EXPERIMENTAL DESIGN OVERVIEW (EDO)

Dynamics of the MJO

(DYNAMO)

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Executive 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; particularly, it is 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 our efforts to improve simulation and prediction of the MJO. DYNAMO consists of four integrated components: a field campaign, 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 campaign is designed to collect observations that are necessary to test hypotheses on three key aspects of MJO initiation: the structure and evolution of cloud populations, their interaction with the large-scale environment, and air-sea interaction. It will include an atmospheric sounding network, a radar network consisting of an island "supersite" with multiple radars (NCAR S-PolKa, Texas A&M SMART-R C-band, DOE AMF2 X-, K_a- and W-bands) and shipborne C- and W-band Doppler radars, and a ship/mooring network to measure air-sea fluxes, marine atmospheric boundary-layer properties, and upper-ocean large-scale and mixing structures.

DYNAMO will target processes deemed critical to MJO initiation but poorly observed and understood, including 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. A better understanding of these processes is essential for improving their representations in numerical models and improving MJO simulation and prediction. The newly available observation technology (e.g., scanning K_a-band radar, dual-wavelength radar, and moored microstructure sensors) and innovative instrument combinations (e.g., at the radar supersite) will allow DYNAMO field campaign to provide unprecedented information of these processes. The field campaign will consist of three observing periods:

– Special Observing Period (SOP): 1 October - 9 November 2011
– Intensive Observing Period (IOP): 1 October 2011 - 15 January 2012
– Extended Observing Period (EOP): 1 October 2011 - 31 March 2012

The SOP is designed to sufficiently resolve the diurnal cycle with the maximum observation capacity of DYNAMO. The IOP will cover initiation of at least one major MJO event using all DYNAMO instruments with a high probability (~90%). Over the course of the EOP, this probability is nearly 100% and likely multiple MJO events will occur. The field observations will be augmented by auxiliary data with longer and broader coverage (from RAMA moorings, satellites, global reanalyses).

The timing of late 2011 – early 2012 is critical for DYNAMO's success. Only during this period, will 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 has never existed before, and will not in the foreseeable future.

The DYNAMO observations will be use to calibrate and validate satellite retrievals to benefit their application to much broader areas beyond MJO-related problems. Improved model simulation and prediction of the MJO born from DYNAMO activities will enhance our capacities of delivering prediction and assessment products on intraseasonal timescales for risk management and decision making, and to strengthen confidence in climate simulation and projection.

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1. Rationale and Hypotheses

Detailed descriptions of the scientific background, rationale, and hypotheses of DYNAMO are given in the DYNAMO Scientific Program Overview (SPO). They are briefly summarize here and in the next section. In short, DYNAMO is motivated by the urgent need to improve the capability of state-of-the-art global models to simulate and predict the MJO, especially its initiation. Such improvement will gain dynamical prediction skills on intraseasonal to interannual timescales to meet societal needs and strengthen confidence in the ability of climate models to project future climate. The foundation for such improvement must be built upon a thorough knowledge of the key physical processes involved. The overarching goal of DYNAMO is to expedite our understanding of MJO initiation processes and our efforts to improve simulation and prediction of the MJO. This goal will be achieved by following an integrated approach of field observations, data analysis, modeling, and forecasting in coordination with other field programs. The opportunity of leverage and synergy among several programs makes October 2011 – March 2012 a critical time for DYNAMO's success.

The equatorial central Indian Ocean is chosen to be the location of the DYNAMO field campaign for several reasons. The Indian Ocean hosts a number of climatological features that are distinct from those over the western Pacific and some of them are unique in the tropics: the strongest monsoon flows, mean subsidence, landmasses on three sides, the absence of an equatorial cold tongue, the Seychelles-Chagos thermocline ridge and Wyrtki jets. MJO initiation over the Indian Ocean is a very different problem from MJO propagation over the western Pacific. At two stages of the MJO lifecycle, the role of the large-scale circulation and its interaction with atmospheric convection in MJO dynamics can differ substantially. Limited sounding and satellite data analyses suggest that the structures of the MJO are not the same over the two oceans, implying different physical and dynamical processes are involved.

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.

In situ observations from the tropical Indian Ocean are sparse. Operational rawinsondes from islands of the region are limited and decreasing with time. The Indian Ocean mooring array (RAMA[1], McPhaden et al. 2009) has yet to be completed. Satellite retrievals, which have rarely, if at all, been calibrated and validated by *in situ* observations from the region, show vertical profiles of temperature and moisture that differ substantially from those of a reanalysis over the Indian Ocean (Tian et al. 2006). Detailed processes of MJO initiation in the tropical Indian Ocean region cannot be reliably studied without *in situ* observations from a field campaign.

A conceptual model of MJO initiation is proposed in the SPO. In this model, MJO initiation consists of three stages: pre-onset, onset, and post-onset. In order to understand MJO initiation, we need to determine the mechanisms that initiate each stage, sustain it for a certain time, and cause its demise. No single field program can solve all problems associated with MJO initiation. DYNAMO hypotheses focus on processes that must be quantified using field observations from the Indian Ocean region and emphasize three key aspects: interaction between convection and environmental moisture, the evolution of the cloud populations, and air-sea interaction. Inadequate representations of these processes in numerical models may inhibit their accurate simulation and prediction of MJO initiation. The DYNAMO hypotheses are:

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 stage.

Hypothesis II: Specific convective populations at different stages are essential for MJO initiation.

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

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.

These hypotheses will be tested using DYNAMO field observations, auxiliary data (from moorings, satellites, and global reanalyses), and numerical models constrained, validated and evaluated by observations (see SPO).

2. Scientific Objectives

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

- Collect observations from the equatorial central 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.

Data to be collected by the DYNAMO field campaign will be a unique contribution to the existing pool of observations from previous field programs (including GATE, EMEX, TOGA COARE, NAME, TWP-ICE, and others). While no single program can completely solve the parameterization problem, these field data in combination have served an irreplaceable role in the effort of developing and testing model physical representations and have allowed a steady progress in the improvement of model parameterizations. The current collection of field observations critical to such a progress is suffering from a pronounced gap in the tropical Indian Ocean. By filling this gap, DYNAMO observations will contribute to the improvement of model physical representations as well as accelerate the progress of studying MJO initiation as GATE did for the study of easterly waves and TOGA COARE for the study of MJO propagation.

3. Experimental Design

The DYNAMO field campaign is proposed as the US component of CINDY2011, an international field program in the equatorial central Indian Ocean (Fig. 1) during October 2011 – March 2012. Four countries (India, Japan, Australia, and the US) will participate. The DYNAMO field experimental design must be described together with the entire CINDY2011 field campaign. In the rest of this document, “DYNAMO” should be taken as “DYNAMO/CINDY2011”. The DYNAMO field campaign will consist of three components:

- A sounding array (section 4.1) formed by two islands, Gan (0.7°S, 73.2°E) and Diego Garcia (7.3˚S, 72.5˚E), and two research vessels, one at 0.7˚S, 79˚E (“northeast point” or NE) and another at 7.3˚S, 79˚E (“southeast point” or SE), as illustrated in Fig. 2. Four ships are planned to be on the SE and NE stations in rotation to form the sounding-radar array. The ships are the *R/V Mirai* (Japan), *Sagar Kanya* (India), *Southern Surveyor* (Australia), and a US ship, preferably the *R/V Roger Revelle*[2,3]. GPS sondes will be launched from all four island and ship sites and wind profilers will operate on Gan and onboard three ships.

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[2] For the purpose of discussion, the *R/V Roger Revelle* is used in this document as the US ship, unless indicated otherwise.

[3] The detailed US ship schedule will be discussed in section 4.3.

- A radar network (section 4.2) including a multi-radar "supersite" on Gan (with the NCAR S-Polka dual wavelength radar, Texas A&M SMART C-band radar, DOE AMF2 X-, K_a- and W-band radar system) and C- and W-band radars on the *R/V Mirai* and *Revelle* to be stationed at the NE and SE points of the sounding array (blue circles in Fig. 2).
- A network for air-sea interaction measurements (section 4.3). Moored buoys with instruments for surface meteorology and high vertical and temporal resolution upper-ocean temperature, salinity, current, and turbulence flux profiles will be deployed at 76˚E and 0, 2, and 8˚S (red diamond in Fig. 2). High-resolution upper-ocean moored turbulence sensors will also be outfit to three existing RAMA moorings at 0˚ 80˚E, 0˚ 90˚E, and 2˚S 80˚E (yellow dots in Fig. 2). Air-sea fluxes, upper-ocean profiles, and atmospheric boundary-layer profiles will be measured from all ships (blue squares in Fig. 2). In addition, aerosol, ozone, water isotopes, and marine biochemical samples will be measured from ships.

The general observational timeline of DYNAMO is outlined in Fig. 3. The main DYNAMO field campaign will start on 1 October 2011 and end on 31 March 2012. It will consist of a Special Observing Period (SOP, 1 October – 15 September 2011, section 3.1), an Intensive Observing Period (IOP, 1 October 2011 – 15 January 2012, section 3.2), and an Extended Observing Period (EOP, 1 October 2011 – 31 March 2012, section 3.3). The DYNAMO field campaign will be supported by data from Long-Term Monitoring (LTM) networks (moorings, satellites, etc.) that provide basin-scale and multi-year statistics and climatology background for DYNAMO field observations. The objectives and detailed observational requirements for each of the observing period are described later in this section and in section 4.

The choice of the equatorial central Indian Ocean as the location and late boreal fall - winter as the time window for the DYNAMO field campaign is supported by MJO statistics. Figure 4 shows initiation of a number of major MJO events (when MJO OLR anomalies first become less than -10 Wm^{-1}) as a function of longitude (in 10˚ bins) and calendar month during 1979 - 2007. It is clear that initiation of major MJO events are concentrated at ~75˚E longitude during October – January. These are the location and time of the DYNAMO IOP. The sounding-radar array of the DYNAMO field campaign will witness all stages of MJO initiation (Fig. 5), including the pre- and post-onset stages with relatively weak precipitation (phases 4-7), the convectively active period of the onset stage (phases 2 and 3), and the transition in between (phases 8 and 1). It is expected that observations taken from the DYNAMO field campaign will capture various large-scale atmospheric and oceanic environments with an embedded full spectrum of tropical convective clouds at different stages of the MJO initiation.

The DYNAMO experimental design has taken into consideration several factors: the accuracy of sounding-based heat and moisture budget estimates, which depends on the size and shape of the sounding array; the probability of covering initiation of major MJO events based on past statistics, which depends on the experiment duration; the given geographical and resource constraints, and lessons from MISMO, the DYNAMO pilot study in 2006 (see SPO). There must be a compromise among these factors. The current DYNAMO experimental design reaches an optimal balance, with relatively small errors in the budget estimate (section 4.1) and a sufficient length to cover initiation of least one major MJO event. A field campaign in the equatorial central Indian Ocean lasting 30-40 days during boreal fall and winter will have about 20-40% probability to cover a major MJO initiation. Because of this low probability, MISMO, which lasted 33 days, missed a major MJO event. The probability increases to 90% for the DYNAMO IOP (section 3.2) spanning 3 - 4 months in October – January. The 6-month (October – March) EOP (section 3.3) will almost guarantee the coverage of initiation of at least one major MJO event and it will perhaps cover multiple MJO events. The radar supersite on Gan is designed partially for cross-instrument calibration and comparison during the IOP to provide a quantitative evaluation of how accurately reduced observation capacity during the EOP (section 3.3) may capture the essential processes of MJO initiation (section 4.2).

MJO behavior is also affected by El Niño – Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). In general, weaker MJO events over the Indian Ocean can be expected during a warm phase of ENSO (El Niño) and a positive phase of IOD (anomalously low SST in the eastern Indian Ocean). However, partially because of the short satellite record and partially because of the decadal variability in the tropics, there is no robust signal as to how MJO events in the Indian Ocean are consistently modulated by the phases and strength of ENSO and IOD. Neither ENSO nor IOD can be predicted beyond 9 months. There is no reliable way to anticipate and prepare for possible their effects on the DYNAMO field campaign at its planning stage. Here, we present the "worst" and "best" scenarios from the past 30 years (Fig. 6) to illustrate the range of possibilities that the DYNAMO field campaign may encounter.

An extraordinary El Niño event occurred in 1982-83. Strong positive anomalies in deep convection over the central Pacific (negative OLR anomalies in the left panel of Fig. 6) shifted the Walker circulation eastward. In consequence, abnormally strong subsidence was located over the eastern Indian Ocean and the Maritime Continent. This led to strong negative anomalies in convection there. There was hardly any MJO event during the period of October – March of this El Niño peak season. But, notice the evident intraseasonal oscillation in OLR at the longitude of the DYNAMO field campaign (marked by vertical lines in Fig. 6) during October – March of 1982-83. Negative intraseasonal OLR anomalies tended to develop and propagate eastward, but were terminated over the Maritime Continent because of the strong subsidence. In this sense, several MJO events were initiated over the central Indian Ocean but failed to survive the detrimental effect of ENSO that year. The consequence is that MJO statistics show no major event over the Indian Ocean. Observations taken over the initiation region (i.e., the DYNAMO field campaign location) would cover the entire MJO initiation processes, regardless of what might happen to these MJO events after their initiation. Therefore, even if this "worst" scenario occurs in 2011-12, the DYNAMO field campaign would still accomplish its objectives of studying MJO initiation. Similar situations can be expected during a positive phase of the IOD when MJO events may still initiate over the western and central Indian Ocean, but not propagate farther eastward because of the anomalously low SST in the eastern Indian Ocean.

Conditions during the period of 1987-88 would have been ideal for DYNAMO (right panel in Fig. 6). There were four major MJO events initiated during October – March (months of the DYNAMO EOP), with one in October (SOP) and three during October – January (IOP). All these events propagated into the western Pacific, where they would also be monitored by AMIE at Manus Island (see SPO) if such events occur during 2011-12. All other years during the past three decades with all possibilities of phases and strengths of ENSO and IOD were in between these two extremes. There was no single year without initiation of any major MJO event at all over the central Indian Ocean in the period of October – March, even though there might not be any major MJO event successively propagating eastward out of the Indian Ocean. In this sense, we expect DYNAMO to successfully observe MJO initiation processes regardless of the phases of ENSO and IOD in 2011-12.

The three observing periods of DYNAMO (SOP, IOP, EOP) are designed to maximize the return of limited resources and minimize possible negative impacts on the field observations by the irregularity of the MJO and unpredictable short-term climate variability.

3.1 Special Observing Period (SOP): 1 October 2011 - 9 November 2011

The objective of the SOP is to sufficiently document the diurnal cycles in the vertical structures of the atmospheric large-scale environment, its embedded convective clouds, and the air-sea interaction using the maximum observing capacity of DYNAMO.

The SOP is designed to fully observe the diurnal cycle of the ocean-atmosphere coupled system. It will cover a 40-day period from 1 October through 9 November 2011 (Fig. 3). GPS sondes will be launched 8 times per day from all island and ship sites. C- and W-band Doppler radars will be operating onboard both *R/V Mirai* (at the SE point of the array – Fig. 2) and R/V

*Revelle (*at the NE point). Three other radar systems (the NCAR S-PolKa, Texas A&M SMART-R, and DOE AMF2) will be operating at the supersite on Gan (section 4.2). During the SOP, and only during the SOP, will all DYNAMO radars be operating simultaneously.

The high-frequency (8 per day) soundings and the maximum radar operation, along with other observations (see section 4) during the SOP will provide an unprecedented capability to sample cloud population statistics (precipitating and non-precipitating clouds), their large-scale environment, and their air-sea interaction processes for a period that would include many synoptic and mesoscale perturbations. Especially, issues related to the diurnal cycle in the DYNAMO hypotheses (see the SPO) will be addressed using the high-frequency soundings plus continuous measurement of radars, wind profilers, surface fluxes, SST, and the upper-ocean structures (section 4), regardless of the MJO phase to be covered during the SOP.

3.2 Intensive Observing Period (IOP): 1 October 2011 - 15 January 2012

The objective of the IOP is to document the evolution in the processes of the atmosphere, upper ocean, and their interface at all stages of MJO initiation using all DYNAMO instruments.

The IOP is designed to observe initiation processes of at least one major MJO event with a high probability (~ 90%). The MJO observations collected during the IOP will be used for case studies and for comparisons to satellite observations and global reanalysis products to extend the statistical robustness of the field data analysis. It will start at the same time as the SOP (1 October 2011) but will continue for a longer period until 15 January 2012 (Fig. 3). From the end of the SOP (9 November 2011) to the end of the IOP, the sounding frequency will be 4 times per day. Other than that, there will be no change in the observations on the two islands. Throughout the IOP, different ships will have their own observational packages (sections 4.3 and 4.4). But atmospheric soundings and surface meteorology will be measured from all island and ship sites, while air-sea fluxes and upper ocean profiles of temperature, salinity, and current will be measured from all ships and moorings (section 4.3).

On 9 November 2011, the *R/V Roger Revelle* will leave the NE point of the array (Fig. 2) for a port call, and come back to the same position on 15 November. There will be a 6-day observation gap at this position during this period (Fig. 3). The *R/V Mirai* at the SE point will be replaced by the *R/V Southern Surveyor* on 24 November 2011. On 17 December 2011 the *R/V Southern Surveyor* will leave the SE position for a port call and the *R/V Sagar Kanya* will take that position and remain there until the end of the IOP. On 20 December 2011, the *R/V Revelle* will leave the NE position; this position will be taken by the *R/V Southern Surveyor* after her port call until the end of the IOP. On 15 January 2012 the *R/V Southern Surveyor* and *Sagar Kanya* will leave their positions and the S-PolKa radar will leave Gan, marking the end of the IOP.

Prior to the start of the IOP, the *R/V Revelle* will take a 15-day mooring cruise to deploy three surface meteorology and upper ocean moorings at 76˚E and 0, 2, and 8˚S (Fig. 2). High-resolution moored turbulence sensors (χpods) will be outfit to these three moorings during this cruise and on three existing RAMA moorings at 0˚ 80, 0˚ 90˚E, and 2˚S 80˚E during an earlier RAMA maintenance cruise. These moorings will take measurements (section 4.4b) until 28 December 2011 – 11 January 2012 when they are retrieved by the *R/V Revelle* during the second mooring cruise immediately following the IOP.

3.3 Extended Observing Period (EOP): 1 October 2011 - 30 March 2012

The objective of the EOP is to expand the DYNAMO observation sample size by documenting MJO initiation of multiple events and to compare the MJO at distinct stages of its lifecycle over the Indian Ocean, Northern Australia, and the western Pacific Ocean using the same instruments.

The EOP will enhance the 90% chance of observing initiation processes of a major MJO event during the IOP to 100%, albeit with reduced observational capacity, regardless of the phases and strength of the tropical short-term climate variability (ENSO and IOD).

After the IOP, there will be no ship observations. Two radar systems, a sounding system, and a full radiation package (SMART-R and AMF2) on Gan (section 4.2) will continue to operate until 31 March 2012 (Fig. 3), which is the end of EOP. DYNAMO moorings and outfit mixing profilers on RAMA moorings will continue taking observations during part of the EOP (until the end of December 2011). During the EOP the combination of SMART-R and AMF2 on Gan would form a package nearly identical to the facilities at the ARM Darwin and Manus sites to document the same MJO events at different stages of their lifecycles. The comparison and cross-calibration among different radars at the Gan supersite and between measurements from Gan and the sounding-radar array during the IOP will provide detailed and quantitative information of how the EOP observations can be optimally interpreted (section 4.2).

3.4 Long-Term Monitoring (LTM)

The LTM is not a direct component of DYNAMO, even though DYNAMO drifters will contribute to it. However, data from the LTM will be an integrated part of the DYNAMO data. The RAMA moorings directly relevant to DYNAMO (i.e., the 67 and 80˚E lines, Fig. 1) will be completed by the time the DYNAMO field experiment starts and thus provide basin-scale and multiyear background information for DYNAMO post-field data analyses. Regular measurements at the ARM sites of Darwin, Manus and Nauru also provide long-term background information of surface radiation/energy flux and cloud evolution associated with the MJO. A constellation of satellites (e.g., TRMM, A-TRAIN) has collected multiple years of data that are useful to the MJO study. These satellite data have rarely, if ever, been validated by field observations over the tropical Indian Ocean. The DYNAMO observations will allow such validation and thereby quantify the extent to which these satellite data can yield reliable statistics for the MJO study.

4. Specific Observational Requirements

Tables 1-3 list respectively DYNAMO land, ship, and mooring instruments.

Table 1 Operation period and sampling frequency of DYNAMO observations from land-based instruments

	Gan	Diego Garcia	Darwin	Cocos	Seychelles
Operational GPS sondes (12 hr regularly)			6 hr, IOP	6 hr, IOP	6 hr, IOP
S-PolKa Radar	Continuous, IOP				
SMART Radar	Continuous, EOP				
C-band Radar			Continuous, EOP		
ISS:		IOP			
GPS sondes		3 hr, SOP 6 hr, IOP			
rain gauge					
10-m surface met	10 min	10 min			
radiometers	10 min	10 min			
915 MHz wind profiler		10 min			
RASS		10 min			
AMF2:	EOP				
W-, K, and X-band radars	Continuous				
GPS sondes	3 hr				
micropulse lidar	10 min				
microwave radiometer	20 sec				
narrow field of view	10 min				
total sky imager	10 min				
ceilometer	20 sec				
915 MHz wind profiler	10min				
solar/IR radiometers	10 min				

Table 2 Sampling frequency of DYNAMO observations from ship-borne instruments

	R. Revelle	Mirai	S. Surveyor	S. Kanya
Instrument/measurement				
radiosondes	3 hr (SOP) and 6 hr (IOP)	3 hr	6 hr	6 hr
surface met/bulk flux	10 min	10 min	1 min	1 min
turbulent flux	10 min	10 min		
Doppler C-band radar	Continuous	Continuous		
Doppler W-band radar	Continuous	Continuous		
scanning Doppler lidar (HRDL)	20 min (wind, turbulence, and aerosol backscatter intensity); 10 min (clouds, precipitation, vertical velocity)			
Mie-scattering Lidar	Continuous	Continuous		
wind profiler (915 MHz)	10 min	10 min		
water vapor radiometer	20 sec			
ceilometer	20 sec	1 min	1 min	
Solar/IR radiometer	10 min	10 min	10 min	
Microwave radiometer	20 sec			
Ozone UV absorbance	1 min			
OS2, Pulsed fluorescence	1 min			
radon	13 min			
Aerosol chemistry, Q-AMS	5 min			
Aerosol chemistry, Impactors	4-12 hrs			
Aerosol light absorption, TSI 3563 nephelometers	1 min			
Aerosol light absorption Radiance Research PSAP	1 min			
Total particle number CNC	1 sec			
Aerosol number size distribution, DMA and APS	5 min			
DMT CCN counter	30 min			
Aerosol optical depth, Microtops	1 hr	10 min		
video sondes		15 times		
ozone sondes		15 times		
Stable water isotope		10 min		
GPS water vapor	10 min	10 min	10 min	
120 kHz echosounder (150m)	1 sec			
Chameleon turbulence profiler (200m)	8-10 per hour			
CTD		3 hr (500m)	12 or 4 hr (1000m)	6 hr
ADCP	5 sec (500m)	5 min (16 m bin)	20 min (8 m bin)	20 min
TSG		1 min	1 min	
SSST		10 min	10 min	
Sea-Soar			6 (1-hr) legs/day	
water sampling (biogeochemical analysis)		3 hr		3 hr

Table 3 Sampling frequency of DYNAMO observations from mooring instruments

	DYNAMO	RAMA
Instrument		
CTD (temperature, salinity, and pressure)	1 min	10 min
Acoustic Doppler Profiler (ocean current velocity profile)	2 sec (300 kHz and 1200 kHz)	1 hr (75 kHz)
χpod (turbulence mixing and flux)	1 sec	1 sec
surface met/bulk flux	10 min	10 min

4.1 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.

DYNAMO Hypotheses I and II focus on interaction between clouds, precipitation and their large-scale environment. Testing these hypotheses is possible only when we have accurate information of atmospheric profiles of temperature, moisture, and wind. These profiles, which describe the large-scale environment for clouds and precipitation, can be observed reliably only from soundings, including rawinsondes, lidars, and wind profilers. The DYNAMO sounding array (Fig. 1) is designed to provide such reliable field observations at different initiation stages of the MJO. All rawinsonde measurements will be available to the operational centers in real time through GTS. These sounding observations will form the basis for estimating atmospheric sources/sinks of diabatic heating (Q_1) and moisture (Q_2). Such observations and derived variables will be used in model and satellite validation, and in data analysis in conjunction with other DYNAMO observations, numerical model experiments, and auxiliary data (see SPO).

The configuration of the sounding array (i.e., a quadrilateral array) was chosen after considering other competing options (a diamond array and a triangular array). Numerical and theoretical calculations of errors in Q_1 and Q_2 estimates were made to guide the selection among these options. Using output from a cloud-resolving model (NICAM) simulation and a theoretical calculation of equatorial waves, sounding samplings from various array configurations were made and their estimates of Q_1 and Q_2 were compared to those using the full resolution data. The currently chosen configuration leads to small errors while allowing sufficient duration of the experiment to catch major MJO events under the constraints of geography and resources.

The DYNAMO sounding array covers a slightly larger area than those of TOGA COARE and MISMO, the DYNAMO pilot study (see SPO). The distance between Gan and Diego Garcia is the major constraint in the design of the sounding array (Fig. 2). While a smaller array such as the IFA for TOGA COARE may result in more accurate estimates of Q_1 and Q_2, it is also ideal to have a nearly square array as currently designed for DYNAMO. So it is not desirable to reduce the area of the DYNAMO sounding array by moving the ship stations westward and make the array a north-south elongated rectangle.

The US participation in the field campaign will be responsible for soundings at three sites: Gan, Diego Garcia, and the *R/V Revelle*. Soundings at Gan will be part of the DOE ARM Mobile Facility (AMF2), which will be deployed for the entire EOP (including SOP and IOP). The NCAR Integrated Sounding System (ISS) will be deployed at Diego Garcia for the IOP (including SOP). The NCAR GPS Advanced Upper-Air Sounding System (GAUS) and a 915 MHz wind profiler will be deployed onboard the *R/V Revelle* for the IOP (including SOP). The other three ships will be responsible for their soundings.

GPS sondes will be launched 4 times per day from all four sites during the IOP (section 3.3). Enhanced soundings (8 per day) will be launched from all sites during the SOP (section 3.1) to fully resolve the diurnal cycle. During the EOP after the IOP, soundings will continue to be launched from Gan.

The sounding systems to be used at both islands and all four ships will be Vaisala RS92 GPS sondes with MW31 Ground Station Processing Subsystem operating on Digicora III software or their equivalence (i.e., NCAR GAUS). The uniform soundings systems at all sites will minimize discrepancies in data quality and biases and maximize the quality in Q_1 and Q_2 calculations. In addition, GPS receivers will be deployed at all US sounding sites and the *R/V Mirai* and *S. Surveyor* to measure total column water vapor, which will be used to calibrate the sounding humidity measurements.

During MISMO, sounding observations were taken on Gan, so we do not anticipate infrastructure and logistics issues there during the DYNAMO field campaign. But the sounding observations will be taken together with the radar and radiation observations (section 4.2). The site feasibility for all Gan observations should be evaluated as a whole.

Permission will be needed from the US Naval base at Diego Garcia for DYNAMO to operate its sounding observations there. Routine operational soundings were launched at Diego Garcia until 2006. At that time, they were launched by civil contractors. From the viewpoint of infrastructure and logistics, there is no obvious obstacle preventing DYNAMO from launching soundings at Diego Garcia. If permission of sounding launch at Diego Garcia is not granted, an alternative sounding array will be adapted (see Appendix A).

In addition to the DYNAMO sounding array showing in Figs. 1 and 2, there will be enhanced operational sounding launches in the region from Seychelles (4.5°S 55.5°E), Cocos (11.8˚S, 97.7˚E), and Darwin (12.5˚S, 131˚E) (Fig. 1 and Table 1). These sounding sites, plus those from the DOE ARM site at Manus (2°S, 147°E) as part of the AMIE and from HARIMOU (see SPO), will form a zonal array of soundings that monitor the vertical dynamical and thermodynamical structures of the same MJO events through their life cycles including their initiation phases over the Indian Ocean and propagation over the Maritime Continent and northern Australia into the western Pacific. At some of these sites (e.g., Darwin, Manus), simultaneous observations of radars (see next section) will help document changes in cloud populations with their large-scale environments.

4.2 Radars

The objective of the DYNAMO radar observations is to fully characterize the ensemble of convection associated with each stage of MJO initiation.

Advancing the understanding of MJO initiation, in particular testing DYNAMO Hypotheses I and II, requires observing the full spectrum of convection, described by as many variables as possible (e.g., areas and heights of radar echoes, types and concentrations of hydrometeors, air motions internal to clouds, cloud and precipitation element movement, separation of precipitating and non-precipitating components of clouds, subdivision of precipitating clouds into convective and stratiform components, structure and organization of cloud ensembles, association with environment moisture field, and propagation characteristics, among others). Moreover, it is essential to determine these observed aspects of the convection statistically and to determine how the statistics of the cloud population evolve from suppressed conditions, consisting of shallow to moderate isolated convection, to active conditions, characterized by ubiquitous, deep, and mesoscale convection. Surface-based radars are the only instruments that can routinely observe these features of the cloud population and resolve them in three-dimensions over a large spatial domain and over a reasonably long time. The diversity in the size and intensity of convection during all of the MJO phases implies that any individual radar can only document a subset of the convective spectrum. DYNAMO's approach will be to use radars over a range of wavelengths, each contributing uniquely to diagnosing the convective population and its properties. In general, shorter (mm) wavelength radars are more sensitive to cloud particles and small hydrometeors, but are more susceptible to attenuation. Non-Rayleigh scattering effects further complicate interpretations of short wavelength radar. Longer wavelength (cm) radars are less prone to attenuation, but are unable to detect cloud particles and small hydrometeors. The most common precipitation radar wavelengths are 10 cm (S-band), 5 cm (C-band) and 3 cm (X-band), while the most common cloud radar wavelengths are ~8 mm (K_a-band) and 3 mm (W-band). Radars of all of these wavelengths will be deployed simultaneously in a supersite located on the island of Gan (0.7° S and 73.2° E, Fig. 2). In addition, shipboard C- and W-band radars will be deployed on the *R/V Revelle* and *the R/V Mirai*. The proposed suite of radars at Gan and shipboard Doppler radars, through their comprehensive diversity of wavelengths and along with accompanying instruments, will capture the evolution of the convective population in unprecedented detail. A variety of scanning strategies will be used to optimize the information gained from each wavelength. Although radars have been deployed over the tropical oceans in previous field experiments, never has such an integrated suite of radars and related instruments been deployed to map the structure and evolution of the full convective spectrum over an equatorial ocean region.

<u>*R/V Revelle* and *R/V Mirai* platforms:</u> The *R/V Revelle* will have onboard the TOGA C-band scanning Doppler radar and NOAA's vertically-pointing (VP) W-band Doppler radar, as well as a scanning Doppler lidar. It is also possible that a DIAL lidar system (from Germany) will be onboard for continuous measurements of water vapor mixing ratios in the lower troposphere. A 915 MHz profiler is also planned for the *R/V Revelle*. The *R/V Mirai* will have scanning C-band and VP W-band Doppler radars, and a 915 MHz profiler. All the radars will be fully stabilized for ship motions using proven techniques based on experience in GATE, TOGA COARE, EPIC and other projects. The periods when these ships will be participating in the experiment are shown in Fig. 3, where US and JPN refer to the *R/V Revelle* and *R/V Mirai*, respectively.

<u>Supersite Gan platform:</u> As noted above, several radar systems will be deployed at the Gan supersite (Fig. 2): The Department of Energy (DOE) Atmospheric Radiation Measurement Mobile Facility No. 2 (AMF2) scanning, polarimetric X- and K_a-band radars and a VP W- or K_a-band radar; the Texas A&M Shared Mobile Atmospheric Research and Teaching scanning C-band radar (SMART-R); and the National Center for Atmospheric Research (NCAR) dual-polarimetric, dual-wavelength S- and K_a-band radar (S-PolKa). All of these radars are instrumented for Doppler velocity measurements to determine internal storm kinematics. The S-PolKa radar is further equipped for dual polarimetric measurements so that the microphysical characteristics of hydrometeors can be inferred. The radar systems will be distributed at three locations on Gan and the Addu Atoll approximately 12-15 km from each other. Other complementary instruments will also be deployed on Gan; AMF2 will include a micropulse lidar, a sounding system, longwave, shortwave and microwave radiometers, a ceilometer, and a wind profiler. S-PolKa will be deployed during the entire IOP. After the IOP, SMART-R and AMF2 will continue operate until the end of the EOP (Fig. 3).

<u>Suitability of a supersite on Gan:</u> Located within the region where the MJO initiates, Gan is in an ideal location for the supersite. Its precipitation cycle amplifies fourfold from convectively inactive periods (phases 4-7 in Fig. 8) to the MJO active phases (phases 1-3). Precipitation at Male, to the north of Gan, also varies substantially with MJO phases, but it undergoes a seasonal cycle strongly related to the Asian monsoon and therefore is not a desirable location for DYNAMO. During MISMO, a C-band Doppler radar was successfully deployed on Gan by JAMSTEC (Yoneyama et a. 2009). Their experience provides an invaluable foundation on which the supersite operation on Gan during DYNAMO will be designed. Japanese scientists who participated in MISMO are already consulting with the U.S. DYNAMO team.

<u>Strengths of the individual radars and of the radar network:</u> In addition to wavelength considerations, other characteristics and capabilities also influence the utility of each radar. The main strengths of the radars proposed are listed below.

(a)VP W-band Doppler radars (onboard the *R/V Revelle* and *R/V Mirai*, and of AMF2 on Gan)
- Document vertical profiles of reflectivity, mean Doppler velocity, and turbulence associated with clouds and light rain
- Retrieve high-resolution profiles of cloud radiative heating and cloud droplet microphysics in conjunction with other measurements (McFarlane et al. 2007)

(b) X- and K_a-band polarimetric, Doppler radars (X-SACR and K_a-SACR of AMF2 on Gan)
- Observe the 3D evolution of reflectivity and Doppler radial velocity in nonprecipitating clouds and lightly-to-moderately raining clouds out to a maximum range of 30-50 km
- Provide a dataset to retrieve high-resolution 3D cloud radiative heating in conjunction with other measurements (McFarlane et al. 2007)
- Retrieve liquid water by pseudo-dual-wavelength applications accomplished by coordinating from separate pedestals

(c) C-band Doppler radars (SMART-R on Gan, and onboard the *R/V Revelle* and *R/V Mirai*)
- Observe 3D reflectivity and Doppler velocity structures associated with the full precipitating cloud spectrum and its evolution from small to deeper and wider convective systems
- Provide dynamic and precipitation context (SMART-R) for the high-resolution AMF2 radars and S-PolKa polarimetric measurements on Gan
- Obtain maps of rain rate within ~120 km of the radar using reflectivity-rainrate (Z-R) relationships derived from raingauge and/or disdrometer data in the array together with S-PolKa polarimetric-based rain estimates
- Apply Z-R relationships to the long-term (EOP) C-band measurements of SMART-R.
- Diagnose convective and stratiform rain fractions (Churchill and Houze 1984; Steiner et al. 1995; Yuter and Houze 1997)
- Provide estimates of latent heating profiles (adapting techniques used by Schumacher et al. 2004 and Shige et al. 2004, 2007) and comparing these with sounding-based heating profiles (Tao et al. 2006, 2007).
- Provide statistical information on the airflow patterns and divergence profiles within the storms from single-Doppler measurements (Houze et al. 2000, Mapes and Lin 2005)

(d) S-PolKa

K_a-band:
- Document the 3D structure and evolution of the small non-precipitating cumulus clouds (Nuijens et al., 2009)
- Observe in detail the development of the isolated non-precipitating cumulus into small cumulonimbus

S-band:
- Observe the convective population as it transitions from isolated cumulonimbus to deeper convection, including precipitating mesoscale systems that have both convective and stratiform components
- Provide information on airflow patterns within the storms from single-Doppler measurements, as for C-band radars (see above)
- Provide highly resolved information on the microphysical nature of the hydrometeors in oceanic tropical convection. This aspect, based on well-tested polarimetric-based hydrometeor identification techniques (e.g. Vivekanandan et al. 1999a), is crucial to fully understanding the physical characteristics of convection in DYNAMO.
- Provide high-quality polarimetric-based precipitation estimates (Brandes et al. 2002)

combined S- and K_a-bands:
- Obtain estimates of mean vertical profiles of lower troposphere humidity by differential atmospheric attenuation measurements (Ellis and Vivekanandan 2010). The environmental humidity in conjunction with the observations of the convective spectrum will be unique among

tropical oceanic experiments and will make a significant contribution to the requirements of DYNAMO. High-resolution moisture profiles will be fundamental in testing Hypothesis I.

- Obtain estimates of total cloud liquid water content (LWC) using the differential liquid water attenuation measurements (Vivekanandan et al. 1999b). The LWC estimates include the contributions from cloud droplets and drizzle/rain, and can be mapped over the spatial extent of the clouds and tracked in time using dual-wavelength radar measurements.
- Investigate the rapid onset of precipitation by coalescence growth (Knight and Miller1998) and how it may be modified by external factors including changes in aerosol

In addition, the AMF2 radar systems and SMART-R on Gan have the following strengths:

- Document more than one full MJO cycle and provide long-term statistics and context for the IOP by being deployed during the six-month EOP
- Provide complementary cloud observations during MJO initiation to those for the mature MJO collected from similar facilities at the DOE/ARM Darwin and Manus sites

Scan design: All the radars will be operated 24 hours per day, continuously, with a mix of attended and remote operation. The VP radars do not require a scanning strategy. The scanning strategy of the remaining radars will be coordinated to optimize information from the radars. Exact details of the scanning will be worked out by the PIs, but in general the scanning will be done as follows:.

The ship-borne and land-based C-band radars will collect Plan Position Indicator (PPI) scans at sequences of elevations angles ("tilt sequences") to form 3D volumes of data with an update cycle of approximately 10-12 min. The shipborne radars will also collect Range Height Indicator (RHI) scans (vertical cross section for a given azimuth) in precipitation areas of interest, but significant effort will be made to ensure similar scan strategies between the ship-based radars and SMART-R for later comparison and analysis.

At the Gan supersite, the AMF2 radars will collect a combination of VP profiles, PPI scans, and RHI scans to document the characteristics of shallow non-precipitating convection and the weakly precipitating portions and anvil clouds of the deeper convective systems. S-PolKa will have two different scanning strategies, one for suppressed and one for active conditions. In suppressed conditions the update cycle will be ~10 min, using a combination of PPI and RHI scans aimed at documenting the 3D structure of clouds, liquid water content, and the moisture profiles in the lower troposphere. During active conditions, S-PolKa scanning will emphasize RHIs in order to determine microphysical properties with physically meaningful fine resolution in the vertical, with SMART-R providing the broad horizontal pattern of echoes within which the RHIs are embedded. Some of the RHI scans will be directly over the AMF2. The transition into active conditions will be determined by a radar scientist or by an automatic algorithm that evaluates a combination of echo coverage area and echo tops. Under convectively active conditions the focus of S-PolKa will be on obtaining high-resolution polarimetric microphysical observations, dual-wavelength, LWC, and moisture information. RHI scans will be collected over many azimuths with high echo coverage (to be selected manually or by using an adaptive scan strategy based on a coverage area check). Low-level PPI scans will also be collected to obtain moisture profiles and rainfall estimation.

Radar data analysis: The analysis of the data obtained by the DYNAMO radars will be based on known technology. Scanning Doppler radars have been used previously in TOGA COARE studies of the MJO (Rickenbach and Rutledge 1998; Houze et al. 2000). Polarimetric S-PolKa data have been used in studies various types of precipitation (e.g., Vivekandan et al. 1999; Medina and Houze 2003; Lang et al. 2007). Non-precipitating clouds have been studied many times using W- and K_a-band (e.g. Cetrone and Houze 2009). The determination of water vapor profiles has been tested in RICO and further developed to the point that it is ready for DYNAMO (Ellis and Vivekandan 2010). These techniques have never been applied simultaneously. To do so in DYNAMO will be unprecedented and a powerful addition to the broad range of radar capabilities to achieve the goal of understanding how the convective population affects the initiation and evolution of the MJO.

<u>Contribution of the radar observations to the DYNAMO hypotheses:</u> The individual radars will complement each other both in terms of their diverse technical strengths and by nesting the SOP and IOP observations within the longer period of the AMF2 and SMART-R observations. The K_a- and W- band radars will document the morphology and structures of smaller, weaker MJO cloud elements. The S-, C-, and X-band radars will provide information on the precipitating convection—precipitation intensity, convective-stratiform structure, air motions, and microphysical information. The dual-wavelength humidity retrieval from S-PolKa will document the evolution of the humidity field within which the convective cloud ensemble forms and evolves. By combining these capabilities, the multiple radars at the Gan supersite and from the ships will obtain fundamental information on the developing spectrum of MJO convection and thus contribute to the testing of Hypotheses I and II.

The radars will contribute to determine cloud heating and moisture profiles during MJO initiation. Dual-wavelength techniques applied to S-PolKa and AMF2 data will determine moisture profiles around convection, thus contributing to the testing of Hypothesis I. The combined observation of precipitation and cloud/precipitation vertical structure by X-, C- and S-band radars leads to retrieval of latent heating profiles (Tao et al. 2001, 2006, 2007; Schumacher et al. 2004). Observations of cloud structures with K_a- and W-band radars leads to quantitative morphology of non-precipitating clouds (small cumuli and anvils of mesoscale systems) from which radiative heating profiles can be achieved (McFarlane et al. 2007). Determination of the combined latent and radiative heating profiles from the radar observations contributes directly to testing hypothesis II. The detection of the population of smaller clouds over the warm ocean in the buildup of the MJO convective population will contribute to testing Hypothesis III. Observations of the microphysical aspects of the convection have been largely lacking in previous oceanic convection field campaigns except by occasional aircraft sampling (e.g. Houze and Churchill 1987). In DYNAMO, the fine-scale K_a- and W-band measurements will document internal cloud structures, and the dual-polarimetric measurements of high-spatial resolution at K_a- and S-band will provide retrievals of both ice-phase and warm-cloud microphysics and microphysics so that factors such as growth by coalescence (Knight and Miller 1998) and the role of aggregation and riming in ice phase microphysics can be determined. These results will contribute to the model validation goals of DYNAMO.

<u>Larger temporal and spatial context of the radar observations:</u> The S-PolKa measurements during the IOP will add value to the longer (EOP) time records of the SMART-R and AMF2 platforms, and vice versa. It will be possible to evaluate the detailed dual-wavelength humidity retrievals and dual-polarization microphysical retrievals in the context of the broad spatial and temporal context of SMART-R and AMF2 observations. The latter radar datasets will provide a basis for extrapolating aspects of the detailed S-PolKa observational results obtained during the IOP to the longer period of the EOP regarding structures of the clouds, precipitation microphysics, and the environmental water vapor field. During the EOP, SMART-R and AMF2 data collected on Gan can be viewed in a larger spatial context by co-analyzing the Gan data with data from similar radar facilities at the DOE/ARM Darwin and Manus sites, enabling a unique monitoring network that will observe the same MJO event over the Indian Ocean, Northern Australia, and western Pacific, ranging from initiation to mature stages, respectively.

The DYNAMO radar observations will be used to construct cloud and precipitation statistics at different initiation stages of the MJO in conjunction with observations of the large-scale environment provided by soundings, satellite data, and reanalyses. Since the DYNAMO radar observations cover only a small portion of the tropical latitudes and periods affected by the MJO, the DYNAMO radar-derived statistics will also be integrated with the long-term statistics provided by geostationary satellite observations (e.g., Meteosat), and polar-orbiting satellite radars (i.e., TRMM, CloudSat and other A-TRAIN satellites). The DYNAMO radar statistics will be used to validate and calibrate the representation of convection in numerical models (especially cloud system resolving models), upon which tests of DYNAMO hypotheses must ultimately rest.

4.3 Air-Sea Interaction

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.

To test Hypothesis III and to understand the processes involved, it is crucial for DYNAMO to thoroughly document the detailed variability at the air-sea interface and on both sides. This will be accomplished by measurements from a ship-mooring-drifter network (Fig. 2). Ship measurements (Table 2) will include surface meteorology, bulk and turbulent air-sea fluxes, near-surface solar/IR radiative fluxes, atmospheric boundary layer structure (Doppler lidar and cloud radar), and upper ocean mixing and large-scale profiles (Chameleon turbulence profiler and Dopper sonar), in addition to the measurement of rawinsondes (Fig. 9). Three moorings will be deployed for DYNAMO at 76˚E and 0, 2, and 8˚S (red diamonds in Fig. 2) before the IOP and retrieved after. These mooring will measure surface meteorology and high vertical and temporal resolution upper-ocean current, temperature and salinity. High-resolution moored turbulence sensors (χpods) will be outfit to these moorings and existing RAMA moorings at 0˚ 80, 0˚ 90˚E, 2˚S 80˚E (yellow dots in Fig. 2). Drifters will be launched from the *R/V Revelle*. They will fill under-sampled regions in the tropical Indian Ocean and provide additional information of surface temperature, salinity, and current between RAMA and DYNAMO moorings. This suite of measurements will provide a coherent dataset of simultaneous variability of atmospheric convection and precipitation, their imprint on the air-sea interface and the boundary/mixing layers above and below the interface.

US Ship Request for DYNAMO

DYNAMO will require a US Global Class Research Vessel (GCRV) for an estimated total experiment period of 131 days (including radar installations, fueling, provisioning, loading and offloading, but not including transit to the region). This duration includes two extended observing periods at the NE station of the DYNAMO array (0˚ 80˚E), and mooring deployment and recovery cruises (Fig. 10). The timing is set by committed (Japan) and requested (India, Australia) ship time for DYNAMO (Fig. 3). Specifically, the *R/V Roger Revelle* will be requested for its superior Doppler sonar, which is an important part of this experiment. However, we have verified that any of the GCRVs (*Thomas G. Thompson, Atlantis, Melville* and *Knorr)* will provide the necessary deck space to accommodate the proposed atmospheric and oceanic instrumentation.

In sum, the DYNAMO US ship request matches the timeline in Fig. 3 with the following preferred dates:

- preferred earliest start date (with TOGA radar installation at a nearby port): 10 September 2011
- preferred latest start date: 10 October 2011
- duration of request (excluding transit to region): 131 days

The rationale for the range of preferred start dates requested above is to maintain a quadrilateral array formed by two islands and two ships (Fig. 2) to collect atmospheric sounding data during the IOP. The quadrilateral array and the duration of the IOP are designed to minimize errors in estimates of atmospheric heat and moisture budgets based on the soundings (section 4.1) and to observe initiation of at least a major MJO event with a high probability during the IOP (section 3). The US ship will be on station to help form the sounding array for 75 days (Fig. 3). To maintain the quadrilateral array without large gaps within the constraints of international ship scheduling we have specified a range of preferred start dates (10 September – 10 October 2011). This is the optimal configuration. If US ship time available to DYNAMO cannot fall into the requested time window, useful information can still be obtained from the field campaign with a different configuration (to be redesigned) and compromised accuracy in the atmospheric budget estimates, as long as the start date is between 20 August and 10 November 2011.

Specifics of US Ship Request:

(i) Radar installation (7 days): Port to be determined, but potential sites (to be negotiated with ship operator) include Cochin, Colombo, Male, and Diego Garcia (Fig. 2). The TOGA radar and other atmospheric instrumentation (wind profiler, lidar, surface meteorology and surface flux mast and sensors, GPS rawinsondes, aerosol instruments) will be loaded and installed. We have requested 7 days for the installation. It is possible to install and offload these equipments at separate ports (including domestic ports) if this helps for planning purposes. In addition three upper ocean / surface flux moorings will be loaded and readied for deployment.

(ii) Mooring deployment cruise I (15 days): Upper ocean / surface flux moorings will be deployed at 0˚ 76˚E, 2˚S 76˚E, and 8˚S 76˚E (red diamonds in Fig. 2). Deep CTD casts will be made at each mooring location, atmospheric sounding instrumentation will be tested, and NOOS drifters will be deployed along the track before the IOP, thereby helping to set initial conditions for DYNAMO.

(iii) NE Atmosphere/Ocean Observatory, Leg 1 (40 days): The ship will be sited at the NE station of the sounding-radar array at the beginning of the DYNAMO IOP, conducting atmosphere, ocean and air-sea interaction measurements.

(iv) NE Atmosphere/Ocean Observatory, Leg 2 (35 days): The ship will return to the NE station after a port call and continue her measurements.

(v) Mooring recovery cruise II (19 days): Retrieval of DYNAMO upper ocean / surface flux moorings (red diamonds in Fig. 2) as well as χpods from RAMA moorings at 0˚ 80˚E and 2˚S 80˚E (yellow dots in Fig. 2). Ship will return to port for final offloading, marking the end of DYNAMO ship-based observations.

In summary, DYNAMO requests 109 days of at-sea operations, preferably starting within a time window of 10 September – 10 October 2011 (first day of radar installation). Including in port periods for loading/offloading and setting up instrumentation, we request 131 days of ship time.

Timing of US ship-based observation

A tentative international ship schedule for the DYNAMO field campaign is given in Fig. 3. This schedule has been generally agreed upon by all international parties, pending final ship availability. Fifty-five days of ship time have been committed to the Japanese *R/V Mirai* in a time window of October – November 2011. Two 25-day legs of the Australian *R/V Southern Surveyor* ship time toward the end of the IOP are proposed. The India *R/V Sagar Kanya* has committed 30 days of ship time but the exact dates have yet to be determined. The US component of the ship operation during the DYNAMO field campaign requests one 40-day leg and one 35-day leg for the sounding-radar array formation, and two legs for mooring deployment (15 days) and retrieval (19 days) immediately before and after the on-station measurements. Based on the international ship rotation schedule in Fig. 3, the proposed US ship schedule is shown in Fig. 10. Both proposed schedules in Figs. 3 and 10 are based on the September 10 US ship starting time.

Ship time requests have been made by J. Moum (OSU) for the projected ONR-funded NE Atmosphere/Ocean Observatory, Leg 1 and will be made by Moum for NE Atmosphere/Ocean Observatory, Leg 2 in his proposal to NSF to accompany the DYNAMO proposals. Requests for mooring deployment and recovery cruises will be made to NSF by R.-C. Lien (UW).

4.3a US Ship On-Station Measurement

Instruments and sampling frequency onboard the US ship are listed in Table 2. Their operational plans are described here.

Surface flux and turbulence (PIs: Simon deSzoeke, Oregon State Universit; Christopher Fairall and Alan Brewer, NOAA/ESRL)

Surface meteorology and surface turbulent fluxes will be measured for estimate of surface fluxes. Good measurements of turbulent fluxes are necessary since subsurface profiles of fluxes and flux divergence must be matched to surface measurements of surface stress, evaporation, and buoyancy flux, thus placing a critical constraint on both atmospheric and oceanic measurements. NOAA High-Resolution Doppler Lidar (HRDL) measures wind profiles in the lower atmosphere and clear-air turbulence using scattering from aerosol particles. Its measurements are useful to connect surface meteorology and turbulent fluxes to the turbulence structure of the marine atmospheric boundary layer.

Subsurface fluxes (PI: Jim Moum, Oregon State University)

Profiling measurements of subsurface currents (Doppler sonars), temperature, salinity, turbulent velocities, and turbulent fluxes (Chameleon turbulence profiler) will be taken. This would be the first subsurface turbulence and flux measurements in the equatorial Indian Ocean and the first detailed velocity and density profiling of the Wyrtki jets (the dominant, and non-steady, equatorial currents in the Indian Ocean). This measurement leads to estimation of *Ri* and potential parameterization of mixing. Moum will request the UNOLS vessel for this experiment and serve as Chief Scientist onboard.

Atmospheric soundings (PI: Richard Johnson, Colorado State University)

This is described as part of the DYNAMO sounding network in section 4.1.

Radar observations (PI: Steven Rutledge, Colorado State University; Christopher Fairall and Alan Brewer, NOAA/ESRL)

This is described as part of the DYNAMO radar network in section 4.2.

Aerosol observations (PI: Tim Bates, PMEL/NOAA)

MJO modulations of aerosols have been documented observationally (Tian et al. 2007). However, there are currently no observations or model simulations that show an aerosol feedback to the MJO. Aerosols affect Earth's radiation balance directly by scattering and absorbing solar radiation and indirectly by affecting the extent, lifetime, and albedo of clouds. Recent modeling and data analyses have indicated the possibility of aerosol effects on large-scale precipitation associated with the Asian and West African monsoons (Lau et al. 2006, 2009; Huang et al. 2009a) and marine ITCZ in the Atlantic Ocean (Huang et al. 2009b). While it is highly uncertain as to how aerosols affect the MJO initiation and lifecycle, continuous measurements of aerosol physical, chemical, optical, and cloud nucleating properties are essential to define or rule out their role. Aerosols may be particularly influential during the suppressed phase, when cloud moistening is competing against large-scale subsidence drying, and warming of the ocean surface is dependent upon the overlying cloud fraction, in turn influenced by aerosol loading (Zuidema et al. 2008). The DYNAMO field campaign will provide an unprecedented opportunity to observe aerosols in a wide range of tropical convective conditions from highly suppressed to very active periods. Aerosol chemical measurements will be used to assess the relative importance of marine vs. continental aerosols in the DYNAMO study area. Optical measurements will be used to determine whether continental black carbon is warming the atmosphere. Aerosol optical depth measurements will be used to quantify how much the total aerosol column is attenuating the solar radiation reaching the ocean surface. Measurements of cloud condensation nuclei concentrations will be used to determine the processes controlling cloud droplet number concentrations. Continuous time series of aerosol physical, chemical, optical, and cloud nucleating properties, in combination with the ship-borne precipitation and cloud radars and soundings, will be used to elucidate the processes and cause-and-effect relationships between aerosols, cloud physics, and precipitation and to constrain numerical models that quantify such relationships. The aerosol time series will complement the aerosol measurements being made downstream of the DYNAMO working area by PAC^{3}E-SA (*Pacific Atmospheric Composition, Cloud, and Climate Experiment – Southeast Asia*)/7SEAS (*The Seven SouthEast Asian Studies*) near Indonesia. 7SEAS is a NASA interdisciplinary atmospheric sciences program to study interactions of pollution with regional meteorology, particularly with clouds covering the DYNAMO period. PAC^{3}E-SA is an intensive multi-aircraft field campaign, augmented by 7SEAS surface measurements of aerosols and meteorology, to study the transport and vertical redistribution of atmospheric constituents by and in proximity to deep convection over the Maritime Continent during August-September 2011. The observations of aerosol-cloud-precipitation during the DYNAMO field campaign and PAC^{3}E-SA/7SEAS will add a new dimension to the DYNAMO data collection.

<u>*4.3b Mooring observations*</u>
(PIs: Ren-Chieh Lien, University of Washington; Jim Moum, Oregon State University; and Michael McPhaden, PMEL/NOAA)

Three DYNAMO moorings, at 0° 76°E, 2°S 76°E, and 8°S 76°E (red diamonds in Fig. 2), will be deployed immediately before the IOP and retrieved immediately after. The moorings will sample surface meteorology: winds, temperature, humidity, rainfall, and radiation; and subsurface properties: temperature and salinity, current velocity, and turbulence flux (Fig. 11). Each mooring's suite of upper ocean sensors will include a chain of 12 CTD sensors in the upper 100 m, an upward looking 300-kHz ADCP at ~100-m depth, an upward looking 1200-kHz ADCP at ~20 m depth, and an array of 5 moored microstructure sensors (χpods). CTD measurements will be sampled every 1 min. The vertical bin size will be 2 m for the 300-kHz ADCP, and 0.5 m for the 1200-kHz ADCP. Both ADCPs will take velocity profiles every 1–2 s. Moored χpods will take turbulence measurements at 1-s intervals. Together these instruments will provide measurements of high vertical and temporal resolution, allowing us to quantify key properties in the upper ocean including temperature, salinity, velocity, shear, heat content, turbulence mixing, turbulent flux, and their spatial structure (1–10s m vertical resolution) and temporal evolution (1 min–months) (Moum and Nash 2009; Moum et al. 2009). Both the atmospheric and oceanic measurements (CTD) will be available to the GTS in real time. An additional 5 χpods will be deployed on each of three existing RAMA (Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction) moorings at 0° 80°E, 1.5°S 80°E, and 0° 90°E (yellow dots in Fig. 2). Combined with measurements from other components of DYNAMO, the affects of the surface mixed layer, the barrier layer, the shallow Seychelles–Chagos thermocline ridge, the Wyrtki jet, and equatorial turbulent flux on the initiation and evolution of Madden–Julian Oscillation (hypothesis III) will be studied. The mooring deployment and retrieval and χpod outfitting schedule are outlined under *Specifics of U.S. Ship Request for DYNAMO*.

5. Observation-modeling connections

The transition of knowledge from DYNAMO to modeling and operational centers will be facilitated by several collaborative and coordinated activities. The participation in the DYNAMO modeling working group by scientists from research and operation centers (NCEP, NRL, NASA, GFDL, NCAR) will make DYNAMO observations directly accessible to the centers to be absorbed into their modeling improvement efforts. The forecast component of DYNAMO will further quantify the prediction barrier of the MJO, help understanding and connecting between the MJO, weather (including extremes), and short- and long-term climate fluctuations. The real-time MJO monitoring, including all essential climate variables, and the delivery of climate prediction and assessment products on intraseasonal timescales will be enhanced and extended. Forecast validation will be further advanced to establish the baseline to quantify model improvement in terms of MJO prediction. DYNAMO activities are particularly relevant to improvement of the NOAA/CPC operational Global Tropics Hazards/Benefits Assessment, whose weekly product is disseminated to a growing international audience (see SPO).

Three research and operation centers (NCEP, NASA, JAMSTEC) plan to produce special post-field reanalyses for the DYNAMO period, assimilating field observations that will not be on the GTS in real time (Table 4). Such data assimilation products will broaden the applications of DYNAMO observations and allow numerical experiments testing the impact of improved initial conditions on MJO prediction.

Table 4 DYNAMO Field Observations for Post-Field Reanalyses

Instruments/variables	Sampling Frequency	GTS	Assimilation into Reanalysis		
			NCEP	NASA	JAMSTEC
rawinsondes	3 hours (EOP) 6 hours (IOP)	√	√	√	√
ship surface meteorology	1 hour		√	√	√
mooring surface meteorology	1 hour	√	√	√	√
land surface meteorology	1 hour		√	√	√
wind profiler (915 MHz)	1 hour		√	√	√
wind profiler (1357 MHz)	1 hour		√	√	√
Surface solar/IR radiometer	1 hour		√	√	
GPS water vapor	1 hour		√	√	√
ship CTD (T, S, P)	3 hours (500m)		√		
TSG	1 hour		√		
SSST	1 hour		√		
Sea-Soar (T, S, P)	6 (1-hr) legs/day		√		
Mooring CTD (T, S, P)	1 hour	√	√		

6. Project management and operational support

The DYNAMO Science Steering Committee (see cover page) provides overall scientific guidance to DYNAMO planning and execution. The Principal Investigator (PI), Chidong Zhang, and the Co-PIs, Robert Houze, Richard Johnson, and Steven Rutledge, are responsible for the overall planning, coordination, and operation of the field experiment. They will work to coordinate activities with the broader DYNAMO science team and Project Office, NSF facility managers (NCAR Earth Observing Laboratory EOL), ship managers, funding agencies, and national modeling centers (NCEP, NASA/GMAO, NCAR, NRL Monterey, etc.). Data management activities will be provided by NCAR EOL as described in the following section.

DYNAMO will request EOL to provide assistance and advice in the development of the US DYNAMO Project Office. The office will consist of the DYNAMO PIs, staff from NCAR/EOL, NSF program officers, and program managers from supporting agencies. The DYNAMO Project Office will be tasked to coordinate all ground-based facilities to be used in the field campaign, project communications, and in-field and post-field data management. The Project Office will participate in planning discussions and meetings as required and assist with the preparation of the DYNAMO Operations and Data Management Plans. Critical tasks in the period prior to the field deployment will include site visit and logistics planning, and coordination for surface-based instrument sites for several participating facilities. The Project Office will also assist with pre-experiment arrangements to ensure that relevant field measurements during DYNAMO are successfully transmitted onto the GTS and used by operational centers.

A “virtual” Operations Center will be established for facilitation of daily project activities through the conduct of a daily planning meeting and the dissemination of critical project planning information; the preparation and implementation of a DYNAMO Field Catalog to provide a record of daily plans and activities and selected data and products to be used for operational planning and decision making Internet chatroom tools.

7. Data policy and management

The DYNAMO data policy is in compliance with the World Meteorological Organization (WMO) Resolution 40 on the policy and practice for the exchange of meteorological and related data and products including guidelines on relationships in commercial meteorological activities: "*As a fundamental principle of the World Meteorological Organization (WMO), and in consonance with the expanding requirements for its scientific and technical expertise, the WMO commits itself to broadening and enhancing the free and unrestricted international exchange of meteorological and related data and products*." Additional DYNAMO data policy requires:

- A DYNAMO Data (field observations and associated satellite data, reanalyses, and model output) Archive Center (DDAC) will be established and maintained by NCAR Earth Observing Laboratory (EOL).
- A real-time web-based Field Catalog will be implemented by EOL to assist the planning and field operation with an overview of the missions carried out during the field campaign. All participants to the DYNAMO field campaign are required to communicate with EOL on a daily basis to report status of their real-time data collection and instruments, which will be included in the Field Catalog. Near real-time Skew-T plots based on atmospheric sounding observations will be provided in the Field Catalog.
- Within six months following the end of the field campaign, all data shall be promptly provided by DYNAMO investigators responsible for data acquisition to other DYNAMO investigators upon request and notification of the intent of data use.
- All DYNAMO investigators participating in the field campaign are required to submit their field data to the DDAC no later than six months following the end of the field campaign.
- During the first 12 months following the end of the field campaign, all DYNAMO data will be accessible only to DYNAMO investigators to facilitate inter-comparison, quality control checks and inter-calibrations, as well as an integrated interpretation of the combined data set. No public release of the data (sharing with non-DYNAMO colleagues, conference presentations, publications, commercial and media use, etc.) is allowed without the permission of the DYNAMO PIs who are responsible for collecting the data.
- Quality control procedures should be carried out by DYNAMO investigators within 12 months following the end of the field campaign, unless unforeseeable issues emerge. After that, DYNAMO field data will be made available to the broader scientific community. Any remaining data quality issues should be made clear in the data documentation files. Improving DYNAMO data quality will be a continuous effort. The suitability of the released data for scientific investigations and publications should be decided at the discretion of the DYNAMO investigators responsible for field data collection and quality control and data users.
- The authorship decision for publications resulting from using DYNAMO data should follow the ethic rules of the journals and professional organizations (e.g., AMS, AGU). DYNAMO investigators responsible for field data collection are encouraged to make contributions to data analysis and writing of manuscripts, in addition to providing the data, to be co-authors of publications using DYNAMO data.
- The following acknowledgements are suggested to be included in all publications using DYNAMO data: The xxxx data were collected as part of DYNAMO, which was sponsored by NSF, NOAA, ONR, DOE, NASA, JAMSTEC, [Indian and Australian funding agencies]. The involvement of the NSF-sponsored National Center for Atmospheric Research (NCAR) Earth Observing Laboratory (EOL) is acknowledged. [The acquisition of the xxx data was carried out by YYYY under the support by wwww (if YYYY is not a co-author)]. The data are archived at the DYNAMO Data Archive Center maintained by NCAR EOL.
- There will be a CINDY2011 data center at JAMSTEC. The CINDY2011 data center and DYNAMO data center at EOL will be linked and the accessibility to publicly released data at either center will be transparent to users.

Appendix A
Alternative Sounding Array (Plan B) without Diego Garcia

In the unlikely event that permission of launching soundings at Diego Garcia is not granted by the US Navy, the sounding array will be formed by Gan and two ships as a triangle (Fig. A1). This sounding array will cover about the same area as the IFA in TOGA COARE and the sounding array of MISMO. In comparison to the quadrilateral array shown in Fig. 6, the major disadvantage of this triangular sounding array is that estimates of divergence will suffer from lower accuracy than those from the quadrilateral array. However, errors will be minimized by forming a triangle that is as close to equilateral as possible. Other observations from Gan, the ships, and the moorings are not be affected by the change of the sounding array. The scientific objectives of DYNAMO will still be achieved based on sensitivity tests that have been conducted with such a triangular array using theoretical and NICAM-based wind fields associated with equatorial convection.

The main reason for forming the triangular array south of the equator, instead of north of the equator as in MISMO is the seasonality of the MJO. Toward the end of the IOP (December and January), main activities of the MJO would have moved south of the equator as part of its seasonal cycle (Zhang and Dong 2004).

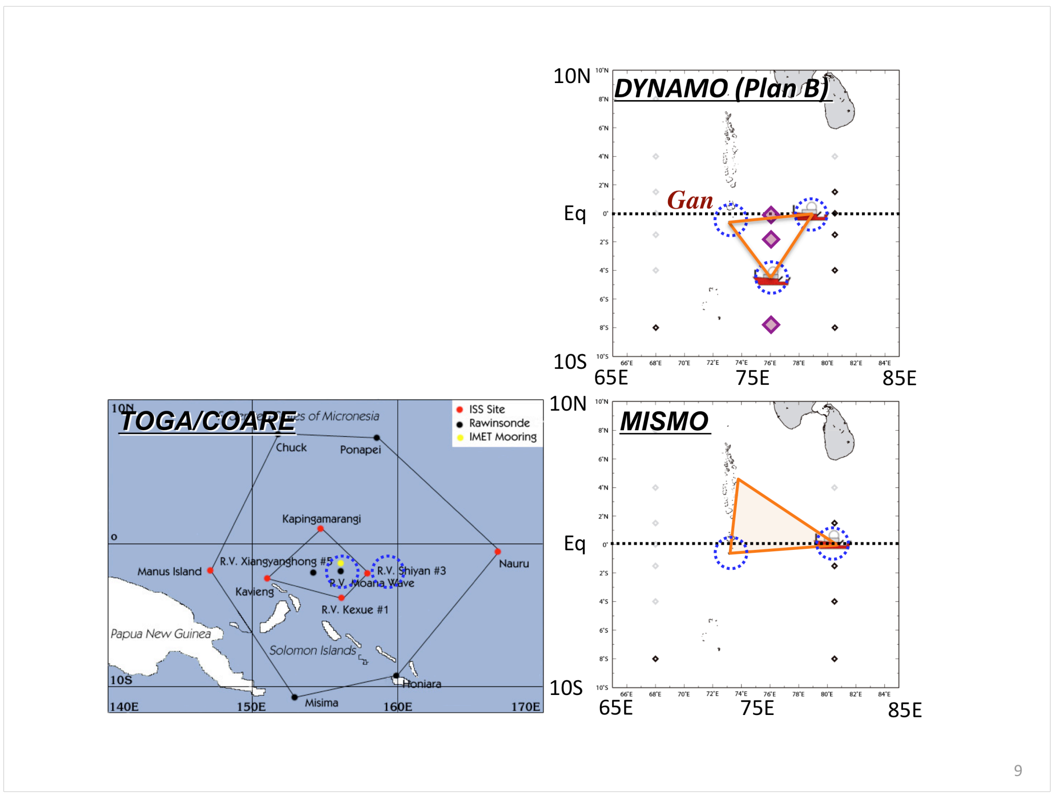

Figure A1 Comparison of the triangular sounding array of DYNAMO to those of TOGA COARE and MISO. Figure legends are the same as in Fig. 1

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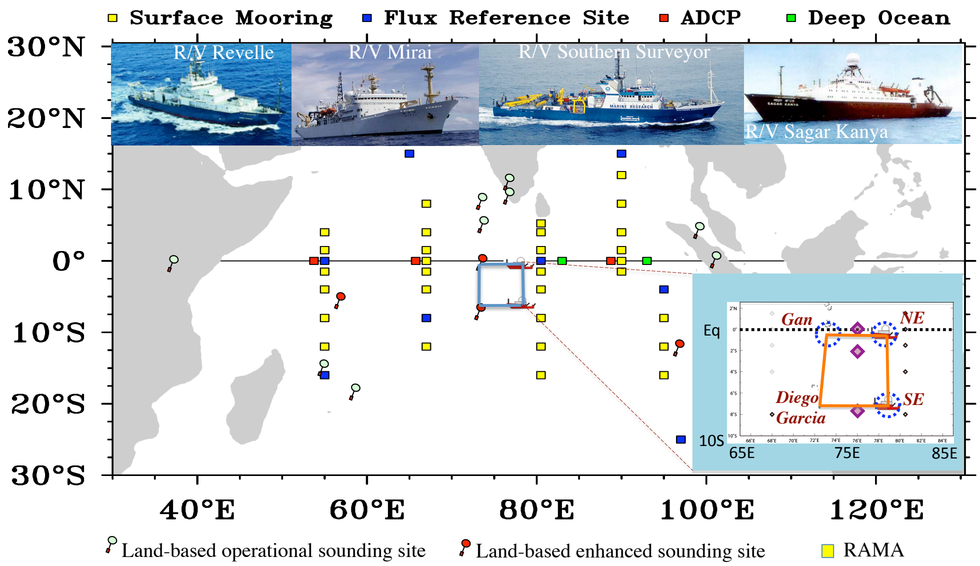


Figure 1 General location and configuration of the DYNAMO field experiment with the background of RAMA (squares) and operational sounding sites in the region. In the inset, radar sites are indicated by the circles and additional moorings by the diamonds. At the top are four ships that are planned to be on station at NE and SE in rotation.

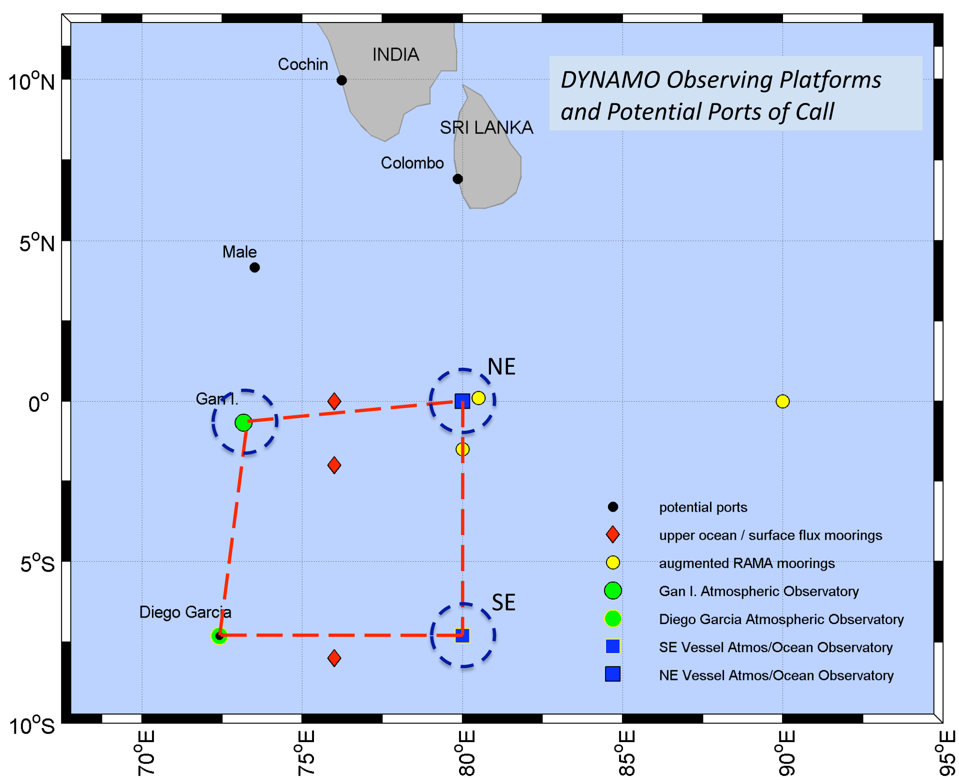


Figure 2 Map of DYNAMO field campaign platforms and potential ports of call. Red dashed lines mark the sounding array. Blue dashed circles indicate the radar sites.

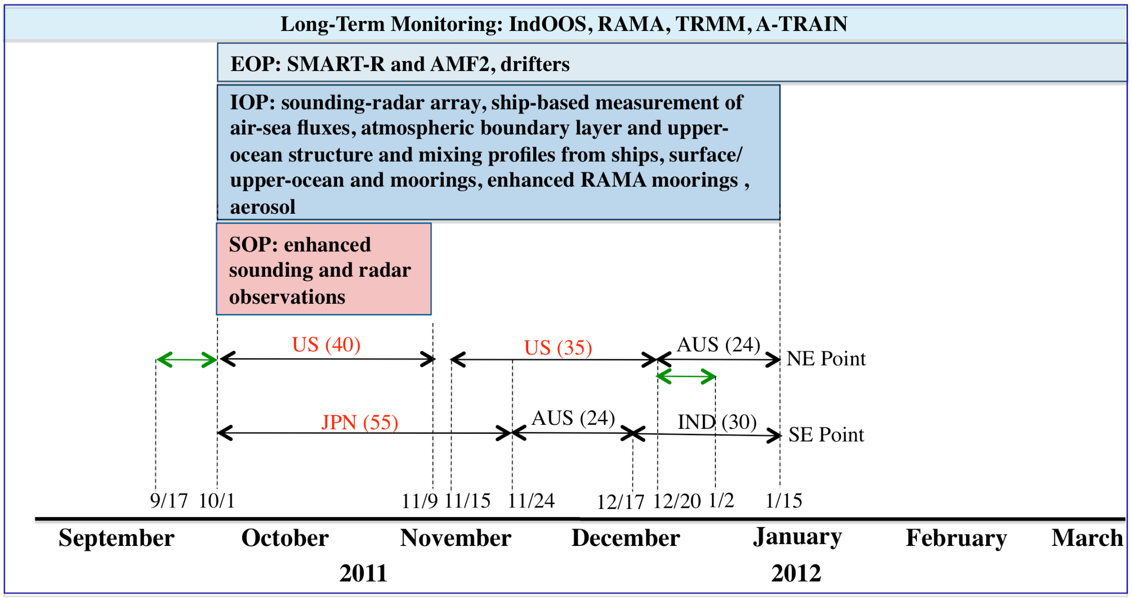


Figure 3 Timeline of DYNAMO field experiment. Horizontal arrows indicate ship rotation schedule with ships and at-sea days labeled (US for the *R/V Revelle*, JPN for the *R/V Mirai*, IND for the *R/V Sagar Kenya*, and AUS for the *R/V Southern Surveyor*). Red labels indicate ships with C- and W-band Doppler radars. Green arrows mark US ship mooring cruises.

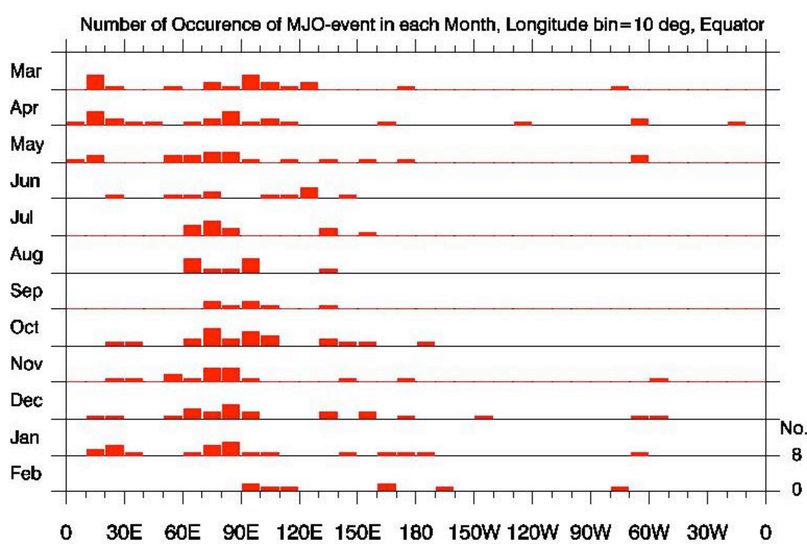


Figure 4 Numbers of major MJO initiation (OLR anomalies < -10 Wm^2) within 10˚ longitude and each month during 1979 – 2007.

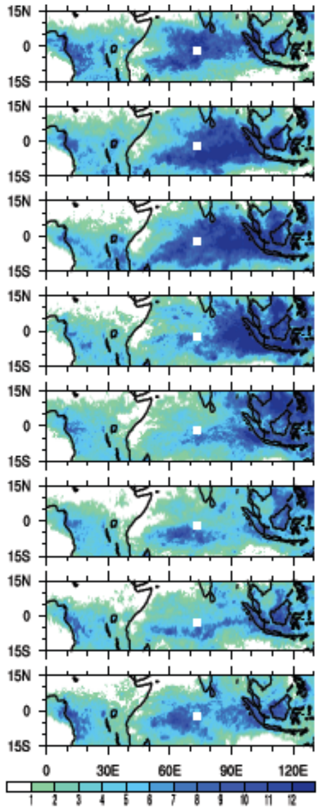


Figure 5 TRMM (3B42) total precipitation (mm/day) composites for 8 MJO phases (marked at the right) during October – January based on the Wheeler and Hendon (2004) MJO index. White boxes indicate the location of the DYNAMO sounding-radar array.

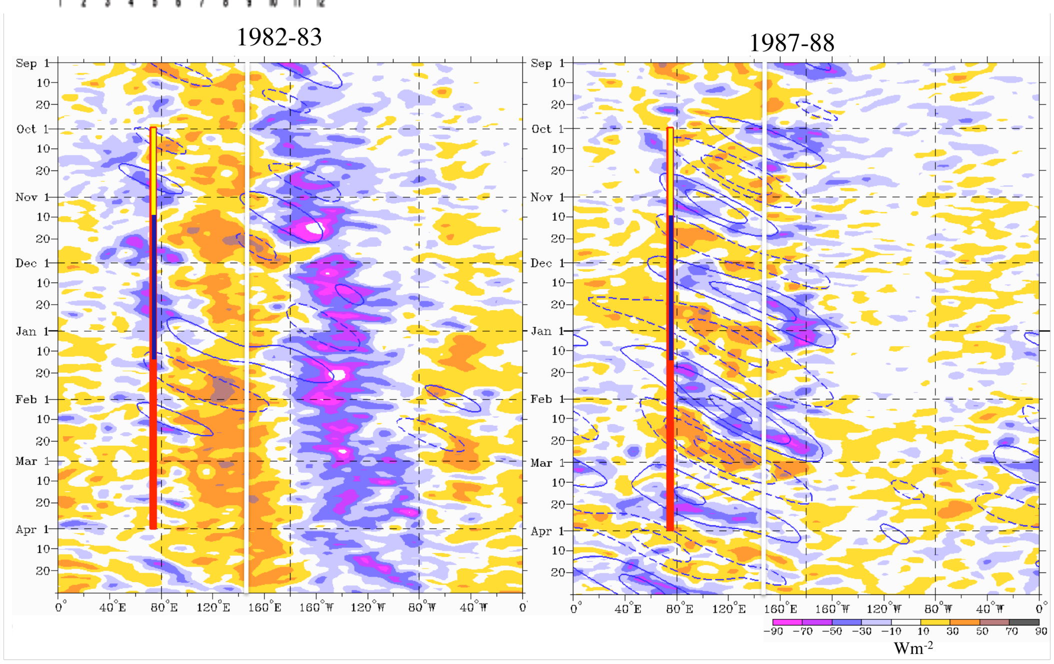
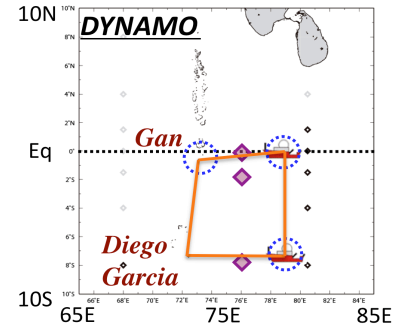
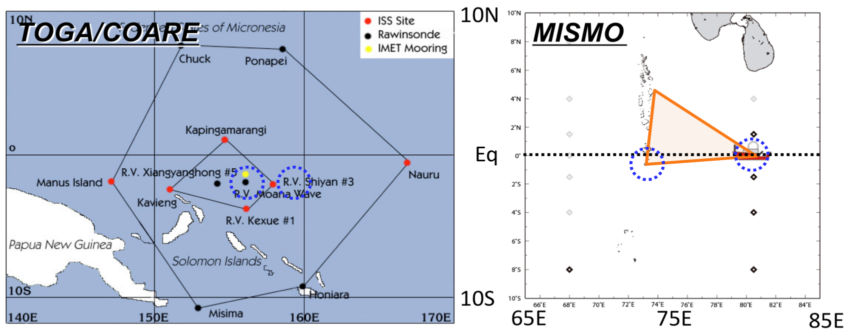


Figure 6 Time-longitude diagrams for total anomalies (seasonal cycle removed) of outgoing longwave radiation (OLR, colors) averaged between 7.5˚S and 7.5˚N and the MJO (contours, 10 Wm^{-2} intervals) for September – April of 1982-83 and 1987-88. The MJO is defined by spectral filtering described in Wheeler and Kiladis (1999) and Wheeler and Weickmann (2001). The vertical lines represent the rough locations and durations for the DYNAMO SOP (yellow), IOP (blue), and EOP (red), and for the ARM Manus Island site (white) where AMIE will take place for the same period of DYNAMO EOP (see DYNAMO SPO).

Figure 7 Comparison of the sounding arrays of DYNAMO/ CINDY2011, TOGA COARE, and MISMO. Figure legends are the same as in Fig. 1.





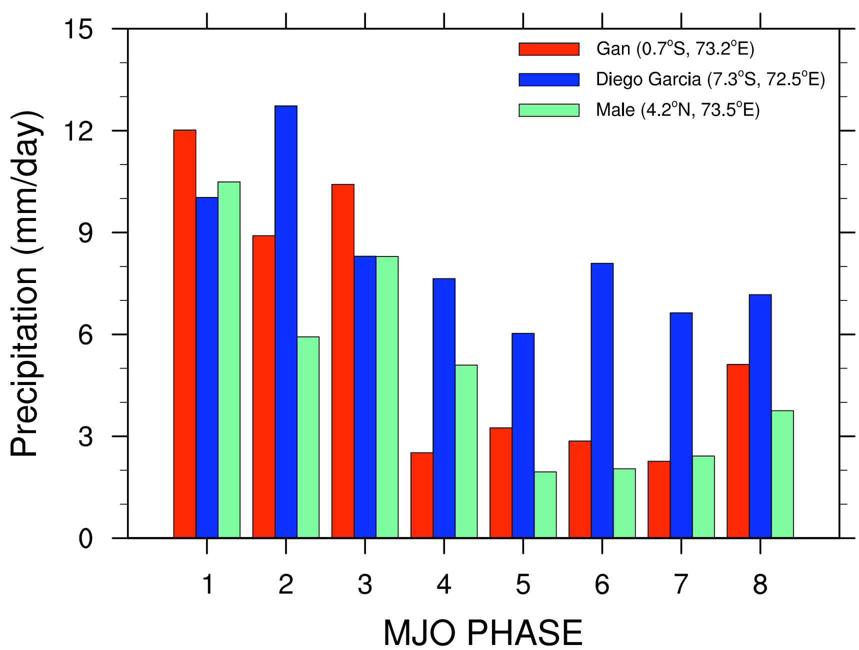


Figure 8 Total precipitation as a function of MJO phases based on TRMM (3B42) data and the MJO index of Wheeler and Hendon (2004).

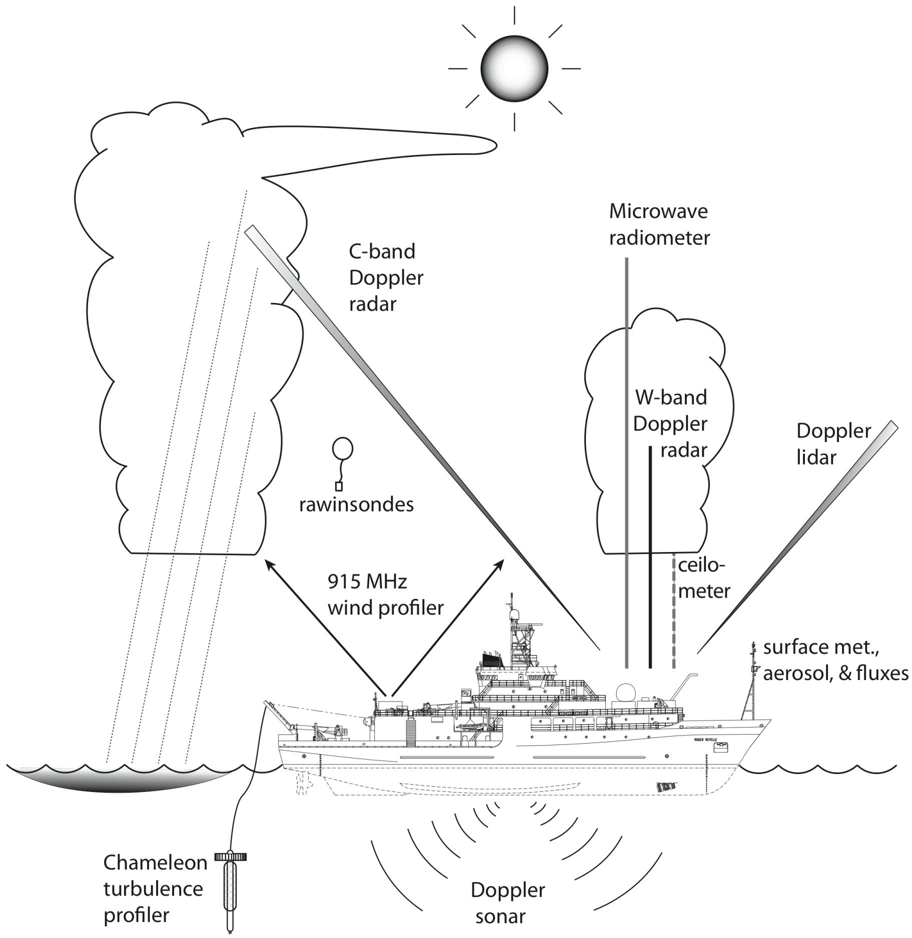


Figure 9 Schematic showing components of US shipboard measurement during the DYNAMO field campaign.

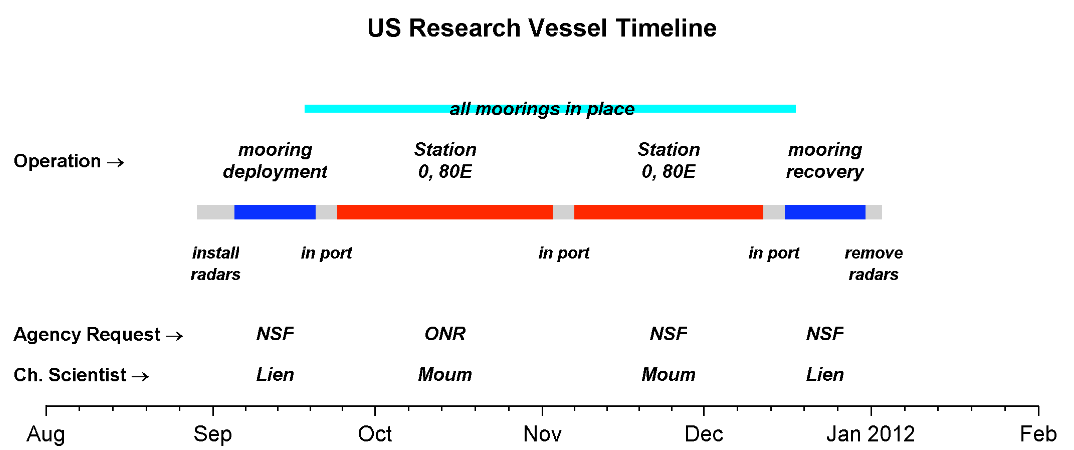


Figure 10 Tentative US ship schedule, supporting agencies and chief scientists for DYNAMO cruises. Blue lines mark mooring cruises. Red lines mark on-station time for the sounding-radar array. Gray lines mark port and transit time. Cyan line marks the time moorings are in place.

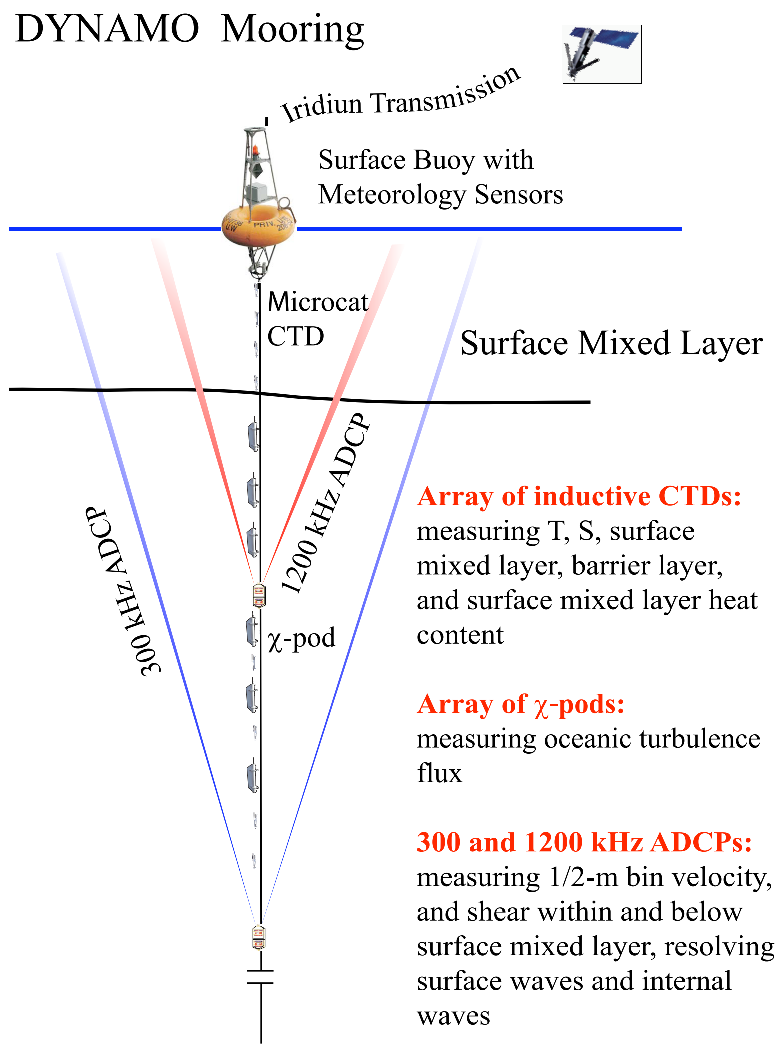


Figure 11 Sketch of DYNAMO moorings.