Integration of DYNAMO Observations and Models

Background
This white paper was written by DYNAMO modeling and observational PIs based on their discussion in a joint breakout session at the July 6-8 Seattle DYNAMO workshop and continued interaction afterward.

1. Limited Domain Models

DYNAMO has the advantage, compared to field programs conducted in past decades such as TOGA-COARE and GATE, in that high-resolution models (e.g. cloud system resolving models [CSRMs], non-hydrostatic regional models) have now become much more common and useful tools. Increases in computer power have made the models accessible to more investigators, and together with advances in theory, have made available a range of new simulation strategies that were previously unavailable. When validated using DYNAMO forcing datasets and process-oriented DYNAMO diagnoses, these models can be profoundly useful for parameterization development as they may provide detailed sub-grid scale information on cumulus mass fluxes, entrainment, and mesoscale organization that present observations simply cannot.

Run either alongside conventional single column models (SCMs) on limited domains, CSRMs provide a valuable source of new information for parameterization development, as well as an extended capability to test the three DYNAMO hypotheses. For example, Hypothesis I states that the deep convection can only be organized into an MJO convective envelope when the moist layer has become sufficiently deep. Models with parameterized convection often produce deep convection in very dry atmospheres (e.g. Derbyshire et al. 2004, Thayer-Calder and Randall 2009). Modifications to the treatment of convective entrainment to make convective parameterizations more sensitive to free tropospheric moisture have been demonstrated to improve MJO simulations in support of Hypothesis I (e.g. Hannah and Maloney 2010). Comparing such modification in SCMs using parameterized convection alongside CSRMs with identical forcing derived from DYNAMO field observations in the buildup to MJO initiation and beyond allows comparison of entrainment rates, mass fluxes, and other fields between conventional and high resolution models (e.g. Kuang and Bretherton 2006). Using simulation strategies in which part of the forcing is parameterized rather than specified (weak temperature gradient and related approaches) allows the total precipitation rate and vertically-integrated heating to be compared directly to observations, allowing DYNAMO hypotheses to be tested from multiple directions. DYNAMO PIs intend to run limited domain CSRM simulations featuring Weather Research and Forecasting Model (WRF) and System for Atmospheric Modeling (SAM) both for testing of DYNAMO hypotheses, and to inform parameterization development in conventional models.

1a. Using DYNAMO Observations in Forcing Limited Domain Models

Summary: The DYNAMO sounding array will provide a high quality dataset for forcing limited domain cloud system resolving models and conventional single column models. This will 1) extend the range of DYNAMO observations to test DYNAMO hypotheses, and 2) aid conventional parameterization development

The quadrilateral DYNAMO sounding array will provide a high quality forcing dataset for use in integrating CSRMs and SCMs during the periods before, during, and after MJO initiation in the Indian Ocean. Dick Johnson and collaborators at CSU will generate large-scale forcing fields from the sounding array. Soundings from which model forcing fields will be generated will be launched 4 times a day from four sites during the IOP, with a 40 day special observing period in which eight soundings per day are conducted from four sites. In addition to the advective forcings provided by the sounding array, an integrated surface flux dataset (turbulent and radiative) will be constructed from aircraft, buoy, and ship measurements, led by Djamal Khalif. Modelers will utilize DYNAMO forcing datasets to force SCMs and CSRMs using both conventional methods in which vertical advective tendencies are prescribed from the sounding array, and relatively new methods in which the large-scale vertical motion is parameterized for SCM or CSRM simulations (e.g. Sobel and Bretherton 2000, Mapes 2004, Bergman and Sardeshmukh 2004, Raymond and Zeng 2005, Kuang 2008). When inaccuracies in the forcing datasets derived from sounding observations are reduced by deploying a quadrilateral sounding array (e.g. Katsumata et al. 2010), varying the forcings across the range of uncertainty in the forcing fields may help us avoid interpreting forcing errors as model errors. Ensemble methods with small initial perturbations will aid the development of parameterizations, including those employing stochastic methods.

1b. Model Validation using DYNAMO Field Observations

Summary: DYNAMO observations will enable unprecedented ability to validate cloud system resolving models (CSRMs) and conventional GCMs. The suite of DYNAMO observational data that will be elemental to this task include 1) sounding and other profiling observations, 2) integrated cloud statistics from millimeter and centimeter wavelength radar, 3) dual band radar water vapor retrievals, 4) radiation measurements, 5) water isotopic measurement, and 6) measurement of the atmospheric boundary layer

CSRMs vary in their treatments of microphysics, surface flux formulations, and other parameterizations (e.g. Blossey et al. 2007), and are also run at varying resolutions. Hence, for CSRMs to be useful for addressing DYNAMO hypotheses and furthering development of conventional models, they need to be well validated. In addition to process-oriented diagnosis that will be used to assess the three DYNAMO hypotheses, DYNAMO observational datasets will provide an invaluable resource for model validation and parameterization improvement.

Technological advances since TOGA-COARE in radar, aircraft, and other remote sensing technology enable us to validate high resolution and conventional models in increasingly insightful ways. An integrated dataset of cloud radar statistics will be generated from DYNAMO data by Steve Rutledge and Courtney Schumacher to provide a resource for modelers. For example, Steve will develop a cloud database from a tracking algorithm that allows the time evolution of individual precipitating and non-precipitating clouds to be captured within radar volumes. A major purpose for developing this database is to compare aggregate cloud statistics between radar and CSRMs. Selected examples of such radar data products to be used by DYNAMO modelers to validate limited domain models are listed here, in addition to observational products from other platforms. While highly desirable quantities such as vertical velocity and mass flux information spanning the spectrum from shallow to deep clouds may not yet be accessible from radar measurements, the suite of radars to be employed during DYNAMO will provide other strict constraints to be applied to CSRMs and conventional models.

W-band and Ka-band millimeter wavelength radars to be employed during DYNAMO will allow comparison of reflectivity fields for non-precipitating clouds between CSRMs and radar observations, supplementing comparisons of reflectivity distributions for centimeter wavelength radars (S-PolKa, shipborne C-band, and SMART-R) for precipitating systems. In addition to cumulative frequency distributions of radar reflectivity (e.g. Blossey et al. 2007), statistical comparisons of echo top height, cloud width and depth, precipitation rate, and basic hydrometeor quantities will be possible as a function of MJO regime. Such comparisons will be aided through application of radar simulators for CSRMs, including Quickbeam developed at CSU (http://reef.atmos.colostate.edu/haynes/radarsim/) and other simulators (e.g. Blossey et al. 2007) that can be used to generate reflectivity fields from the CSRMs. SAM and WRF include a radar simulator that can be readily used for comparison to radar reflectivity fields. Radar will also provide information on cell size distributions for direct comparison to CSRMs, and more indirect comparisons to convective parameterizations that implicitly include cell size in entrainment rate. The scanning Ka-band (mm) radar at the Gan radar supersite will provide information on the distribution of cloud radii and height for non-precipitating systems for comparison to models, and several centimeter wavelength radars in the DYNAMO array will characterizing the distribution of radii and height for precipitating cells. Although microphysical parameterizations in CRMs and conventional models vary substantially in complexity in terms of hydrometeor species simulated, hydrometeor identification (HID) algorithms that can be applied to radar data (e.g. Lerach et al. 2010) provide a rich dataset against which to compare CSRM simulations**.** Use of dual wavelength (Ka and S-band) radar at the Gan supersite allows humidity retrievals at the midpoint along a path between the radar site and cloud edge, and thus radar-derived vertical profiles of humidity in the vicinity of a cloud field will generated (e.g. Ellis and Vivekandan 2010). These may allow higher temporal resolution retrievals of the humidity profile in the vicinity of clouds for comparison with CSRM fields.

The possibility of a multichannel microwave radiometer for use at Gan with corresponding ceilometer measurements will provide the opportunity to compare temperature and humidity conditions at cloud base with those under cloud-free conditions at high temporal resolution, as a means of characterizing subgrid-scale variability in temperature and humidity. Such information will test findings from CSRMs that clouds preferentially form in association with the subset of boundary layer parcels that are warmest and moistest. Such multichannel radiometers allow resolution of 100's of meters in the boundary layer, and order one kilometer aloft, with error bounds of +/- 2^{o}C and 2 g m^{-3} for temperature and humidity, respectively. Besides being useful for CSRMs, such "subgridscale" information (from the point of view of lower-resolution models with parameterized convection) will be important for parameterization development as stochastic methods move into wider use, as is already beginning to happen. Overall, the rich radar data set provided by DYNAMO will be invaluable for stochastic parameterization, as such parameterization requires not only grid-averaged information but also subgridscale statistical distributions of a range of quantities which can be, to some extent, constrained by radar observations. Such observations are not available routinely over much of the tropical Indian ocean, a key region for MJO development and thus for the performance of convective parameterizations. DYNAMO will fill a key gap in allowing stochastic parameterizations to be observationally constrained in this region.

Plans also exist to collect isotopic measurements of water vapor to characterize rain re-evaporation and convective entrainment processes. These provide a powerful tool to constrain parameterizations when combined with SCM studies of convective processes during the DYNAMO period.

1c. Model Applications of Aircraft Measurements

Summary: Aircraft missions will contribute to integrated surface flux datasets for forcing limited domain models, extend ship observations of the boundary layer, and provide cloud modules for process-oriented study of MJO initiation and validation of limited domain CSRMs and SCMs.

The DYNAMO aircraft operation will examine convective processes and surface fluxes/boundary layer processes. It presents many opportunities for model diagnosis and development. A request for 200 hours of NOAA WP-3D for FY12 has been submitted in support of DYNAMO. Aircraft missions would consist of 10-12 IOPS of 9 hours each. Many of these individual missions would support generation of surface flux datasets including measurements of boundary layer eddy correlation and TKE diagnostics in addition to areal extensive flux information for use in model forcing datasets. However, opportunities exist to develop a specific module on convection that could provide strict tests of CSRM and SCM simulations, as well as direct measurements to address DYNAMO hypotheses I-III. Several systematic aircraft flight strategies (e.g. horizontal, vertical stack, cross sections, etc) can provide through dropsondes and in-situ measurements dense networks of temperature, humidity, pressure, and wind measurements to aid in budget analysis and model comparison. A dense set of dropsonde observations would allow the thermodynamic environment and transports to be constrained much more tightly than the regular DYNAMO sounding array; even a small number of such flights would be a valuable check on the sounding array results, which in turn are critical to so much of the modeling work for DYNAMO. These would be supplemented by in-cloud retrievals from in-situ, aircraft radar, and dropsondes. One hour flight time can cover a horizontal area of 80 by 80 km with a horizontal scanning pattern. Other methods of using the aircraft to study convective processes were also discussed. These included a less-systematic, but more process-oriented, adaptive investigation of atmospheric and oceanic conditions within and around developing organized convective systems during MJO initiation, as well as sampling of organized mesoscale convective structures during the moistening period leading up to MJO initiation. A consensus was reached that more discussion is necessary to develop appropriate aircraft modules in support of DYNAMO hypotheses and modeling.

2. Large-Scale Models and Datasets

2a. Large-Scale Modeling Activities

Summary: Large-scale modeling activities with global conventional and high-resolution models allow MJO initiation to be examined in a global context, and when properly validated against DYNAMO observations, these models extend the reach of DYNAMO field observations (upscaling)

Recent advances in computational resources have allowed use of regional and global non-hydrostatic models to the extent not possible before. For DYNAMO, these provide unique opportunities to extend the information provided by the field observations. DYNAMO PIs intend to use global non-hydrostatic versions of WRF, a tropical channel version of WRF (with nested inner domain), the NICAM model, and a high-resolution regional version of the coupled COAMPS/NCOM/SWAN system (ocean, atmosphere, and wave models).

Running high resolution global and regional models in support of DYNAMO allows the large-scale context for MJO initiation to be represented, and in particular, allows detailed diagnosis of scale interactions including the evolution of mesoscale systems during MJO onset into organized synoptic-to-large scale systems, as well as upstream large-scale precursor disturbances that may contribute to MJO initiation. Such models will be used to analyze the effects of organized convection on the MJO, including convective momentum transport, convectively-generated gravity waves, and may suggest mesoscale physics and their interactions with larger scales that are missing in coarse resolution parameterized models that are essential for MJO initiation. Data assimilation is proposed to be employed in high-resolution global versions of WRF as well as conventional models, in addition to ingestion of DYNAMO field observations into reanalysis products to initiate the transpose-AMIP type forecasting experiments with global models, which will be described in section 3. Rich Neale intends to develop a community resource consisting of several reanalysis datasets in which DYNAMO field observations are ingested (e.g., ECMWF, ECMWF-INTERIM, NASA-MERRA, NCEP-GFS, JMA-JRA25) that will enable hindcast experiments with global models in the CAPT framework. These will also provide large-scale datasets against which to compare the fidelity of climate model integrations with control and modified parameterizations of moist physics. Data denial experiments in which DYNAMO field observations are removed from initialization and assimilation products will be used to test the impact of high quality DYNAMO field observations on MJO forecasts and process-oriented diagnostics.

Much of the activity within DYNAMO involves improving conventional general circulation models, and as such, DYNAMO PIs have proposed modifications to parameterization of deep convection (moisture triggers, entrainment, rain evaporation processes), large-scale clouds, the atmospheric boundary layer, and horizontal and vertical resolution aimed improve simulations of MJO initiation and propagation. The hindcast/forecast experiments discussed below are one way of assessing the fidelity of such improvements. SCM versions of models provide an intermediate testbed to assess parameterization improvements, particularly when compared to CSRM simulations, before parameterization modifications are implemented in large-scale models, especially operational models.

2b. Process-Oriented Diagnostics and Large-Scale Datasets

Summary: Modeling groups plan to develop process-oriented diagnostics on MJO initiation that can be used to determine the reasons for some models' success in simulating MJO initiation, and others' failure.

Many modeling groups are proposing the development of process-oriented diagnostics (emergent properties) using DYNAMO observations that help us not only to address DYNAMO hypotheses on initiation, but also can guide modelers in validate their parameterizations and assess MJO initiation in the Indian Ocean. Such diagnostic datasets would include cloud-scale parameters as mentioned above. This effort provides a synergy with efforts of the YOTC WCRP/WWRP MJO Task Force that is developing a suite of processes-oriented diagnostic to determine why some climate models produce good MJO simulations and some do not. Several DYNAMO PIs are on this Task Force (Zhang, Kim, Maloney, Neale, Vintzileos, Waliser [co-chair]).

Supplemental large-scale datasets generated for model evaluation (e.g. YOTC-GS and YOTC-ARM/TWP datasets), as well as integrated satellite fields such as those from CloudSAT will aid evaluation of model integrations in a large-scale context. High-resolution analysis datasets will be provided by NCEP that ingest DYNAMO observations (T574 analysis and T384 reanalysis) to aid efforts of setting the large-scale DYNAMO context.

3. Forecast/Hindcast Experiments

Summary: Hindcast experiments allow assessment of the ability of models with parameterized physics to simulate MJO initiation, and guide improvements to model physics that lead to better predictions

Several groups have proposed hindcast and forecast exercises using conventional models and high-resolution global and regional models (including coupled versions). When initialized during different phases of an MJO lifecycle (before, during, and after initiation), these simulations can expose successful versus unsuccessful models, indicate regimes (e.g. shallow versus deep convection) in which simulations break down, and also indicate where model physics are deficient (e.g. where missing moistening processes are found). The seminal study of Bechtold et al. (2008) in which convective entrainment modifications improved the MJO forecast skill of the ECMWF model is a prime example of how such hindcast experiments can be used to assess improvements in MJO prediction skill. Large-scale analyses that ingest DYNAMO fields will provide realistic initial conditions and validation datasets for sensitivity experiments.

Such hindcast/forecast experiments will be done in the context of parameterization modifications, at times guided by using CSRMs as an intermediate step to improve convectional parameterizations. In addition to the community resource for users running various versions of NCAR CAM to aid in transpose-AMIP type runs using the CAPT framework, some modeling groups propose data assimilation efforts to help initialize and diagnose their respective simulations. Further, serial integration strategies are proposed using the ECMWF forecast model to provide real time support for DYNAMO as well as archived forecasts that provide diagnostic fields and initial conditions.

4. Ocean Mixed Layer Processes

Summary: DYNAMO integrated surface flux data will be used in forcing ocean models. DYNAMO observations of the upper ocean will be used to validate ocean and coupled models and improve their representation of the mixed layer processes in MJO initiation.

Hypothesis III emphasizes the importance of oceanic processes for MJO initiation through controlling SSTs that influence atmospheric convection. High-resolution ocean models that can adequately resolve mixed layer processes are required to test this hypothesis. For example, the formation and erosion of barrier layer before, during, and after MJO initiation must be accurately simulated by models. DYNAMO PIs intend to use high-resolution ocean general circulation models (OGCMs) and one-dimensional ocean models validated by DYNAMO observations to examine the role of oceanic processes in MJO initiation. Upper ocean measurements of DYNAMO provide high quality and high resolution temperature, salinity, and velocity data which are adequate to validate model simulations of mixed layer, barrier layer, upper ocean currents (e.g., Wirtki Jet) and thermocline structures.

The use of accurate surface fluxes is crucial for ocean modeling, as it is for atmospheric modeling. Surface fluxes estimated from the DYNAMO observations will provide the forcing fields to integrate one-dimensional ocean models. Also, these measurements will be used to evaluate surface fluxes derived from reanalyses and satellite observations to be used to force OGCMs. DYNAMO upper ocean observations include micro-structure measurements. The turbulence dissipation rate derived from micro-structure measurements will be compared with that in one-dimensional ocean models with many different mixing schemes in order to evaluate the upper ocean mixing parameterization in global ocean models.

Convincing evidence exists that simulating coupled air-sea interactions are required to increase MJO forecast skill (e.g., Vitart et al. 2007). It has been shown that one of the issues hampering the forecast skill of the MJO is the poor representation of intraseasonal variability in the oceanic initial state and poor representation of ocean mixed layer processes. For example, it has been found at NCEP that when subseasonal information is assimilated into CFS to generate the initial ocean state, the MJO forecast skill increases.

During DYNAMO, oceanographic data (velocity, temperature and salinity) will be assimilated to generate 'enriched' oceanic initial states that when used with hindcast experiments will refine our understanding of the ocean processes relevant to MJO. This improved process understanding will lead to ocean model improvements that will be tested with coupled hindcast experiments to assess improvements on MJO forecast skill. Sensitivity to the quality of the initial state will be a focus. This framework will directly benefit the development of the CFS. Related work will be undertaken with the fully coupled regional COAMPS/NCOM/SWAN system maintained at NRL, as well as the HYCOM OGCM.

In all of these studies, DYNAMO ocean and air-sea flux observations will provide a rich validation dataset against which to assess model skill. The synergy among modeling, data assimilation and the DYNAMO observations will not only provide new knowledge on oceanic processes but also lead to direct improvements of MJO forecast skill.

5. Summary

DYNAMO will integrate observations and modeling in the following ways:

- **Use sounding observations in forcing atmospheric CSRMs and SCMs**
- **Develop an integrated surface flux dataset in forcing atmosphere and ocean models**
- **Validate CSRMs, high-resolution regional atmospheric models, and conventional GCMs using sounding observations, radar cloud statistics and complementary vapor datasets, aircraft measurement of the boundary layer properties, and water isotopic measurement**
- **Develop process-oriented diagnostics using DYNAMO observations for model evaluation**
- **Use DYNAMO upper-ocean observations to validate the ability of ocean and coupled models to reproduce the large-scale structure of the Indian Ocean**
- **Use DYNAMO upper-ocean mixing observations to improve parameterization of mixing in coupled models for MJO prediction**
- **Use well-validated models to provide the large-scale context of DYNAMO field observations, to supplement DYNAMO observations with variables not directly measureable, to extend the range of DYNAMO observations for quantitative test of DYNAMO hypotheses, and to facilitate parameterization development and improvement**
- **Use hindcast experiments for the DYNAMO period to guide model improvement**

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