B. PROJECT SUMMARY

DYNAMO is a US research program motivated by two outstanding problems:

(i) Current prediction skill for the Madden-Julian Oscillation (MJO) is very limited and, particularly, the lowest for the MJO initiation phase over the Indian Ocean.

(ii) The inability of state-of-the-art global models to produce the MJO degrades their seasonal to interannual prediction and lessens our confidence in their ability to project future climate.

The overarching goal of DYNAMO is to expedite our understanding of processes key to MJO initiation over the Indian Ocean and efforts to improve simulation and prediction of the MJO.

DYNAMO consists of four integrated components: field observations, data analysis, modeling, and forecasting. The DYNAMO field campaign is proposed as the US component of CINDY2011 (*Cooperative Indian Ocean Experiment on Intraseasonal Variability in Year 2011*), an international field program planned for October 2011 – March 2012 in the equatorial central Indian Ocean region. Four countries (Australia, India, Japan, and the US) will participate. This field program is designed to observe the structure and evolution of cloud populations, their interaction with the large-scale environment, and air-sea interaction processes during MJO initiation. Measurements of the surface and atmospheric profiles will take place from a quadrilateral sounding array. Multiple radars over a span of five wavelengths will operate at an island "supersite" and aboard two ships. Air-sea fluxes, marine atmospheric boundary layer, and upper-ocean large-scale and mixing structures will be measured from ships and moorings. The DYNAMO data analysis will compare and integrate field observations with auxiliary data (from moorings, satellites, and global reanalyses), and provide model constraint, validation and evaluation. The DYNAMO modeling activity will adopt a hierarchy of numerical models of different configurations and complexities from research and operation institutes to quantify empirical results, test hypotheses, and experiment with new physical representations. The DYNAMO forecasting activity will, in the long term, explore multi-model ensemble MJO prediction and its improvement through better model physical representations and, in the short term, develop new empirical methods for predicting MJO initiation based on DYNAMO data.

The timing of late 2011 – early 2012 is critical for DYNAMO's success. Only during this period can DYNAMO benefit from multi-nation coordinated efforts, a climate observing system (RAMA), and a constellation of environmental satellites (TRMM, A-TRAIN) all at the same time. Such an opportunity for a research program on the air-sea coupled climate system in the tropical Indian Ocean region is extremely rare: never before, not in the foreseeable future.

Intellectual Merit: DYNAMO hypotheses focus on three aspects key to MJO initiation: interaction between environmental moisture and convection, the dynamic evolution of the cloud population, and air-sea interaction. DYNAMO will particularly target processes deemed critical to MJO initiation but poorly observed and understood: shallow cloud moistening, convective sensitivity to environmental moisture, low- vs. upper-level diabatic heating, cloud microphysics, convective organization, large-scale moisture advection and convergence, surface evaporation, 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.

Broader impact: DYNAMO will introduce young scientists, including graduate students, to complex multi-scale and air-sea interaction problems in the tropical climate system. DYNAMO observations will be used to calibrate and validate satellite retrievals, benefiting their application to much broader areas beyond MJO-related problems. Improved MJO simulation and prediction born from DYNAMO activities will enhance the capacity to deliver prediction and assessment products on intraseasonal timescales for societal risk management and decision making, and to strengthen confidence in climate simulation and projection.

D. PROJECT DESCRIPTION

1. Background

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 (Fig. 1)[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 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 US 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).

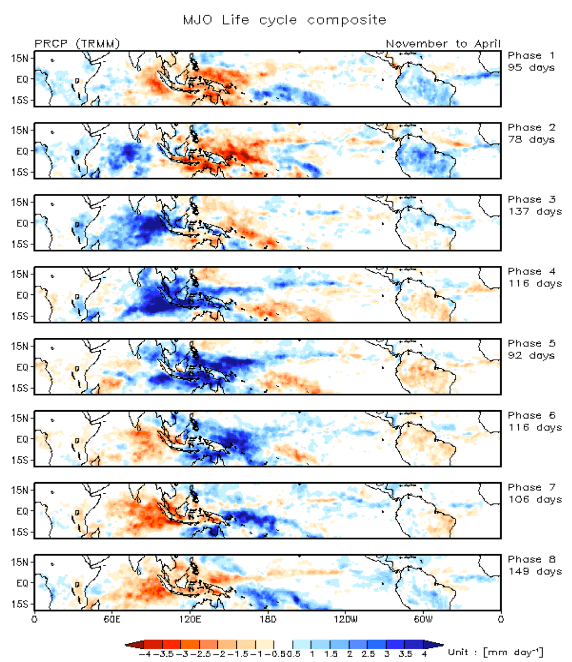

Figure 1 Composite MJO precipitation anomalies in eight phases (Courtesy of US CLIVAR MJO Working Group)

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/NCEP/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), US government (e.g., 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 (Fig. 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 under-estimate the strength of the MJO over the Indian Ocean (Zhang et al. 2006; Benedict and Randall 2009) or are unable to

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[1] Because the DYNAMO field campaign is planned for October – March, all discussions in this document pertain to the MJO in boreal winter.

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.

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 2007; 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.

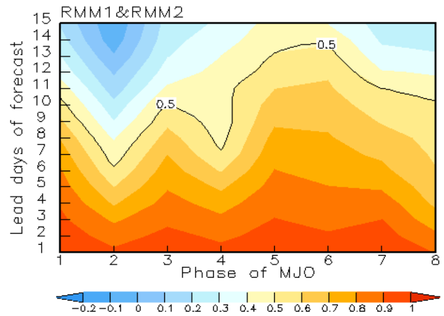

Figure 2 Correlation between observed Wheeler and Hendon (2004) MJO index and its prediction by the NCEP Global Forecast System (GFS). (Courtesy of Jon Gottschalck and Qin Zhang)

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., GATE, TOGA COARE). The stunning 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 (*Cooperative Indian Ocean Experiment on Intraseasonal Variability in Year 2011*), 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 proposed as the US component of CINDY2011. This international collaboration and program synergy (see sections 4 and 6) will provide integrated and complementary observations of MJO events at different stages of their lifecycle. The timing of late 2011 – early 2012 is critical for DYNAMO to be an integrated part of the multi-nation coordinated efforts and maximize the value of its observational products.

2. Scientific Problems and Hypotheses

2.1 Nature of the Problem

Examples of MJO events in Fig. 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[2]. 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. They 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?

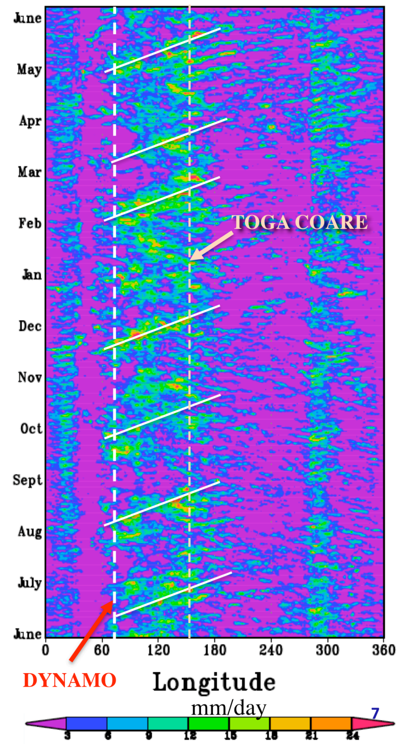

Figure 3 Time-longitude diagram of daily GPCP combined precipitation (Huffman et al. 1997) averaged over 10°S-10°N from June 2000 through May 2001. Solid lines, corresponding to eastward speed of 5 ms^{-1}, mark MJO events. The longitudes of TOGA COARE and DYNAMO are indicated by the dashed lines.

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 Tropical Western Pacific sites at Manus, Nauru, and Darwin have also provided long-term observations for the study of the MJO, especially regarding cloud-radiation interactions (Mather et al. 2007). In contrast, there is a stunning 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[3], McPhaden et al. 2009) has yet to be completed.

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 lifecycle over the two oceans. A well-established large-scale circulation pattern (Wang and Rui 1990) is closely

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[2] In this document, "MJO scale" refers to spatial scales of 10^3 – 10^4 km in longitude and 10^3 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.

[3] The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction

coupled with deep convection for the mature MJO propagating over the western Pacific but 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 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:

(i) 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).

(ii) 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).

(iii) 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 (i) is to instigate local processes in (ii) 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 (Fig. 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 Fig. 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 meso- 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 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 2.3a and b).

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 2.3b). Low-level cooling typically associated with stratiform precipitation remains minimal until the end (section 2.3b).

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 2.3c).

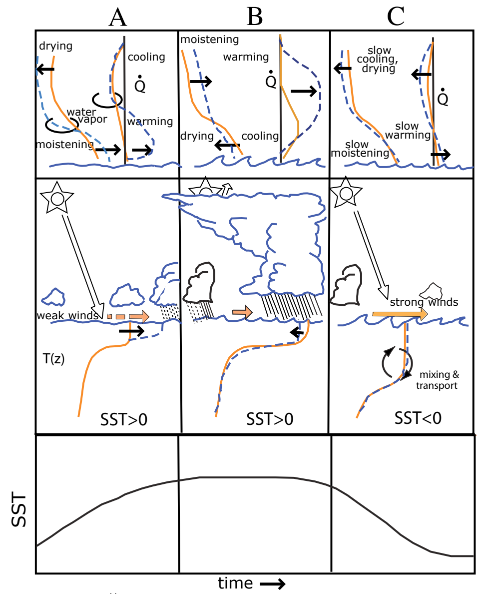

Figure 4 Schematic of a conceptual model for MJO initiation processes at a fixed location over the Indian Ocean. Upper panels illustrate tendency of moisture and diabatic heating profiles; middle panels depict cloud compositions, surface winds, and upper-ocean temperature profiles; lower-panel shows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

The transitions from stages A to B and B to C can occur relatively quickly compared to the duration of each stage (Fig. 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. DYNAMO will focus primarily on processes that need to be quantified via field observations from the Indian Ocean region. DYNAMO hypotheses emphasize three aspects key to MJO initiation: interaction between convection and environmental moisture, the evolution of cloud populations, and air-sea interaction. Inadequate representations of these processes in numerical models may inhibit accurate simulation and prediction of MJO initiation.

2.3a 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 Fig. 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. 2006). These results have yet to yield a clear understanding of the essential physics of the convective sensitivity to environmental moisture. Meanwhile, tuning model parameterizations for better MJO simulations often degrades 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 I: 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 II (section 2.3b). 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 2007), and surface evaporation (Sobel et al. 2008, 2010), which may include positive SST feedbacks to the MJO (Waliser 1999). The strengths of these and other effects may determine the timescales of MJO initiation, such as the prolonged stage A (Fig. 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 DYNAMO field data and on large scales using global reanalysis products and numerical models, after their reliability for this purpose is assessed using DYNAMO observations. DYNAMO 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 and radars). Hypothesis I 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 2010), vertical wind shear (Moncrieff and Green 1972), and momentum transport (Moncrieff and Klinker 1997; Moncrieff 2004; Majda and Stechmann 2009).

2.3b 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 lifecycle stages, different cloud types take on greater or lesser importance, with a different predominant cloud type in each stage (Lau and Wu 2009). The same type of convective cloud may play different roles at different stages. DYNAMO focuses on two possible roles of clouds in MJO initiation: moistening through detrainment 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. 2009), global reanalyses (Sperber 2003), and modeling (Thayer-Calder and Randall 2009). The prolonged (≥ 30 days) pre-onset stage (A in Fig. 4) implies that this moistening is a slow process against large-scale drying effects (subsidence, advection, etc.) and alone 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 and Held 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 Fig. 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).

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 II: 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 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 Q_1 and moisture sink Q_2 (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 II.

A large-scale tilt in latent heating profiles is also implied in Hypothesis II, 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 (section 6) 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 Q_1 derived from the DYNAMO sounding and radar observations will be used to investigate the large-scale evolution in heating profiles during MJO initiation. 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.

2.3c 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: the Seychelles-Chagos thermocline ridge and the Wyrtki jets, let alone detailed characteristics of upper-ocean mixing. Most of these studies used slab mixed-layer models with no ocean dynamics at all. 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.

Air-sea interaction processes associated with the MJO in the Indian and western Pacific Oceans can differ for several reasons. An MJO convective center and maximum large-scale surface wind anomalies tend to be collocated over the western Pacific (Zhang and McPhaden 2000, Fig. 5a). The combined enhancement of surface evaporation and reduction in insolation leads to strong surface cooling, which is quickly redistributed downward by strong wind-driven mixing that can erode away a barrier layer (Lukas and Lindstrom 1991; Cronin and McPhaden 2002). Because of the deep thermocline, only occasionally does entrainment cooling significantly contribute to the upper ocean heat budget (Cronin and McPhaden 1997). Intraseasonal perturbations in mixed-layer temperature and SST are controlled mainly by surface fluxes (Shinoda and Hendon 2001). SST rapidly decreases underneath the MJO convection center, where deep convection draws energy from surface evaporation enhanced by strong MJO-scale winds (Maloney and Sobel 2004) and large-scale moisture convergence (Maloney 2009).

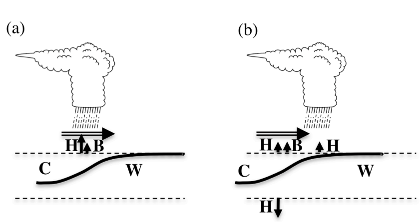

Fig. 5 Schematic diagrams illustrating air-sea interaction processes in the western Pacific (a) and Indian Ocean (b). Cloud symbols represent MJO convective centers. Horizontal arrows indicate maximum surface wind. Parallel dashed lines mark the ocean mixed layer. Letters H, B, C, and W denote heat and buoyancy fluxes, and cold and warm mixed layer, respectively. Thick curves illustrate changes in SST.

It is a different story in the Indian Ocean. There, strong surface zonal wind anomalies tend to start at the end of a convectively active phase (stage B in Fig. 4) and extend west of an MJO convective center (Zhang et al. 2005, Fig. 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, the

the upper-ocean mixing is not very strong and the barrier-layer is strengthened due to freshwater input from rainfall. Night-time 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:

Hypothesis III: 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.

With anticipation that surprises may present themselves, the following questions related to this hypothesis are posed to focus on specific processes during MJO initiation:

- What are the relative contributions from perturbations in wind (on both large and meso scales), surface humidity, and SST to the surface flux feedback? (also see Hypothesis I.)
- How does the barrier layer evolve through the MJO initiation stages and what controls it? What is its role in intraseasonal perturbations of the upper-ocean heat content and SST?
- How is the intraseasonal evolution in the upper-ocean structure affected by diurnal mixing, fluctuations in surface momentum and buoyancy fluxes, and current shears?
- What are the contributions from surface fluxes, entrainment, and horizontal advection by transient currents to the evolution in the upper ocean heat budget and SST?

Detailed DYNAMO field measurement of air-sea interaction (section 3.1) will provide necessary information for quantitatively addressing these questions and thereby testing Hypothesis III through data analyses and modeling. In addition, DYNAMO oceanic observations, in combination with the RAMA data, will help explore the unique role of the MJO in modulating the basin-wide seasonal ocean heat transport in the Indian Ocean (Loschnigg and Webster 2000).

3. Program Objectives and Structure

The overarching goal of DYNAMO is to expedite our understanding of MJO initiation processes and efforts to improve simulation and prediction of the MJO. The specific 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 DYNAMO Science Steering Committee, 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 DYNAMO field campaign is to collect observations of MJO initiation processes that are urgently needed for DYNAMO hypothesis testing through data analysis and modeling.

The DYNAMO field campaign is an integrated part of CINDY2011. As such, "DYNAMO" in the context of the field campaign should be taken as "DYNAMO/CINDY2011". The field campaign, described in detail in the DYNAMO Experimental Design Overview (EDO), 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.

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. Ships from Australia, India, Japan, and the US will participate in the formation of the array. 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 (see below). After the IOP we will continue the observations on Gan with reduced capacity through an Extended Observing Period (EOP) lasting until 31 March 2012. Detailed discussions of the timing and location of the DYNAMO field campaign in the context of climatology are given in the EDO. 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 8 times per day during the SOP and 4 times per day during the rest of the field campaign. The sounding observations are critical to testing all three DYNAMO hypotheses. The value of the sounding network in relation to the science objectives of DYNAMO is its ability to provide (i) diagnosed divergence and diabatic heating profiles to aid interpretations of evolving convection during MJO initiation, (ii) a robust estimate of the large-scale state of the atmosphere, and (iii) forcing fields for 1-dimensional (1-D) and limited-domain models (section 3.3).

Radars: The objective of the DYNAMO radar observations is to fully characterize the ensemble of convection associated with each stage of MJO initiation. Three radar systems (NCAR S-PolKa, Texas A&M SMART-R, and DOE/ARM AMF2), providing five wavelengths (S, C, X, K_a 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 SMART-R and AMF2 (including soundings) will operate through the entire EOP. 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 S-PolKa radar will provide key information on the microphysics of precipitating clouds via S-band polarimetric measurements. The K_a-band capability of S-PolKa will provide unprecedented observations of non-precipitating clouds, total cloud liquid water content, and 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 during DYNAMO 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 I and II and extremely useful for validating and analyzing satellite retrievals and model simulations.

Air-sea interaction measurements: The objective of the air-sea interaction measurements is to document the variability of surface fluxes of momentum, heat, and buoyancy at all stages of MJO initiation and the simultaneous evolution in the large-scale and mixing structures of the upper ocean and the marine atmospheric boundary layer (MABL). The ship-based Doppler lidar will provide continuous profiles of horizontal wind, vertical dynamics and turbulence within the clear MABL. The combined lidar and collocated W-band radar measurements will be used to characterize the strength of the vertical mixing and dynamics driving MABL evolution, coupling of the MABL to the lower free troposphere, and possible preconditioning associated with convective initiation (Hypotheses I and II). Special instruments measuring high resolution mixing in the upper ocean will be outfit on three new moorings and three existing RAMA moorings inside and near the sounding array. Bulk estimate of surface fluxes of sensible and latent heat, surface solar/IR radiation, rainfall and other surface meteorological variable, SST, vertical profiles of upper-ocean temperature, salinity, velocity, and mixing will be measured from the ships and moorings. Turbulent surface fluxes of sensible and latent heat will be continuously measured from the ships. These measurements are central to test Hypothesis III through analyses of upper ocean heat and energy transport/budgets, structure and evolution of the surface mixed layer, barrier layer and thermocline; and to test Hypotheses I and II through using surface fluxes.

3.2 Data Analysis

The objective of the DYNAMO data analysis is to assist hypothesis testing through exploring empirical relationships among observed variables, evaluating auxiliary data of longer and broader coverage for statistical robustness of the empirical relationships, and preparing data to constrain, validate and evaluate model simulations

DYNAMO observations to be collected by individual instruments will be analyzed in depth to reveal useful information on their own. But the value of DYNAMO observations will be maximized through integration of data from various instruments, the auxiliary data (from moorings, satellites, and reanalyses), and other partner programs (section 5). For example, the evolution of the cloud population (observed by the radars) with their large-scale environmental moisture field (observed by soundings) will be monitored for testing Hypothesis II; the modulation of the moist layer by local processes such as surface evaporation (measured by air-sea instruments) and by the local or external large-scale circulation (measured locally by soundings and described globally by reanalysis products) will be compared for testing Hypothesis I.

DYNAMO field observations will be extremely useful to validate and calibrate satellite data (e.g., TRMM, CloudSat, AIRS, SeaWinds, MODIS, and Megha Tropiques). For example, DYNAMO radars will provide the first ground validation for CloudSat over the tropical Indian Ocean. Validated satellites will be used to assess the representativeness and statistical robustness of DYANMO field observations. It is extremely important to use DYNAMO field observations to assess the quality of global reanalysis products for the study of MJO initiation, because many key variables (e.g., humidity, precipitation, surface wind and evaporation) are highly influenced by physical parameterizations in the models used for data assimilation and thus of uncertain quality. A case in point is that profiles of temperature and moisture from the NCEP/NCAR reanalysis and AIRS satellite differ significantly over the Indian Ocean (Tian et al. 2006), indicating the need of *in situ* observations. In a similar vein, DYNAMO oceanic data will be used to quantify the extent to which RAMA data can accurately describe air-sea interaction processes during MJO initiation.

Estimates of heating profiles based on sounding data from previous field campaigns have served as the ground truth for those using TRMM data (Tao et al. 2006) and reanalysis products (Hagos et al. 2009). DYNAMO sounding observations will provide the only time series of heating profiles through the MJO lifecycle in the Indian Ocean. Both standard objective analysis schemes and constrained variational analysis procedures (Zhang and Lin 1997) will be used to compute heating profiles. In the latter case, it is advantageous to obtain precipitation mapping over the entire area enclosed by the sounding array. Because the DYNAMO radar coverage is not sufficient to encompass the entire array, other constraints such as satellite-based TOA radiative fluxes, surface fluxes, etc., will be used. To extend the period of computations beyond the IOP, single-sounding and radar data from Gan Island will be combined with numerical weather prediction data to estimate latent heating profiles using a procedure described by Xie et al. (2004). Budget estimates thus derived and other observations will be used to constrain 1-D and limited-domain models and to validate/evaluate all model simulations.

3.3 Modeling

The objectives of the DYNAMO modeling activity are to quantitatively test the DYNAMO hypotheses, identify deficiencies in numerical models critically responsible for the low prediction skill and poor simulations of MJO initiation, and provide a better physical basis for model improvement.

DYNAMO is in large part motivated by modeling problems, namely poor representation of the MJO in the Indian Ocean and low prediction skill for MJO initiation. MJO modeling studies have strongly informed the basis for the DYNAMO hypotheses (section 2). DYNAMO field observations will be essential to constrain, validate, and evaluate numerical models for hypothesis testing and model improvement investigations. The DYNAMO modeling working group brings together expertise in using atmosphere and ocean models of different complexities and configurations from universities and operation/research centers.

One-dimensional (1-D) and limited-domain modeling: A direct interface between field observations and modeling is through 1-D models (Randall et al. 1996), including atmospheric single-column models and ocean mixed-layer models. Forcing datasets from DYNAMO and complementary ARM products provide opportunities to assess the ability of model parameterizations to respond to factors such as tropospheric moistening and temperature variations in advance of MJO initiation. These models, when constrained by field observations (e.g., soundings and surface fluxes) and data assimilation products, will be used to calibrate and improve parameterizations and for hypothesis testing. The sensitivity of convective closures (Neale et al. 2008) and entrainment specifications (Bechtold et al. 2008) to environmental humidity will be optimized by 1-D model experiments, which have given demonstrable improvements to MJO simulations and predictions. Synergy exists with recent studies that use satellite-derived thermodynamic profiles to derive convective entrainment rates (Luo et al. 2009).

Cloud system resolving models (CSRMs) and large-eddy simulation (LES) models over limited domains will be used to gain insight into convective processes in DYNAMO. Simulations driven with forcing derived from DYNAMO observations provide an important test for these models. To the extent the models perform well, the results from these simulations can provide information on fields and processes that are not measured directly. In addition to standard ways of forcing by vertical velocities or advective tendencies, methods exist to constrain convection less directly by parameterizing, rather than prescribing, large-scale dynamics (Sobel and Bretherton 2000; Mapes 2004; Derbyshire et al. 2004; Raymond 2007; Kuang 2008). These methods can provide new information, e.g. for parameterization improvement (Raymond and Zeng 2005), but have not yet been used in conjunction with field observations. Experimental efforts to do this will be undertaken in DYNAMO.

Three-dimensional (3-D) modeling: Field observations and auxiliary data (section 5) will be used to evaluate 3-D models of the atmosphere, ocean, and coupled system, focusing on their ability to simulate the processes associated with MJO initiation. Emphases include the moisture budget (the role of clouds, advection, and surface fluxes), cloud population distributions and their aggregated effects (heating and moistening), and the upper-ocean structure (thermocline, mixed layer, barrier layer, and mixing profiles). Numerical sensitivity experiments will be performed to substantiate hypothesis testing in combination with data analysis.

DYNAMO is unique relative to other major field programs of the last several decades (e.g., GATE, TOGA-COARE) because it will occur after the advent of global CSRMs and the multi-scale modeling framework, both of which show great improvements in MJO simulation compared to GCMs (e.g., Miura et al. 2007, Khairoutdinov et al. 2008, Benedict and Randall 2008). These models, validated and evaluated by observations in DYNAMO, will help examine the multi-scale interactions that trigger Indian Ocean MJO convective events.

A major component of the DYNAMO modeling effort will involve forecast experiments, with operational forecasting models, global climate models, and regional coupled models. Operational forecasts and reforecasts and their validation may reveal root causes for low prediction skill. An instructive example is the recent improvements in MJO forecast skill at ECMWF provided by modifications to the parameterization of convective entrainment (Bechtold et al. 2008). Extended-range (beyond 15 days) reforecasts and recovery from archived real-time operational forecasts will be used to establish baseline forecast statistics to measure future improvement in MJO prediction.

Climate models as well as CSRMs (e.g., NICAM, NRCM) will be initialized using assimilated DYNAMO observations (section 4) and run in transpose AMIP mode, that is, short integrations with initial and boundary conditions taken from observational analyses (Boyer et al. 2008). Forecast errors can then be analyzed to identify physical deficiencies and improve parameterizations. These exercises, including comparison of GCM and CSRM results, will help to validate and evaluate multiscale model forecasts with DYNAMO observations, and provide guidance for improving the representation of processes in models with parameterized convection. Participation of multiple models in the reforecast exercises will help formulate strategies of multimodel ensemble forecast of the MJO. With the field observations, data denial experiments can be done to further identify sensitivities of forecast to certain variables at particular geographical locations and MJO phases. So far, several national operation/research centers and universities plan to participate in the DYNAMO forecast/reforecast exercises (section J).

3.4 Forecasts

The objectives of the DYNAMO forecast component are to provide real time forecast support to the DYNAMO field campaign, to develop prediction indices for MJO initiation, and to benchmark improvement in MJO prediction due to better model physical representations.

At NOAA/NCEP/CPC, operational MJO prediction has been established over the last few years with beneficiary products. Statistical forecast techniques and MJO composites, as well as dynamical model predictions from six operational forecast centers around the world (Gottschalck et al. 2009), perform well during established MJO events. However, operational prediction of MJO initiation currently remains very difficult, and is often forced to react to the MJO development after the fact rather than able to reliably predict its initiation (Fig. 2).

DYNAMO will help in this area in two ways. In the long-term effort, improving MJO representations in numerical models will benefit from the DYNAMO observational-modeling framework. The current operational forecast implementation provides practical measures for when and where MJO prediction skill is particularly limited and model results diverge. The ultimate legacy of DYNAMO will be an improvement of the operational MJO prediction based on more realistic model physical representation born from DYNAMO activities. Meanwhile, a better documentation of all stages of the MJO initiation process from the field observations, especially focused on important MJO variables and the hypothesized mechanisms outlined in Section 2, can yield immediate benefit to operational MJO prediction. For example, the current MJO monitoring is mainly based on the Wheeler-Hendon (2004) MJO index. While it is an excellent index to track the propagation of the MJO, it does not provide sufficient information about MJO initiation. Through DYNAMO, an empirical MJO initiation index will be developed, taking into account variables that may serve as critical precursors to MJO initiation.

Support for DYNAMO will be provided by a US CLIVAR MJO prediction project currently underway at NCEP/CPC, where real-time dynamical MJO forecasts are being made based on multiple numerical model output. Real-time MJO forecasts as a part of operational support for the DYNAMO field campaign will be provided by NCEP/CPC/EMC and NASA/GMAO.

4. DYNAMO data

DYNAMO data will consist of observations from its field campaign, auxiliary data from other sources, and output from numerical model simulations. A complete list of DYNAMO/CINDY2011 field instruments is given in the EDO. The auxiliary data will include those of longer and broader coverage from RAMA, satellites (e.g., TRMM, A-TRAIN), real-time prediction, and global reanalyses. In addition to real-time forecast support for the DYNAMO field campaign, NCEP/EMC/CPC, NASA/GMAO, and JAMSTEC all plan to provide post-field special reanalysis products that cover the field campaign period and assimilate field data not available to the GTS in real time (see EDO). Results from numerical modeling activities (section 3.3) supported by DYNAMO will be included in the DYNAMO data archive.

5. Readiness and Program Synergy

It is timely for the US research and operation communities to make significant contributions to the study of the MJO initiation by conducting a field campaign in late 2011 – early 2012. The DYNAMO observation-analysis-modeling-forecasting integrated approach will greatly benefit from the experience and framework of the WCRP-WWRP Year of Tropical Convection (YOTC, Waliser and Moncrieff 2008) and from the organized research activities regarding MJO simulation (CLIVAR MJO WG 2009; Kim et al. 2009a) and prediction (Gottschalck et al. 2009) under the guidance of the US CLIVAR MJO Working Group (Sperber and Waliser 2008), now reformed as the joint WCRP-WWRP MJO Task Force with a continued focus on model and forecast diagnostics/metrics and improvements. These research-operation frameworks will pave the way to connect field observations to modeling and forecasting activities. By late 2011, RAMA moorings directly relevant to the study of MJO initiation will be completed to provide climatic background information for the field campaign. The DYNAMO field campaign can serve as a science field experiment for the A-TRAIN satellite constellation and a ground validation experiment for Megha Tropiques, a France-India satellite mission to monitor the tropical water and energy cycles and associated convective evolution (scheduled to launch in early 2010). Recent advancement in observing technology (e.g., scanning K_a-band radar, dual-wavelength radar, and moored high-resolution mixing profilers) makes measurements unavailable before possible now. Most importantly, international collaboration of CINDY2011 and other programs to be in place in the time window of late 2011 – early 2012 and in the surrounding region of the Indian Ocean will collectively provide a comprehensive and complementary suite of observations across a large region covering the equatorial Indian Ocean, Maritime Continent, Northern Australia, and western Pacific Ocean (Fig. 6).

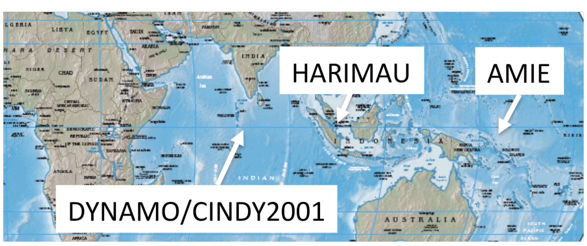

Figure 6 Partner programs of DYNAMO.

International participations in CINDY2011, including Japan, India, Australia, along with US, will be essential for the success of DYNAMO. The US support to this international program is expected to come from NSF, ONR, DOE, NOAA, and NASA. In addition to the DOE/ARM AMF2 to be proposed for DYNAMO, DOE has funded an enhanced observational period at the ARM western Pacific site on Manus Island (AMIE) during a six-month period overlapping with the DYNAMO EOP, with instrumentation almost identical to on Gan (see EDO for additional details). At the Darwin ARM site, instruments similar to those on Gan and Manus (see EDO) will operate and enhanced operational soundings (4 per day) will be launched during the DYNAMO field campaign. Through this DYNAMO-ARM collaboration, DYNAMO will also benefit from the considerable experience and expertise of the ARM modeling community in addressing tropical convection problems using modeling-observation integrated approaches.

HARIMAU is a joint project led by Indonesian and Japanese institutes. Its observational network (six sites equipped with C- and X-band Doppler radars, wind profilers, GPS sondes, and surface meteorological measurement including rain gauges) over the Indonesian Archipelago provides unique observations of MJO weakening over the Maritime Continent, an unsettled problem to both MJO understanding and prediction.

The joint effort of DYNAMO/CINDY2011 and these other activities will capture the same MJO events and their interaction with the ocean and land as they initiate over the Indian Ocean and propagate over the Maritime Continent and Northern Australia into the western Pacific (Fig. 6). This in situ monitoring of the MJO through its different stages of lifecycle across the two oceans has never been done. The resulting synergy will make the DYNAMO field campaign much more productive than it would as a stand-alone project. Such a rare opportunity of leveraging has never happened before and would probably not come again in the foreseeable future. This makes late 2011 – early 2012 a critical time for DYNAMO's success.

6. Relationship of DYNAMO to prior field campaigns

TOGA COARE: Data collected from the field campaign of Tropical Ocean Global Atmosphere (TOGA) Coupled Ocean Atmosphere Response Experiment (COARE) over the equatorial western Pacific during November 1992 – February 1993 helped elevate our awareness and understanding of the MJO, especially its air-sea interaction, multi-scale interaction, and convective sensitivity to moisture, to a new level. As pointed out many times in this document, knowledge from TOGA COARE helped plant the seeds for the DYNAMO hypotheses, but there are significant differences between the MJO over the Indian and western Pacific Oceans and between the background states of the two oceans. It suffices to say that DYNAMO will play as significant a role in expediting the study of MJO initiation as TOGA COARE did for the study of MJO propagation and maintenance.

MISMO (*Mirai Indian Ocean cruise for the Study of the Madden–Julian oscillation (MJO) - convection Onset*): As a pilot study of DYNAMO, it took place during 24 October - 25 November 2006 over the equatorial central Indian Ocean to investigate MJO initiation (Yoneyama et al. 2009). Because of its short duration, MISMO missed initiation of a major MJO event. MISMO results are beginning to emerge in the literature. MISMO experience is invaluable for DYNAMO in the scientific program, experimental design, and operational preparation and execution.

Vasco-Cirene: An air-sea interaction research cruise studying the MJO and Indian Ocean Dipole took place over the region of the Seychelles–Chagos thermocline ridge in January – February 2007 (Vialard et al. 2009). Measurements of upper-ocean profiles and air-sea interface were made, but without radar or oceanic mixing observations. This cruise provided supporting observations that serve as part of the basis for Hypothesis III of DYNAMO.

INDOEX, JASMINE, BOBMEX: These field campaigns all took place in the Indian Ocean in 1999. The Indian Ocean Experiment (INDOEX) focused on the radiative effects of South Asian aerosols (Ramanathan et al. 2001). The Joint Air–Sea Monsoon Interaction Experiment (JASMINE) studied the intraseasonal variability of the Indian summer monsoon (Webster et al. 2002). The Bay of Bengal Monsoon Experiment (BOBMEX) targeted at the variability of organized convection in that region (Bhat et al. 2001). They all deployed a single research vessel in the Asian summer monsoon season and did not capture MJO initiation.

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