Dynamics of the MJO (DYNAMO)

The United States Participation in

an International Indian Ocean Field Campaign in 2011-12

Table of Content Page

Executive Summary

There is considerable evidence for the importance of the MJO in weather and climate (e.g., hurricane activity, U.S. West Coast flooding events, and ENSO), and in their seamless prediction. But our ability of simulating and predicting the MJO is severely limited due to model misrepresentation of processes key to the MJO. Development, improvement, validation 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. All these point to an urgent need of a field observation campaign in the tropical Indian Ocean region to study the tropical intraseasonal variability with a focus on the MJO.

The US research, operations and applications communities are poised to join CINDY2011, an international field program that 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. DYNAMO is the program that organizes the US interest of partaking in CINDY2011. The DYNAMO/CINY2011 campaign will coordinate with other field programs (AMIE, HARIMAU, PAC^{3}E-SA/7SEAS, ONR air-sea interaction) also planned to take place 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.

The field campaign of DYNAMO/CINDY2011 consists mainly of a sounding-radar array formed by research vessels and island sites and enhanced moorings inside and near the array. The design of the field campaign and the selection of observational objectives (e.g., vertical profiles of moistening and heating, structure and evolution of cloud and precipitation systems, surface fluxes, atmospheric boundary-layer and upper-ocean turbulence and mixing) have been and will continue to be guided by the DYNAMO modeling activities, which provide hypotheses on potentially crucial processes of MJO initiation. DYNAMO field observations will serve as constraints and validation for models to quantitatively test these hypotheses. This integrated modeling-observational approach will be pursued by a proposed climate process team (CPT) and will lead to targeted information to assist model improvement.

The expected outcome of DYNAMO will be (i) a unique in situ data set available to the broader research and operations communities, (ii) advancement in understanding of the MJO dynamics and initiation processes necessary for improving MJO simulation and prediction, (iii) identification of misrepresentations of processes key to MJO initiation that are common in models and must be corrected to improve MJO simulations and predictions, (iv) provision of baseline information to develop new physical parameterizations and quantify MJO prediction model improvements, and (v) enhanced MJO monitoring and prediction capacities that deliver climate prediction and assessment products on intraseasonal timescales for risk management and decision making.

1. Introduction

In recognition of the important role that the tropical intraseasonal variability, especially the Madden-Julian Oscillation (MJO), plays in weather and climate, scientists from Australia, France, India, Japan, Seychelles and the United States are planning for a field experiment during late 2011 – early 2012 in the equatorial Indian Ocean to advance our understanding and improve simulations and predictions of intraseasonal variability with a focus on initiation processes of the MJO. This international program is referred to as *Cooperative Indian Ocean Experiment on Intraseasonal Variability in the Year 2011*, or CINDY2011. The US participation in CINDY2011 is being organized into a program DYNAMO (Dynamics of the MJO). This document describes the background, scientific rationale and objectives, and plan of action of DYNAMO.

2. **Background**

Societal Context

There is considerable evidence for the importance of the MJO in weather, climate, and their connection. The MJO often spawns tropical cyclones, modulates their activity in all ocean basins, and hence affects their prediction, including hurricanes near the Americas. It affects the onset and intraseasonal fluctuations of the monsoons and rainfall in general over Asia, Australia, Americas, and Africa. As an effective source of stochastic forcing, the MJO influences the onset, intensification, and irregularity of ENSO and its prediction. Tropical large-scale convective centers organized by the MJO excite teleconnection patterns that emanate into the extratropics and thereby induce remote fluctuations in rainfall and temperature. Some torrential rain events along the US west coast are directly related to such teleconnection patterns (e.g., the terms "atmospheric river" and "Pineapple Express" have been used to describe this phenomenon).

Consequently, the potential benefits of a cohesive program to improve MJO prediction span social, economic, and security interests, both in the United States and around the world. The impacts of climate variability on intraseasonal timescales are generally greater in the eastern hemisphere. It is therefore essential for U.S. investments in an intraseasonal prediction program to include global capacities and products to ensure the maximum return on U.S. economic and national security interests. Improved global prediction of the MJO will provide the greatest return on U.S. interests including decision support for vulnerable populations, regional economic and political stability, water resources, food/crop availability, and international aid, among others. The US CLIVAR MJO Working Group web site http://www.usclivar.org/mjosci.php provides more information of the roles of the MJO in weather and climate and their potential benefits to society.

Climate and its effects on society, including those on intraseasonal timescales, are likely to change in the future. Science-based information is required to improve understanding and prediction of these changes to inform planning and decision-making. The expected outcomes of a cohesive program to improve climate forecasts on intraseasonal timescales, for a more climate resilient society, reduced life and economic losses, enhanced security, and new opportunities, greatly exceed the monetary investment.

Technical Context

The MJO also play other roles in the global climate system. The Indian Ocean Dipole (IOD) Zonal Mode, while modulating MJO activity, can be affected by the MJO through nonlinear air-sea interaction. The MJO strongly influences the Indonesian Throughflow, the main artery connecting the Pacific and Indian Oceans through the Maritime Continent. The global angular momentum, the Earth's rotation rate and the length of the day all fluctuate on intraseasonal timescales because of the MJO. The MJO also causes intraseasonal perturbations in chemistry in the atmosphere (e.g., ozone, carbon dioxide, and aerosols) and ocean (e.g., chlorophyll).

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. Australia, Taiwan, Japan, UK). However, current MJO prediction suffers from low skill at particular 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. This MJO prediction problem is compounded by the fact that most global climate models fail to reproduce the MJO with fidelity. The goal to fill gaps in a seamless suite of weather and climate forecast products (e.g. 2 weeks – 2 months) can only be realized when the MJO is properly simulated and predicted in numerical models. The MJO has thus become a standard model validation target and its representation is commonly taken as a milestone of model improvement. 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 importance of the MJO in global weather and climate and the urgency for accelerating research advances to operations are well recognized by the research and operations communities. The THORPEX International Science Plan[1] lists the MJO as one of the targets in its research objectives. Three international workshops organized by ECMWF[2], WCRP/THORPEX[3] and CLIVAR in 2003, 2006, and 2007, respectively, focused on the MJO. The WCRP/THORPEX workshop specifically recommended a field experiment, preferably in the Indian Ocean, to target MJO initiation. Substantial improvement of extended-range/subseasonal forecasts of the MJO is one of the overarching goals of the WCRP-WWRP/THORPEX international initiative Year of Tropical Convection (YOTC)[4]. US CLIVAR established an MJO Working Group[5] with tasks on several issues related to simulation and prediction of the MJO. The important role of the MJO in modulating tropical cyclones is emphasized in a report of the US Climate Change Science Program[6].

---

[1] http://www.wmo.ch/pages/prog/arep/thorpex/documents/brochure_e.pdf
[2] http://www.ecmwf.int/newsevents/meetings/workshops/Intra-seasonal_variability/index.html
[3] http://cdsagenda5.ictp.trieste.it/pdf_display.php?ida=a04205
[4] http://www.wmo.ch/pages/prog/arep/wwrp/new/documents/WCRP_WWRP_YOTCscienceplan_final.pdf
[5] http://www.usclivar.org/Organization/MJO_WG.html
[6] http://www.climatescience.gov/Library/sap/sap3-3/final-report/

3. Scientific Rationale, Hypotheses, and Objectives

Current Knowledge

MJO initiation in the equatorial Indian Ocean features 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 mechanism is among the least understood aspects of the MJO.

To a large extent, our current observational knowledge of the MJO is mainly based on data from the western Pacific. The in situ observations of TOGA COARE in 1992-93 captured three MJO events over the western Pacific 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. Atmospheric sounding observations over Pacific islands also allow us to examine the vertical structure of the MJO. 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, is still limited. None of the earlier atmospheric field campaigns in the Indian Ocean (INDOEX, JASMINE, MISMO, Vasco-Cirene) provided adequate data to study MJO initiation.

From satellite data and limited sounding observations we know that the structure of the MJO and its embedded synoptic-scale perturbations vary in longitude from the Indian Ocean to the western Pacific. Noteworthy in this regard is that a recent study comparing NCEP/NCAR reanalysis and AIRS satellite profiles of temperature and moisture differed significantly over the Indian Ocean, particularly in the boundary layer, which further highlights the need for in-situ observations. Model simulations have suggested that the mechanisms for MJO initiation in the Indian Ocean could be different from those for MJO propagation in the western Pacific. The large-scale dynamical component of the MJO always interacts with the convective component to provide a mechanism to maintain the MJO propagation in the western Pacific. Such a dynamical factor may or may not exist for MJO initiation in the Indian Ocean. One unique climatic feature of the Indian Ocean is the Seychelles-Chagos thermocline dome above which the mixed layer is shallow. Over this dome, SST perturbations in the intraseasonal frequency band are extraordinarily large, 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. Upper-ocean mixing is an essential element in air-sea interaction. Its detailed vertical profile in the equatorial Indian Ocean with unique shear structures has, however, never been systematically observed and analyzed. The same can be said to its counterpart of turbulence mixing in the atmospheric boundary layer. No doubt, what we know about the MJO in the western Pacific cannot always be applied to the Indian Ocean, and there is gaping hole in our observations and knowledge of the physical processes related to the MJO in the Indian Ocean.

Hypotheses

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. These include

(i) slow energy recharge in the troposphere due to sea surface fluxes, moisture advection and convergence, moistening of the lower troposphere by shallow convection, and radiative cooling;

(ii) forcing from extratropical perturbations related to Rossby waves, cold surges, global wind oscillation and eddy momentum transport, etc.,

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

(iv) dynamical response to tropical and extratropical stochastic processes.

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

Currently, there is no consensus on these mechanisms. They can be consolidated into two competing but not mutually exclusive hypotheses:

A. Dynamical (or 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 organizes into large-scale patterns that feed back to the large-scale circulation, giving rise to the MJO.

B. Convective (or local) 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 atmospheric energy buildup, multi-scale interaction, air-sea interaction, or other processes.

A common aspect of the two hypotheses is the essential role of convection-circulation interaction in MJO development. The primary differences are external (extratropics or upstream) vs internal (tropical Indian Ocean) triggering mechanisms. Hypothesis A 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. In contrast, Hypothesis B places the internal processes in the tropical Indian Ocean at the center of MJO initiation and its prediction. There is no reason that the two hypothesized MJO initiation mechanisms cannot both be at work. In addition to these two hypotheses, whether and how Asian continental pollution aerosol may interact with clouds and precipitation associated with MJO initiation are completely open questions.

Quantitatively testing these hypotheses, evaluating all possible mechanisms, identifing the most critical processes, and forming new ideas on MJO initiation require an integrated approach involving observations, modeling, theories, analyses, and forecast. 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, especially B, extremely difficult, if possible at all.

Readiness

The need for advancing our understanding of the processes governing MJO initiation in the Indian Ocean and improving our ability of forecasting MJO initiation is beyond doubt, and time is ripe for a field campaign in the Indian Ocean to collect in situ observations to meet this need. 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 1 and 2 illustrate 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 interaction in the Indian Ocean will take place for the time period of CINDY2011 (late 2011). A French program TRIO has been proposed in 2011 with a focus on air-sea interaction over the Seychelles-Chagos thermocline dome. A proposal have been submitted to the ARM Program to conduct an enhanced observational period of six months (AMIE) embedding the CINDY2011 period to document the MJO on the east side of the Maritime Continent. 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. In late 2011, 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. 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.

Objectives

The overall goal of DYNAMO is to expedite the progress of advancing our understanding of MJO initiation processes and improving our ability to simulate and forecast the MJO. This goal shall be achieved in coordination with DYNAMO's international and national partner programs following an integrated observation-modeling-analysis-forecasts approach. The scientific objectives of DYNAMO are:

(1) to collect in situ observations from the equatorial Indian Ocean that are urgently needed to advance our understanding of the processes key to MJO initiation and to facilitate testing existing hypotheses and forming new ones on these processes;
(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.

Expected Outcome

The data to be collected by the DYNAMO field campaign will be a unique contribution to the existing pool of in situ observations from previous field programs (GATE, TOGA COARE, NAME, TWP-ICE, etc.). This pool of in situ data has served an irreplaceable role in the painstaking and persevering effort by the research and operations communities to improve, develop and test model parameterizations. While no single program can completely solve the parameterization problem, these data have collectively allowed the improvement of model parameterizations to make slow but persistent progress. By filling the gap in the existing pool of in situ data, DYNAMO observations will make it possible for the effort of parameterization improvement to reach a higher level.

The modeling component of DYNAMO in combination with the observations will, through hypotheses testing, identify from a range of possible mechanisms for MJO initiation the most critical ones whose misrepresentation in models are mainly responsible for the infidelity in simulating and predicting MJO initiation. This information on the critical mechanisms for MJO initiation will be a new starting point to accelerate the efforts toward solving the problem of MJO simulation and prediction.

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 modeling and operational centers (NCEP, NRL, NASA, GFDL) in the form of a climate process team (CPT) will make modeling research of DYNAMO transparent to these centers and its results directly accessible for the centers to absorb into their modeling improvement efforts. The forecast component of DYNAMO will further expose the prediction barrier of the MJO, help understanding and predicting linkages between the MJO, weather (including extremes) and long-term climate fluctuations. Its real-time monitoring of the MJO, including all essential climate variables, and its delivery of climate prediction and assessment products on intraseasonal timescales will be enhanced and extended. Its 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.

Planned DYNAMO activities for achieving its objectives and ensuring its legacy are described in the next section.

4. Plan of Action

DYNAMO consists of three main integrated components: modeling, field observations, and forecast. The three components will be closely linked through a proposed climate process team (CPT).

Modeling

Modeling activities constitute an integrated component of DYNAMO. The DYNAMO field campaign is motivated by the low prediction skill of numerical models at the MJO initiation stage, by the relatively poor reproduction of the MJO in the Indian Ocean in models that show some capability of capturing MJO signals in the western Pacific, and by the hypotheses on MJO initiation processes proposed from model simulations and experiments. Numerical experiments have been used to help optimize the field campaign design. The field campaign of DYNAMO is designed to acquire in situ observations needed to test the hypotheses using numerical models. A DYNAMO modeling working group has been formed by scientists from national laboratories and universities (see Appendix A) to coordinate modeling activities contributing to the DYNAMO objectives. How to best utilize models to both gain a deeper understanding of the processes and guide model improvements is a difficult and complex task. 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.

<u>(1) Model-based hypotheses</u>

Differing success of simulating MJO initiation among numerical models have suggested several potentially critical processes. Moistening of the tropospheric environment prior to MJO initiation, coupling between column saturation fraction and precipitation, and dependence of convective triggering on criteria other than CAPE alone in models with better simulations of MJO initiation all point to the need of a realistic sensitivity of parameterized convection to the large-scale environment, especially humidity. Model convection parameterizations often do not allow sufficient column moistening to occur before deep convection is triggered. It is hypothesized that this deficiency might explain their poor MJO simulations. The vertical structure of diabatic heating produced by a model appears to strongly regulate its ability to simulate the MJO. Recent GCM studies have revisited and substantiated an earlier proposal based on simple models that shallow heating is essential to the MJO and its initiation. Shallow convection may play active roles in both the moistening and diabatic heating processes. Extensions of useful MJO prediction skill by coupling an interactive ocean to atmospheric models indicate a potential role of the upper ocean processes to the MJO and its initiation. Realistic simulations of intraseasonal perturbations in sea surface temperature (SST) require accurate reproductions of, in addition to air-sea fluxes related to the MJO, the diurnal cycle, oceanic mixed-layer structure and depth, and upper ocean heat content. In the Indian Ocean, some of these processes are closely related to the Seychelles-Chagos thermocline dome.

(2) Observational requirements for numerical hypothesis testing

Further testing and refining hypotheses on MJO initiation processes need observational data to constrain and validate numerical models. These processes include the impact on moisture, temperature, and moist static energy budgets by (i) shallow and deep convective heating and stratiform heating, (ii) horizontal advective processes, (iii) radiative heating/cooling, and (iv) surface turbulent fluxes. Hence, high temporal and vertical resolution estimates of thermodynamic, dynamic, and radiative variables are required that can be used to diagnose the preconditioning and triggering processes of the MJO. The sounding array for DYNAMO should provide measurements of sufficiently high quality so that column-integrated moist static energy budgets can be accurately estimated with adequate temporal resolution, and sufficiently long duration to increase the likelihood of capturing the initiation of at least one MJO event.

Configuration of the DYNAMO sounding array to produce high quality and high vertical resolution retrievals of apparent heat source (Q_1), apparent moisture sink (Q_2), radiative heating (Q_R), and vertical mass fluxes will be invaluable for examining the evolution of shallow convective heating in advance of MJO initiation, and its impacts through divergent circulations on the column-integrated humidity and moist static energy budgets. Surface energy budget components should be also adequately measured to assess their impacts on the column-integrated moisture and moist static energy budgets. Adequate vertical and temporal resolution in thermodynamic measurement are necessary to assess the convective inhibition process in the MJO initiation region and how model behavior differs from reality.

Given the potential importance of the ocean to MJO initiation, high vertical resolution ocean temperature, salinity, current, and mixing information is needed to diagnose how ocean mixed layer structure, heat content, and SST evolve in advance of and during MJO initiation. Observations and models should be coordinated in providing information on the upper ocean. Aspects such as whether SST warming and build up of ocean heat content can contribute to MJO initiation should be adequately measured. Most likely, this SST feedback would be through the direct influence of modulated surface (latent and sensible heat, and longwave and shortwave radiative) fluxes on convection. These components in the surface energy budget must be accurately measured. Given the hypothesized importance of the diurnal cycle to MJO initiation as found by modeling studies, data collection should be at high enough temporal resolution to capture the diurnal cycle in the surface energy budget, surface stress, and mixed layer structure. Further, measurements that capture contributions to the mixed layer heat budget from horizontal advection by currents, including the contributions of equatorial waves, should be conducted. The IndOOs and RAMA arrays will be important for these measurements: as well as in-situ DYNAMO data (drifters, gliders, microstructure profiles).

These data can be readily acquired through technologically feasible and affordable observational instruments. These model-required observations form one basic rationale for the field campaign of DYNAMO.

As the spatial footprint and duration of the DYNAMO intensive observing network will inevitably be limited, complementary datasets should be included in validating models and testing hypotheses. For instance, data of hourly global precipitation and latent/radiative heating compiled for YOTC will be very useful for informing investigations of convection initiation and triggering hypotheses in models. Satellite and operational analyses will be crucial for providing the larger context in which conditions in the equatorial central Indian Ocean reside, including the role of remote forcing mechanisms for triggering MJO convection. Data assimilation products such as global reanalyses and operational analyses will also be valuable asset to DYNAMO modeling activities. While limitations of such assimilated products are often used as justifications for field campaigns such as DYNAMO, they serve as necessary tools for validating climate models on the large scales.

<u>(3) Hypothesis testing and parameterization improvement</u>

Parameterization improvement for climate and forecasting models will require careful and creative diagnostics of field observations, complementary observations, and use of output from a variety of models. The DYNAMO modeling group will first work to develop improved and/or targeted diagnostics specific for the MJO initiation processes that can be applied to all models. These should include diagnostics that test the hypothesized contributions to the preconditioning process from shallow and other types of convection, vertical and horizontal advection, and surface fluxes, as well as triggering mechanisms. Heat, moisture, and moist static energy budgets can be compared across models in the time before Indian Ocean convective events are initiated in a model, regardless of how poorly they might be represented. When properly designed, the DYNAMO field campaign should provide data that model diagnostics can be directly compared to in terms of these quantities. Results from these diagnostic efforts can also be used to develop suitable mechanism denial or modification experiments to judge the importance of selected processes such as wind-induced fluxes, shallow convection, and horizontal advection to the initiation process. These sensitivity experiments should include the role of the ocean in the MJO initiation process, as further discussed below. These sensitivity tests can be coordinated among the DYNAMO modeling community, as well as those in the greater community with similar interests.

The potential role of the ocean in MJO initiation needs to be assessed using coupled models to investigate their sensitivity to surface flux and mixed layer schemes, vertical resolution, and 1-D vs 3-D processes. These experiments can be constrained and validated by the high temporal and vertical resolution measurements of temperature, salinity, current, and mixing profiles to be collected during DYNAMO and from IndOOS and RAMA. Targeted diagnostics for MJO initiation to assess coupling processes and coupled model performance can be developed in a way similar to those for atmospheric measurements. These diagnostics should at minimum include SST, ocean heat content, mixed-layer structure and depth, barrier layer thickness, and surface fluxes.

(4) Experimental forecast and reforecast

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).

(5) Linkage to other modeling efforts

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. Three-day forecasts in the CAPT (a.k.a. transpose-AMIP) framework that will be conducted for the whole YOTC period could conceivably be repeated through the DYNAMO period. For the different DYNAMO sounding array configurations, a sequence of CAPT-prepared initial conditions can be used as inputs for single column models or CRMs. The global data from CAPT can also be used by the operational forecast models or research GCMs such as NCEP's CFS in much the same way as the CAPT forecasts. YOTC data can also be used with GCMs in a more traditional way, i.e. perform simulations and compare the statistics with the observations of the period.

Field Observations

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, the 2011-2012 international field program in the Indian Ocean. The DYNAMO field campaign is designed as an integrated component of CINDY2011. Thus, it is appropriate to describe DYNAMO field observations together with CINDY2011. The general plan is to conduct an intensive observation period (IOP) for 3 – 4 months in late 2011 – early 2012 aiming to capture the initiation of at least one major MJO event and its full life cycle with a possibly maximum observing capacity. The IOP will be embedded in an extensive observation period (EOP) of 6 months or longer that, with reduced observing capacity, will cover more than one MJO events. The main observational facilities will be deployed onboard research vessels and on islands. Aircraft observation remains an option. A tentative observation list is given in Appendix B. The field observation 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/simulation.

(1) Intensive Observation Period (IOP)

The CINDY2011 IOP will be an international cooperative effort including Japan, Australia, Seychelles, India, France, and the US. The exact time for the IOP has yet to be finalized, pending the availability of ship time from the US. At the current stage, it is anchored around the committed ship time of R/V Mirai from mid October to the end of November 2011. Based on one field design option, the earliest starting time of the IOP can be in September 2011 and the latest ending time in February 2012.

(i) Sounding-radar array

At center of the DYNAMO/CINDY2011 IOP is a sounding-radar array over the central equatorial Indian Ocean formed by islands and research vessels. The sounding array will collect data for budget estimates that will provide vertical structures and variability of diabatic heating and moistening profiles. Such profiles are essential to describe convective effects on the large-scale circulation, to validate numerical models, and to constrain models for numerical experiments to test hypotheses regarding MJO initiation processes. The coinciding array of Doppler precipitation radars will provide detailed descriptions of structures and evolution of cloud and precipitation systems associated with the heating and moistening processes detected by the sounding data. Rainfall estimates by the radars, together with surface flux and precipitation data collected by upper-ocean and surface meteorology moorings in the center of the array, are needed to help close the budget estimate based on the sounding data. The new K-band scanning capability of the NCAR S-PolKa radar is particularly useful to study non-precipitating clouds that dominate the period leading to MJO initiation. Measurement of surface fluxes, upper-ocean mixing, and atmospheric boundary layer turbulence from the ships are essential part of the integrated data set that describe air-sea interaction processes during MJO initiation.

The sounding-radar array will be formed by a combination of ship- and island-based facilities. Ships available to CINDY2011 include Mirai (Japan), Saga Kanya (India), and possibly Southern Surveyor (Australia), Ron Brown (US) and/or a US UNOLS ship. Only Mirai and Ron Brown are currently equipped with C-band Doppler precipitation radars. It is planned to install the NASA TOGA C-band radar on a UNOLS ship, which has been done before. GPS sondes will be launched from all ships with daily frequencies yet to be determined.

Possible island sites for the sounding-radar array include Gan (0.7°S, 73.2°E) and Hulhule (4.2°N, 73.5°E), both belonging to Maldives, and Diego Garcia (7.3˚S, 72.5˚E), which is a British territory with a US Navy base. Permission from the US Navy will be needed to operate DYNAMO/CINDY2011 observations on Diego Garcia. It is planned to deploy the NCAR S-PolKa dual polarization, dual wavelength radar and ISS on one island and the SMART radar (SMART-R) with the DOE/ARM AMF2 on another island.

The final design of the sounding-radar array will have to be made after the availability of ship time from the US and permission for observational operation on Diego Garcia are known. Before that, several options are considered. Figure 2 illustrates one such option. In this option, a triangle array is formed by two islands (Gan and Diego Garcia) and a ship. An alternative option would be a diamond or rectangular array formed by the two islands and two ships. There are tradeoffs between triangular and diamond or rectangular designs: A triangular array would allow for a longer sampling period (3 – 4 months) with different ships (e.g., Ron Brown, Mirai, Southern Surveyor, and Saga Kanya) on station in relay and thereby enhance the probability of capturing at east one major MJO event. A diamond/rectangular array, on the other hand, improves the accuracy of the divergence field in atmospheric budgets at the cost of a shorter sampling period. The pros and cons of these two types of design will continue to be evaluated using model simulations and will be determined in consultation with other CINDY2011 participants.

In case that Diego Garcia is not available to DYNAMO observational operation, the sounding-radar array will have to be formed by two Maldive islands (e.g., Gan and Hulhule) and the ship station moved northward to the equator. While this “northern array” will work almost equally well from an atmospheric point of view, the “southern array" including Diego Garcia and Gan is closer to the Seychelles-Chagos thermocline dome, whose role in MJO initiation remains unclear but deserves to be investigated. This leads to the following discussions of air-sea and oceanic observations.

(ii) Observations of air-sea interaction and boundary layers

Air-sea flux measurement is crucial to DYNAMO/CINDY2011 for two reasons. First, as stated earlier, closing budget estimates based on soundings needs accurate information of surface fluxes. Second, the role of air-sea interaction in MJO initiation remains unclear. To fully understand the potential role of air-sea interaction in MJO initiation, measurements of high-resolution mixed profiles of the upper ocean and atmospheric boundary-layer turbulence are needed as well as surface fluxes. These measurements can take place from ships (air-sea fluxes, upper ocean mixing, atmospheric boundary layer) and moorings (air-sea fluxes, upper ocean mixing). Various modern instrument with unprecedented accuracy and relatively low cost can be deployed, such as lidar, high-resolution ADCPs, gliders, rapid profilers, and χpod. To facilitate the budget estimate for the sounding array, it is necessary to deploy additional moorings within the sounding-radar array to measure surface precipitation and air-sea fluxes.

(iii) Observations of aerosol

Aerosol measurement from a ship will help investigate its possible role in cloud and precipitation formation in the context of the MJO initiation and life cycle. Continuous time series of physical, chemical, optical, and cloud nucleating properties of aerosols, in combination with the ship-borne precipitation and cloud radars, can be used to elucidate the processes and cause-and-effect relationships between aerosols, cloud physics, and precipitation and to constrain numerical models to quantify such relationships. This aerosol time series will be a supplementary and comparative dataset for the aerosol measurement downstream by PAC^3E-SA/7SEAS near Indonesia (Fig. 1).

(2) Extended Observation Period (EOP)

The major component of the EOP of DYNAMO is the SMART C-band radar bundled with AMF2. This combination would form an almost identical package as the facility of DOE ARM site on Manus Island, where a permanent C-band radar is planned to be deployed in early 2011. The ARM AMIE program on Manus with enhanced sounding launches and this DYNAMO SMART-R+AMF2 site would form a pair of radiation-radar observations that provide unique comparisons of the MJO at two distinct stages of its life cycle. Drifters to be deployed before and at the beginning of the CINDY2011 IOP constitute another component of the EOP. These drifters can fill undersampled regions in the tropical Indian Ocean and provide additional information of surface temperature, salinity, and current. Meanwhile, 7SEAS observations will be in place during the EOP.

(3) Long-Term Monitoring

Long-term monitoring is not a direct component of DYNAMO/CINDY2011. But the existing long-term monitoring network in the Indian Ocean, namely, the IndOOS and RAMA to be nearly completed by 2011, provides basin-scale and multiyear background information for DYNAMO/CINDY2011. RAMA in particular provides infrastructural opportunities to add supplementary instrumentations for DYNAMO. For example, high-resolution mixing profiles (χpod) can be added to RAMA moorings near the CINDY2011 sounding-radar array. Regular continuous measurement at ARM sites of Darwin, Nauru and Manus also provide long-term background information of surface radiation/energy flux and cloud evolution associated with the MJO.

Forecast

A US CLIVAR MJO prediction project (led by Jon Gottschalck) is currently underway at NCEP/CPC, where real-time 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). 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. This real-time MJO forecast activity is a complementary counterpart to the reforecast exercises. For DYNAMO, the same real-time forecast procedures can be adapted to reforecasts before and after model modifications to quantify improvement in a practical sense. If needed, the real-time MJO forecasts from the various international centers will be a part of operational support for the DYNAMO/CINDY2011 field campaign.

Program Synergy

In late 2011 – early 2012, other field observation programs will potentially take place across the Indian Ocean, Maritime Continent, and western Pacific (Fig. 1). With careful coordination, these programs and DYNAMO/CINDY2011 can form an observation alliance to complement each other's effort, to integrate their data collections and to maximize their values beyond what could be reached by each of them alone.

AMIE has been proposed to enhance the existing ARM western Pacific site at Manus Island with increased sounding launches to 8 per day 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.

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

PAC^{3}E-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^{3}E-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^{3}E-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^{3}E-SA/7SEAS. Observations taken from these programs can be highly complementary, with data covering different longitudes featuring aerosols of different sources and characteristics.

A field program is being planned by ONR for late 2011 to study air-sea-wave interaction on meso- and synoptic-scales in the Indian Ocean. 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/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.

The DYNAMO MJO forecast team can provide real-time field support to PAC^{3}E-SA/7SEAS and the ONR air-sea field experiment when they take place in coordination with DYNAMO/CINDY2011.

All observations and numerical model products (data assimilation, prediction, simulations) related to the DYNAMO/CINDY2011 field experiment will be collected under the protocol of YOTC. A hallmark of the YOTC protocol is the integration of high-resolution (including cloud-system resolving) numerical modeling, satellite measurements, field-campaign measurements, and theoretical-dynamical insights. This approach is intended to add value to field campaigns in the following way. Extensive numerical experimentation would take place prior to the field phase in order to sharpen and add to the scientific objectives, unify satellite measurements and field-campaign measurements, and be a practical basis for improved prediction within the tropics and its interaction with the extratropics. Such activities would continue through the post-campaign analysis phase. In other words, the proposed Indian Ocean field experiment can be an intensive observation phase for an extended YOTC beyond the present YOTC timeframe of May 2008-November 2009.

Most importantly, DYNAMO will closely work with the other partners of CINDY2011 in designing and executing the field campaign. Especially, the issues that remain unsettled (e.g., design of the sounding-radar array) will have to be addressed by all CINDY2011 partners together.

This white paper is prepared by the DYNAMO Science Steering Committee:

Simon Chang (NRL/MRY)
Chris Fairall (NOAA/ESRL)
Wayne Higgins (NOAA/NCEP/CPC)
Richard Johnson (CSU)
Chuck Long (PNNL)
Steve Lord (NOAA/NCEP/EMC)
Eric Maloney (CSU)
Mike McPhaden (NOAA/PMEL)
Mitch Moncrieff (NCAR)
Jim Moum (OSU)
Steve Rutledge (CSU)
Duane Waliser (JPL)
Augustin Vintzileos (NOAA/NCEP/EMC)
Chidong Zhang (UM)

Figure 1 Global perspective and partner programs of CINDY2011/DYNAMO.

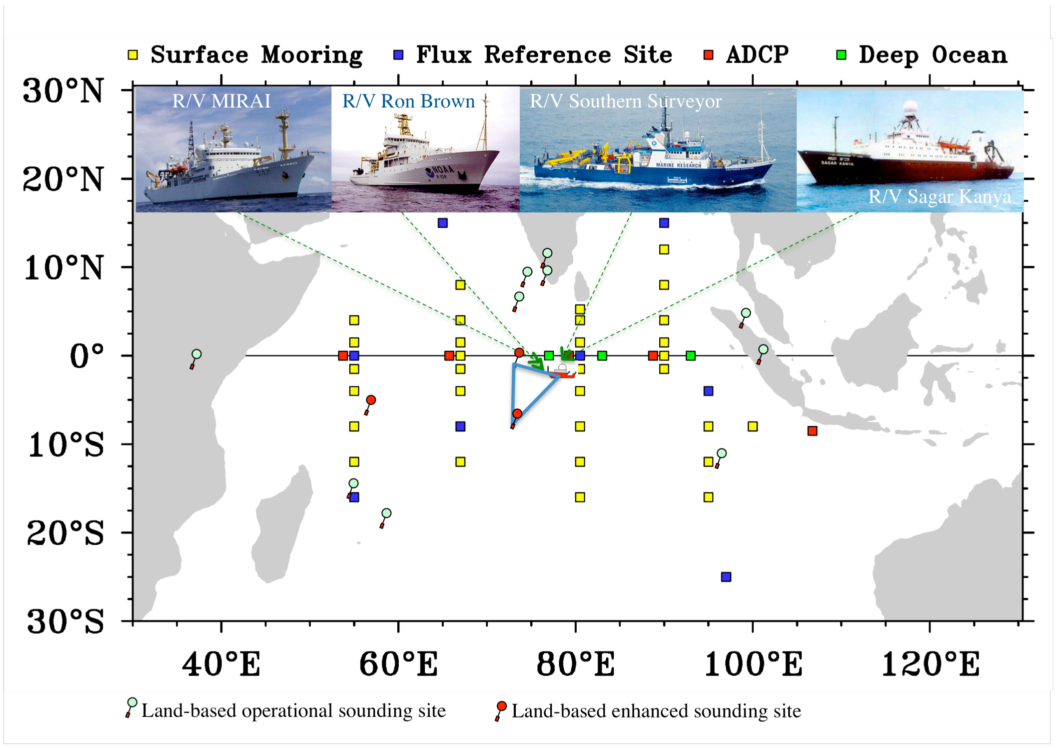

Figure 2 CINDY2011 observing network. The triangle illustrates an option of the sounding-radar array formed by Gan Island, Diego Garcia, and four ships on station in relay. Squares are IndOOS and RAMA moorings.

Appendix A   DYNAMO Modeling Working Group

Su Chen (NRL)
Leo Donner (GFDL)
Maria Flatau (NRL)
Isaac Held (GFDL)
Ben Kirtman (UM)
Tim Li (UH)
Eric Maloney (CSU)*
Mitch Moncrieff (NCAR)
Siegfried Schubert (NASA)
Justin Small (NRL)
Bill Stern (GFDL)
Max Suarez (NASA)
Augustin Vintzileos (NCEP)*
Duane Waliser (JPL)
Xiaoquing Wu (ISU)
Guang Zhang (UCSD)

* Co-Chairs

Appendix B DYNAMO Observations

Observation/Instrument (observation period)	PI (Institution)	Funding Agency
Ship-based (Ron Brown and/or UNOLS ship):		
soundings (IOP)	R. Johnson (CSU)	NSF
NASA TOGA radar (IOP)	S. Rutledge (CSU)	NSF, NASA
air-sea flux (IOP)	C. Fairall (NOAA/ESRL)	NOAA
lidar (IOP)	A. Brewer (NOAA/ESRL)	NOAA
aerosol (IOP)	T. Bates (NOAA/PMEL)	NOAA
high-resolution mixing (IOP)	J. Moum (OSU)	NSF, ONR
drifters (EOP)	R. Lumpkin (NOAA/AOML)	NOAA
gliders, rapid profilers (IOP)	P. Flatau (UCSD)	NSF, ONR
Land-based (Gan, Hulhule, and/or Diego Garcia):		
ISS/soundings (IOP)	R. Johnson (CSU)	NSF
SMART radar (EOP)	C. Schumacher (Texas A&M)	NSF, JAMSTEC
AMF2 (EOP)	C. Long (PNNL)	DOE
S-PolKa radar (IOP)	S. Medina (UW)	NSF
turbulence (IOP)	Q. Wang (NPS)	NSF
lidar, surface fluxes (IOP)	P. Flatau (UCSD)	NSF
Mooring-based:		
upper ocean/ surface meteorology moorings (EOP)	M. McPhaden (NOAA/PMEL)	NOAA
mixing profiles on RAMA moorings (EOP)	J. Moum (OSU)	NSF, NOAA
high-resolution wave-propagation mixing moorings (EOP)	R-C. Lien (UW)	NSF, ONR
Aircraft-based (NOAA P-3):		
atmospheric boundary-layer turbulence (IOP)	Q. Wang (NPS)	NOAA, ONR

Appendix C Acronym List

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
CFS	Coupled Forecast System
CINDY2011	Cooperative Indian Ocean Experiment on Intraseasonal Variability in the Year 2011
COAMPS	Coupled Ocean-Atmosphere Mesoscale Prediction System
CPC	Climate Prediction Center
CRM	Cloud Resolving Model
CSU	Colorado State University
CTB	Climate Test Bed
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
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
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^{3}E-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
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
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