DYNAMO

Dynamics of the MJO

SCIENTIFIC PROGRAM OVERVIEW

Project Summary: DYNAMO is the US component of CINDY2011 (*Cooperative Indian Ocean Experiment on Intraseasonal Variability in the Year 2011*), an international field program planned for late 2011 – early 2012 in the tropical central Indian Ocean region. DYNAMO is motivated by two facts: (i) Current MJO prediction skill is very limited (< 15 day) and it is the lowest at the MJO initiation stage in the Indian Ocean. (ii) The inability of reproducing the MJO by current state-of-the-art climate models has weakened our confidence in their fidelity. The ultimate goal of DYNAMO is to expedite progress in understanding the mechanism for the tropical intraseasonal variability in the Indian Ocean region and improving our ability to simulate and predict the tropical intraseasonal variability, with a focus on convective initiation of the Madden-Julian Oscillation (MJO). DYNAMO consists of four integrated components: field observations, modeling, analysis, and forecasts. The field campaign is designed to collect in situ observations necessary to test five working hypotheses that have been developed through a combination of models and observations. A climate process and modeling team (CPT) is being formed to efficiently integrate field observation and modeling activities.

Intellectual Merit: DYNAMO is intended to test the importance of several factors to MJO initiation. These hypothesized factors include convective suppression mechanisms, shallow convection moistening and heating in transition from convectively suppressed to active phases of the MJO, zonal asymmetry in MJO convective activity due to zonal circulations induced by stratiform heating, extratropical and upstream influences on MJO initiation, and the role of wind-induced fluxes and air-sea interaction. Assessment of these mechanisms with DYNAMO observations will improve knowledge on specific processes relevant to cumulus parameterization in global weather prediction and climate models. Information gained by DYNAMO relevant to the parameterization problem will include cloud entrainment and detrainment rates, convective precipitation efficiency, structures and evolution of convective and precipitating systems, and a newly defined variable moist convective inhibition.

Broader impact: DYNAMO will provide an excellent opportunity to train young scientists (graduate students and postdoctoral fellows) to face the challenge of studying complex multi-scale and air-sea interaction problems in the tropical climate system. The unique observations to be collected by DYNAMO will fill a gap in the existing data archive and assist the broad research and operations communities in their persistent efforts of improving numerical models. Improved model simulations and predictions of the MJO will promote credibility in climate simulations and projection, and enhance our capacities of delivering climate prediction and assessment products on intraseasonal timescales for risk management and decision making.

D. PROJECT DESCRIPTION
1. Introduction

The Madden-Julian Oscillation (MJO, Madden and Julian 1971, 1972) dominates tropical intraseasonal (20 – 100 days) variability. As it propagates from the Indian Ocean eastward across the western and central Pacific (Fig. 1), the MJO interacts with many weather and climate systems and influences their prediction. The MJO often spawns tropical cyclones, modulates their activity in all ocean basins, including hurricanes near the Americas (Liebmann and Hendon 1994; Hall et al. 2001; Bessafi and Wheeler 2006; Frank and Roundy 2006). An example of MJO modulation on Gulf of Mexico and Caribbean Sea hurricanes and tropical storms is given in Fig. 2. The MJO affects the onset and intraseasonal fluctuations of the monsoons and rainfall in general over Asia (Annamalai and Slingo 2001), Australia (Hendon and Liebmann 1990), Americas (Higgins and Shi 2001; Lorenz and Hartmann 2001), and Africa (Poh et al. 2007). As an effective source of stochastic forcing, the MJO influences the onset, intensification, and irregularity of ENSO (Kessler et al. 1995; Moore and Kleeman 1999; Zhang and Gottschalck 2002; Zavala-Gary et al. 2005). Tropical large-scale convective centers organized by 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). Some torrential rain events along the US west coast are directly related to such teleconnection patterns (Jones 2000), which are also known as "atmospheric rivers" and "Pineapple Express".

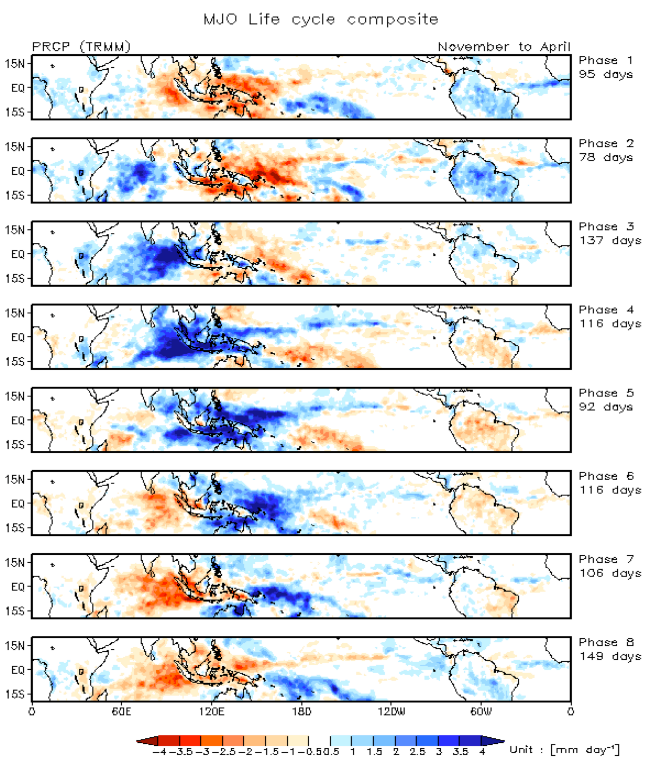

Figure 1 Composite MJO precipitation anomalies in eight phases (Courtesy of US CLIVAR MJO Working Group)

The MJO also interacts with the North Atlantic Oscillation (Lin et al. 2009), Arctic Oscillation (Zhou and Miller 2005) and Antarctic Oscillation (Carvalho et al. 2005). The Indian Ocean Dipole Zonal Mode, while modulating MJO activity, can be affected by the MJO through nonlinear air-sea interaction (Rao et al. 2008). Fluctuations in Indonesian Throughflow, a main

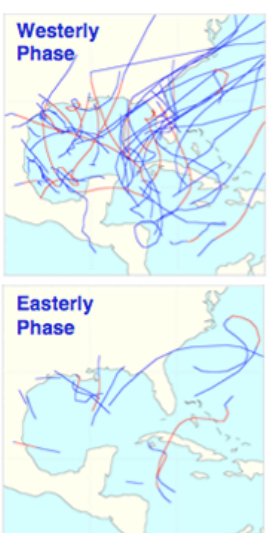

Figure 2 Tracks of hurricanes (red) and tropical storms (blue) in MJO westerly and easterly phases during 1979 – 1999. (After Maloney and Hartmann 2000)

artery connecting the Pacific and Indian Oceans through the Maritime Continent, are strongly influenced by the MJO (Waliser et al. 2003; 2004). The global angular momentum, the Earth's rotation rate and the length of the day all fluctuate on intraseasonal timescales because of the MJO (Weikmann et al. 1997). The MJO also causes intraseasonal perturbations in atmospheric composition, such as ozone, carbon dioxide, and aerosols (Tian et al. 2007; 2008) and in ocean chlorophyll (Waliser et al. 2005).

Because of the important role played by the MJO in weather and climate, there is an increasing demand from the society for accurate MJO prediction. Routine operational MJO prediction is carried out by NOAA/NCEP/CPC with input from other NOAA organizations and several operational centers around the world (e.g. NCEP, ECMWF, CMC, BOM, UK Met Office, JMA, CCS; planned to join by CWB, IMD, and US Navy FNMOC). Their prediction products reach a wide range of end users, 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, NWS Regional Headquarters), and private industry (American Electric Power, Earth Satellite Corporation, Moore Capital Management, and many more). Influences of the MJO have apparently penetrated into many sectors of the society.

Current MJO prediction, however, suffers from low skill, particularly at two stages of its life cycle: when it is initialized in the Indian Ocean and when it is about to propagate across the Maritime Continent (Fig. 3). This MJO prediction problem is compounded by the well known fact that most start-of-the-art global climate models fail to reproduce the MJO with fidelity (e.g. Zhang et al. 2006; Kim et al. 2009). Even models that can produce robust MJO signals over the western Pacific suffer from insufficient MJO strength over the Indian Ocean (Benedict and Randall, 2009). Arguably, the MJO is the keystone of a seamless weather-climate prediction system (Brunet et al. 2009; Shapiro et al. 2009). The inability of reproducing MJO signals by climate models used to project future global climate change (Lin et al. 2006) weakens our confidence in their fidelity. While deficiencies in cumulus parameterization schemes are commonly thought of as a major culprit for problems with MJO simulation and prediction, the root causes for these deficiencies remain uncertain. The MJO has thus become a common model validation target and its representation is often taken as a milestone of model improvement and development (e.g., Miura et al. 2007; Benedict and Randall, 2009).

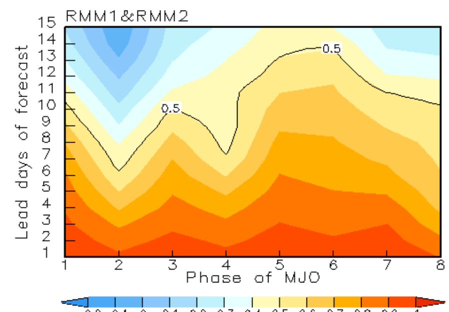

Figure 3 Correlation between predicted (by GFS) and observed Wheeler and Hendon (2004) MJO indices. The Phase of MJO corresponds to those in Fig. 1. (Courtesy of Jon Gottschalck and Qin Zhang)

Development and improvement of parameterizations for weather and climate models critically rely on in situ observations. A lack of in situ observations in the region of the tropical Indian Ocean has impeded the progress on the study of MJO, especially its initiation. A field observation campaign in the tropical Indian Ocean region is therefore urgently needed to expedite the study on the tropical intraseasonal variability with a focus on the MJO initiation.

An international field program, CINDY2011 (*Cooperative Indian Ocean Experiment on Intraseasonal Variability in the Year 2011*), will take place in the central equatorial Indian Ocean in late 2011 – early 2012 to collect in situ observations to advance our understanding of MJO initiation processes and to improve MJO prediction. The US research, operations and applications communities are poised to join CINDY2011 and make unique contributions to this international effort on the study of the MJO. DYNAMO is the program that organizes the US interest of participating in CINDY2011. DYNAMO will coordinate with its CINDY2011 partners (Japan, Australia, Seychelles, India, France) and other field programs (AMIE, HARIMAU, PAC^{3}E-SA/7SEAS, ONR air-sea interaction) that are being planned to take place also in late 2011 – early 2012. The integrated observation data set from these programs will cover MJO events at different stages of their life cycle with complimentary observational emphases. The opportunity to be an integrated part of these coordinated programs to maximize the value of observational products makes the timing of late 2011 – early 2012 critical for DYNAMO.

2. Scientific Problems and Hypotheses

MJO initiation in the equatorial Indian Ocean generates atmospheric deep convection organized into a large-scale center that, in coupling with the large-scale circulation, propagates eastward into the western Pacific Ocean. A key challenge for the prediction of the MJO is capturing the initiation of deep convection in this region. The challenge is magnified by the lack of in situ observations of the atmospheric vertical structure over the Indian Ocean. As a result, the initiation process is among the least understood aspects of the MJO.

To a large extent, our current knowledge of the MJO directly from in situ observations is mainly based on data from the western Pacific, although satellite remote sensing and global reanalysis products have helped gain substantial insight of MJO structures. The in situ observations of TOGA COARE in 1992-93 (Webster and Lukas 2003) captured three MJO events over the western Pacific (Lin and Johnson 1996; Yanai et al. 2000) and the long record of the TAO mooring array provides reliable MJO statistics at the surface and in the upper ocean across the entire equatorial Pacific (Zhang and McPhaden 200l; Roundy and Kiladis 2006). The established ARM Tropical Western Pacific sites at Manus, Nauru, and Darwin have provided long-term observational data of the surface and atmosphere that have been used to help understand the role of cloud-radiation-moisture interaction in the MJO (Mather et al, 2007).

In contrast, there is a stunning lack of in situ atmospheric observations covering the life cycle, including the initiation, of the MJO in the Indian Ocean region. Time series of air-sea processes in the Indian Ocean from the RAMA array, yet to be completed, are still limited to date. None of the earlier atmospheric field campaigns in the Indian Ocean, such as INDOEX (Ramanathan et al. 2006), JASMINE (Webster et al. 2002), MISMO (Yoneyama et al. 2008), and Vasco-Cirene (Vialard et al. 2009), provided adequate data to study MJO initiation.

Satellite data and limited sounding observations indicate that the structure of the MJO and its embedded synoptic-scale perturbations vary in longitude from the Indian Ocean to the western Pacific (Kiladis et al. 2005). The phase relationship between MJO low-level westerlies and precipitation is roughly quadrature in the Indian Ocean but almost in phase in the western Pacific (Zhang et al. 2005). Profiles of temperature and moisture from the NCEP/NCAR reanalysis and AIRS satellite differed significantly over the Indian Ocean, particularly in the boundary layer (Tian et al. 2006), which further highlights the need for in-situ observations. The large-scale dynamical component of the MJO may more strongly interact with the convective component to provide a mechanism to maintain the MJO propagation in the western Pacific (Wang and Rui 1990). Such a dynamical factor may or may not exist for MJO initiation in the Indian Ocean (Matthews 2008). One unique climatic feature of the Indian Ocean is the Seychelles-Chagos thermocline ridge (SCTR) above which the mixed layer is shallow. Over the SCTR, SST perturbations in the intraseasonal frequency band are extraordinarily large (~ 1 – 2K) (Harrison and Vecchi 2001; Saji et al 2006; Vialard et al. 2009), signaling that the air-sea interaction process during the MJO initiation stage could be different from that for the MJO propagation in the western Pacific where the thermocline is much deeper and intraseasonal SST perturbations generally weaker (≤ 1K). Upper-ocean mixing is an essential element in air-sea interaction. Its detailed vertical profile in the equatorial Indian Ocean with unique shear structures related to the Wyrtki jets (Wyrtki 1973) has, however, never been systematically observed and analyzed. The same can be said of its counterpart of turbulence mixing in the atmospheric boundary layer. In short, what we know about the MJO in the western Pacific cannot always be applied to the Indian Ocean, and there is a gaping hole in our observations and knowledge of the physical processes related to the MJO in the Indian Ocean.

Among many unknowns associated with the MJO in the Indian Ocean, its initiation stands out. Here, MJO initiation is defined as the time when deep convection is organized into a large-scale center (convective envelope) that begins to move eastward slowly (~ 5 m/s) as the typical MJO circulation pattern known as the Rossby-Kelvin wave couplet (Rui and Wang 1990) start to emerge. In the absence of in situ observations in the region of the tropical Indian Ocean, numerical models have been employed in conjunction with global data assimilation products to elucidate several possible mechanisms for MJO initiation. The following mechanisms for MJO initiation have been proposed:

(i) slow energy recharge of the atmospheric column due to sea surface fluxes, moisture advection and convergence, moistening of the lower troposphere by shallow convection and its dynamical impacts, and radiative cooling (Blade and Hartmann 1993; Kemball-Cook and Weare 2001; Raymond 2001; Maloney 2009). Ocean heat storage and discharge may also contribute to this preconditioning process (Sobel and Gildor 2003);

(ii) forcing from extratropical synoptic to intraseasonal perturbations related to Rossby waves, cold surges, global wind oscillation and eddy momentum transport, etc. (Lau and Peng 1987; Hsu et al 1990; Lin et al. 2007; Ray et al. 2009);

(iii) forcing from upstream due to previous circumnavigating MJO events (Matthews 2007), and

(iv) dynamical response to tropical and extratropical stochastic processes (alby and Garcia 1987; Yu and Neelin 1994).

Each of these mechanisms operates under the influence of short-term climate variability, such as ENSO and IOD.

Currently, no consensus exists on which mechanisms are most important for MJO initiation. Their common features allow them to be consolidated into two scenarios:

A. Internal initiation: The MJO is initialized over the tropical Indian Ocean through local interaction between the large-scale circulation and convective activity that self-organizes into large-scale patterns through a slow buildup of tropospheric moisture content, multi-scale interaction, air-sea interaction, or other processes without interference from the extratropics or upstream.

B. External Initiation: Perturbations from either the extratropics or upstream (west) lead to changes in the large-scale circulation and/or thermodynamics over the tropical Indian Ocean. Deep convection subsequently is enhanced and organized into large-scale patterns that feed back to the large-scale circulation, giving rise to the MJO.

A common aspect of the two scenarios is the essential role of convection-circulation interaction in MJO development. The primary differences are internal (tropical Indian Ocean) vs. external (extratropics or upstream) triggering mechanisms. Scenario A places the internal processes in the tropical Indian Ocean at the center of MJO initiation and its prediction. In contrast, Scenario B suggests that processes local in the tropical Indian Ocean are passive or responsive and, from a viewpoint of prediction, the key to MJO initiation resides outside the tropical Indian Ocean. Also common between the two scenarios but not explicitly stated is that convective suppression immediately precedes convective initiation of an MJO event. Scenario A implies that deep convection is suppressed primarily because in the absence of large-scale forcing the buildup of a favorable large-scale environment is a slow process. In Scenario B, suppression mechanisms come from the large-scale circulation (e.g., dry air advection). There is no reason that MJO initiation and suppression mechanisms described in the two scenarios could not both be at work. In addition to these two scenarios, whether and how Asian continental pollution aerosol may interact with clouds and precipitation associated with MJO initiation are completely open questions.

One of the most challenging issues of the MJO is its scale selection, especially, the mechanisms that determine its intraseasonal temporal scale. In the context of MJO initiation, the questions are why deep convection prior to MJO initiation remains isolated and unorganized on the large scale for a prolonged period (≥ 20 days) and how organized deep systems are sustained for a prolonged period (≥ 10 days) once they are developed. An equally challenging and related issue is the mechanisms for the transition from inactive to active phases. These two issues will be discussed under the two MJO initiation scenarios.

<u>Internal Initiation</u>

Under this scenario, in the absence of pre-existing external influences, all large-scale motions engaging with the MJO initiation process originate from the tropical Indian Ocean region. It is well known that the pattern and strength of the tropical large-scale circulation are very sensitive to diabatic heating, especially its latitudinal location (Gill 1980) and vertical profile (Hartmann et al. 1984). The latitudinal location of large-scale diabatic heating can be well inferred from satellite observations of precipitation (e.g., TRMM) and clouds (e.g., outgoing longwave radiation). Its vertical profiles can be most accurately estimated from in situ sounding observations, and we know well how it can be done (e.g. Yanai et al 1977). Recent studies have found that, if global climate models are tuned to reproduce reasonably well mean horizontal distributions of precipitation, their reproductions of vertical profiles of diabatic heating have substantial biases in comparison to sounding-based estimates (Hagos et al. 2009). DYNAMO, thus, will focus on the vertical structure of diabatic heating in the context of convection-circulation interaction during MJO initiation.

There is mounting 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). The variability of column water vapor in this relationship comes mostly from the lower troposphere above the cloud base and leads precipitation (Sobel et al. 2004; Holloway and Neelin 2009). Such a relationship is presumably established by entrainment of moist (dry) environmental air into convective plumes to maintain (reduce) high updraft buoyancy (Brown and Zhang 1997; Raymond 2000). Numerical simulations have clearly demonstrated the sensitivity of tropical deep convection, either parameterized or resolved, on tropospheric moisture (Derbyshire et al. 2004;). The second focus of DYNAMO in the context of convection-circulation interaction during MJO initiation is the vertical structure of humidity and moisture advection. Hence, moisture budgets derived from DYNAMO soundings will be critical to assess the processes controlling moistening of the atmospheric column in advance of MJO initiation.

These two focuses, the vertical structures of diabatic heating and moisture, lay the foundation for the following discussions for the three stages of MJO initiation: prolonged convective suppression, transition from convectively suppressed to active phases, and sustained convectively active phase of the MJO.

Convective Suppression

Prior to MJO convective initiation, this phase, even though commonly labeled as "suppressed" or "inactive", is characterized by convective systems of all kind: shallow, congestus, and deep. But these convective systems often appear to be randomly scattered and isolated. They can be organized, but only into synoptic-scale perturbations, such as convectively coupled Kelvin waves. The terms "suppressed" and "inactive" therefore refer to a lack of deep convection organized into a large-scale pattern. The reason for the absence of large-scale organization of deep convection in an inactive phase of the MJO is a major gap in our understanding. It has been shown that some numerical models fail to reproduce the MJO because they cannot maintain a convectively suppressed state in the tropics: simulated deep convection is too easily triggered, and therefore perpetually too frequent and too strong (Zhang and Mu 2005). Therefore, understanding convectively suppressing mechanisms is as important as understanding the processes responsible for the suppressed to active phase transition during MJO initiation and for the sustained deep convection in active phases.

Observational, modeling and theoretical studies have suggested two main possible mechanisms for convective suppression. One is related to convective inhibition (CIN) and other to dry-air entrainment in the low to mid troposphere.

CIN is normally defined as the amount of energy required to overcome the negatively buoyant energy in the environment between the surface to the level of free convection (LFC). Commonly, large CIN is associated with a temperature inversion that may be caused by adiabatic warming associated with subsidence. During the suppressed phase of the MJO, large-scale subsidence can be related to the zonal overturning circulation of the MJO. Strong sub-cloud layer updraft is needed to overcome CIN and initiate deep convection (Mapes 2000).

As mentioned earlier, we have recently gained considerable insight to the role of tropospheric moisture in tropical deep convection generally and in the MJO specifically. Persistent anomalously dry troposphere during a suppressed phase of the MJO can be a sufficient reason for the lack of deep convection organized on large scales (ref). While both the CIN and dry-air entrainment suppressing mechanisms are viable, it is unlikely that they work in isolation from each other. For example, strong subsidence can both create an inversion at the boundary layer top as well as an anomalously dry atmosphere with deleterious effects on convection. However, there has yet to be, however, a measure that quantifies their combined effect on suppressing deep convection. Such a measure can be defined from field observations and numerical experiments to assist model diagnostics and cumulus parameterization improvement. Hereafter, the combined suppressing effect of stability (CIN) and dry-air entrainment will be referred to as moist CIN, or MCIN.

But MCIN along is insufficient to explain why deep convection is suppressed on intraseasonal timescales but exists on smaller scales in the inactive phase prior to MJO initiation. One possible reason for this is a lack of an energy supply that supports multiple convective systems. Over the tropical open ocean, the main moisture sources for sustained deep convection in a large-scale region are moisture convergence and surface evaporation, both depending on the large-scale circulation. Without any pre-existing large-scale circulation for moisture convergence, surface evaporation might be too slow to allow deep convective systems to sustain and self-aggregate into a large-scale pattern. Locally, deep convection can still occur. But it consumes available moisture quickly and decays quickly because of MCIN. Net vertical moisture fluxes from the boundary layer to the lower troposphere by shallow convection to prepare for massive deep convective development may occur on synoptic scales. But on the MJO spatial scale (see discussion on the transition period below) it is a very inefficient and slow process. This leads to the first working hypothesis of DYNAMO:

Hypothesis I*: Convective suppression prior to MJO initiation is prolonged because, in the absence of external influences, the moisture source through surface evaporation over warm sea surface with weak to moderate surface wind is insufficient to support precipitating systems on the MJO scales. The timescale of the suppressed phase prior to MJO initiation is determined by the low efficiency of lower-troposphere moistening by shallow convection alone.*

The essence in this hypothesis is the population of clouds. Too many clouds with zero or low precipitation efficiencies would accelerate lower-tropospheric moistening and lead to premature onset of deep convection. Too many isolated deep convection would leave insufficient moisture and energy for convective systems to be organized into large-scale patterns needed for MJO initiation (see discussion below). Radar observations of DYNAMO during suppressed phases will provide statistics of cloud populations. The DYNAMO sounding observations will provide heating and moisture profiles over a large-scale domain (the sounding-radar array) that measure the aggregated effect of the embedded cloud population that must be accurately reproduced by cumulus parameterizations in global climate models to simulate well the suppressed phases of the MJO. Characterizing the large-scale atmospheric and oceanic environment (including surface fluxes) in which these particular cloud population compositions exist will also be important.

<u>*Convective Transition*</u>

MJO convective initiation is marked by transition from convectively suppressed to active periods. Central to the transition are processes that help overcome MCIN on a spatial scale comparable to the MJO convective envelope. In the absence of non-local dynamical influences, recent studies have pointed to two candidates for such processes: moistening of the low-mid troposphere by shallow convection and convection-circulation interaction through low-level diabatic heating.

Data analyses have repeatedly shown graduate moistening in the lower troposphere preceding the convectively active phase of the MJO (Kiladis et al. 2005). As mentioned earlier, a moister troposphere is an environment more favorable to deep convection. This "moisture preconditioning" has been postulated as a necessary step leading to MJO convectively active phase and even a fundamental mechanism for the MJO (Thayer-Calder and Randall 2009). In the absence of large-scale moisture convergence, such moistening can happen only through detrainment of cloud with low or zero precipitation efficiency.

As discussed earlier, in the absence of pre-existing large-scale influences, moistening of the lower troposphere can be efficient and slow. There must be sufficient energy/moisture source to sustain deep convection on intraseasonal timescale over the MJO spatial scale. This requires a feedback from the large-scale circulation. It has been suggested from theoretical and modeling perspectives that shallow convection, with its latent heating concentrated in the lower troposphere when its precipitation efficiency is high, is effective in inducing surface and low-level wind convergence in spite of its relatively small amplitude (Mapes ; Fig. 5a). Such surface and low-level convergence acts as a major moisture and moist static energy supply that may support subsequent deep MJO convection (e.g., Wang, Maloney). The need of low-level heating for the MJO has also been suggested as a mechanism for its slow phase speed by reducing the effective equivalent depth of the atmosphere (Lau and Peng 1987; Chang and Lim 1988). Its role in the MJO through interacting with the large-scale circulation has recently been increasingly recognized (Wu 2003; Zhang and Mu 2005; Li et al. 2009). Models, however, generally do not simulate shallow convection and congestus populations well (Inness et al. 2001, Maloney 2009).

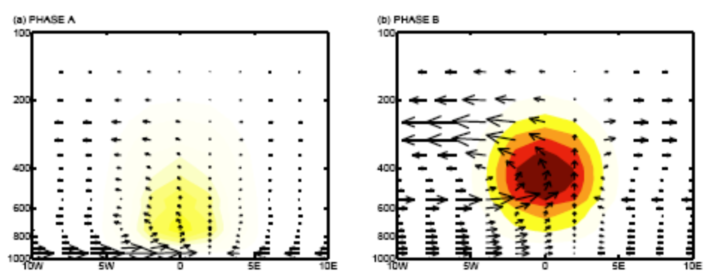

Figure 5 Zonal-vertical circulation (arrows) responding to (a) shallow and (b) deep heating (colors). Vertical axis is pressure (hPa). Vertical velocity is amplified 50 times. (From Zhang and Hagos 2009)

The above discussion can be summarized into the following working hypothesis:

Hypothesis II*: Population of shallow convection plays a two-stage role in the transition period of MJO initiation: when the precipitation efficiency is low, the moistening effect in the lower troposphere dominates, which slowly creates a favorable condition for deep convection; when the precipitation efficiency becomes high, the low-level heating effect dominates, which induces surface and low-level moisture convergence as an energy source for deep convection and accelerates the initiation process.*

Crucial information needed to test this hypothesis is the change in the cloud population that accompanies a gradual shift of the large-scale conditions. Radar observations that carefully document statistics of the evolution in cloud structures, precipitation efficiencies, and diabatic (latent and radiative) heating profiles will be compared to the large-scale temperature and humidity profiles and areal mean heating profiles measured the sounding observations. It should be pointed out that, while radiative heating is usually dwarfed by latent heating when deep convection is strong, the two can be comparable during the early stage of the transition period. Cloud radiative heating generally peak in the mid troposphere (e.g., Liebmann and Hendon, Mather) and is effective in induce low-level convergent flow. Moisture convergence due to the large-scale circulation measured by the soundings will be compared to surface flux measurement to quantify fractional contribution from these two energy sources to convective development during this critical transition period. The aggregated heating and moistening effects by developing convective system over the sounding-radar domain and the accompanying surface fluxes must be accurately reproduced in global climate models to successfully reproduce MJO initiation.

Convective Maintenance and Termination

After deep convective systems are initiated over a large-scale domain, a immediate challenging problem is how they are sustained over the MJO scales in both time and space. Again, this is a scale selection problem, which is at the crux of a successful theory and hypothesis for the MJO and a successful of a numerical simulation of the MJO. Instability due to coupling between deep convection and the large-scale circulation (e.g.,), due to interaction among perturbations of different scales (Biello et al 2007; Maloney 2009), and possibly due to air-sea interaction and wind-induced surface heat exchange (Sobel et al. 2009) have been suggested as the core mechanisms for the MJO. In the context of MJO initiation under Scenario A, two key issues must be addressed. One is what determines the large-scale response to initiated deep convection that leads to an MJO event vs. a synoptic-scale wave perturbation, such as the convectively coupled Kelvin wave, which happens more often than the MJO. The MJO and convectively coupled equatorial Kelvin wave share many common features (eastward propagation, albeit with different phase speed, westward vertical tilt, moistening of the lower atmosphere east of the convective center, etc.). The major differences are their frequencies, spatial scales, and potential vorticity (PV) structures: the Kelvin wave has minimum PV, whereas the MJO has large PV (Schubert and Masarik 2006). One possible clue for distinguishing the two is PV generation by deep convection.

The second key issue is the moisture source that must be in place to sustain deep convective precipitation on the MJO time and space scales. As discussed before, the main moisture sources are large-scale low-level moisture convergence and surface evaporation.

In this regard, shallow convection with high precipitation efficiency is needed again. It is known that mature tropical mesoscale convective systems are dominated by stratiform precipitation, whose diabatic heating profiles is top heavy with heating peaks in the upper troposphere and cooling due to precipitation evaporation in the lower troposphere (Houze and others). This top-heavy heating profile tends to generate a mid-level inflow and near surface divergent outflow. If somehow such statiform heating is projected onto the large scale, the near surface divergent flow would terminate deep convective period immediately. To sustain deep convective period, the low-level cooling due to stratiform precipitation must be balanced by low-level heating by shallow convection. When this balance happens on the large scale, the responding circulation provides a deep low-level moisture advection and convergence (Fig. 5b) with a strong surface wind component that enhances surface evaporation. All these act as major moisture supplies to help sustain deep convective period to the MJO time scale.

Meanwhile, the mid-level inflow due to stratiform heating may play a dual role in this stage of the MJO. First, adiabatic cooling due to melting and sublimation right below the freezing level forces the mid-level inflow to sink (Houze). Such mid-level inflow is mainly from the west due to the stronger response of the Rossby component than the Kelvin component (Fig. 5b). When the sinking westerly reaches the surface, it enhances the westerly wind burst of the MJO and associated surface evaporation. It is possible that downward and upscale westerly momentum transport is another ingredient of the MJO to sustain its surface moisture supply for deep convection. Meanwhile, however, this mid-level westerly inflow tends to bring air that is much drier than air in the convective updraft and thereby tends to reduce the updraft buoyancy at the west side of the MJO convective center. This zonal asymmetry may help initiate the eastward movement of MJO convection before the large-scale dynamics presumably responsible for the MJO eastward propagation is fully established.

Based on the above discussions, over a certain time, shallow convection may lose the competition to deep convection and when this happens, the stratiform-like heating profiles on the large scale would determinate local convection and forces it to move eastward because of the zonal asymmetry. This possible sequence of actions can by summarized into the next DYNAMO working hypothesis:

Hypothesis III*: A balance between precipitating shallow, deep, and stratiform precipitation is needed to sustain convective period over the MJO space scale. In the absence of pre-existing large-scale influences, the time scale of the active phase of the MJO is determined by a graduate shift from this balance to a dominance of stratiform precipitating systems on the MJO spatial scale*.

Testing this hypothesis needs the same field observations as for the other two hypotheses: a careful documentation of the evolution of the cloud population by radar observations and the aggregated effects of all convective systems on large-scale heating and moisture profiles by sounding observations. It is paramount for a global climate model to reproduce the aggregated heating profiles due to the balanced cloud population in order to simulate sustained convective period over a large-scale domain. Theories and models that include the cloud population change may help explore the fundamental mechanisms for the timescale selection.

Role of the Upper Ocean

Unique and relevant features of the tropical Indian Ocean are high mean sea surface temperature, or a warm pool, as in the western Pacific, the Wyrtki jets and the Seychelles-Chagos thermocline ridge (SCTR). Since neither the detailed vertical structure nor the long-time-scale variability of these features has been examined, our understanding of their contributions to MJO initiation and evolution is rudimentary at best. Near the SCTR, intraseasonal perturbations in SST are much larger than in the western Pacific (e.g.,), because of the shallow mixed layer. While the means by which atmospheric deep convection over the warm pool is suppressed on intraseasonal timescales must be explored (see Hypothesis I), the warm sea surface makes the tropical Indian Ocean a favorable location for MJO initiation. During convectively suppressed phase prior to MJO initiation, with relatively low surface wind speed and in the absence of large-scale moisture convergence, evaporation from the warm sea surface is the primary moisture source to maintain the humidity content in the boundary layer and balances the moisture sink into the troposphere by atmospheric shallow convection. This boundary-layer moisture reservoir serves as a major energy source for convection development at the beginning of the transition from suppressed to active phase of the MJO. As atmospheric shallow convection becomes more precipitating over a large area, the stronger surface westerly response west of the enhanced shallow convection region (Fig. 5a) tends to cool the surface faster than to the east. This zonal SST asymmetry may be another local mechanism that helps to push the MJO convective center eastward before large-scale atmospheric dynamics presumably responsible for the MJO eastward propagation are established. Because the strength of the Wyrtki jets varies on intraseasonal timescales associated with the MJO (e.g.,), its associated shear would also. Thus, turbulent mixing will undoubtedly evolve differently than in the western Pacific and therefore play a quantitatively different role in air-sea interaction. In this regard, the next DYNAMO working hypothesis is:

Hypothesis IV*: Upper-ocean processes contribute to MJO initiation through maintaining high SST prior to the initiation and rapid surface cooling during the transition and early active periods. Turbulent mixing plays a critical role in these because of the shallow mixed layer associated with the SCTR, the current shear associated with the Wyrtki jets, and their intraseasonal variability.*

Testing Hypothesis IV requires comprehensive knowledge of upper-ocean dynamics and thermodynamics as well as surface fluxes. What we learned from TOGA COARE serves as a solid background for DYNAMO investigation on air-sea interaction. But the shallow mixed layer atop the SCTR and the current shear in the tropical Indian Ocean make it a unique problem. TOGA COARE data have shown that entrainment at the bottom of the mixed layer can play a major role in the upper ocean heat budget but not always because of the existence of the barrier layer and the depth of the thermocline. This may be different near the SCTR. The shallow thermocline there makes entrainment cooling a more viable mechanism for the upper ocean heat budget. To what degree mixing process can be adequately reproduced in global ocean models so that air-sea interaction in MJO initiation can be correctly simulated in coupled climate models has always been a challenge. A thorough test of Hypothesis IV would help address the controversial issue on the role of air-sea interaction in the MJO. While some studies showed a benign or even detrimental role of air-sea coupling to MJO simulations (Hendon 2000; Liess et al 2004; Grabowski 2006), others suggested enhancement of MJO simulations and prediction by air-sea coupling (Waliser et al. 1999,). None of these modeling studies adequately resolves either the SCTR or the Wyrtki jets (if at all), let alone mixing profiles in the upper ocean. Detailed, high-resolution measurement of upper-ocean vertical mixing profiles through the entire cycle of MJO initiation in the vicinity of the SCTR is an essential component of DYNAMO. These measurements will provide the subsurface fluxes that, in combination with the atmospheric fluxes at the sea surface, govern the SST variability on intraseasonal timescales.

External Initiation

Pre-existing external influences can make the MJO initiation process quite different from what discussed under the scenario of Internal Initiation. MCIN can be maintained by dry-air advection from extratropics and subsidence of a large-scale overturning circulation associated with deep convective activity at a remote location. The absence of such external influences would make the local processes more efficient at overcoming MCIN. Intrusions of extratropical or upstream perturbations can provide lifting, moisture convergence and other incentives that further help overcome or remove MCIN. But it is unlikely that external influences would dictate MJO initiation. Many external perturbations (such as cold surges, extratropical Rossby waves) are transient with frequencies higher than that of the MJO. They along cannot sustain tropical deep convection in an active phase of the MJO and cannot explain the selection of the time scale for the MJO, even though "MJO-like" tropical perturbations have been generated in dry models by external influences (Lin et al. 2007; Ray et al. 2009). If shallow convective systems with their low-level heating are essential to sustained energy supply to the MJO, as discussed earlier, it is not clear how external perturbations may help maintain these shallow convective systems. It is possible that external influences are effective only when the local processes make the condition for MJO initiation ripe, and if local processes help maintain the initial convective anomaly triggered by extratropical processes. It is thus perhaps essential that convection is sustained on the MJO scales in both time and space only when the local processes are engaged. This leads to the final hypothesis of DYNAMO:

Hypothesis V*: External (extratropical and upstream) perturbations, with their large-scale ascents and low-level convergence, play an activating role to accelerate MJO initiation primed by internal processes.*

Testing this hypothesis requires the in situ measurement from the other hypotheses plus information of external perturbations which will have to be from global reanalyses or satellite data. This combination of data would allow a detailed diagnosis of how cloud population changes with the large-scale environment under the influence of external perturbations.

In summary, quantitatively testing all these hypotheses, evaluating various mechanisms, identifying critical processes, and forming new ideas on MJO initiation requires an integrated approach involving observations, modeling, theories, analyses, and forecasts. A systematic testing of these and other hypotheses is a necessary step toward improving existing, and designing new model parameterization schemes, whose deficiencies are always considered the culprit for model infidelity. Satellite observations and global reanalysis products are very useful in providing the information on the large-scale background for deep convection. Certain variables can, however, be accurately and simultaneously obtained only from in situ observations. They include surface fluxes, vertical profiles of diabatic heating and moistening, structures and evolution of cloud and precipitation systems, upper ocean and atmospheric boundary-layer structure and mixing. A lack of these in situ observations from the tropical Indian Ocean makes the testing of the hypotheses extremely difficult.

3. Program Objectives and Components

The overall goal of DYNAMO is to expedite our understanding of MJO initiation processes and improving our ability to simulate and forecast the MJO. This goal shall be reached adapting an integrated observation-modeling-analysis-forecasts approach, which will be described in this section, and in coordination with DYNAMO's international and national partner programs, which will be outlined in section 4. The scientific objectives of DYNAMO are:

(1) to collect in situ observations from the equatorial Indian Ocean region that are urgently needed to advance our understanding of the processes key to MJO initiation and to improve their representations in models;

(2) to identify critical deficiencies in current numerical models that are responsible for the low prediction skill and poor simulations of MJO initiation and to assist the broad community effort of improving model parameterizations.;

(3) to provide guiding information to enhance MJO monitoring and prediction capacities that deliver climate prediction and assessment products on intraseasonal timescales for risk management and decision making over the global tropics.

To achieve its objectives, DYNAMO is composed of four main components: field campaign, modeling, analysis, and forecast. These components are closely connected. The DYNAMO field campaign is designed under the guidance provided by the DYNAMO modeling activities. Measurement will target quantities identified by modeling exercises as potentially important to MJO initiation and its prediction and simulation.

3.1 Field Observations

The DYNAMO field campaign is an integrated element of CINDY2011, the 2011-2012 international field program in the equatorial central Indian Ocean. Thus, it is appropriate to describe the DYNAMO field campaign together with CINDY2011. The general plan of CINDY2011 is to conduct an intensive observing period (IOP) for 3 – 4 months in late 2011 (October – December) – early 2012 (January) aiming to capture the initiation of at least one major MJO event and its full life cycle during the period with possibly maximum observations. The IOP will be embedded in an extended observing period (EOP) of 6 months or longer that, with reduced observing capacity, will cover more than one MJO event. The climatological background for the field observations is provided by the long-term monitoring networks of IndOOs and RAMA. Detailed descriptions of the DYNAMO field observations are provided in the Experimental Design Overview (EDO).

3.2 Modeling

Modeling activity has been a cornerstone of DYNAMO. The DYNAMO field campaign is motivated by

– The low prediction skill of numerical models at the MJO initiation stage;
– The relatively poor reproduction of the MJO in the Indian Ocean even in models that show some capability of capturing MJO signals in the western Pacific, and
– Hypotheses on MJO initiation processes proposed from model simulations and experiments.

The DYNAMO modeling component covers both research and operational models of various configurations. It will be closely connected to a Climate Process and Modeling Team (CPT) on the MJO to be proposed, which includes PIs from the DYNAMO modeling group.

3.2.1 Research Modeling

a) Use of models for field campaign design

Numerical experiments have been used to help optimize the field campaign design. The field campaign of DYNAMO is designed to acquire in situ atmosphere and ocean observations needed to test the hypotheses developed from numerical models. As an example, prior work has shown that model convection parameterizations often do not allow sufficient moistening of the free troposphere to occur before deep convection is triggered (Derbyshire et al. 2004). Increasing convective sensitivity to free tropospheric humidity through use of explicit moisture triggers and other methods that account for moist convective inhibition processes (see Hypothesis I) has been demonstrated to improve MJO simulations (Wang and Schlesinger 1999, Tokioka et al. 1988). This points to deficiencies in mixing and closure assumptions in model convective parameterizations that might explain their poor MJO simulations. Implementing moisture triggers has been shown to be an effective way to improve model intraseasonal oscillations and their initiation, but many methods to date have been ad hoc and have degraded other aspects of the model climate. Hence, a sounding array that produces high vertical and temporal resolution moisture and temperature profiles is necessary to assess the convective inhibition process in the MJO initiation region and how model behavior differs from reality.

As a further example, a realistic simulation of shallow convection and congestus has been shown to improve tropospheric moistening processes in advance of MJO convective initiation in support of Hypothesis II (Zhang and Song 2009). Many models clearly are not able to capture the trimodal structure of convection that is observed (Inness et al. 2001), although the extent to which shallow heating and congestus are important for MJO maintenance and initiation remain an open question (Maloney 2009) to be tested during DYNAMO. Models have similarly generated highly suggestive, although not conclusive, evidence supporting the importance of stratiform heating, air-sea coupling, and external excitation for initiation and maintenance of fledgling MJO events.

The DYNAMO sounding array has thus been designed to produce high quality and high vertical resolution retrievals of temperature, humidity, horizontal velocity components, and other fields that allow calculation of apparent heat source (Q_1), apparent moisture sink (Q_2), radiative heating (Q_R), and vertical mass fluxes that will be invaluable for diagnosing the evolution and role of clouds in advance of MJO initiation. These soundings accompanied by radar data will be used to assess the convective suppression mechanisms active before MJO convective events, the population of clouds and their role in overcoming convective suppression, and the evolution of heating profiles during the initiation of MJO events. The design of the upper ocean observing strategy for DYNAMO has been similarly motivated by hypotheses developed from coupled models.

b) Diagnostic development for model improvement

Careful evaluation of the field observations as well as complementary data sets, such as from satellite and the YOTC virtual field campaign, can be used to evaluate models and improve parameterizations. How to best utilize observations to both gain a deeper understanding of the processes and guide model improvements is a difficult and complex task. DYNAMO modelers are working to develop improved and/or targeted diagnostics tuned to the MJO initiation process that can be applied across all models. These should include diagnostics that test the hypothesized contributions of shallow convection (and other vertical modes), vertical and horizontal advection, and surface fluxes in priming the atmosphere for an MJO convective event, as well as a suite of similar common diagnostics focused on triggering. DYNAMO field observations have been designed such that model diagnostics can be directly compared to those from the sounding array. As an example, from the DYNAMO IOP and complementary radar data, it can be determined how cloud populations vary as a function of large-scale environment in observations and models. Do convectively suppressed regimes exist that are dominated by shallow clouds in both models and observations? If the models do not show this, it would suggest that moist convective inhibition is not being properly simulated in models and requires improvement. Maybe convective plumes in models are too undiluted and hence not responsive to environmental conditions? How do entrainment and detrainment profiles from the model compare to what is obtained from the sounding array for similar environmental conditions (Yanai and Johnson 1993)? Judicious use of single column modeling and CRMs will aid these model-observation comparisons.

The role of clouds in moisture and moist static energy budgets are a common thread in many of the hypotheses for MJO initiation presented above. Recent model budget diagnoses have assessed the role that clouds, horizontal advection, surface fluxes, and radiative feedbacks have played in moistening and energizing the column in models (Benedict and Randall 2009, Maloney 2009). Budgets derived from the DYNAMO sounding array can for example suggest which models are properly simulating the role of shallow convection in the moisture budget (possibly in advance of MJO convection), and if not, suggest that shallow convective processes need improvement. Targeted diagnostics for MJO initiation to assess coupled model performance can be developed in a similar way to those for atmospheric measurements, and these diagnostics should at minimum include SST, ocean heat content, mixed layer depth, barrier layer thickness, and surface heat and radiative fluxes.

Diagnostic development in advance of the DYNAMO field phase will also be aided by leveraging existing external efforts. For example, the undertaking of a "virtual field campaign" through YOTC will aid development of advanced diagnostics that can be used for model comparison and hypothesis testing. The challenge of how best utilize a hierarchy of models to gain process understanding of MJO initiation and also improve parameterization is common to both YOTC and DYNAMO, and thus DYNAMO has much to learn from YOTC efforts at such integration. Key as well will be use of CRMs to complement the observational datasets to aid improvement of models with parameterized convection.

c) The DYNAMO Model Working Group and Ties to External Efforts

The DYNAMO modeling group brings to the table an impressive hierarchy of models, including non-hydrostatic tropical channel models, cloud resolving models, global and regional operational forecast and research models in various atmospheric, oceanic, and coupling configurations. A DYNAMO modeling working group was formed by scientists from national modeling centers and universities to coordinate modeling activities contributing to the DYNAMO objectives. These participants are listed in Table 1. To further tighten the connection between DYNAMO field observations, modeling, and model improvement, a climate process and modeling team (CPT) is being formed in response to the announcement of 2009 NOAA Climate Program Funding Opportunities, whose letter of intent has been submitted. There is substantial overlap of participants in the DYNAMO modeling working group and this proposed CPT effort. This CPT, to be led by Eric Maloney, Duane Waliser, and Chidong Zhang, will partner with DYNAMO to carry out many of its modeling improvement tasks, particularly as they relate to MJO initiation in the Indian Ocean. In this CPT, three national modeling centers (NCEP/EMC, NCAR, NASA/GSFC) will team up with PIs from seven universities, to systematically work on model cumulus parameterization problems using the MJO as a target to identify deficiencies in models. The CPT effort will also leverage existing NOAA and NASA projects led by Adam Sobel to improve MJO simulation in global models at GFDL and NASA/GISS. Dedicated postdoctoral researchers will be located at each participating modeling center with the sole task of engendering parameterization improvements that will produce more realistic simulations of MJO initiation and maintenance, with the goal of engendering improvements that can be universally applied across models and not be ad hoc. The models to be involved are known to span a wide range of MJO simulation capability (from little MJO signals to robust MJO signals with unrealistic distributions). This CPT will work closely with the WCRP/WWRP MJO Task Force to develop and demonstrate a new set of process-oriented MJO diagnostics that emphasize the vertical structure of the MJO in terms of its diabatic heating, moistening, cloud and precipitation structure and evolution, diagnostics suitable for testing the DYNAMO hypotheses presented above. The DYNAMO field campaign will provide unique observations on these quantities in the context of MJO initiation. Recent satellite (TRMM, A-Train) data will be used to derive global statistics and the DYNAMO/CINDY2011 field observations will be used to validate and calibrate the global statistics. After diagnostics are developed and parameterization improvements are proposed on the basis of this diagnostic evaluation, the CPT will conduct coordinated numerical experiments with common parameterization sensitivity tests and modifications across all models involved. These experiments will reveal physical processes (e.g., convective entrainment and detrainment rates, closure assumptions, triggering, momentum transport, and autoconversion) whose treatment perturbation might lead to similar sensitivities in the reproduction of the MJO signals by models with different configurations. DYNAMO field observations will be used to constrain and validate simulations by single column versions of the global models, which will also be used in common sensitivity experiments. The outcome of this CPT will be targeted information for parameterization improvement for each participating model and a guideline of common procedures to conduct diagnoses and sensitivity tests again observations to identify the root causes of model parameterization deficiencies that lead to failure of MJO reproduction with fidelity.

Table 1 Core DYNAMO Modeling Working Group

PI	Affiliation	Modeling Expertise
Sue Chen	NRL/Monterey	regional coupled forecast model (COAMPS)
Maria Flatau	NRL/Monterey	global coupled forecast model (NOGAPS)
Tim Li	UH	global and regional research models
Eric Maloney	CSU	climate model (CCSM)
Mitch Moncrieff	NCAR MMM	cloud resolving and tropical channel models
Justin Small	NRL/Stennis	regional coupled models
Augustin Vintzileos	NCEP/EMC	global coupled forecast model (CFS)
Duane Waliser	NASA/JPL	Global and regional models
Xiaoqing Wu	ISU	cloud resolving and climate models and parameterization development
Guang Zhang	SIO	climate models and parameterization development

3.2.2 Forecast Modeling

Low skill in predicting the MJO serves as a major motivation for DYNAMO. Improving MJO prediction will be a major testament of the legacy of DYNAMO. Operational forecast and reforecast (hindcast) and their validations provide data that, when wisely diagnosed, may reveal root causes for the low prediction skill. Based on the preliminary results from CAPT, model deficiencies found in forecast/reforecast and climate simulations of the MJO should converge. If so, commonly identified model deficiencies would lead to high priority targets for model improvement and also help set priorities for future in-situ and satellite observations.

In addition to global forecast, it would also be desirable to have forecast based on high-resolution regional models with boundary conditions from global models. For such high-resolution limited area forecast, different metrics to evaluate its success need to be established. Extended-range reforecasts (beyond 15 days) and recovery from archived real-time operational forecasts should be used to establish the baseline forecast statistics to measure future improvement in MJO prediction.

We expect that the forecast products relevant to DYNAMO will be multivariate.

Reforecasting and its verification will help categorize model performance in terms of variables, initial conditions, lead time, and MJO phases. Participation of multiple models in the forecast and reforecast exercises will help formulate strategies of multimodel ensemble forecast of the MJO. With field observations at hand, data denial experiments can be done to further identify sensitivities of forecast to certain variables at certain geographical locations and MJO phases. These would be complementary to the hypothesis testing using research models as described in the previous subsection.

So far, three national forecast/modeling centers plan to participate in the DYNAMO forecast/reforecast exercises. They are NOAA (CFS), NRL (COAMPS and NOGAPS), and NASA (GEOS5).

3.3. Analysis

It is extremely important to provide a global and long-term context to the limited DYNAMO observational coverage in both time and space. This must be done through using existing global data sets. The analysis component of DYNAMO will compare DYNAMO field observations to available satellite and mooring data and reanalysis products and to quantify the degree to which these data can be used to describe the atmospheric and oceanic structures and processes relevant to MJO initiation. Long-term statistics based on these data will be compared to case studies based on DYNAMO field observations. Particularly useful in this regard are data from TRMM, A-TRAIN (especially CloudSat, AIRS, CALIPSO), and RAMA that provide vertical structures of the atmosphere and ocean. The utility of these data sets in the MJO studies have been demonstrated recently (e.g.,).

Meanwhile, analysis using global data sets in combination with the field observations may reveal large-scale mechanisms for MJO initiation that field observations alone are unable to. Such large-scale mechanisms include dry-air advection and other perturbation intrusion into the tropical Indian Ocean region from the extratropics, subsidence connected to remote convective activities, etc.

3.4 Forecast

As outlined in Section 1, the MJO influences weather and climate – both in the Tropics and mid-latitudes – and it is gaining increasing use as a predictor in extended range weather prediction. At the CPC, operational MJO prediction has been established over the last few years and has benefited this area, however, anticipation of MJO event development or demise has made operational prediction very difficult. Statistical forecast techniques and MJO composites perform well during established MJO events. Dynamical model predictions are also improving during these times. However, daily monitoring of key MJO related variables, both in the atmosphere and ocean, remains the most important and reliable method for anticipation of MJO initiation. At the current time, operational MJO prediction is often forced to react to the development of the MJO after the fact rather than have the ability to reliably anticipate its initiation. Moreover, there is limited ability to reliably forecast the demise of an established MJO event.

The DYNAMO project is expected to help in this area in two ways. First, the extensive and targeted field observations will contribute to improved documentation of all stages of the MJO initiation process – especially focused on important MJO variables and the hypothesized mechanisms outlined in Section 2. The benefits of this contribution from DYNAMO to operational MJO prediction may be immediate as important precursors for the development of the large-scale MJO signal may be identified more clearly than in the past. For example, the current MJO monitoring is mainly based on the Wheeler-Hendon (2004) MJO index, which is formed using zonal winds and OLR. It is an excellent index to track the propagation of the MJO. But it does not provide sufficient information about MJO initiation, especially under Scenario A. Through DYNAMO, an MJO initiation index can be developed, which may take into account other variables in addition to zonal winds and OLR that are critical to MJO initiation. Second, the observational-modeling framework outlined as part of DYNAMO will accelerate improvements in operational MJO prediction over time through extensive model development keyed to the MJO initiation problem. These advances are likely to occur more quickly than would be the case in the absence of DYNAMO.

An example of what may be possible through the second pathway described above is illustrated in Fig. 6. During January 2009, CPC made a successful prediction for MJO onset in large part from dynamical model predictions (Figure 6a-b). This was the first time CPC made a prediction of this type and allowed for atypical lead time to users. The subsequent observational data is shown in Fig. 6c. It is important to note that future forecasts (not shown) produced a MJO forecast closer to the observations than what is shown in the later days of this forecast. It is hypothesized that an external forcing from the extratropics (East Asian cold surge – Fig. 6d) may have contributed to MJO initiation in a manner outlined in Section 2 (Scenario A, Hypothesis V).

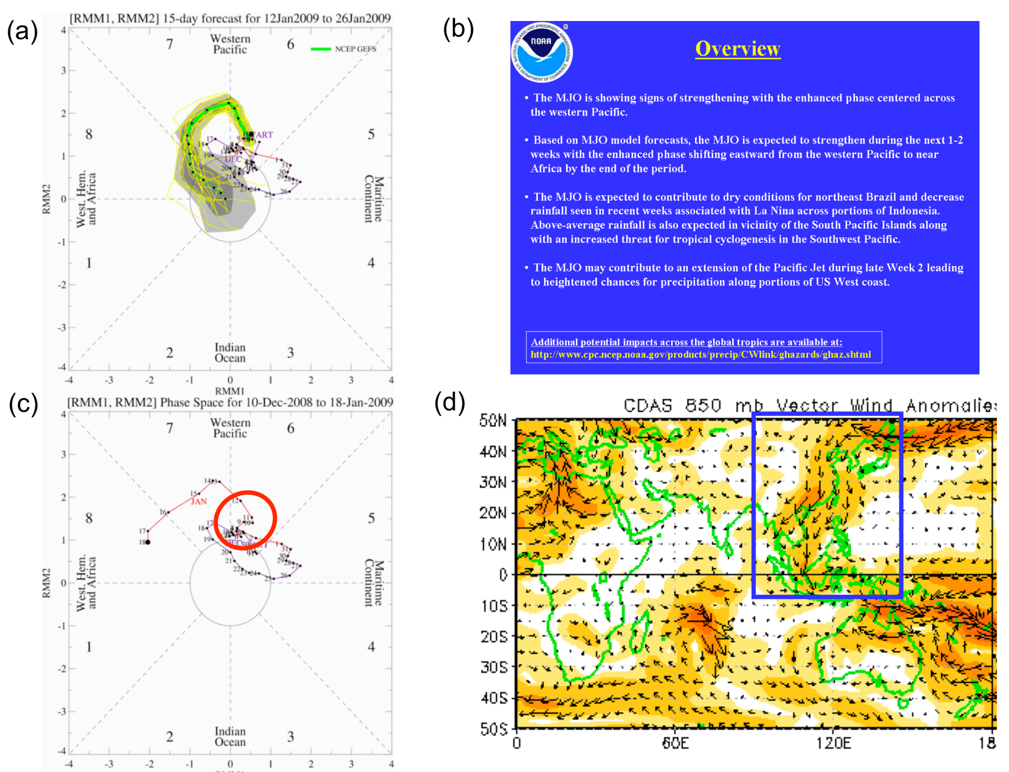

Figure 6 Example illustrating how a better understanding of MJO initiation will increase forecast lead time for users. (a) GEFS MJO index forecast indicating a developing MJO signal in the western Pacific which propagates eastward; (b) Official CPC MJO forecast for a developing MJO and its expected impacts; (c) Subsequent observations (red circle is 5 day period of low level wind average in lower right), and (d) Pentad low-level wind anomalies indicating a east Asian cold surge that may have contributed to MJO initiation.

Further support for DYNAMO can be provided by a US CLIVAR MJO prediction project (led by Jon Gottschalck) currently underway at NCEP/CPC, where real-time dynamical model MJO forecasts are being made based on numerical model output from several operational forecast centers around the world (e.g., NCEP, UKMO, ECMWF, ABOM, CMC, JMA; Gottschalck et al. 2009)[1]. Such operational forecast implementation provides practical measures for when and where MJO prediction skill is particularly limited and model results diverge. Continuous forecast verification leads to physical insights to factors that potentially hinder MJO prediction and to recommendations for field campaign targets. Archived forecast products serve as a statistical base to quantify model improvement. If needed, the real-time MJO forecasts as part of this activity from the various international centers will be a part of operational support for the DYNAMO/CINDY2011 field campaign and its partner program (PAC^{3}E-SA/7SEAS and the ONR air-sea field experiment).

4. Readiness and Program Synergy

It cannot be more timely for the US research and operations communities to make significant contributions to the study of the MJO initiation problem by participating in CINDY2011. First, the ongoing YOTC activities will provide experience and organizational infrastructure for an international observation-modeling-analysis-forecast integrated approach to tackle the problem of MJO initiation. MJO prediction has been practiced in an organized way under the guidance of the US CLIVAR MJO Working Group. These research-operation infrastructures will pave the road to directly connect field observations to modeling and forecasting activities. By 2011, the IndOOS and RAMA mooring array will be nearly completed, providing climatic background information for the field campaign on basin- and multi-year scales. Since TOGA COARE, observing technology has been greatly advanced to make measurement at either unprecedented accuracy (e.g., GPS sondes, shipboard Doppler current profiles) or relatively low cost (mixing profiles in the upper ocean). Lastly, but most importantly, international cooperation and other US programs will be in place in late 2011 – early 2012 to provide a comprehensive suite of observations across a large region covering the equatorial Indian Ocean, Maritime Continent, and western Pacific Ocean, as briefly described below. The resulting synergy will make the DYNAMO field campaign much more productive than it would be as a stand alone project. This makes late 2011 – early 2012 a critical time for DYNAMO.

Figures 7 illustrates potential DYNAMO partner programs that are being planned for late 2011 – early 2012. Committed international participations in CINDY2011 include Japan (50-day ship time of Mirai with a Doppler precipitation radar, radiosondes, and surface and upper-ocean observations) and India (30-day ship time of Sagar Kanya with radiosondes). Australian scientists are planning to join the campaign (30 day ship time of Southern Surveyor, with radiosondes, surface and upper ocean observations). Enhanced radiosonde observations will be conducted at Seychelles during CINDY2011, in addition to the operational sounding launches in the region.

An ONR supported field experiment on meso- and synoptic-scale air-wave-sea

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[1] http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/CLIVAR/clivar_wh.shtml

Figure 7 Global perspective and partner programs of CINDY2011/DYNAMO. The exact site of the ONR Air-Sea experiment has yet to be determined.

interaction in the Indian Ocean will take place for the period of CINDY2011 (late 2011). This field program may complement DYNAMO/CINDY2011 very well by focusing on more detailed measurement of processes at the air-sea interface and in the boundary and mixed layers at each side of the interface. DYNAMO/CINDY2011, on the other hand, can provide the measurement of the large-scale context within which such detailed processes take place. The two programs can share observing platforms, instrument and expertise. Ultimately, the combined data set will cover multi-scale processes in the Indian Ocean that advanced numerical models must accurately reproduce.

A proposal has been submitted to the ARM Program to conduct an enhanced observational period of six months (AMIE). At the ARM western Pacific site on Manus Island increased sounding (8 per day) are proposed during a six-month period embedding the DYNAMO/CINDY2011 field campaign. Manus is a location where the MJO just starts to regain its strength after suffering from its usual weakening over the Maritime Continent. The combination of AMF2 and SMART C-band radar to be deployed on an Indian Ocean island under the DYNAMO plan would form an observational package almost identical to that at the ARM Manus site. Data collected from these two sites will contrast same MJO events at two different stages of their life cycles. Meanwhile, DYNAMO can interact with and benefit from the ARM modeling community, which has considerable experience and expertise in simulations and parameterization of tropical convection and its interaction with the large-scale circulation. They also have been working on the modeling-observation integration.

Between the CINDY2011 site in the central equatorial Indian Ocean and the AMIE Manus site is an observational network of Doppler radars and wind profilers over the Indonesian Archipelagos (HARIMAU) to document the propagation of the MJO over the Maritime Continent. HARIMAU (http://www.jamstec.go.jp/iorgc/harimau/) is a project jointly conducted in Indonesia by Indonesian and Japanese institutes. Its objective is to collect and diagnose observations to further physical understandings of intraseasonal variation in terms of convective and rainfall activities over the Maritime Continent, to help prevention from natural disasters due to extreme events, and to provide useful information for local management and capacity building. Its observational network consists of six sites equipped with C- and X-band Doppler radars, wind profilers, GPS sondes, surface meteorological measurement including rain gauges. It's first phase lasts from April 2005 to March 2010 and its follow-on project is now being proposed. Data from HARIMAU provide unique information of the MJO weakening over the Maritime Continent, an unsettled problem to both MJO understanding and prediction. Integrated observations from DYNAMO/CINDY2011, HARIMAU, and AMIE would allow some

MJO events to be monitored at three different stages of their life cycles.

A proposed NASA interdisciplinary atmospheric sciences program to study the interactions of pollution with regional meteorology, particularly with clouds, the Seven SouthEast Asian Studies (7SEAS), and an intensive field campaign, the Pacific Atmospheric Composition, Cloud, and Climate Experiment – Southeast Asia (PAC^3E-SA), will be in place over the Maritime Continent. PAC^3E-SA is a NASA field program for August-September 2011 to study the transport and vertical redistribution of atmospheric constituents by and in proximity to convection in the Southeast Asian region. While PAC^3E-SA will have comprehensive atmospheric chemistry components, one of its primary foci is the role of convection in pumping aerosol and evolving boundary layer air into the free troposphere. It is anticipated that the PAC^3E-SA mission will be a multi-aircraft field campaign, augmented by surface and shipboard measurements of aerosol and meteorology from 7SEAS. Potential interaction between aerosol and the MJO is an open question challenging both DYNAMO and PAC^3E-SA/7SEAS. Observations taken from these programs can be highly complementary, with data covering different longitudes featuring aerosols of different sources and characteristics.

By joining this suite of field programs in late 2011 – early 2012, the DYNAMO observations will be part of an integrated data set to monitor the MJO from its birthplace in the Indian Ocean to it mature stage over the western Pacific. Such an opportunity to capture the whole life cycle of the MJO and its interaction with the ocean, land and aerosol as it propagates from the Indian Ocean over the Maritime Continent into the western Pacific would probably not come again in the foreseeable future.

Appendix Acronym List

ABOM	Australia Bureau of Meteorology
ACRF	ARM Climate Research Facility
AIRS	The Atmospheric Infrared Sounder
AMF2	ARM Mobile Facility 2
AMIE	ACRF MJO Investigation Experiment
ARM	Atmospheric Radiation Measurement
CAM	Community Atmosphere Model
CAPT	CCPP-ARM Parameterization Testbed
CCPP	Climate Change Prediction Programs
CCS	Centre for Climate Studies (Brazil)
CFS	Coupled Forecast System
CINDY2011	Cooperative Indian Ocean Experiment on Intraseasonal Variability in the Year 2011
CMC	Canadian Meteorological Centre
COAMPS	Coupled Ocean-Atmosphere Mesoscale Prediction System
CPC	Climate Prediction Center
CRM	Cloud Resolving Model
CSU	Colorado State University
CTB	Climate Test Bed
CWB	Central Weather Bureau (Tawain)
ECMWF	European Centre for Medium-Range Weather Forecasts
EDO	Experimental Design Overview
EMC	Environmental Modeling Center
EOL	Earth Observing Laboratory
DRI	Departmental Research Initiative
DOE	Department of Energy
DYNAMO	Dynamics of the MJO
ENSO	El Niño – Southern Oscillation
ESRL	Earth System Research Laboratory
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GDAS	Global Data Assimilation System
GEFS	Global Ensemble Forecast System
GEOS-5	Goddard Earth Observing System Model Version 5
GPS	Global Position System
HARIMAU	Hydrometeorological Array for ISV-Monsoon Automonitoring
HcGCM	Hybrid coupled GCM
INDEOX	The Indian Ocean Experiment
IndOOS	Indian Ocean Observing System
IOD	Indian Ocean Dipole
IPRC	International Pacific Research Center
IROAM	IPRC Regional Ocean-Atmosphere Model
ISU	Iowa State University
ISV	Intraseasonal Variation
JASMINE	Joint Air-Sea Monsoon Investigation

JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JMA	Japan Meteorological Agency
IMD	India Meteorological Department
JPL	Jet Propulsion Laboratory
LOI	Letter of Intent
MISMO	Mirai Indian Ocean cruise for the Study of MJO-convection onset
MJO	Madden-Julian Oscillation
MMM	Mesoscale and Microscale Meteorology
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NOAA	National Ocean and Atmosphere Administration
NOGAPS	Navy's Operational Global Atmospheric Prediction System Model
NPS	Naval Postgraduate School
NRCM	NCAR Nested Regional Climate Model
NRL	Navy Research Laboratory
NSF	National Science Foundation
ONR	Office of Navy Research
OSU	Oregon State University
PAC^3E-SA	Pacific Atmospheric Composition, Cloud and Climate Experiment – Southeast Asia
PNNL	Pacific Northwest National Laboratory
PSMIP	Process Study and Model Improvement Panel
RAMA	Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction
R/V	Research Vessel
7SEAS	The Seven SouthEast Asian Studies
SCTR	Seychelles-Chagos thermocline ridge
SMART-R	Shared Mobile Atmosphere Research and Teaching Radar
SPO	Science Planning Overview
THORPEX	The Observing System Research and Predictability Experiment
TRIO	Thermocline Ridge of the Indian Ocean
TOGA COARE	Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Research Experiment
UCSD	University of California at San Diego
UH	University of Hawaii
UKMO	UK Met Office
UM	University of Miami
UW	University of Washington
UNOLS	University-National Oceanographic Laboratory System
YOTC	Year of Tropical Convection
WCRP	World Climate Research Program
WWRP	World Weather Research Program