Initiation and Structure of MJO Disturbances in Observations and a Superparameterized GCM Simulation

Doctoral Preliminary Examination Research Prospectus

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1. Background and Motivation

The Tropics act as an engine that drives global atmospheric circulation patterns. Greater than one-third of Earth's precipitation falls within 15° of the Equator, and three-fourths of the total energy fueling planetary-scale atmospheric circulations is derived from tropical latent heat release as clouds and precipitation form (Simpson et al. 1988, Kummerow et al. 2000). Cloud systems are ubiquitous in the Tropics and are a critical component in the local and global energy budgets. Clouds are not only involved in latent heat release, they also alter the three-dimensional (3D) distribution of radiation absorption and emission. A firm understanding of tropical atmospheric variability and its structure is therefore necessary for a wide range of weather and climate studies.

Tropical precipitating systems are organized into several wave types with characteristic space and time scales (Matsuno 1966, Wheeler and Kiladis 1999). One such atmospheric disturbance is the Madden-Julian Oscillation (MJO; Madden and Julian 1994). The MJO is characterized by a slow (5 m/s) eastward propagation of anomalous deep convection and its associated Kelvin-Rossby wave response in the Indian and West Pacific Ocean areas. Although the disturbance tends to weaken near the dateline as deep convection decouples from the wave dynamics, its signal often continues eastward as a fast-moving (15-50 m/s) dry Kelvin wave (Lin et al. 2005). The MJO dominates atmospheric variability within the equatorial regions on intraseasonal (20-100 day) timescales (Wheeler and Kiladis 1999) and involves numerous variables and physical processes. Figure 1 depicts the general vertical and temporal structures of an MJO disturbance. The MJO has been linked to monsoons, El Niño, tropical cyclone frequency in all ocean basins, significant midlatitude weather events, and even the Arctic and

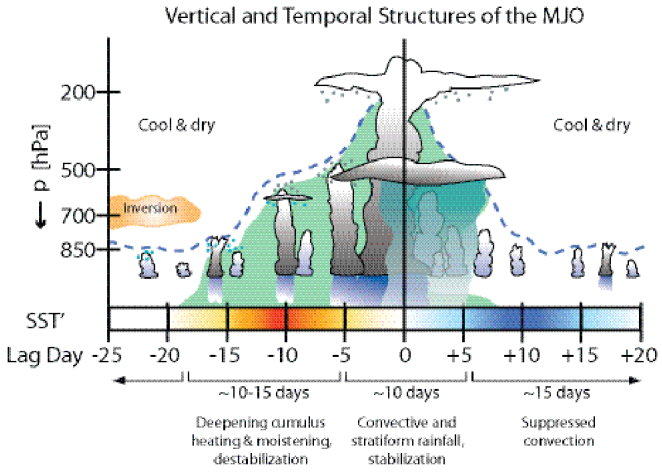


Figure 1. Schematic diagram of the vertical and temporal MJO wave structure. The x-axis shows SST [red (warm), blue (cool) anomalies] and the lag days relative to maximum rain (day 0). Stages of MJO processes, as seen in observations, are listed below the lag days. The dashed blue line shows the top level of convective cloud activity, and green shading represents positive moisture anomalies. Convective rain is indicated by dark blue rain shafts, stratiform rain by light blue and slightly transparent shading. Dotted areas indicate moistening by evaporation.

Antarctic Oscillations (see review in Lin et al. 2005). Clearly, regional fluctuations within the tropical atmosphere, especially those on intraseasonal timescales, can have widespread dynamic and thermodynamic impacts.

Unfortunately, and despite recent improvements in current general circulation models (GCMs), realistic simulations of tropical intraseasonal variability remain elusive. A recent model intercomparison report by Lin et al. (2005) concluded that, compared to observations, most of the 14 model simulations examined had spectral peaks associated with the MJO that were either grossly underestimated or indistinguishable from the spectral power in other frequency bands. The study pointed out, however, that even a reasonable MJO spectral signature does not guarantee that the disturbance's physical structure is realistic. Additionally, the choice of parameterization scheme—semiempirical statistical theories governing how subgrid-scale processes manifest themselves on the resolved grid—might produce more desirable results for one attribute (e.g., MJO signal) but unwanted results for others (e.g., annual rainfall).

The combination of a poor representation of intraseasonal variability in most GCMs and a lack of comprehensive understanding of several of its mechanisms highlights the need for continued research of the MJO. This study aims to address both of these issues through an analysis of (a) the wave structure of the MJO as seen in a simulation from a GCM with a realistic MJO spectral signal, (b) the atmospheric behavior preceding the development of intraseasonal convective events using parcel trajectory and statistical methods, and (c) the vertical and temporal structure of the departing MJO deep convective phase using observational data obtained during the Tropical Warm Pool International Cloud Experiment (TWP-ICE; May et al. 2006). These objectives are expected to advance our knowledge of the MJO and contribute uniquely to improved simulations of tropical intraseasonal variability.

2. Primary Scientific Objectives

Details of the proposed research endeavors are as follows:

Objective A

As part of the first objective we will examine 16 years of simulated daily data from a realistic, full-physics global circulation model (GCM) with an embedded cloud-resolving model (CRM) (Khairoutdinov et al. 2005). The GCM employed here is the National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM), with a 312 km horizontal resolution, 26 vertical levels, a 30-60 minute time step, and a semi-Lagrangian

dynamical core. Positioned within each CAM grid cell is a CRM with 64 grid columns oriented west-east (4 km resolution), 24 vertical levels, periodic lateral boundaries, and a 20-second time step. Unlike traditional GCMs that parameterize many small-scale physical features, inclusion of the embedded CRM allows the explicit simulation of fine-scale cloud and boundary-layer processes in a set-up termed "superparameterization" (SP-CAM; Khairoutdinov et al. 2005).

As mentioned in Section 1, previous model intercomparison studies have focused only on basic statistical results, such as spectral power in zonal wavenumber-frequency space and variances calculated from filtered atmospheric variables over a few years (Slingo et al. 1996, Lin et al. 2005). Using spectral characteristics to grade and compare GCMs conveniently summarizes intraseasonal variability, but examining space-time wave structures as proposed here is equally important. A comparison of intraseasonal variability and structure between the SP-CAM and observations will highlight deficiencies in the model. Knowledge of these deficiencies and the physical processes related to them will enhance our understanding of the MJO and will ultimately lead to more accurate simulations of weather and climate.

Diagrams of outgoing longwave radiation (OLR) spectral power for observations (left), the traditional CAM (middle), and the SP-CAM (right) appear in Figure 1 (from Khairoutdinov et al. 2005). The depiction of intraseasonal variability associated with the MJO (wavenumbers 1-3, frequencies less than 0.03) has improved dramatically in the SP-CAM (right) compared to

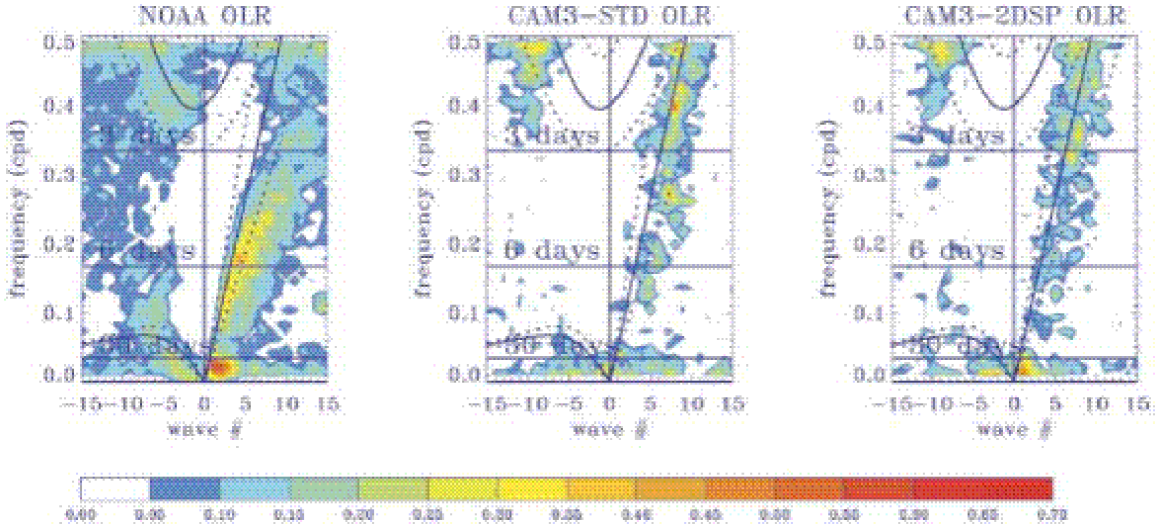


Figure 2. Spectral diagrams of log-10 power of signal-to-noise ratio for satellite-based observations (left), a standard GCM simulation (middle), and the superparameterized GCM simulation (right) for outgoing longwave radiation (OLR). Signal-to-noise ratio is calculated as in Wheeler and Kiladis (1999). Note the relatively weak MJO signal in the standard GCM near wavenumber +1 and periods greater than 30 days (frequencies less than 0.03). Graphic source: Khairoutdinov et al. 2005.

the standard CAM (middle) in light of the observations. This raises several related questions:

i. What does the physical wave structure as seen in various simulated atmospheric fields look like?
ii. Does an improved spectral signature of the MJO in the SP-CAM correspond to a realistic depiction of the dynamic and thermodynamic wave structure as compared to observations?
iii. Aside from the fundamental spectral features displayed in Fig. 1, do the simulated MJO events resemble observations in terms of distinct wave structures based on season, geographic location, and relative intensity? Significant structural differences of this type are noted in the observations (Kiladis et al. 2005).
iv. Is the simulated data realistic enough to extend the analysis and investigate MJO triggering mechanisms based on parcel trajectory and other statistical methods?

The answers to these questions will aid in assessing the reliability and accuracy of the SP-CAM and perhaps the SP theory in general. Deficiencies in the resulting SP-CAM intraseasonal wave structure will provide some insight into the appropriateness and effectiveness of the model set-up (specific parameterizations used, orientation and other details of the CRM, etc.).

Objective B

We will investigate the initiation of intraseasonal convective events using parcel trajectory and other statistical analyses as part of the second scientific objective. Analysis of this type as applied to the MJO has not been undertaken in previous studies. The initiation of MJO-related deep convection and its irregular periodicity remain a challenging, wide-debated yet unresolved issue within the atmospheric and oceanic sciences. Proposed theories are differentiated based on the origin of the forcing that initiates the MJO-like disturbance and the state of the tropical environment in which the forcing acts. The four leading theories of wave triggering, depicted schematically in Figure 3, are:

1. Extratropical forcing from wave trains impinging on the Tropics (e.g., Matthews and Kiladis 1999)
2. Forcing from an upper tropospheric Kelvin wave circumnavigating the globe (e.g., Knutson and Weickmann 1987)
3. Time-dependent localized destabilization, the "discharge-recharge" theory (e.g., Bladé

and Hartmann 1993)

4. Local stochastic forcing (e.g., Yu and Neelin 1994)

Whether one, several, or all of these mechanisms participate in the initiation of an intraseasonal oscillation remains unclear.

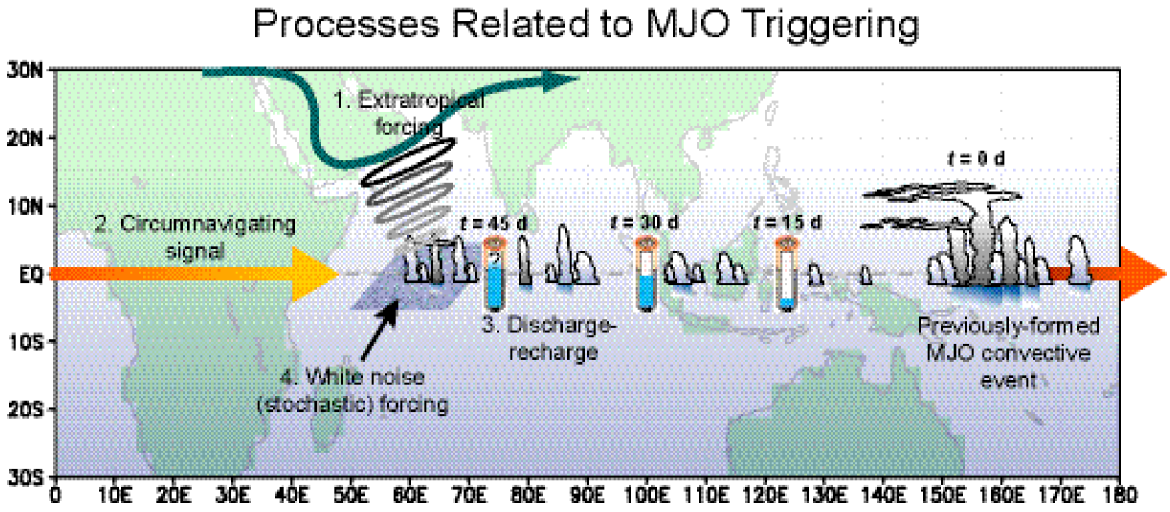


Figure 3. Schematic diagram of the four proposed physical mechanisms that might be involved in initiating an MJO-like disturbance. The diagram depicts the character of the atmosphere in the west-central Indian Ocean about 45 days after an MJO disturbance has developed and propagated away to the east (deep convective feature approaching date line). Forcings that might contribute toward the development of a new MJO convective event include: (1) wave trains impinging from the subtropics, (2) upper tropospheric Kelvin wave circumnavigating the globe, (3) time-dependent localized destabilization ("discharge-recharge"), or (4) local stochastic forcing. It is possible that all processes partake in the MJO development. Green shading represents the ECMWF land-sea mask.

Examination of parcel trajectories in the days leading up to the formation of an MJO convective event will show the parcel origins as well as the general flow pattern. Questions to be addressed include:

i. For parcels located in the immediate vicinity of a developing MJO disturbance, what were their (3D) spatial locations several days before?

ii. How do atmospheric variables change along the parcels' paths leading toward the developing convection? How quickly was the parcel moistened? How does its vertical velocity change? Such information could support or refute certain MJO triggering theories outlined above.

iii. Do the parcels preferentially enter the area of deepening convection from the west or east, Northern or Southern Hemisphere? Are there preferential synoptic circulation patterns associated with the development, and do these vary with season or relative event intensity?

Utilizing additional statistical analyses, additional questions arise:

iv. What is the behavior and intensity of high-frequency (synoptic-scale) signals in the vicinity of a developing MJO? This might help to explain the importance of extratropical forcing.

v. Is there a fundamental interaction between the intensity of the forcing and the readiness of the atmosphere (i.e., is there a preferred balance between the intensity of the forcing and the instability, or is it more common to have strong forcing interact with an "unprepared" atmosphere?).

vi. Similar to the accepted SST requirements for hurricane formation (e.g., Gray 1968), is there a particular state the atmosphere must typically be in before an MJO event can form (e.g., minimum value of boundary layer moist static energy)?

Resolution of these stated issues will provide information on how the proposed triggering mechanisms interact or cooperate and the relative importance of each.

Objective C

The sounding array data collected at the month-long TWP-ICE field study provide a multitude of high-resolution observations from Darwin, Australia during a time of intense MJO activity. As part of Objective C, we will characterize the transition from intense convection (wet phase) to suppressed convection (dry phase) in the context of synoptic and mesoscale patterns of circulation, temperature, and humidity. We anticipate some collaboration with Dr. John McBride from the Australian Bureau of Meteorology Research Centre. A key area of interest is the structure of atmospheric drying during the transition phase. Such analysis would add to the author's Masters project (Benedict 2005) in which atmospheric drying following intense MJO-related convection appeared to be accomplished initially by horizontal advection and later by deep-layer subsidence. Points to be considered include:

i. What is the vertical structure of winds, temperature, humidity, and moist static energy during the intense convection, the transition phase, and the suppressed phase? How do these high-resolution measurements compare to those from reanalysis datasets?

ii. How is the drying accomplished during the transition phase: horizontal advection, subsidence, or a combination of the two?

Financial expense and logistical considerations limit the frequency of atmospheric science field

campaigns, so TWP-ICE is a welcome opportunity. We expect the proposed analyses to shed light on the dynamic and thermodynamic behavior of a departing MJO convective event.

3. Methodology

As part of Objective A, we propose to review intraseasonal wave structures seen in the SP-CAM using composite analysis. This technique involves first locating individual MJO convective events based on specified criteria. Event identification algorithms are applied to a filtered atmospheric variable (e.g., rainfall, OLR, or zonal wind) and involve parameters such as the longitudinal span of the disturbance, its time duration, and its maximum magnitude/intensity. These thresholds are adapted from Rui and Wang (1990) and are further developed in Benedict and Randall (2006, submitted). Once individual events are identified, we will composite them based on the date and location of maximum rainfall because latent heating associated with precipitation formation helps to drive multiscale tropical circulation systems. These composites—time-height cross-sections of any chosen variable (or simply a timeseries for 1D variables such as OLR)—are derived from the SP-CAM simulated dataset and will be compared to the same composite cross-sections found in observations (Benedict and Randall 2006, submitted). We expect to have a sufficiently large sample of MJO events (>18) and thus statistically significant results given the extensive 16-year dataset.

Following the basic compositing methods, we will scrutinize the SP-CAM's ability to produce MJO-like dynamic and thermodynamic structures in space and time. This review process will focus on the key physical mechanisms noted in observations, including a gradual destabilization, low-level moistening, and deepening cumulus clouds prior to intense rainfall; a stratiform temperature profile during maximum rainfall; and lingering upper-level moisture and increasing low-level west winds following the event (see Fig. 1). We also propose to examine additional statistics such as spatial patterns of variability, rainfall persistence in the Tropics [overestimated in many current GCMs (Lin et al. 2005)], and structural differences based on season, geography, and relative event intensity.

The initial stages of an MJO event will be reviewed as part of Objective B. Using observation-based (ECMWF 40-year reanalysis) and model-based (SP-CAM) datasets, we propose to track 3D parcel trajectories and characteristics (temperature, moisture, height/pressure, moist static energy, etc.) leading up to the initial development of deep

convection associated with the MJO. We envision approaching the trajectory analysis as follows: first, an individual MJO convective event will be located. We will then back-track the event to its earliest recognizable stages, based on some minimum threshold, and flag that geographic location as the *formation zone* and that day as the *formation day*. We could also flag the location and day of most intense rainfall as another option. Back-tracking several days before the formation day, we would then position inert, neutrally-buoyant "balloons" (parcels) at regularly-spaced 3D increments throughout the global domain and allow the parcels to be advected by the 3D wind. We will call the time at which the parcels are first released the *release day*. Weighted interpolation will be used to calculate all variables at the exact parcel location. The parcel will be advected by the time-interpolated mean wind and will take on the characteristics of the surrounding air (temperature, moisture, etc.).

The trajectories of released parcels that are found in the *formation zone* on the *formation day* will be examined. A hypothetical trajectory analysis is displayed in Figure 4. In this example three parcels are found to be involved in the development of the MJO event. In panel (a), the formation zone is shown as the area in the west-central Indian Ocean where all three parcel paths (red, blue, black) converge. The red parcel has been rapidly advected toward the formation zone from the Northern Hemisphere subtropics, the blue parcel has slowly meandered toward the formation zone, and the black parcel has moved toward the formation zone with moderate speed. Parcel trajectory pressure/heights are depicted in panel (b). The red parcel has undergone prolonged subsidence followed by rapid lofting, while the blue parcel has steadily risen. This spatial information, along with the parcels' temperature and moisture values, might suggest the importance of certain MJO triggering mechanisms. For example, one might expect a gradual moistening and weak advection (weak large-scale convergence) to be associated with the discharge-recharge theory (Bladé and Hartmann 1994).

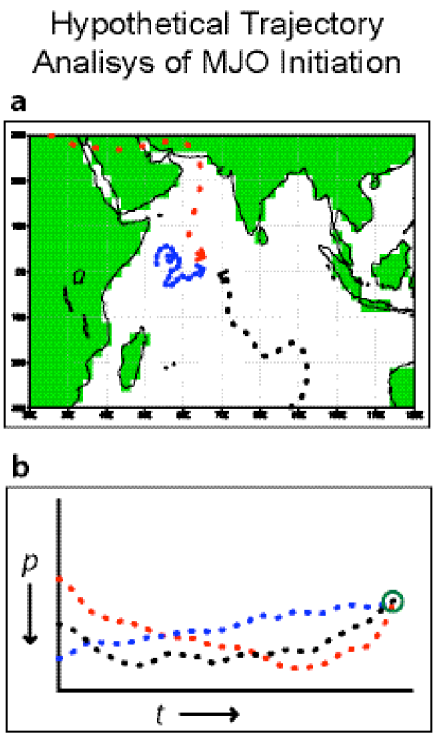


Figure 4. Diagram of hypothetical parcel trajectories in the days preceding the initiation of an MJO-like convective disturbance. (a) Plan view, (b) time-pressure view. The parcel's history might provide information about the initiating mechanism(s) involved (see Fig. 3).

Additional statistical analyses will aid in understanding the origins of the disturbance. Possible statistical avenues include time-filtering the data to investigate the intensity of high-frequency signals (<10 day periods) emanating from the subtropics and impinging on the formation zone.

For Objective C, data from the TWP-ICE sounding array will be utilized to highlight the basic differences in the vertical atmospheric structure between the MJO wet and dry phases. Vertical velocities within the sounding array domain will be derived from the horizontal wind velocities and mass conservation. Other quantities such as precipitable water, equivalent potential temperature, and convective available potential energy (CAPE) will also examined. Time-height cross-sections of these variables will then be compared to the wave structure in Benedict and Randall (2006, submitted).

4. Comments on Results

The goals of this proposal are constructed so that the questions posed are open-ended. We believe the scope of this project encompasses many aspects of the MJO and allows different avenues of exploration should they appear to be of interest. The project does not appear to have any potentially insurmountable obstacles, as might be expected if building and testing a model was involved. However, mild difficulties are certainly plausible. For example, we may need to reassess the trajectory analysis if initial results fail to provide clear results. This could be accomplished by adjusting the number of released parcels, extending the release date to an earlier time, etc. No foreseeable problems exist concerning the examination of the SP-CAM output or the TWP-ICE data.

Each research objective outlined above will contribute uniquely to the atmospheric science community. Examination of the wave structure of intraseasonal variability seen in the superparameterized, realistic GCM simulation has not been undertaken owing to the relatively recent formulation of this novel modeling approach (Grabowski 2001, Khairoutdinov and Randall 2001, Khairoutdinov et al. 2005). In the past, studies on the performance of models in capturing realistic intraseasonal wave structure utilized traditional GCMs that did not have a well-defined MJO spectral signal (e.g., Hayashi and Golder 1993). Other modeling studies have focused on intraseasonal wave structure using very coarse horizontal and vertical resolutions (Wang and Schlesinger 1999) or an atmosphere-only GCM (Inness and Slingo 2003). The parcel trajectory

and other statistical analyses of Objective B (see Section 3) offer a unique and insightful perspective into the flow patterns and wave activity observed during MJO formation. Trajectory analysis has not been used extensively, if at all, to study the MJO. The recently organized TWP-ICE dataset to be utilized in Objective C contains atmospheric vertical profiles of unprecedented temporal resolution and duration (May et al. 2006). This dataset captures in detail the departure of anomalous deep convection associated with a highly-amplified MJO event, and Objective C will undoubtedly contribute toward an understanding of the dynamics involved in this transition phase.

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