantially with MJO phases, but it undergoes a strong seasonal cycle and becomes very weak during the later months of the proposed campaign period. The variability in precipitation is an indication that the Gan location should experience the entire range of cloudiness scenarios that the supersite concept is aimed at documenting.

Gan Island also supports a significant power and communications infrastructure that lends itself well to an AMF2 deployment. Mirai Indian Ocean cruise for the Study of the MJO-convection Onset (MISMO), which took place in the central Indian Ocean from late October to early December 2006, fielded a scanning X-band radar and other instruments on Gan. While deploying the number of radars envisioned for the Gan supersite, as well as the AMF2 instrumentation, does pose challenges, there are no known issues that preclude the feasibility of an AMF2 deployment. A coordinated visit to Gan at the end of February 2010 included scouting sites for the various radars and the AMF2, as well as meeting with local officials. Participants in the visit included representatives of JAMSTEC, NOAA, the National Center for Atmospheric Research (NCAR), and the ARM Tropical Western Pacific (TWP) Site Scientist Office. The infrastructure and local support on Gan was found to be well suited for deploying and operating the AMF and other scanning radars, and a scouting report including local government and business contact information is included in an appendix to this document.

Acronyms and Abbreviations

1D	one-dimensional
AERI	atmospheric emitted radiance interferometer
AERIPROF	AERI Profiles of Water Vapor and Temperature
AMF2	ARM Mobile Facility 2
AMIE	ARM MJO Investigation Experiment
AMIE-Gan	ARM MJO Investigation Experiment on Gan Island
AMIE-Manus	ARM MJO Investigation Experiment at the ARM TWP Manus site
AOD	aerosol optical depth
ARM	Atmospheric Radiation Measurement Climate Research Facility
ARSCL	Active Remotely Sensed Cloud Locations
ASR	Atmospheric System Research
CAWCR	Centre for Australian Weather and Climate Research
CINDY2011	Cooperative Indian Ocean experiment on intraseasonal variability in the Year 2011
CPC	Climate Prediction Center
CRM	cloud-resolving model
CSRM	cloud-system-resolving models
DSD	drop size distribution
DYNAMO	Dynamics of the Madden-Julian Oscillation
ECMWF	European Centre for Medium-Range Weather Forecasts
EOL	Earth Observing Laboratory
EOP	Extended Observing Period
GATE	GARP Atlantic Tropical Experiment
GCM	global climate model
GndRad	ground radiation measurements
HARIMAU	Hydrometeorological Array for ISV-Monsoon Automonitoring
HSRL	high spectral resolution lidar
IndOOS	Indian Ocean Observing System
IOP	Intensive Observing Period
ITCZ	intertropical convergence zone
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
MFRSR	multifilter rotating shadowband radiometer
MFRSRCLDOD1MIN	Cloud Optical Properties from MFRSR Using Min Algorithm
MISMO	Mirai Indian Ocean cruise for the Study of the MJO-convection Onset
MJO	Madden-Julian Oscillation

MMS	Maldives Meteorological Service
MPL	micropulse lidar
MPRCOD	Micropulse Lidar Cloud Optical Depth
MWR	microwave radiometer
MWRRET	MWR Retrievals
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NFOV	narrow field-of-view radiometer
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
ONR	Office of Naval Research
QCRAD	Data Quality Assessment for ARM Radiation Data
R/V	Research Vessel
RAMA	Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction
SCM	single-column model
SCTR	Seychelles-Chagos thermocline ridge
SGP	Southern Great Plains
SkyRad	sky radiation measurements
SMET	surface meteorological measurements
SONDE	Balloon-borne sounding system
SOP	Special Observing Period
SST	sea surface temperature
TOGA COARE	Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment
TWP	Tropical Western Pacific
UNOLS	University-National Oceanographic Laboratory System
USAID	United States Agency for International Development
VAP	value-added product
VCEIL	Vaisala ceilometer
WACR	W-band ARM cloud radar

Contents

Figures

1.0 Introduction

The Madden-Julian Oscillation (MJO, Madden and Julian 1971, 1972) dominates tropical intraseasonal (20 – 100 days) variability. As it propagates eastward from the Indian Ocean to the western and central Pacific during the boreal winter (Figure 1), the MJO interacts with many weather and climate systems. It modulates tropical cyclone activity in all ocean basins, including that near the Americas (Liebmann et al. 1994, Maloney and Hartmann 2000, Hall et al. 2001, Frank and Roundy 2006, Camargo et al. 2009). It affects the onset and intraseasonal fluctuations of the monsoons and rainfall over Asia (Annamalai and Slingo 2001), Australia (Hendon and Liebmann 1990), the Americas (Higgins and Shi 2001, Lorenz and Hartmann 2001), and Africa (Pohl et al. 2007, Maloney and Shaman 2008). As a source of stochastic forcing, the MJO influences the onset, intensification, and irregularity of the El Niño Southern Oscillation (ENSO) (Kessler et al. 1995, Moore and Kleeman 1999, Zavala-Gary et al. 2005, Wu et al. 2007, Neale et al. 2008). Convective centers of the MJO excite teleconnection patterns that emanate into the extratropics (Higgins and Mo 1997) and thereby induce remote fluctuations in rainfall and temperature (Bond and Vecchi 2003), such as torrential rain events along the U.S. West Coast (Jones 2000). The MJO also interacts with the North Atlantic Oscillation (Lin et al. 2009), Arctic Oscillation (Zhou and Miller 2005), Antarctic Oscillation (Carvalho et al. 2005, L'Heureax and Higgins 2008), Indian Ocean Dipole (Han et al. 2006), the Wyrtki Jets (Masumoto et al. 2005), and the Indonesian Throughflow (Waliser et al. 2003, 2004). It contributes to the seasonal meridional heat transport of the Indian Ocean (Loschnigg and Webster 2000) and causes intraseasonal perturbations in atmospheric ozone, carbon monoxide, and aerosols (Tian et al. 2007, 2008; Wong and Dessler 2007) and in ocean chlorophyll (Waliser et al. 2005).

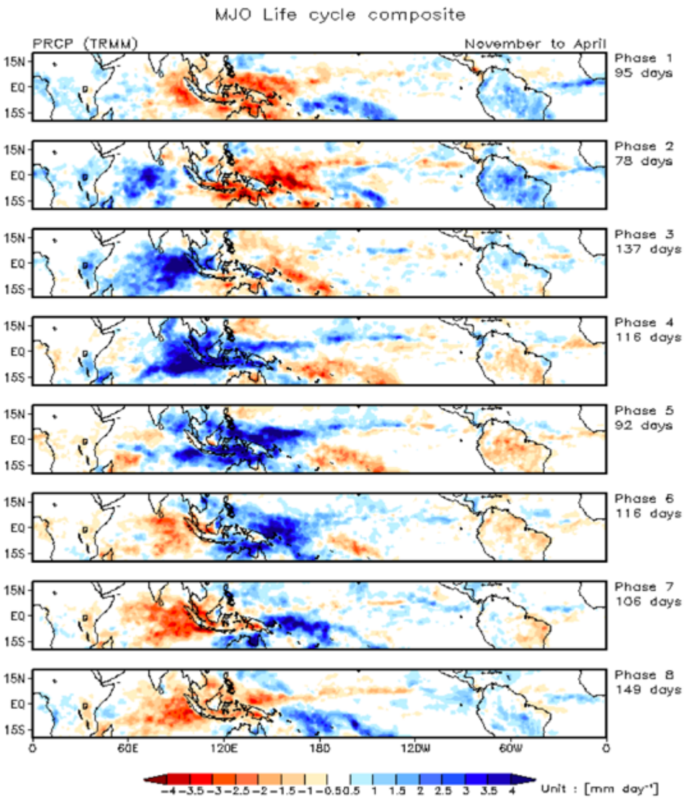

Figure 1. Composite MJO precipitation anomalies in eight phases (figure courtesy of US CLIVAR).

Because of the important roles of the MJO in weather and climate, society increasingly demands its accurate prediction. MJO forecasts are currently issued by NOAA, National Centers for Environmental Prediction (NCEP), and Climate Prediction Center (CPC), with input from other NOAA institutions and a number of operational centers around the world. These forecasts reach a wide range of end users (Gottschalck et al. 2009), including emergency response organizations (e.g., American and International Red Cross), U.S. government (e.g., the United States Agency for International Development [USAID], Forest Service, National Marine Fisheries Service, River Forecast Centers), and private industry (e.g., American Electric Power, Earth Satellite Corporation, Moore Capital Management). The capability to accurately forecast the MJO is also the keystone of a seamless weather-climate prediction system (Brunet et al. 2009, Shapiro et al. 2009).

Current prediction of the MJO, however, suffers from very low skill (Figure 2), particularly during its initiation over the Indian Ocean (Phase 2) and when it is about to propagate across the Maritime Continent (Phase 4). This happens in both coupled and atmosphere-only models (Kim et al. 2009b). Meanwhile, state-of-art global climate models either underestimate the strength of the MJO over the Indian Ocean (Zhang et al. 2006, Benedict and Randall 2009) or are unable to reproduce any salient feature of the MJO at all (Lin et al. 2006). The representation of cumulus convection is believed to be the primary limiting factor in MJO simulation and prediction. Poor simulations of the MJO in climate models expose deficiencies in their cumulus parameterizations and therefore lessen our confidence in their ability to project future climate. Particularly because of the close connections between the MJO and extreme events mentioned above, the inability of climate models to simulate the MJO and its potential response to climate change seriously limits the application of these models to predict the statistics of extreme events in the future.

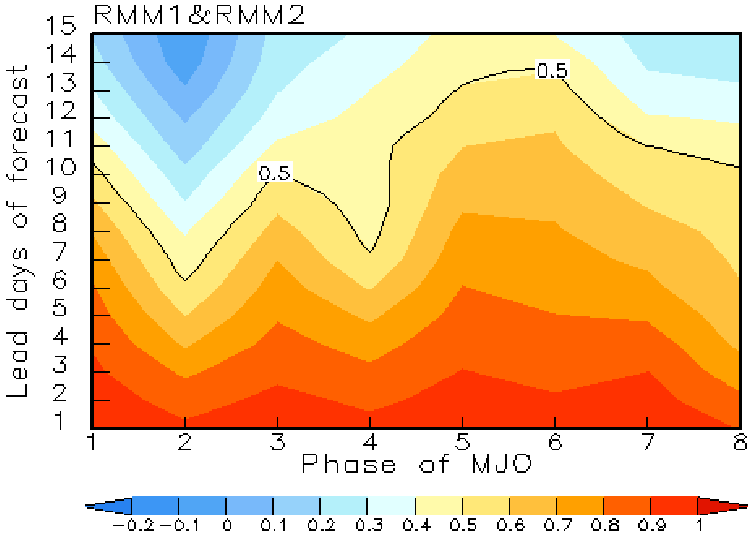

Figure 2. Correlation between observed Wheeler and Hendon (2004) MJO index and its prediction by the NCEP Global Forecast System (GFS). (Courtesy of Jon Gottschalck and Qin Zhang)

Substantial improvement in MJO simulation has been shown by new capabilities in global cloud-system-resolving models (CSRM) (Miura et al. 2007) and cloud-resolving convection parameterization (Grabowski 2001, Benedict and Randall 2009, Khairoutdinov et al. 2008). Since these new generations of models are still in their experimental stages, their representations of convection need to be carefully evaluated against observations, and their direct applications to global weather and climate prediction will not become practical soon. In the near term, and most likely in the foreseeable future, models with parameterized convection will be essential components of our global prediction arsenal. Improved simulations of the MJO will continue to serve as a benchmark of the advancement and development of model cumulus parameterizations.

Development and improvement of physical parameterizations in weather and climate models have greatly benefited from observations of past field campaigns in the tropics (e.g., GARP Atlantic Tropical Experiment [GATE], Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment [TOGA COARE]). The astonishing lack of such in situ observations in the region of the tropical Indian Ocean has impeded progress on understanding atmospheric and oceanic physical processes related to weather and climate in that region, including those associated with MJO initiation. A field campaign in the tropical Indian Ocean region is urgently needed (ICTP, 2006).

An international field program, CINDY2011 will take place in the equatorial central Indian Ocean in late 2011–early 2012 to collect in situ observations for the purpose of advancing our understanding of MJO initiation processes and improving MJO prediction. DYNAMO is the U.S. component of CINDY2011, with AMIE-Gan playing a crucial role. This international collaboration and program synergy will provide integrated and complementary observations of MJO events at different stages of their life cycle. The timing of late 2011–early 2012 is critical for AMIE-Gan/DYNAMO to be an integrated part of the multi-national coordinated efforts and to maximize the value of its observational products.

2.0 Scientific Problems and Hypotheses

2.1 Nature of the Problem

Examples of MJO events in Figure 3 illustrate several types of MJO initiation. Some of them are easy to identify (e.g., in November and February). Others are mixed with various types of variability (e.g., in August and September–October), but their tendency toward eastward propagation (as marked by white lines) is discernable. They all begin over the western Indian Ocean and exhibit several stages of initiation.

In most cases, MJO convection is initiated without upstream (west) convective precursors, in sharp contrast to that over the western Pacific. In some cases (e.g., May), weak convective systems emanate from Africa and amplify into an MJO event. Prior to MJO convective onset, there can be a prolonged period (> 30 days) with little convective activity (e.g., in November) or with various types of synoptic-scale convectively coupled perturbations (Kelvin waves, mixed Rossby-gravity waves, e.g., in February). These periods immediately prior to the onset of MJO convection will be referred to as *inactive* and *active pre-onset stages*, respectively. There is a quick transition featuring convective aggregation into a convective center or envelope on the MJO scale. (In this document, “MJO scale” refers to spatial scales of 1000–10,000 km in longitude and 1000 km in latitude, and temporal scales of 30–90 days that are specifically associated with the MJO. “Large scale” refers to comparable spatial scales that may not be associated with the MJO.) After the transition, the establishment of a convectively active phase of the MJO is marked by sustained deep convection in the MJO convective envelope (onset stage) that begins to move slowly eastward (~ 5 m/s). In most cases, the onset stage is terminated sharply and replaced by a suppressed or inactive phase (post-onset stage).

All three stages are essential elements of MJO initiation and raise several fundamental questions:

- What determines the timescales of the prolonged inactive pre-onset stage and the sustained onset stage?
- How does the transition from an inactive pre-onset to an onset stage start, and how does an onset stage terminate?
- Why are synoptic and mesoscale convective systems randomly distributed during an active pre-onset stage but organized into an MJO envelope in the onset stage?
- Are there fundamental differences between MJO initiation with and without external influences from higher latitudes and upstream?

Currently, these questions cannot be adequately addressed because existing in situ observations of the MJO have come mainly from the western Pacific. TOGA COARE (Webster and Lukas 1992) captured three MJO events (Lin and Johnson 1996, Chen et al. 1996) and their associated mesoscale convective systems (Rickenbach and Rutledge 1998; Kingsmill and Houze 1999a, b; Houze et al. 2000). In addition, the long record of the TAO mooring array provides MJO statistics at the surface and in the upper ocean across the equatorial Pacific (Zhang and McPhaden 2000, Roundy and Kiladis 2006, Araligidad and Maloney 2008). The ARM TWP sites at Manus, Nauru, and Darwin have also provided long-term observations for the study of the MJO (Wang et al., 2010, Chen and Del Genio 2009), especially regarding cloud-radiation interactions (Mather et al. 2007). In contrast, there is a distinct lack of in situ observations of the intraseasonal variability in both atmosphere and ocean in the Indian Ocean region (Schott and McCreary 2001). Operational sounding launches from islands of the region are limited and decreasing with time. Satellite retrievals have rarely, if at all, been calibrated and validated by in situ observations from the Indian Ocean. The mooring array there (RAMA, McPhaden et al. 2009) has yet to be completed.

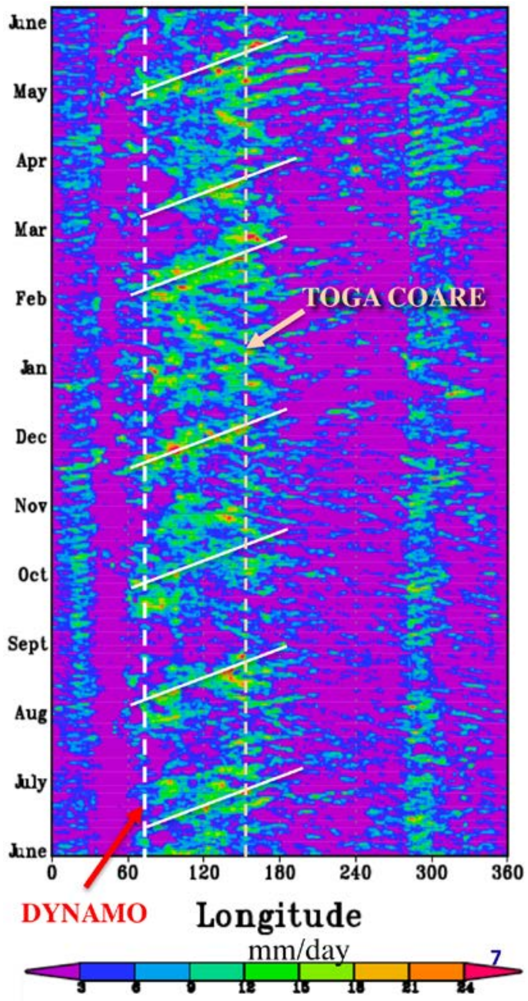

Figure 3. Time-longitude diagram of daily GPCP combined precipitation (Huffman et al. 1997) averaged over 10°S–10°N from June 2000 through May 2001. Solid lines, corresponding to eastward speed of 5 ms^{-1}, mark MJO events. The longitudes of TOGA COARE and DYNAMO are indicated by the dashed lines.

Satellite data and limited sounding observations indicate that the structure of the MJO varies in longitude from the Indian Ocean to the western Pacific (Kiladis et al. 2005), suggesting that our knowledge of the MJO over the western Pacific may not apply to the MJO over the Indian Ocean. This is so mainly for two reasons. First, the MJO is at different stages of its life cycle over the two oceans. A well-established large-scale circulation pattern (Wang and Rui 1990) is closely coupled with deep convection for the mature MJO propagating over the western Pacific, but it may not exist over the Indian Ocean where many MJO events are initiated. Second, the climatological environments of the two oceans are very different. Surrounded by landmasses on three sides, the Indian Ocean has many unique features. Its atmosphere is often characterized by basin-scale mean subsidence due to overturning circulations forced by deep convection over the adjacent land and the Walker circulation (Webster 1983). The seasonally varying surface wind over the Indian Ocean is part of the strongest monsoon system in the world. In sharp contrast, the mean ascending branch of the Walker circulation is located over the western Pacific, where mean surface wind is weak. The lack of mean equatorial surface easterly wind makes the Indian Ocean the only ocean without an equatorial cold tongue (Schott et al. 2009). Because of this, the Indian Ocean hosts the only marine intertropical convergence zone (ITCZ) that migrates seasonally across the equator between the two hemispheres (Zhang 2001). Over the Seychelles-Chagos thermocline ridge (SCTR), another unique feature of the Indian Ocean (Vialard et al. 2009), intraseasonal SST perturbations are extraordinarily large (~ 1–2K) (Harrison and Vecchi 2001, Saji et al 2006), suggesting that air-sea interaction processes during MJO initiation are more vigorous than in the western Pacific where the thermocline is much deeper and intraseasonal SST perturbations are generally weaker (≤ 1K). Upper-ocean mixing is an essential element in air-sea interaction. Its detailed vertical profiles in the equatorial Indian Ocean with unique shear structures related to the Wyrtki jets (Wyrtki 1973) have, however, never been systematically observed and analyzed. The same can be said of its atmospheric counterpart, turbulent mixing in the planetary boundary layer.

The overarching DYNAMO proposition is: The physical and dynamical processes key to MJO initiation are closely connected to the unique features of the tropical Indian Ocean; they must be adequately understood using local observations.

2.2 Current Knowledge on MJO Initiation

A large body of literature on the MJO (see reviews by Lau and Waliser 2005, Zhang 2005), has investigated the following mechanisms for MJO initiation:

1. Forcing by perturbations upstream (west) related to previous MJO events (Sperber 2003, Matthews 2008) or incoming Kelvin waves (Straub et al. 2006), or from the extratropics related to Rossby waves, cold surges, global wind oscillations and synoptic eddy momentum transport, etc. (Lau and Peng 1987, Hsu et al. 1990, Lin et al. 2007, Pan and Li 2007, Ray et al. 2009).
2. Evolution in the large-scale environment of atmospheric convection due to local changes in air-sea fluxes, upper-ocean heat content, moisture advection and convergence, cloud moistening, and radiative cooling, known as energy “recharge” in the MJO literature (Blade and Hartmann 1993, Hu and Randall 1994, Waliser 1996, Raymond 2000, Stephens et al. 2004, Sobel and Gildor 2003, Li et al. 2008, Zhang and Song 2009, Maloney et al. 2009).
3. Response of existing dynamical modes to tropical and extratropical stochastic processes (Salby and Garcia 1987, Yu and Neelin 1994).

These initiation mechanisms are not necessarily mutually exclusive. For example, it is possible that the role of external perturbations in (1) is to instigate local processes in (2) or to make them more effective. DYNAMO will concentrate on the local processes serving as necessary conditions for MJO initiation that must be met with or without external influences.

2.3 Hypotheses

To guide the discussion on MJO initiation processes, we propose a conceptual model (Figure 4) that highlights some of the fundamental aspects of MJO initiation included in the DYNAMO hypotheses. This model consists of the three stages introduced in Section 2.1. Stage A (left panels in Figure 4) corresponds to the pre-onset stage, which can be inactive (many non-precipitating shallow clouds and an increasing number of precipitating shallow clouds) or active (precipitating clouds may be organized into randomly scattered mesoscale or synoptic-scale systems). Atmospheric diabatic heating concentrates in the lower troposphere. SST and upper-ocean heat content gradually increase. As low-level moisture slowly increases due both to shallow cloud detrainment, rain evaporation, and moisture convergence, the column moist static energy is “recharged” (Hendon and Liebmann 1990, Blade and Hartmann 1993, Hu and Randall 1994). In consequence, the atmosphere is gradually destabilized (Sections 2.3.1 and 2.3.2).

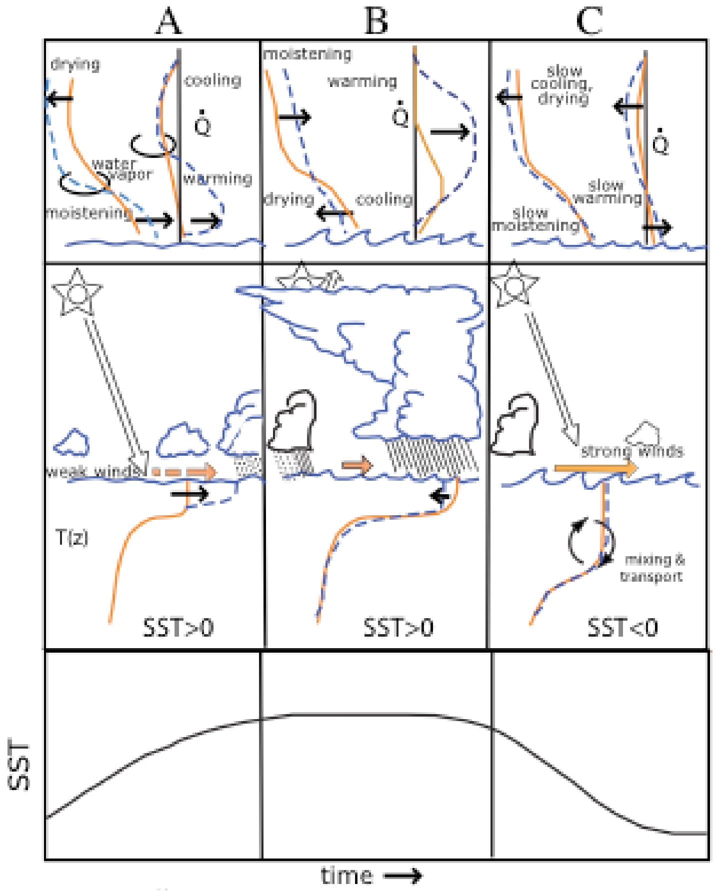

Figure 4. Schematic of a conceptual model for MJO initiation processes at a fixed location over the Indian Ocean. Upper panels illustrate tendency of moisture and diabatic heating profiles; middle panels depict cloud compositions, surface winds, and upper-ocean temperature profiles; lower-panel shows the SST evolution. (After Stephens et al. 2004)

Stage B (middle panels) is the onset stage. Various types of convective clouds aggregate into the MJO envelope. The peak of atmospheric diabatic heating is elevated from the lower to upper troposphere. Surface winds are moderate, and SST decreases only slightly. Low-level moisture convergence and surface evaporation in the MJO convective center supply energy for deep convection (Section 2.3.2). Low-level cooling typically associated with stratiform precipitation remains minimal until the end (section 2.3.2).

Stage C (right panels) is the post-onset stage. It features sustained strong surface westerlies wind and strong surface evaporation. Vigorous ocean mixing promotes entrainment cooling at the bottom of the mixed layer. The upper-ocean heat content and SST rapidly become anomalously low and remain so for a long time when this stage gradually transforms into the pre-onset stage (Section 2.3.3).

The transitions from stages A to B and B to C can occur relatively quickly compared to the duration of each stage (Figure 3). In order to understand MJO initiation, we need to determine the mechanisms that initiate each stage (particularly B and C), sustain them for a certain time (all three stages), and cause their rapid demise (particularly A and B).

No single field program can solve all problems associated with MJO initiation. AMIE-Gan/DYNAMO will focus primarily on processes that need to be quantified via field observations from the Indian Ocean region. The hypotheses emphasize three aspects key to MJO initiation: (1) interaction between convection and environmental moisture, (2) the evolution of cloud populations, and (3) air-sea interaction. Inadequate representations of these processes in numerical models may inhibit accurate simulation and prediction of MJO initiation.

2.3.1 Role of Moisture

There is ample observational evidence that tropical precipitation is positively related to column water vapor on a wide range of timescales and over all oceans (Bretherton et al. 2004, Peters and Neelin 2006). Such a relationship may come from entrainment of dry environmental air into convective plumes to reduce updraft buoyancy (Brown and Zhang 1997, Raymond 2000, Kuang and Bretherton 2006, Holloway and Neelin 2009), effects of convective downdrafts (Johnson 1976, Zipser 1977, Cheng 1989), or suppression of convection due to dry-air intrusion (Mapes and Zuidema 1996, DeMott and Rutledge 1998). Numerical simulations have clearly demonstrated the sensitivity of tropical deep convection to tropospheric moisture (Tompkins 2001, Derbyshire et al. 2004), especially to moisture variations in the lower troposphere above the cloud base (Sherwood and Wahrlich 1999, Sobel et al. 2004, Holloway and Neelin 2009). MJO simulations can be improved when this sensitivity is altered through changes in model physics, such as eliminating non-entraining plumes in an Arakawa-Schubert scheme (Tokioka et al. 1988), increasing a humidity threshold for deep convection (Wang and Schlesinger 1999), including a dependence of entrainment rate on relative humidity (Bechtold et al. 2008), increasing rain re-evaporation (Maloney and Hartmann 2001, Grabowski and Moncrieff 2004), or by explicitly simulating some aspects of cloud dynamics and physics (Benedict and Randall 2009). Consistently, an increase in lower-tropospheric moisture leading to MJO active phases (stage A to B in Figure 4) has been documented in observations and reanalysis data (Johnson et al. 1999, Kemball-Cook and Weare 2001, Kiladis et al. 2005) and in models for climate (Thayer-Calder and Randall 2009, Zhang and Song 2009) and weather prediction (Agudelo et al. 2008). These results have yet to yield a clear understanding of the essential physics of the moistening process or the convective sensitivity to environmental moisture. Meanwhile, tuning model parameterizations for better MJO simulations often degrade the model mean climate (Sobel et al. 2010). Nonetheless, the modeling results focus our attention on specific cloud and mesoscale processes and on mechanisms for the large-scale variability of moisture. Our understanding of both suffers from substantial uncertainties.

To quantify the role of moisture in MJO initiation, we define a moist layer atop the surface, within which relative humidity is higher than a given threshold to be determined. The role of environmental moisture in MJO initiation can then be summarized by the following hypothesis:

Hypothesis 1: Deep convection can be organized into an MJO convective envelope only when the 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 state.

Specific cloud and mesoscale processes, such as the entrainment rate, precipitation efficiency and re-evaporation rate, and downdraft strength, must be quantified using numerical models constrained, validated, or evaluated by field observations to produce the most realistic cloud structure and population distribution in a given large-scale environment. To make the moist layer grow on the large scale, any moistening mechanism has to work against drying due to mean large-scale subsidence, a typical climatic feature of the tropical Indian Ocean. A weakening or absence of the subsidence would make moistening processes more efficient. Moistening effects of cloud detrainment will be discussed in the context of Hypothesis 2 (Section 2.3.2). The large-scale circulation can affect the moist layer depth in several ways: boundary-layer moisture convergence (Wang 2005, Hendon and Salby 1994), horizontal moist or dry advection (Maloney 2009, Benedict and Randall 2009), and surface evaporation (Sobel et al. 2008, 2010), which may include positive SST feedbacks to the MJO (Waliser 1996). The strengths of these and other effects may determine the timescales of MJO initiation, such as the prolonged stage A (Figure 4) and the relatively quick transition from A to B. Some of these large-scale circulations can be part of external perturbations impinging from the extratropics or upstream. Quantifying their effects on the depth of the moist layer demands careful moisture budget estimates. This will be done locally using AMIE-Gan/DYNAMO field data and on large scales using global reanalysis products and numerical models, after their reliability for this purpose is assessed using the campaign observations gathered by the sounding array. The field observations and auxiliary data will be used to empirically relate convective cloud types and precipitation amount (from radars) to the moist layer or other column moisture measures (from soundings, AERI, radars, surface met, and microwave radiometers). Hypothesis 1 is falsified if, statistically, different cloud populations are found in a similar moisture environment or similar cloud populations found in different moisture environments. This would motivate investigations of other possible factors for MJO initiation, such as variability in atmospheric boundary layer properties (Young et al. 1995, Moncrieff and Liu 1999, Johnson et al. 2001), tropospheric temperature profiles (Mapes 2000, Deng and Wu 2009), vertical wind shear (Moncrieff and Green 1972), and momentum transport (Moncrieff and Klinker 1997, Moncrieff 2004, Majda and Stechmann 2009).

2.3.2 Role of Cloud Population

MJO initiation should not be simply characterized as shallow convection becoming deep. Satellite and other data over tropical oceans suggest that the cloud population is broad, consisting of a range of cloud sizes and types at all times. As the MJO progresses through different life cycle stages, different cloud types take on greater or lesser importance, with a different predominant cloud type in each stage (Lau and

Wu 2009, Chen and Del Genio 2009). The same type of convective cloud may play different roles at different stages. AMIE-Gan/DYNAMO focuses on two possible roles of clouds in MJO initiation: moistening through detrainment and rain evaporation, and vertical heating profiles.

Moistening by detrainment of shallow and congestus clouds prior to the onset of deep convection has been suggested based on field observations (Johnson et al. 1999, Yoneyama et al. 2008), global reanalyses (Sperber 2003), and modeling (Thayer-Calder and Randall 2009). The prolonged (≥ 30 days) pre-onset stage (A in Figure 4) implies that this moistening is a slow process against large-scale drying effects (subsidence, advection, etc.) and alone is insufficient to directly precondition the onset of MJO convection (stage B). At stage A, diurnal solar insolation forms a diurnal warm layer in the upper ocean under light-wind conditions as observed in both the western Pacific (Soloviev and Lukas 1997) and Indian Ocean (Bellenger and Duvel 2009). The corresponding diurnal cycle in the SST (Webster et al. 1996) leads to a diurnal cycle in the atmospheric mixed-layer depth and non-precipitating cloud development (Johnson et al. 2001), causing cloud moistening to take place over a deeper layer than without the diurnal cycle. As a consequence, shallow clouds with higher precipitation efficiency grow over a large-scale domain near the end of stage A. While such clouds remove more moisture from the atmosphere, their shallow convective heating and ascent drive low-level convergence and import moisture (Mapes 2000, Haertel et al. 2008, Zhang and Hagos 2009), leading to negative gross moist stability (Neelin et al. 1987, Neelin 1997, Raymond 2000, Sobel 2007, Raymond et al. 2009). This is key to a robust MJO in an intermediate-complexity model (Raymond and Fuchs 2009). The rapid transition from stage A to B in Figure 4, and the selective growth and maintenance of deep convection on the MJO scales at stage B may depend on this feedback to the low-level large-scale circulation from shallow and congestus clouds with high precipitation efficiency. By reducing effective equivalent depth, low-level heating was proposed as a reason for the slow phase speed of the MJO (Lau and Peng 1987, Chang and Lim 1988). Its role in the MJO through interacting with the large-scale circulation has become more prominent in theoretical studies (Wu 2003, Khouider and Majda 2006) and numerical simulations (Zhang and Mu 2005, Li et al. 2009).

A recently published technique (Giangrande et al, 2010) uses W-band (95 GHz) Doppler cloud radar spectra to perform automated long-term retrievals of vertical air velocity and exponential precipitation drop size distribution (DSD) slope parameter (lambda) during light to moderate rainfall (roughly 1 to 30 mm/hr) at high spatial and temporal resolutions. The technique has a maximum vertical operating range from the surface up to the melting layer. This range reduces at rainfall rates greater than about 10 mm/hr where severe attenuation at 95 GHz reduces the useful range of the radar. Although the technique cannot reliably determine the DSD intercept parameter (N_0), complementary information from a collocated radar not susceptible to attenuation at these rainfall rates allows the opportunity to determine N_0, and thus, full DSD retrievals. The technique has been demonstrated at the ARM Southern Great Plains site (SGP); Niamey; and Black Forest, Germany. At the first two of these sites, retrievals were substantially from areas of stratiform rain associated with convective events. Vertical air velocity accuracy is estimated to be within 10 cm/s, and retrievals are generated at the native spatial (e.g. < 45 m) and temporal (e.g. < 5 s) resolutions of the radar. At the SGP, where disdrometer measurements are available, good agreement has been demonstrated between ground-based and radar-retrieved exponential DSD slope parameters. Apart from vertically pointing W-band (co-polarized) Doppler radar spectra, the only other requirement for the technique to operate at full accuracy is the availability of regular atmospheric soundings.

There are different convective compositions at stage B. Stratiform heating (with low-level cooling) associated with mesoscale convective systems (Houze 1997, 2004) generates a gravity wave-like response that can trigger new convection locally (Mapes 1993). On the MJO scale, however, deep convection at stage B can be sustained (≥ 10 days) only if low-level heating of convective clouds, deep and shallow, compensates for the stratiform low-level cooling over a large-scale domain. When stratiform heating becomes dominant over the MJO convective center, both consequential large-scale low-level divergence and mid-level inflow (Kingsmill and Houze 1999a, b; Zhang and Hagos 2009) can be detrimental to deep convection and act as a discharge of moist static energy (Peters and Bretherton 2006), leading to the termination of stage B.

The differential roles of various types of convective clouds during MJO initiation can be summarized by the following hypothesis:

Hypothesis 2: *Specific convective populations at different stages are essential to MJO initiation.*

Implied in this hypothesis is the growth of the moisture layer at stage A accompanied first by a shift of the cloud population distribution from a dominance of shallow clouds with zero or low precipitation efficiency to those with higher efficiency, then by an increase in low-level heating and corresponding large-scale surface evaporation and low-level moisture transport/convergence. During the AMIE-Gan/DYNAMO field campaign (Section 3.1), radar observations will document the evolution in cloud populations, their moisture environment, and diabatic heating (Schumacher et al. 2004); sounding observations will be used to estimate vertical profiles of the apparent heat source Q1 and moisture sink Q2 (Yanai et al. 1973), which together will also document the transition from non-precipitating shallow clouds (Nitta and Esbensen 1974, Johnson and Lin 1997) to precipitating clouds (Katsumata et al. 2009). Surface flux measurements from ships and moorings will quantify the effect of low-level heating on surface wind and evaporation. In combination, these observations are crucial for evaluating Hypothesis 2.

A large-scale tilt in latent heating profiles is also implied in Hypothesis 2, with a low-level heating maximum toward the end of stage A, deep heating (maximum in the mid troposphere) in the most of stage B, and elevated stratiform heating near its end. This tilt has been shown from GATE data (Houze 1982), TOGA COARE data and a reanalysis product (Lin et al. 2004, Haertel et al. 2008). Other studies using different reanalyses, satellite retrievals, and MISMO field observations have, however, led to inconsistent results (Masunaga et al. 2005, Morita et al. 2006, Lau and Wu 2009, Katsumata et al. 2009, Zhang et al. 2009). Profiles of Q1 derived from the AMIE-Gan/DYNAMO sounding and radar observations will be used to investigate the large-scale evolution in heating profiles during MJO initiation, including radiative heating rate profiles (Mather et al. 2007). Numerical experiments will be conducted to determine the relative importance of low-level cooling and its associated low-level divergence and mid-level inflow to the termination of stage B in comparison to other factors, such as dry-air advection by the large-scale circulation and the effects of shear on convective organization.

2.3.3 Role of Air-Sea Interaction

The role of air-sea interaction, including dynamical coupling, in the MJO has been controversial. Including representation of coupling processes in GCMs leads to improvement in simulations (Waliser et al. 1999, Zheng et al. 2004) and prediction (Pegion and Kirtman 2008) of the MJO or can have deleterious effects (Hendon 2000, Liess et al 2004, Grabowski 2006) depending on how realistically the MJO structure and mean state are reproduced (Sperber et al. 2005). Models used in the study of MJO air-sea interaction, however, do not adequately resolve the unique climatic features of the equatorial Indian Ocean, let alone detailed characteristics of upper-ocean mixing. Observationally, neither the detailed vertical structure nor the intraseasonal variability of oceanic mixing and its connection to SST has been systematically examined in the Indian Ocean. Our understanding of their contributions to MJO initiation and evolution is therefore rudimentary at best.

In the Indian Ocean, strong surface zonal wind anomalies tend to start at the end of a convectively active phase (stage B in Figure 4) and extend west of an MJO convective center (Zhang et al. 2006, Figure 5b) into stage C. At stage B, with reduced insolation alone, the surface cools only slightly. If surface buoyancy flux anomalies due to reduced insolation and enhanced precipitation cancel each other as observed over the western Pacific, then the upper-ocean mixing is not very strong and the barrier layer is strengthened due to freshwater input from rainfall. Nighttime convective mixing helps maintain the ocean surface mixed layer (Anderson et al. 1996), but is insufficient to overcome a 10–25 m thick barrier layer (Sprintall and Tomczak 1992). The upper-ocean heat content and SST remain high (Matthews 2008), which help maintain surface fluxes driven by mesoscale convective systems (Saxen and Rutledge 1998, Redelsperger et al. 2000) and supply energy to deep convection. As large-scale surface winds increase, so do surface evaporation and the Wyrtki jets (Masumoto et al. 2005). Upper-ocean mixing driven by both wind and shear can now effectively erode away any barrier layer, reach the shallow thermocline, and promote entrainment cooling. The resulting decreasing upper-ocean heat content and SST tend to prevent deep convection from spreading westward, terminate stage B, and start stage C. As the convective center moves eastward, the large-scale surface wind anomalies maintain the upper-ocean cooling over a large zonal extent (Saji et al. 2006). Recovering from this cooling and transforming from stage C to A are slow because of constant shear-driven mixing. This scenario can be summarized by the following hypothesis:

<u>Hypothesis 3</u>: *The barrier layer, wind- and shear-driven mixing, shallow thermocline, and mixing-layer entrainment all play essential roles in MJO initiation in the Indian Ocean by controlling the upper-ocean heat content and SST, and thereby surface flux feedback.*

Although some AMIE-Gan measurements of the boundary layer may contribute to testing Hypothesis III, the primary measurements for addressing air-sea interactions will be the ship and buoy observations. Therefore we will not focus on this question, although it is an important element of the DYNAMO program.

3.0 Campaign Objectives and Structure

The overarching goal of AMIE-Gan/DYNAMO is to expedite our understanding of MJO initiation processes and efforts to improve simulation and prediction of the MJO. The specific AMIE-Gan/DYNAMO objectives are to:

- collect observations from the central equatorial Indian Ocean region that are urgently needed to advance our understanding of the processes key to MJO initiation
- identify critical deficiencies in current numerical models that are responsible for their low prediction skill and poor simulations of MJO initiation

- provide unprecedented observations to assist the broad community effort toward improving model parameterizations
- provide guiding information to enhance MJO monitoring and prediction capacities for delivering better climate prediction and assessment products on intraseasonal timescales for risk management and decision making over the global tropics.

These objectives will be achieved by following an integrated approach of four closely connected components: field campaign, data analysis, modeling, and forecasting. The AMIE-Gan and DYNAMO Science Steering Committees, composed of scientists from universities and government laboratories with expertise in the atmosphere and ocean, and in observations, theories, data analyses, modeling, and prediction, will provide general guidance to the program and oversee its progress.

3.1 Field Campaign

The objective of the coordinated field campaign is to collect observations of MJO initiation processes that are urgently needed for hypothesis testing through data analysis and modeling.

The AMIE-Gan/DYNAMO field campaign is an integrated part of CINDY2011. As such, "AMIE-Gan/DYNAMO" in the context of the field campaign should be taken as "AMIE-Gan/DYNAMO/CINDY2011". The field campaign will collect observations of the atmosphere, ocean, and the air-sea interface during October 2011–March 2012 in the central equatorial Indian Ocean. The core observations include atmospheric soundings, cloud and precipitation radars, and air-sea fluxes and upper-ocean measurements. For the more targeted ASR science community, observations of surface radiation and meteorology, column vapor and water amounts, and other standard ARM measurements will also be collected on Gan Island, matching those that will be collected on Manus as part of the AMIE-Manus campaign.

For DYNAMO, a quadrilateral sounding-radar array will be formed in the central equatorial Indian Ocean consisting of two islands (Gan and Diego Garcia) and two research vessels (Figure 6). Ships from Australia, India, Japan, and the U.S. will participate in the formation of the array. As the timeline graphic in Figure 7 shows, an Intensive Observing Period (IOP) will last 107 days (1 October 2011–15 January 2012), during which field observations will be collected by all DYNAMO facilities. Embedded in the IOP is a 40-day Special Observing Period (SOP, 1 October–9 November 2011), which is designed to fully resolve the diurnal cycle with enhanced soundings and all radars. After the IOP we will continue the observations on Gan with similar capacity and concurrent with the AMIE-Manus campaign through an Extended Observing Period (EOP) lasting until 31 March 2012. Based on 1979–2007 statistics, the chance to capture a major MJO event during the IOP is nearly 90%. The EOP increases this probability to 100%. Multiple MJO events are likely over the course of the EOP.

Atmospheric Soundings: The objective of the DYNAMO sounding network is to observe the vertical structure of the large-scale environment for convective cloud populations and their feedbacks at each stage of MJO initiation. GPS rawinsondes, wind profilers, and lidars will collectively measure vertical profiles of temperature, humidity, pressure, and winds. Rawinsondes will be launched for DYNAMO eight times per day during the SOP and four times per day during the rest of the field campaign, from the ships and second island site. The sounding observations are critical to testing all three AMIE-Gan/DYNAMO hypotheses. The value of the sounding network in relation to the science objectives of the campaign is its ability to provide (1) diagnosed divergence and diabatic heating profiles to aid interpretations of evolving convection during MJO initiation, (2) a robust estimate of the large-scale state of the atmosphere, and (3) forcing fields for one-dimensional (1D) and limited-domain models. The ARM Variational Analysis product will be used for all of these purposes.

For AMIE-Gan, the eight-per-day frequent sonde launches for the entire campaign, along with the microwave radiometer and surface meteorological measurements, are required to document the atmospheric environment. These are essential for input into the production of a Variational Analysis product and are needed for modeling studies which are the overarching aim of the campaign. Additionally, the surface meteorological, atmospheric emitted radiance interferometer (AERI), and wind profiler measurements are instrumental in characterizing the boundary layer that feeds the convection.

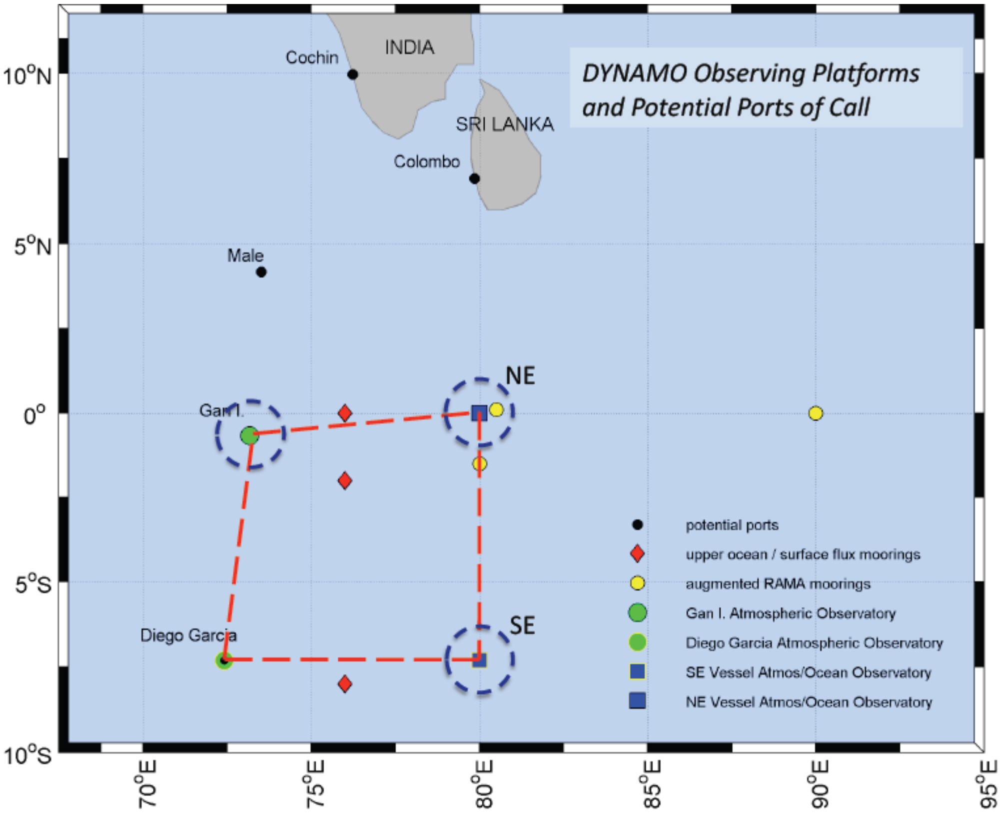

Figure 5. Map of DYNAMO field campaign platforms and potential ports of call. Red dashed lines mark the sounding array. Blue dashed circles indicate the radar sites.

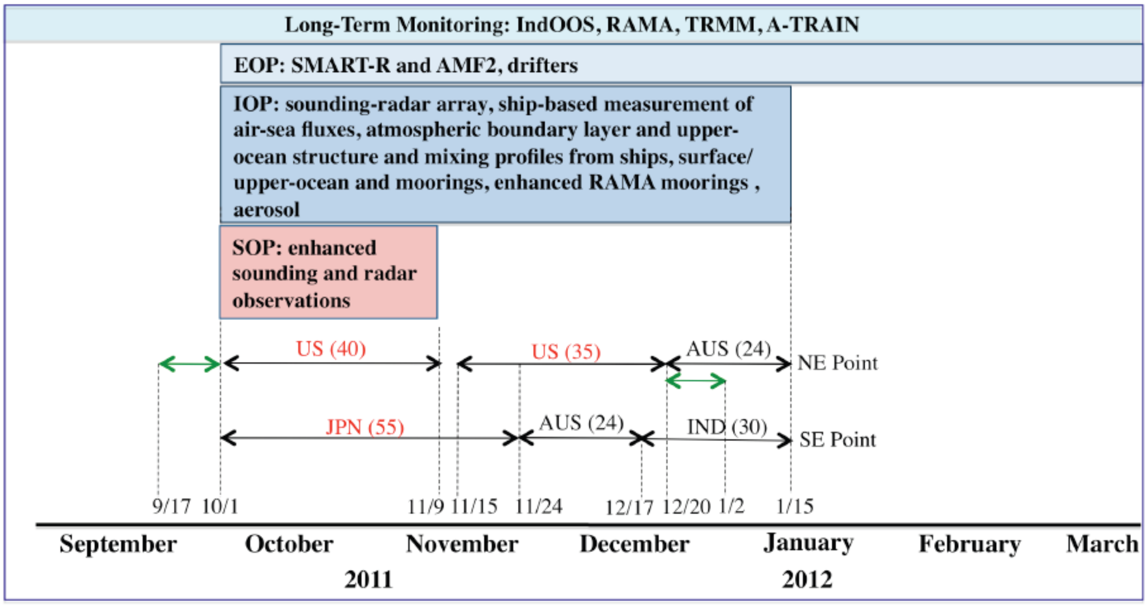

Figure 6. Timeline of AMIE-Gan/DYNAMO field experiment. Horizontal arrows indicate ship rotation schedule with ships and at-sea days labeled (US for R/V Revelle, JPN for R/V Mirai, IND for R/V Sagar Kenya, and AUS for R/V Southern Surveyor). Red labels indicate ships with C- and W-band Doppler radars. Green arrows mark U.S. ship mooring cruises.

Radars: The objective of the AMIE-Gan/DYNAMO radar observations is to fully characterize the ensemble of convection associated with each stage of MJO initiation. Three radar systems (AMF2, Texas A&M SMART-R, and NCAR S-PolKa) providing five wavelengths (S, C, X, Ka, and W-bands) will be deployed at a supersite on Gan to document the full spectrum of tropical convective clouds from non-precipitating to precipitating clouds and their environmental moisture characteristics. C- and W-band Doppler radars will operate onboard two research vessels. During the SOP, all radars will operate simultaneously. The AMF2 and SMART-R (including soundings) will operate through the entire EOP in conjunction with the observations of AMIE-Manus. The C-band radars will document the three-dimensional structure of precipitation echoes, detailed rainfall patterns, and Doppler measurements of air motions on the convective and mesoscales. The ARM X- and Ka-band scanning radars will provide documentation of the spatial distribution of clouds, both modestly precipitating and non-precipitating, as well as cloud microphysics. The S-PolKa radar will provide important observations of integrated lower tropospheric moisture. The ship-based W-band radar and AMF2 shorter wavelength radars will provide in-cloud vertical velocity turbulence profiles and information on cloud microphysics and morphology. Cloud microphysics and aerosol measurements will be used to determine whether parameterized and explicitly microphysical schemes in models are functioning correctly. In addition, they will help explore whether MJO cloud and precipitation formation is sensitive to differences between marine and continental aerosols. The radar observations are critical to testing Hypotheses 1 and 2 and extremely useful for validating and analyzing satellite retrievals and model simulations.

The AMF2 and associated instrumentation are central to the success of AMIE-Gan/DYNAMO as a whole and particularly the concept of the Gan supersite, and are essential for testing of Hypotheses I and II. The X- and Ka-band scanning capability, when combined with the C-band radar, provide the primary documentation across the scale of precipitating and non-precipitating cloud particle size distributions. The vertically pointing W-band radar, in conjunction with the micropulse lidar and ceilometer, provide the input needed for the already mature Active Remotely Sensed Cloud Locations (ARSCL) value-added-product, which in turn is essential for Micro-Base style retrievals of cloud microphysics. Significant research is needed to provide similar spatially representative products from the ARM scanning radars (see next section on proposed research), as well as combining all the available scanning radar frequencies into the best documentation of the cloud populations and characteristics. In particular, combining the ARM radars with C-band radar is applicable to and needed for both the AMIE-Gan and AMIE-Manus campaigns.

Satellites: Large-scale cloud properties and radiative fluxes are important for completing the characterization of the large-scale ensemble. Changes in total cloud water path and microphysics occur even in the absence of precipitation and affect the radiative loss/gain of the ensemble that impacts the development of the convective systems. Estimates of cloud cover, height, thickness, phase, effective particle size, and water path will be retrieved at the pixel scale (1–5 km) and complemented by estimates of the radiation budget at temporal resolutions up to 1 hour. The retrievals will be based on 1-km data from MODIS on Terra (1030/2230 LT) and Aqua (0130/1330 LT) and hourly 5-km data from the imager on FY-2E. These data will be provided in near-real time accompanied by top-of-atmosphere and surface radiative fluxes based on narrowband-broadband conversion functions. Both digital and image formats will be provided. Averages of all parameters will be computed over the diurnal cycle and in total for different time periods covering the campaign. Other potential data sources are the AVHRRs on NOAA 15-18, the VIRS on the TRMM satellite, and CERES on Aqua and Terra. If time permits, these data would be analyzed after the experiment providing the same parameters as the near-real time analyses.

4.0 Synergy between AMIE-Gan and AMIE-Manus Campaigns

As noted previously, MJO modeling difficulties include not only those associated with initiation, but also propagation through the maritime continent and into the western Pacific Ocean (Figure 7). Sobel et al. (2008) suggest that perhaps surface energy fluxes drive the MJO. This is based on the observation that although mean precipitation is comparable over the tropical West Pacific Ocean and the islands of the Maritime Continent, the variance of precipitation in the 30-90 day period band is much weaker over the islands. An additional result that supports this idea is that several global climate models (GCM) produce incipient MJOs in the Indian Ocean, only to have them weaken and terminate as they propagate eastward and cross the Maritime Continent.

Conducting both AMIE-Gan and AMIE-Manus during the same time frame as CINDY2011 will further expand the context of AMIE observations by documenting the initiation of MJO events in the Indian Ocean before they propagate east past Manus. This will be important for the question of how the MJO changes as it passes over the Maritime Continent, and how this differs in observations versus models. Generation of the advective forcing data sets from both AMIE sites through the experimental period will be used to drive single-column models (SCMs) and cloud-resolving models (CRMs) to test whether either are capable of reproducing the progression of the MJO. By this effort, it is likely that further insights into the reasons for the model failures will be gained.

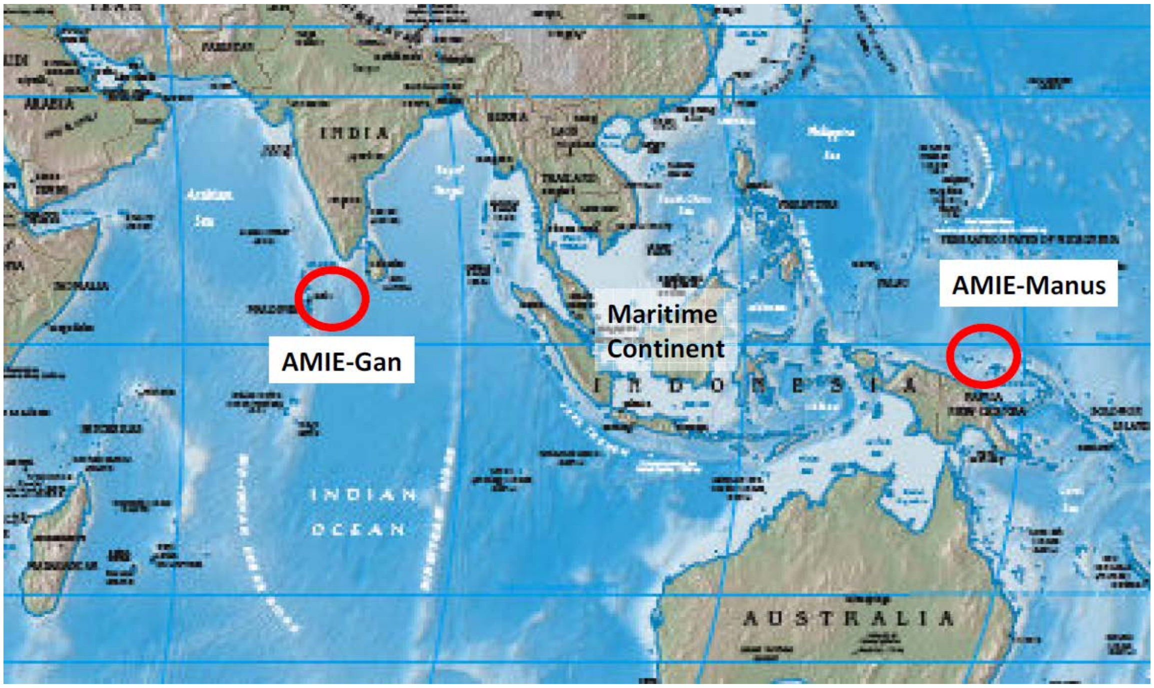

Figure 7. Overview map showing the spatial relationship between AMIE-Gan, AMIE-Manus, and the Maritime Continent.

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6.0 ARM Resources Required

This campaign requires the deployment of an ARM Mobile Facility. The second marine-deployable AMF would likely be the best option, given the small island deployment in a salty marine environment. Gan Island has ample infrastructure to support an AMF deployment. A collaborative scouting trip to Gan, covering both DYNAMO and AMIE-Gan issues, occurred during February of 2010. The brief scouting report (including contacts information) is included in the “Other” section of this document, as well as ancillary information on horizon elevation measurements for the proposed scanning radar sites, and a panorama of the proposed AMF “main” site. We propose to field the AMF scanning radars either along with the SPolKa near the main wharf (the “wharf” site), or possibly at a small spit of land that sticks out from the main island (the “spit” site) (Figure 8). The “spit” site would require some expansion build-up (material easily dredged from the nearby ocean bottom by local contractors) to give a wide enough area where the radars would sit, but affords less possibility of scanning blockage by the other radars and frequency interference than if all the scanning radars are located at the wharf site. Both of these sites afford a good scanning field-of-view with the main expected horizon blockage of only about 1-2° elevation toward the west. Toward the east, which looks into the DYNAMO campaign area, it is virtually all ocean surface with no blockage. We propose to deploy the main AMF (all but the scanning radars) near the Maldives Meteorological Service (MMS) Gan office at the airport (M in Figure 8) where sondes are currently launched. Mr. Ali Wafir, head of the Gan MMS Office, seemed receptive to the idea of his personnel providing help in launching sondes for the AMIE-Gan project.

The new scanning radars, as well as the vertically pointing cloud radar, micropulse lidar, and ceilometer, are critical for the documentation of the cloud populations needed for the primary hypothesis testing described previously. In addition, sonde launches at a rate of eight per day are requested for the campaign period, or at a minimum eight per day are needed for the SOP (1 October–9 November 2011), and launches at a minimum rate of four per day are needed for the rest of the campaign period (10 November 2011–31 March 2012).

Critical AMF instruments (taken from the AMF2 webpage) are as follows:

- Balloon-borne Sounding System (SONDE)
- Scanning dual frequency X-band/Ka-band radar
- Vertically pointing W-band (95 GHz) ARM Cloud Radar (WACR) or similar
- Micropulse Lidar (MPL)
- High Spectral Resolution Lidar (HSRL)
- Vaisala Ceilometer (VCEIL)
- Surface radiation (SkyRad and GndRad)
- Meteorological measurements (SMET)
- Microwave Radiometer (MWR)
- Total Sky Imager (TSI)
- Atmospheric Emitted Radiation Interferometer (AERI)
- Multifilter Rotating Shadowband Radiometer (MFRSR)
- 915 MHz or 1290 MHz wind profiler
- Narrow Field-of-View Radiometer (NFOV)

Figure 8. Proposed sites for the scanning radars (S) at the wharf and spit sites, and the rest of the AMF instruments and housings (AMF2 main, M) for AMIE-Gan.

In addition, in order to adequately address the goals of the campaign, several ARM value-added products (VAPs) are also needed. These VAPs, in decreasing order of importance, include:

- ARSCL (Active Remotely-Sensed Cloud Locations)/WACR-ARSCL VAP/Micro-ARSCL as applicable
- MWRRET (MWR Retrievals)
- Merged Sounding VAP
- AERIPROF (AERI Profiles of Water Vapor and Temperature)
- MPLCOD (Micropulse Lidar Cloud Optical Depth)
- MFRSRCLDOD1MIN (Cloud Optical Properties from MFRSR Using Min Algorithm)

- QCRad (Data Quality Assessment for ARM Radiation Data)
- AOD (Aerosol Optical Depth, derived from MFRSR/NIMFR)

Though not currently provided, an additional area of European Centre for Medium-Range Weather Forecasts (ECMWF) (or other source) analysis output is needed for production of the Variational Analysis forcing data set in the Indian Ocean area. For years, the ARM Data Archive has been collecting the ECMWF analysis data for the TWP, which covers 20N–20S latitude and 110E–280E (100 W) longitude, with temporal resolution available every six hours. These data will be used to generate the forcing data sets for Manus and Darwin for AMIE. In order to generate the forcing data set for AMIE-Gan, the area covered must be extended over the Indian Ocean area. In addition, to quantify the larger-scale characteristics over the region in order to put the AMIE-Gan/DYNAMO study area in context, ECMWF analysis data is needed extending from the current western boarder (110E) to 30E, which would cover the Indian Ocean. But perhaps it is more prudent to include the area extending into the Atlantic on the western side of Africa.

There are fundamental questions on what large-scale dynamic and thermodynamic characteristics of the Indian Ocean area lend themselves to MJO initiation, while other equatorial areas around the globe do not, even the to first-order similar TWP warm pool area. There is some speculation that a concurrence of larger-scale phenomena contribute to the unique characteristics of the Indian Ocean area with respect to MJO initiation, including the atmospheric flow over the Himalayas to the west on the African continent. Having the ECMWF analysis extend across the Indian Ocean area through the western side of Africa, to about 20W, would allow study of the Himalayan flow as it impacts the Indian Ocean area characteristics for the duration of the AMIE/DYNAMO campaigns. Thus we request that the additional area of ECMWF analyses, similar to that already being stored for the Pacific basin, stretching from 110E through 20W, also be gathered and archived as External Data for the campaign.

The current cost of the existing ECMWF analysis area being archived is on the order of $10K/year, which scales about linearly with area (Jim Mather and Richard Wagener, personal communication). The larger extended area we are requesting into the Atlantic area is less than the size of the current area; thus, the added cost should be less the $10K to gather and archive the additional area.

There are several ships involved in manning two of the “corners” of the campaign area. These ships include the already committed Research Vessel (R/V) Sagar Kanya from India and the JAMSTEC R/V Mirai. Other proposed ships include the Australian R/V Southern Surveyor and either the U.S. NOAA R/V Ron Brown or a University-National Oceanographic Laboratory System (UNOLS) ship as available. The expendables such as sondes will also be covered by these research organizations. In addition, JAMSTEC is in collaboration with other international organizations in increasing the buoys included in the RAMA array, shown in Figure 9. The RAMA (Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction) is a multi-nationally supported element of the Indian Ocean Observing System (IndOOS). JAMSTEC also has been supporting the HARIMAU (Hydrometeorological Array for ISV-Monsoon Automonitoring) effort located at several sites in the Maritime Continent area between the Indian Ocean and the tropical western Pacific (see Figure 10). The JAMSTEC participants in Cindy2011 are seeking funding to continue operations of these sites through the end of the Cindy2011 campaign, which would add measurements beneficial for the synergistic MJO propagation and evolution aspects of the AMIE-Gan and AMIE-Manus campaigns.

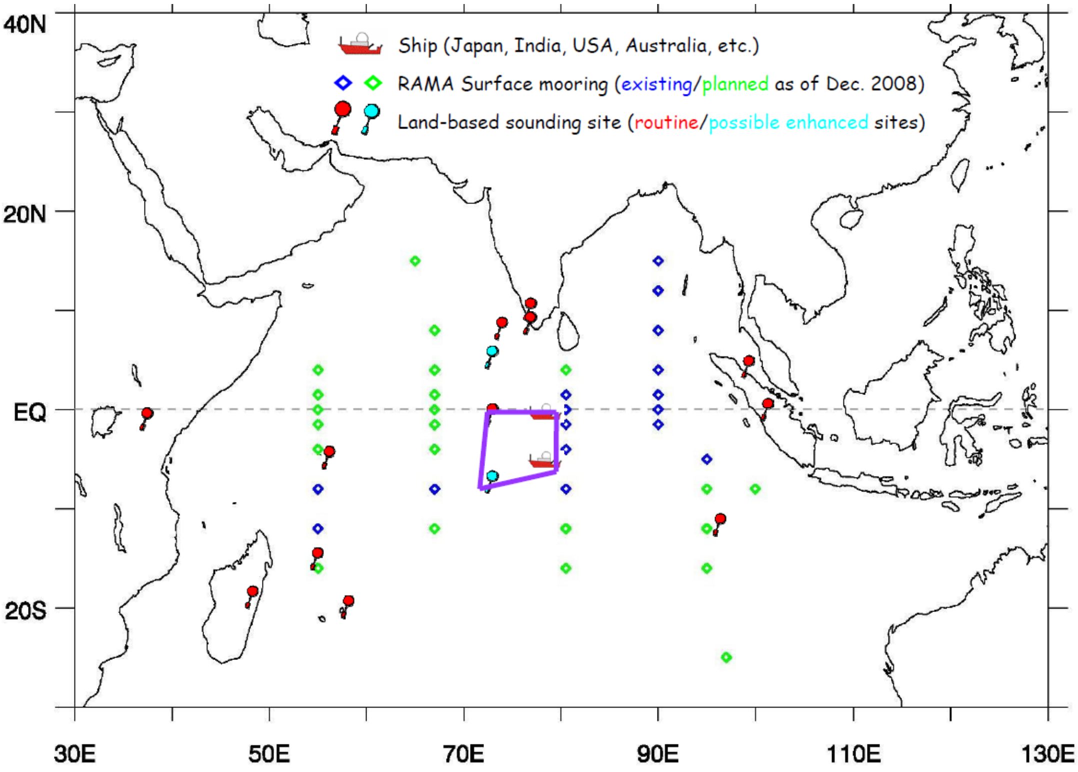


Figure 9. Buoys, ships, and soundings proposed for the coordinated Cindy2011/DYNAMO/AMIE-Gan campaigns in the Indian Ocean area.

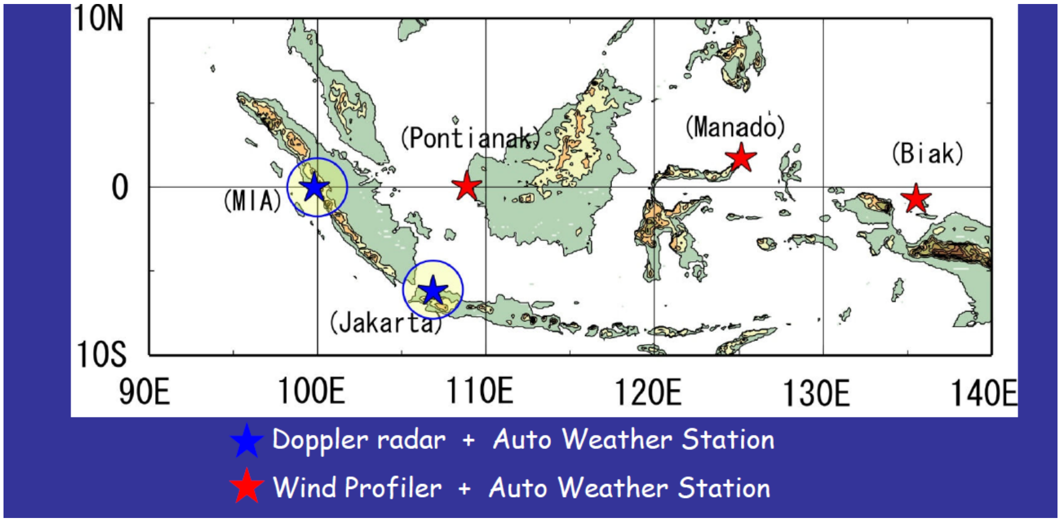


Figure 10. Sites and measurements associated with Hydrometeorological ARray for ISV-Monsoon Automonitoring (HARIMAU) in the maritime continent area.

Appendix A

Gan Site Survey Trip Report

Appendix A

Gan Site Survey Trip Report

DYNAMO Site Survey Trip Report
18–26 February 2010

Prepared by: Jim Moore, Jim Wilson, Jeff Bobka
(with contributions from Chuck Long)

Locations: Hulule Island, Maldives; Male Island and Male (capitol city), Maldives; Addu Atoll, Maldives (including Gan, Feydhoo, Maradhoofeydhoo, and Hithadhoo). Male lies at 6°N, 73°E. Addu Atoll lies at 0.5°S, 73.8°E.

Participants: From NCAR at all locations: Jim Moore, Jim Wilson, Jeff Bobka and from JAMSTEC, Kunio Yoneyama. On Addu Atoll: Chuck Long from DOE/ARM PNL, Miki and Shiruyiki from JAMSTEC.

A.1 Overview

The NCAR participants arrived in the Maldives (Male) on 20 February. It takes much of 3 days to get from the U.S. to the Maldives flying east. After heading eastbound from the U.S., a layover in Dubai, United Arab Emirates was required after flying from the evening of 18 February to the evening of 19 February. The outbound journey was completed in the evening of 20 February. As a footnote, it is also possible to fly westbound from the U.S. through Tokyo, with stops in Hong Kong or Bangkok or Delhi, and a layover in Singapore. Travel time is again much of 3 days, and there is no significant difference total flight time: ~25 hours in the air, not including airport layover times.

As a summary comment, we very much appreciate all of the support given to us by a number of people in The Maldives. The success of our trip was only possible because of the efforts of our local hosts to answer questions and show us the various instrumentation sites on Addu Atoll.

We have divided the report into several sections addressing issues raised in Male and on Addu Atoll. We have summarized discussions with all the organizations that will need to assist us in making this project happen. Information here applies specifically to S-Pol as well as the ARM AMF and SMART-R deployments being considered. We introduce the specific radar site survey results in this main document.

A large number of photographs were taken by the participants and are combined into two Powerpoint presentations and a detailed set of site panoramas. These are available from the Earth Observing Laboratory (EOL) DYNAMO Web site at: http://www.eol.ucar.edu/projects/dynamo/.

This documentation includes detailed photo analysis of clutter and blockage for radar sites as well as documentation of local logistics, lodging, and other support.

A.2 Detailed Discussion (by location and organization)

Meetings in Male and on Hulule Island 21 February 2010.

Figure A.1. Primary locations on Male and Hulule (Airport Island) relevant to DYNAMO Site Survey.

A.2.1 Shipping

A meeting was held with *Asian Forwarders Shipping Company*, the group that will handle the shipment of NCAR equipment in coordination with Seajet. Seajet made contact with this group in advance of our trip and arranged for the meeting. The route of NCAR (likely SMART-R and ARM as well) will be out of Long Beach, California, by ship. The Pacific and Indian Ocean crossing will take a total of 50–60 days. Once in Male, all the containers and the radar truck will be transferred to small vessels for transport to Addu Atoll. There is sufficient equipment in Male and Addu to handle all containers including the 15-ton S-Pol items. The plan will be for the SMART-R radar to be driven on and off ships in Male and Addu Atoll using a “landing craft.” Further details on the handling of equipment are discussed in the Addu Atoll section below.

A.2.2 Maldives Meteorological Service (MMS) Headquarters

A meeting in the afternoon was held at the *Maldives Meteorological Service (MMS)* Headquarters Office on Hulule Island to introduce the project to the staff and discuss the procedures for and timing of receiving government approval to bring facilities to the Maldives for the project. Moore Wilson and Bobka were in attendance, along with a JAMSTEC representative (Yoneyama). There were a number of important points to come out of these discussions.

- The MMS is interested in the project and will provide support at several levels.
- The MMS Gan Office will act as our local contact point for all activities on Addu Atoll.
- The MMS Headquarters will handle the “official” requests for approval to conduct the project with the various affected national ministries.
- A unified request from all parties interested in locating DYNAMO instrumentation on Addu Atoll is preferred by MMS.
- The process of gaining these approvals should be started as soon as possible. (As a footnote, it took JAMSTEC nearly 2 years to gain site approval for their radar used in MISMO in 2006).
- Information from this trip report will include the background material required to send proposal letters to other Maldives government agencies.
- Other Maldivian agencies likely involved in DYNAMO support include the Ministries of Environment, Customs (waiver of 25% import duty on the value of each facility), Home Affairs (Province Office), Tourism (work permits), and the Addu Atoll Police.
- We did gain a sense of land ownership/responsibility for the several possible sites. (This information will be described in detail for each site below).
- The MMS will try to assist with manning for the supplemental RAOB site on Gan being provided by ARM.

Meetings and Site Visits on Addu Atoll 22–25 February 2010

A.2.3 Gan Office of MMS

The NCAR team met with Mr. Ali Wafir, Head of the Gan MMS Office, on the morning of 22 February. His office will be the project’s and EOL’s primary contact for support on Addu Atoll. We provided an overview of the meetings held in Male. Mr. Wafir and Mr. Mohamed drove us all around the atoll to look at potential sites reachable by road. Their support was essential to our ability to discover and assess potential sites as well as to learn more about the permissions and logistical details needed to bring our facilities to Addu Atoll. Chuck Long from ARM/PNL joined the survey on the second and third day and met with Wafir regarding siting of the ARM main facility near the Gan MMS facilities. Together we evaluated six sites for possible location of “supersite” facilities on the atoll. Below is a complete assessment of the final sites that meet criteria for logistics and exposure for the radars, lidars, and other instrumentation.

A.2.4 Bluelink Ltd (Local Representative of Asia Pacific Shipping on Addu Atoll)

We met with the Gan shipping agent, Mr. Ali Nizar, General Manager of Bluelink Pvt. Ltd. He was very helpful with describing the handling and placement of facility containers and vehicles coming to Addu Atoll for DYNAMO. We received a tour of the port facilities on the atoll where radar facilities would be received and transported to their respective site locations. There is a 25-ton crane to handle the offload of all containers at the main port (long wharf). The rental rate for the crane is 1400 Rufiyaa (~$110) per hour. Two different-sized forklifts are available. Rental rates for the smaller one likely used at the S-Pol site are 500 Rufiyaa ($40/hour). There is a truck and trailer (one each for 20- and 40-ft sea containers) to transport containers one at a time to any site on Addu Atoll (west side).

The special transport requirements of the SMART-R can be accommodated. It will be possible to bring the radar truck on a landing craft from Male to Adu Atoll. It can then be driven off of the landing craft directly on to shore at a site available for this type of unloading.

It is important to note that all shipping and handling arrangements in the Maldives will be arranged through the Asia Pacific contacts rather than directly with a shipping representative on Gan.

Mr. Nazir did offer advice related to obtaining the sites for the radars. It includes deciding on the sites as soon as possible and making application with the land representatives (Province Office, Ministry of Fisheries, etc.) as well as the Ministry of the Environment. (Note: These requests will be done through the MMS (part of the Ministry of the Environment), who will handle the details within the government.) In addition, if the SMART-R is used at different sites near the road, it is wise to alert the local police.

A.2.5 Dhiraagu Communications

We met with the Manager of Southern Operations (Mr. Hussain) to discuss the communications support requirements for DYNAMO including high-speed internet access and telephone service. Dhiraagu should be able to support all of the project needs. It appears that T1-T3 and possibly up to 10–15 MBits-per-second data links will be possible using copper (lower) or microwave relay (higher rate). We also were given the impression that services will continue to improve over the next 18 months. For example, Hussain noted that 2 Mb-per-second 3G service should be available all over the atoll by the end of summer 2010. Communications (cell and Internet) on the island should be just fine. The problem is the international internet links beyond the Maldives. Their main trunk lines are strung to Sri Lanka (undersea cable), and then they move on through India to Italy to join the international backbone.

The time for setup of service at any of the sites on Addu Atoll is estimated by Dhiraagu at 45 days or less. Depending on location and the actual service requirements, the setup time will likely be more like 1–2 weeks. It will be possible to set up a purchase order for this work.

There are a number of pre-paid and monthly cell phone service plans. In addition the EOL DSM phone did work all over the Maldives. It is recommended that local cell service be established for staff during the deployment for all local support needs.

A.2.6 Electrical Power

The power company in the Addu Atoll is called the *Southern Utilities Company*. The power is 240V/50Hz single phase all over the island. There are no 3-phase options. They have modernized the power grid with all power lines now underground over the entire atoll. All power is produced using diesel generators. Our experience is that the power is reliable and stable, even during an impressive electrical storm and heavy rain event (57mm in 2 hours) that occurred during our visit. Power is near all of our potential sites because the sites are reasonably close to the main road where all the underground power is drawn. We did not speak with a power company representative. We need to have more details about sites and facility power requirements before contacting the company. We were told that the utility company is responsive to temporary installation requests. Details will be provided through the MMS contacts once specific site locations are finalized.

A.2.7 South Province Office

The survey team met with staff from the South Province Office that is part of the Ministry of Home Affairs. The Deputy State Minister, Mr. Ali Mohamed, and Mr. Abullah Solig, Atoll Councilor, described the role and support function that this office provides on Addu Atoll. This agency is responsible for handling individual or special requests for land access in the area. In our case, this agency will be responsible for granting access to sites for the DYNAMO radars and ARM main site, unless another federal agency has responsibility. The process for requesting and receiving permission to access sites will take many months. We were encouraged to begin this process as soon as possible. We were told that once the Province Office receives a request for land access, they should be able to issue an approval within 1.5 months. I caution that this time can be much longer when other agencies are involved in the approval process for a site. We know this will be the case in at least one of the principal sites.

There is one data point for consideration related to getting site permissions. The JAMSTEC folks noted it took them nearly two years to receive permission to use the site near Gan airport for their radar during MISMO. In that case, they were working with the Gan MMS office and the Airport Authority.

During the rest of the day, Mr. Solig provided excellent support by providing a crane manual lift that allowed Wilson and Bobka to take accurate measurements at two preliminary sites. These measurements allowed the team to eliminate one of the sites in an undeveloped residential section. It is our impression that the Province Office really wants to help allow DYNAMO to locate facilities on the Addu Atoll.

A.2.8 Equator Village Resort

We stayed two of our three nights in Gan at the Equator Village Resort. This is a very modest resort in appointments and price. The cost per night was $98 inclusive of 2 meals (breakfast and dinner in our case). This rate is during the high season. The rooms are adequate with good working air conditioning and a reasonably comfortable firm bed. There is hot water provided by a flash heater on the wall in the shower. There is no hot water for the sink. When you take a shower you can heat the water flowing through the device to temperatures maybe as high as 110°F. There is no phone and no TV. There is good cell phone coverage with the local phone system (Dhiraggu) as well as GSM system access. There are two TVs in the lobby/commons area that seem to have a few channels. We only saw BBC World and the German News channel. The high point of this location is a very large and clean pool area with a swim-up bar. There is a small area of beach, but swimming is risky on the feet with lots of coral in the reef. We did see snorkelers in the water near the hotel beach front, and the hotel organizes two snorkel trips a day. The clientele of this resort is mostly German, British, and Russian with a few others mixed in. As near as I could tell we were the only Americans at the resort at that time.

We met with the general manager of the Equator Village resort. I discussed the possibility of renting from 10–15 rooms continuously from 1 September 2011 through April 2012. This would cover the setup and operations period of most of the facilities. Note I was being inclusive of all facilities, not just focused on S-Pol. The manager noted that providing all the rooms we needed at a competitive (i.e., discounted) rate is possible from September through 15 December and after 15 March. The period from before Christmas to 15 March is the high season. They typically have room blocks set up with international travel agencies that fill the hotel. We should be hearing from the manager by the end of March about accommodating our request.

A.2.9 Dhoogas Hotel

This is the only other hotel on Gan Island with reasonable access to the instrument sites. There are two quite expensive resorts on other islands in the Addu Atoll. The Dhoogas is very basic with no resort-type amenities. It is a former British base that has been modernized at a very basic level. The room is air conditioned but with no phone, no TV, no hot water, no potable water, no toilet paper (though we understand some did show up after we left), soap, or shampoo. It is likely that some folks may have to stay in this hotel for some period of time, especially during the high season, if rooms are not available at the Equator. The hotel can provide three meals a day. It is local Maldivian (Indian and Sri Lankan mostly) cuisine with curry dishes being a staple of the diet. The room cost us $25 a night plus $9 for three meals so it is very cheap.

A.2.10 Banking

Banking is a challenge on Addu Atoll. We tried three different ATMs (two at Bank of Maldives and one at Bank of India), and none worked with our Visa cards (U.S. Bank or Elevations Credit Union). We were advised that it may be possible to fix this by talking with the bank to open up credit cards, one at a time. We did not pursue this on this visit. We did get cash from the HSBC Bank (Hong Kong) ATM in Male with no difficulty. The hotel in Male (Relax Inn) and the Equator Village both provide money exchange but recognize that all hotel expenses can be paid with the U.S. dollar.

The currency is the Maldivian rufiaa, and about 12 of them are equivalent to one US dollar. That said, the U.S. dollar is legal tender in most hotels on the islands and places of business in the city of Male. In the more rural areas we have the impression that the rufiaa is preferred.

A.2.11 Fuel

There do not seem to be any issues with getting diesel #1 or regular unleaded gasoline for system generators and/or vehicles. Diesel prices at this time are running about $0.90 U.S. per liter or around $3.50/gallon. It is reasonable to guess that prices might be around $4.00/gallon during the 2011–12 field deployment. There are several fuel trucks on Addu Atoll to supply the sites as needed. All the sites being considered will have road access.

A.2.12 Frequency Allocation

The project will need to register and get approval to transmit at all the frequencies planned for the radars and lidars. This request and registration will be made with the Communications Authority of the Maldives through the MMS. We have been requested to prepare a table with all frequencies and associated power output planned for DYNAMO. This approval process will take six months, based on previous experience.

A.3 Radar Sites Detailed Evaluation

The focus of the trip to Addu Atoll was to assess the potential sites for the multiple radars proposed for DYNAMO. FiguresA.2 and A.3 summarize the potential sites assessed during our visit. Other detailed photos are available from EOL.

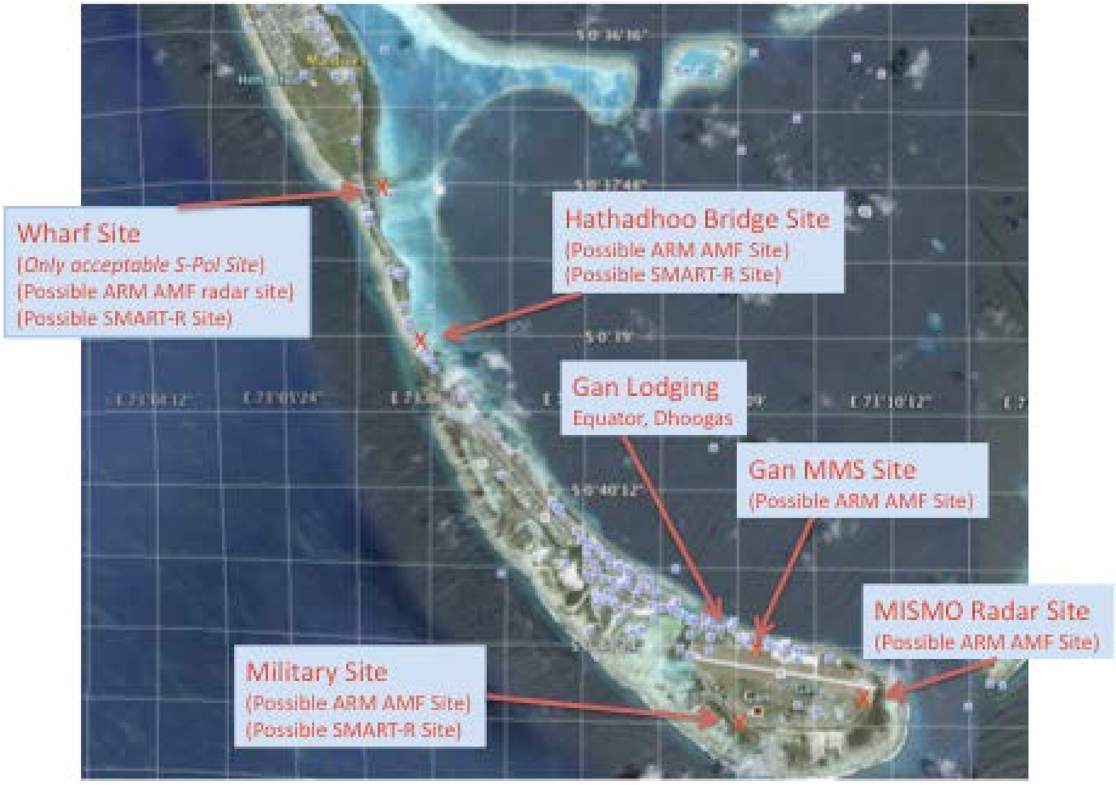


Figure A.2. Potential sites for DYNAMO radars on southern portion of Addu Atoll.

All islands in the Addu Atoll that are linked by road from the island of Gan were thoroughly searched for radar sites. The islands are flat and forested by tall Palms and Iron Wood trees that can reach heights of 100-150 ft. All sites have tree obstructions that limit the quality of low-level scans. Since the ocean is easily seen from all sites sea clutter will also be a data quality issue.

This report is focused on possible sites for the scanning radars. This means the ability to have unobstructed horizon views down to almost zero degrees is desirable. Figures A.2 and A.3 show how the surveyed sites sit on the islands that make up the west side of the atoll.

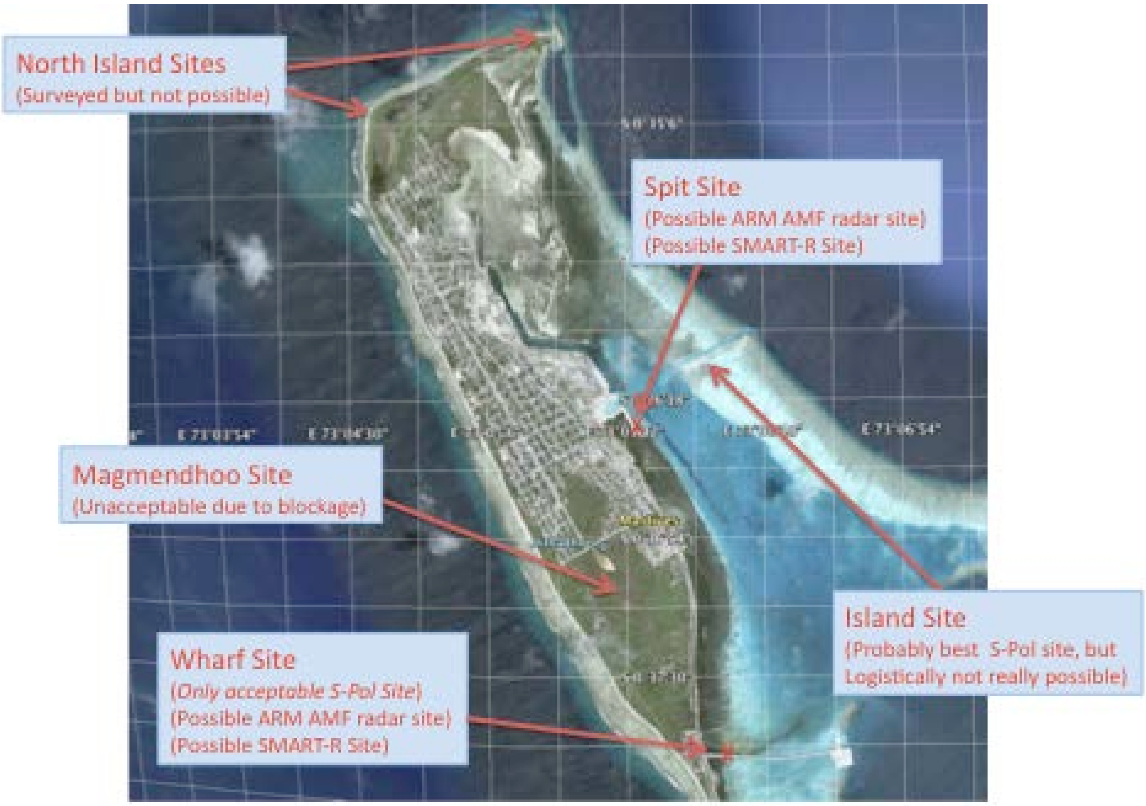


Figure A.3. Potential sites for DYNAMO radars on northern portion of Addu Atoll

Photographic panoramas were prepared for the discussed sites and are available from EOL. Chuck Long transferred our pictures into panoramas using some newly available software from Microsoft. The panoramas include rough estimates of the elevation angle of the horizon and direction of view. The direction and horizon elevation angles should be considered rough estimates, for they were obtained with hand-held devices atop a 20-ft shaky ladder contraption

Site Name	Latitude	Longitude
Military	00° 41.05' S	73° 08.30' E
Gan MMS	00° 41.251' S	73° 09.00' E
Hithadhoo Bridge (West)	00° 39.085' S	73° 06.467' E
Hithadhoo Bridge (East)	00° 39.047' S	73° 06.475' E
Wharf	00° 37.826' S	73° 06.175' E
Spit	00° 36.453' S	73° 05.748' E
Magmendhoo	00° 37.188' S	73° 05.894' E

There are only two sites that provide reasonable low-elevation angle 360° azimuth views. They are called the Wharf and Spit Sites. We note two other locations called the Hithadhoo Bridge and Military sites that offer at least 180° unobstructed views over the water. These sites may be of interest to the SMART-R if it chooses to be mobile to focus on precipitation in a specific direction.

The Wharf Site is the only site suitable for S-Pol, with the exception of a small island off the coast from the Spit site that would present some very interesting logistic challenges. The Wharf Site would also be the desired location for the scanning DOE radars. Because of the lower height of the DOE and SMART-R radars, the blocking will be somewhat greater at the Wharf Site than indicated by the measurements taken at 20 ft. If the SMART-R chooses to be only at a fixed site, suitable locations would be limited to the Spit and Wharf Sites.

The entire eastern semicircle exposure from the Wharf Site is an unobstructed view over the ocean with the exception of a 5–10 degree sector extending to a maximum of 1.5 degrees directly to the east caused by the buildings at the far end of the man-made wharf. It is roughly estimated that sea clutter will extend to a radar range of at least 20 km, but this will require further analysis.

Palm trees and ironwood trees make up the horizon in the western semicircle. The highest obstruction is 3 to 3.5 degrees centered at roughly 320 degrees caused by 150-ft high ironwood trees. Tree blockage of 2 degrees or more extends over 60 degrees from an azimuth of 270 to 330 degrees. Tree blockage greater than 1 degree is present between roughly 220 and 330 degrees. It is possible the ironwood trees will be cut back some.

The Spit Site is suitable for the SMART-R and possibly one or two components of the ARM AMF. Access is via a narrow sand/coral road. The road will require some widening and repair. The site has a 360° view that is as good or better than the Wharf site. There is a 200-degree unobstructed eastern view over the water from about 170° through 90° to 330°. The western horizon has tree blockage that is mostly between 1 and 2 degrees. There is one small group of trees less than 10 degrees in azimuth near 230° (SW) that extends to an elevation of 5 degrees.

We examined the potential for a radar site on the very southern tip of the Addu Atoll on Gan Island. This is the Military Site and is south of the airport along the southern edge of the island. It could be a possible site for the SMART-R. This site has a 210 degree unobstructed view over the Ocean towards from SE (120°) through S to NW (330°). In all other directions there is major blockage by underbrush and trees. The Maldives Defense Force would have to clear a site for the radar.

An additional panorama is provided for a site called Magmendhoo, although it was rejected because of excessive blockage. Much time was spent around this location with the 20-ft ladder in hopes of finding a suitable S-Pol site. Two other panoramas are included for the proposed ARM AMF2 main site: one near the Gan MMS office and the other at the former MISMO radar site. Of these, the Gan MMS office site is the preferable location for the AMF2 main site and was discussed with Mr. Wafir by Chuck Long.

A.3.1 Radar Issues

Male Radar – The Male Weather Service has a recently acquired an EEC, S-band, 1- or 1.5-degree, Doppler Radar. It is on a tower near the Male airport. It was given to them by a disaster relief organization following the tsunami that occurred in that part of the world a year or two ago. The radar has very limited archive capability and presently the link between the radar and weather service is broken. I saw one reflectivity image. They have no expertise in how to use the radar. This is an opportunity for some technology transfer by the project. I would think data from this radar would be of use to DYNAMO since it should be quality data.

Radar sea clutter and clear air return – Sea clutter could be a significant issue, particularly at S-band. The Male radar would be very useful for evaluating the degree of clutter and for testing sea clutter mitigation software. When S-Pol was in the Caribbean, clear-air Bragg return was common over the ocean. This can be very useful for mapping winds. Again the Male radar could be helpful in determining if this may be the case in the Maldives also.

Lightning and outflows – We were told that lightning was infrequent during the October–December period and more common at other times. We experienced lightning on three different occasions while on Gan. One occurred during the middle of the night, dumping 57 mm of rain in less than an hour. One afternoon we experienced a large gust front from a line of storms over the ocean. It was accompanied by a roll-cloud and little rain.

RHI's over the Gan airport – DOE will probably install their vertically pointing radar and lidar at the Gan airport. Thus, RHI scans over the Gan airport are desirable. From both the Wharf and Spit sites there is no blockage in the direction of the airport, while from the spit site the wharf building is in line-of-sight. However, given that the Spit Site is about 2.5 km to the north of the wharf (thus the building is low in the view), and given the lower range gate limits of the ARM vertically pointing radar, excellent RHI will be possible from either site.

A.4 Other Comments of Note

- Do not drink the tap water on Addu Atoll; bathing in it seems to be okay.
- A large quantity of drinking water will be required for a DYNAMO deployment on Addu Atoll. Judging from water consumption by the participants, I would estimate no less than 2 liters per person per day while in the field.
- The GSM telephone worked well throughout our visit. Service was reliable near Gan Island. There do seem to be some "dead areas" for cell coverage.
- We recommend purchasing local cell phone service (using local phones from Dhriaggu Telephone Co.). Same rates apply for all calls throughout the island chain.
- While we will work with the local ISP to have Internet Service at the project sites, one can also purchase wireless "hot spot" access throughout the islands. It was reliable in two locations but did not work in a third. In addition, it appears the NCAR spam filters block messages coming through that system, at least for some folks.
- There is electrical activity in the storms in this region. We experienced lightning and thunder in nocturnal storms on two evenings during our stay.
- The composition of the surface layer on the Addu Atoll is basically coral and sand. Surface water from heavy rains seeps through the surface layer very quickly, although the road areas did have large puddles following the heavy rain.
- We were told that rental cars are available on the island but we did not see a named rental agency (Hertz, Avis, etc.) sign or office during our visit. Motor scooters may be an option. There do seem to be rental locations but only by local shop owners that I saw.

- A major caution in the scheduling of air travel to the Maldives: one must allow ample time to connect from one flight to another in Dubai. It appears a minimum of 3 hours between flights in Dubai is required to avoid being closed out of a flight an hour before scheduled departure.
- We stayed at the Relax Hotel in Male City the first night we arrived. It was okay, with internet access.
- We stayed at the Dhoogas Hotel our first night in Gan. It was very basic and is definitely the second choice to the Equator Village.
- We stayed at the Equator Village Resort for 2 nights on Gan. It was adequate lodging with meals served three times a day if required. It had Internet access that we judged to be the most expensive we have ever heard of ($17 for 15 minutes).
- We stayed at the Hulule Island Resort on our last night in the Maldives. It is very nice but over-priced. It had Internet access.

A.5 Contact Information During the DYNAMO Site Survey Trip

International Calling country code +960

Maldives Meteorological Service:		
Mr. Ali Wafir	MMS Director, Gan MSS Office	778-7564
Mr. Mohamed	MMS Meteorologist (Our Guide)	779-4710
Asia Forwarding Shipping Agent in Maldives (Male and Gan):		
Mr. Mohamed Ahmed Ziyadh	Asia Forwarding Private Limited	777-5917
Mr. Ishan	Asia Forwarding	-
Mr. Ali Nizar	Asia Forwarding, Gan Agent, (Bluelink Maldives)	777-5729
Maldives South Province Office:		
Mr. Ali Mohamed	Deputy State Minister	688-8657
Mr. Abdullah Sopig	Atoll Council	792-4030
Equator Village Resort:		
Mr. T R Sathya Narayanan	Hulule Island Resort, Rooms Division Manager	777-7726
Mr. S. Visvalingam	Hotel Manager	689-8019 689-8721
Dhiraagu Communications (Cell phone and Internet provider):		
Mr. Mumthaz Hussain	-	688-7545

Appendix B

Gan Radar Sites Panoramas and Elevations

Appendix B:

Gan Radar Sites Panoramas and Elevations

WHARF SITE
S 00 deg, 37.826 min
E 073 deg, 06.175 min

Comments:

This is the only site suitable for S-Pol. This is because of the overall horizon and logistics. Logistically it is very easy, since it can be driven onto directly off the main road. The surface is flat, reclaimed land of hard-packed sand/coral. Power is readily available along the road, which is no more than 350 m away. Also, wide-band high-speed internet is easily available. This site is large enough to accommodate any other instrumentation.

The entire eastern semicircle is an unobstructed view over the ocean with the exception of a 5–10 degree sector extending to a maximum of 1.5 degrees directly to the east caused by the wharf buildings. It is roughly estimated that sea clutter will extend to a radar range of at least 20 km, but this is uncertain.

Palm trees and ironwood trees make up the horizon in the western semicircle. The highest obstruction is 3 to 3.5 degrees, centered at roughly 320 degrees caused by 150-ft high ironwood trees. Tree blockage of 2 degrees or more extends over 60 degrees from an azimuth of 270 to 330 degrees. Tree blockage greater than 1 degrees is present between roughly 220 and 330 degrees. It is possible the ironwood trees will be cut back some.

Panoramas and selected elevations:

SPIT SITE
S 00 deg 36.453 min
E 073 deg 05.748 min

Comments:

This site is not suitable for the S-Pol, but is suitable for the SMART-R and ARM scanning radars with some modest expansion. Access is via a narrow sand/coral road. The road will require some minor repair. The site has a 360-degree view that is as good as or better than the Wharf Site. There is a 200-degree virtually unobstructed eastern view over the water from about 170 degrees through 90 degrees to 330 degrees.

The western horizon has tree blockage that is mostly between 1 and 2 degrees. There is one small group of trees less than 10 degrees in azimuth near 230 degrees that extends to an elevation of 5 degrees.

Note: Just east of this location is a small reclaimed island that would make an excellent S-pol site. It is marked in the panorama .The entire horizon might be below 1 degree. It would be a significant challenge but worth keeping in mind if difficulties arise with the Wharf Site.

Panoramas:


180
230


270
360

Appendix C

Gan MMS Site Panorama and Description

Appendix C:

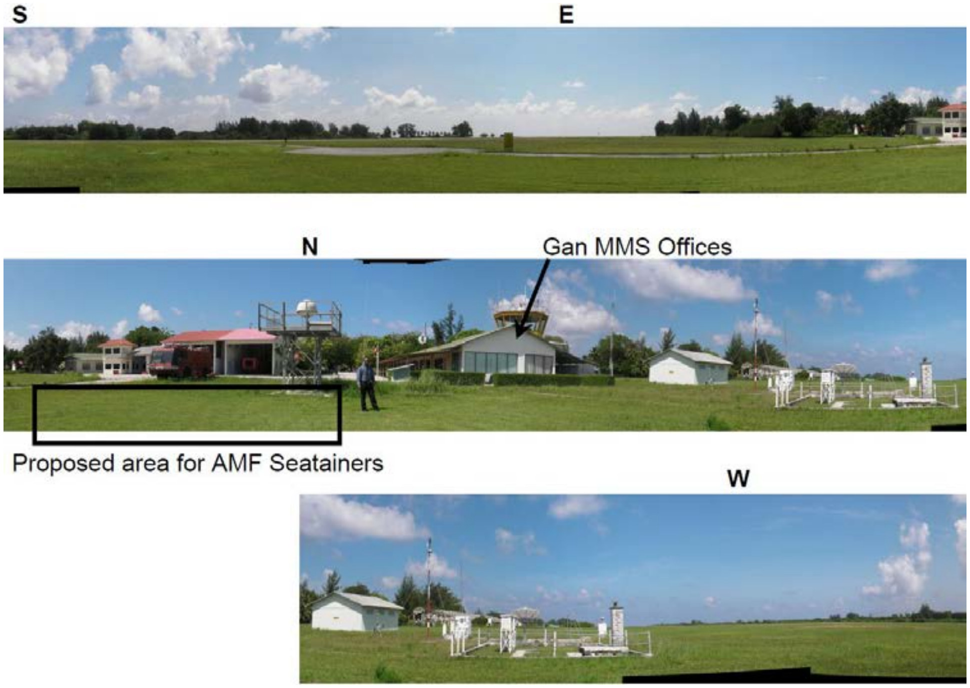
Gan MMS Site Panorama and Description

Gan MMS Main Site
S -0.0690481 deg
E 73.150048 deg

Comments:

This site is at the airport and next to the Gan MMS offices headed by Mr. Ali Wafir. This site is intended for all the AMF equipment with the exception of the scanning X- and Ka-band radar, which will be deployed along with the SMART-R at either the Wharf or Spit sites. The MMS site affords adequate room for the AMF seatainers as well as the other instrumentation, such as the surface radiometry, microwave radiometer, etc. The MMS sondes are currently launched at this location, and Mr. Wafir was open to the possibility of arrangements for his staff helping with the additional sonde launches for AMIE. There are restrictions on the height allowed based on a formula depending on distance from the center of the airport runway. Given the GPS sonde antenna (to the left of Mr. Mohamed, MMS Meteorologist pictured below) and the red and white MMS tower to the left of the MMS instruments area (just to the right below the "s" in Offices), it was determined that locating the 10-m MET and downward-facing radiometers tower nearby will meet the restrictions. Additionally, the runway runs roughly E-W, thus causing minimal line-of-sight blockage for the sunrise/sunset direct-sun or MWR tipcals if oriented that way. Overall, given the available space, power, communications, and MMS Office help, this is an ideal location for the AMF "main" site.

Panorama photos:



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