Banff Workshop on Stochasticity and Organization of Tropical Convection

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1 Overview

The Madden-Julian Oscillation (MJO) is the most dominant subseasonal variability in the tropics. Understanding its physics and correctly represent it in numerical weather prediction and climate models have been a challenging problem since MJO was first documented in 1972. There are two general approaches to tackle this problem in numerical models: (a) continue improve and develop cumulus parameterization schemes; (b) by-pass cumulus parameterization for deep convection by using cloud-permitting models. Cloud-permitting models are promising but computational demanding. Without a revolution in the computer industry that would yield new computing capability not available today, cloud-permitting models will not be feasible for operations of weather forecast and climate projection, and cumulus parameterization will have to be used in weather and climate models.

Development and improvement of cumulus parameterization has been a diligent but painstaking process. Exciting and promising recent advancement in this field includes incorporating the stochastic nature of convection in cumulus parameterization and theoretical models. At the same time, it is know that tropical convection can be organized into repeatable structures with trackable dynamics in multiscale characteristics. Mesoscale convective organization has been a known key element for convective-largescale interaction and must be represented in cumulus parameterization schemes. Synoptic and intraseasonal convective organizations are main targets of tropical prediction.

Meanwhile, the study of the tropical atmosphere has progressed into a new era in which mutiscale interaction and nonlinear process can be explicitly investigated within newly developed theoretical and numerical models. Multiscale and nonlinear models have been furthered to include the stochastic behavior of tropical convection. Two outstanding examples are the stochastic multi-cloud model and stochastic skeleton MJO model.

This workshop was motivated by the need to better measure and understand stochasticity and organization of tropical convection and to better represent them in numerical and theoretical models.

2 Presentations and scientific progress highlights

Thirty-two presentations were given (see Appendix A for the agenda). They discussed stochastic and organized convection associated with the MJO from observational, theoretical, and modeling perspectives.

2.1 Organized Convection

Slantwise overturning circulation in MSCs and simultaneous eastward and westward propagation of tropical multiscale disturbances. Coherent structures are a challenging problem for climate models. Parametrization are to blame. CRM simulations are important tools to understand dynamics and momentum transport effect due to mesoscale systems and their influence on synoptic and planetary scale organized convection such the MJO that are at the intersection between weather and climate. New perspective for the parametrization of mesoscale systems are emerging. Multicloud models with two baroclinic modes capable to represent overturning circulation and downdrafts associated with stratiform clouds. (Moncrieff)

Stepwise evolution of the tops of convection and a moisture layer, troposphere-stratosphere interaction; diurnal air-sea interaction during MJO suppressed phases. Stratospheric gravity waves are believed to play a central in creating pockets of humid air in the upper troposphere that further destabilize the troposphere through radiation feedback and help trigger new convection. (Johnson)

Shallow to deep convective transition is more related to large-scale (200 km x 200 km) than small-scale (20 km x 20 km) moisture increase at 4 km, which is due mostly to increasing vertical moist advection and decreasing meridional dry advection. (Hagos)

Moistening by shallow cumulus is much larger than clear-air turbulent flux. According to various studies, the mesoscale moisture tendency associated with shallow convection can be interpreted as the resultant of the individual action of shallow clouds. Although on the same order of magnitude, large-scale advection can be stronger than moisture tendencies associated with shallow convection. On the other hand the later are less variable so that shallow convection appears as an important steady background moistening. (Bellenger)

Conventional definition of convective organization: size ($<$ 100 km), lifetime ($>$ 6 hrs), shape (linear), dynamics (updraft); organization mechanisms: warm-moist PBL, wind shear, tropospheric moisture, cold pools, gravity waves, synoptic-meso-scale boundaries, self-aggregation; upscale impact: Q1, Q2, Q3. (Schumacher).

2.2 Stochastic convection

There is an anology between tropical cycle dynamics and the MJO. In both cases, stochastic processes on different scales lead to different predictability limit. This stochasticity imposes a natural barrier for grid resolution in cloud resolving modeling (CRM) ; cold pool recovery time depends on surface fluxes, which in turn depends on surface wind speed influenced by downward convective momentum transport. (S. Chen)

Among the stochastic aspects of tropical variability, the variance of higher-frequency perturbations within MJO convective envelopes is found to vary substantially from events to events. The MJO increases the overall convective activity at all scales within its envelope, but it does not change the overall characteristics of any one scale. For example the distribution of sizes, lifetime, propagation, and cloud top characteristics of mesoscale systems remain similar within and outside the MJO envelope. Also, while the frequency of equatorial waves coupled to convection increases within the MJO, the distribution (probability density function) of these waves is not appreciably altered, with the possible exception of more equatorial Rossby wave (ER) activity. On the other hand, mixed Rossby-gravity (MRG) and eastward inertio-gravity (EIG) wave variance is enhanced over the central and eastern Pacific ocean during the enhanced phase of the MJO over the warm pool. (Kiladis).

Single-column and Spatiotemporal stochastic models were used to study spectral power and statistical physics (precipitation phase transition, cloud size distribution, self-organized criticality). Close attention was payed to the background noise observed to characterize tropical rainfall and circulation variability. It is found that a simple linear stochastic Langevin-like equation, with forcing and damping, is able to reproduce bulk features of the tropical red noise spectrum. Space-time plots suggest a self-criticality behaviour of organized convective systems (Stechmann).

2.3 Multicloud Model

MJO initiation by dry Kelvin waves, according to aquaplanet simulations using the HOMME GCM (at coarse resolution) coupled to the deterministic multicloud model; Northward vs eastward propagation depends on latitude of heating (Ravindran). Higher latitude heating leads to westward propagation.

Stochastic cloud transition: Based on a lattice multiple particle interacting system where lattice site are either cloudy, occupied by a certain cloud type, of are clear sky. Random transition between lattice site states occurs accoridng to intuitive propability rules depending on the background state, namely, convective instability and moisture.

Warm pool helps organizing convection into lower-frequency variability of the MJO, which depends on strong stratiform heating, when the SMCM is tuned to produce the right proportions of congestus versus deep convective clouds. Moreover, smaller startiform heating fraction lead to synoptic scale Kelvin wave-type organization. (Deng)

Including coupling to large-scale convergence in the stochastic generation and transition of shallow/congestus and deep convection leads to enhanced equatorial waves. (Brenowitz)

A Bayesian inference model was used to calibrate the stochastic cloud transition timescales in the multi-cloud model using in-situ and simulated data. Fast and slow transitions are distinguished. Transition may depend on grid size but invariant parameters are desirable. (De La Chevrotiere)

Conditional Markov Chains have been used to train the cloud transition parameters using observations of cloud types, large-scale conditions in terms of CAPE, vertical velocity, low-level humidity (Siebsma).

2.4 MJO Skeleton Model

MJO events can be identified by projecting reanalysis data onto skeleton model solution with a zonally varying background and stochasticity. This leads to an MJO index based on skeleton Model. One important advantage is that the MJO skeleton solution, combines information based on shear, geopotential gradient (potential temperature) low-level moisture, and ORL, which provides robustness, unlike traditional indices that are based solely on ORL and/or the velocity potential. In addition, this approach does not need filtering or orthogonality assumption like the RMM index for example which is based on EOFs (Ogrosky).

The warm pool affects MJO statistics (length, location, primary vs. successive) in the stochastic skeleton model. Not all MJO events are mirror reproductions of previous events. They vary substantially one another in shape and strength rather caotically. The stochastic skeleton model reproduces this highly intermittent behavior quite well (Stachnik).

Adding a second baroclinic and a multi-cloud heating profile, with the natural transitions from congestus to deep and from deep to stratiform, to the MJO skeleton model produces vertical tilted structure of convection consistent with observations. It also allows the simulation of MJO wave trains as in nature (Thual).

The model of barotropic and baroclinic wave interaction for the skeleton model is proposed. A multiscale asymptotic analysis of resonant triads was performed. It leads to three-wave consistent of wither of an MJO, baroctropic Rossby and Kelvin triad or MJO, baroctropic Rossby and baroclinic Rossby triad. It allows a clear distinction and interpretation of tropical-extratropical interactions involving the MJO dynamics such as the influence of the MJO on midlatitude weather patterns (Rossby waves) and extra-tropical initiation of primary MJO's. (S. Chen)

2.5 Parametrization

Two stochastic parameterization methods to improve simulations in different ways: Spectral Kinetic Energy Backscatter (SKEB) improves the mean, and Stochastically Perturbed Parametrisation Tendencies (SPPT) improves variability. (Christensen)

A unified parameterization is built upon a probabilistic plume model with a pdf in mixed-layer temperature. (Park)

Super parameterization in CFS improves simulations of the Indian summer monsoon in the amplitude of the annual cycle of rainfall, tropospheric temperature, intraseasonal spectral power. (Goswami)

Both cumulus and microphysics parameterization need to be improved for better simulations of intraseasonal variability. Putting back advective tendencies into large scale cloud condensate (liquid and ice) mixing ratios is found to improve large scale/stratiform precipitation to convective precipitation ratio (Mukhopadhyay).

Triggering functions and closures can be quantitatively evaluated using field observations and CRM simulations. Some are scale-aware, others are not. Eight trigger functions were considered and compared. They include dilute CAPE and non-dilute CAPE triggers. The dilute are found to out perform the non-dilute ones in many ways including the diurnal cycle and many stastical climate properties. CRM simulations suggest a

20 minute lead time of moisture convergence prior to deep convection. Both moisture convergence and dilute CAPE closure are found to be scale aware while pure CAPE closures are not (Zhang).

Stochastic parameterization needs to meet several criteria: resolution dependent, larger variability than initial uncertainties, improved forecast skill, unique interaction with large-scale environment not reproducible by deterministic schemes. (Craig)

Parameterization of cold pools needs to consider: entrainment, cloud size, organization, and randomness. Simulation of orographic convective systems highlighted the importance of cold pools in convective organization. An outline for a particle model for cold pools was proposed (Boeing).

2.6 Tools

Permutation Entropy can be used to identify dynamical signals prior to MJO initiation. The process of MJO initiation is broken down into local dynamical chnages and MJO lifecycle. The Nonlinear Laplacian Analysis (NLSA) framework is extended to the MJO mode and explained in term of SVD by analogy to EOF analaysis. A time lagged embedding procedure was integrated into NLASA and the resulting model was applied to local low-level winds and moisture changes. Moisture buildup prior to initiation was observed. Perturbation TKE and vertical integrated moisture budget partitioned time series were used. The permutation entropy metric was used on the partitioned data to assess convection organization under the assumption the whole MJO sequence is a Markov according to the partitioned time series. (Tung)

NLSA recovers MJO and BSISO modes without bandpass-filtering or spatial orthognality. Kernel analog forecasts of the MJO and BSISO based on NLSA show skill up to 45 50 days. (Giannakis)

Effects of moisture in convective boundary layer: buoyancy flux peaked at smaller scales, more overlap between forcing and dissipation spectra, shallow cloud moistening. (Waite)

A multi-scale model with intraseasonal and diurnal components demonstrates effects from the latter on the former. Multiple scale asymptotic analysis was used to derive model for interaction of intraseasonal disturbances and the diurnal cycle. It is found that tilted heating is important for diurnal cycle to have impact on intra-seasonal scale. The modulation of diurnal cycle by intra-seasonal variations is also evidenced from the model (Yang).

A Low-Order Nonlinear Stochastic Model is built to predict the two MJO modes derived from the nonlinear Laplacian spectral analysis with skills up to 40, 25 and 18 days in strong, moderate and weak MJO years. (N. Chen)

Based on LES, direct entrainment is sensitive to buoyancy, vertical velocity, but independent of cloud size; detrainment depends on critical mixing fraction in shallow convection. (Austin)

Insentropic stream function analysis was extended to moist dynamics and convective motions. It is based on a stream function calculation in the (θ_e,z) space so that parcels move along constant surfaces in this space. This allows among other things a direct diagnostic of diabatic heating; the velocity component in the $theta_e$ direction is obtained by a simple derivative with respect to z of this stream function. Comparison with Eulerian formulation demonstrates ability of the new procedure to capture mesoscale and synoptic scale flows in the Hadley circulation which are otherwise filtered out in the Eulerian framework (Pauluis).

A clustering approach applied to isentropic analysis identifies the patiotemporal evolution of 7 different convective regimes in OLR, precipitable water and precipitation rate. (Slawinska)

3 Breakout group discussion sessions and recommendations

In addition to the 35 talks, the workshop included breakout sessions where participants were separated into small groups of about 7 people each, in separate rooms. Each group was assigned a specific topic to discuss and asked to address specific questions and prepare a report to be presented by the a group designate on the last day of the workshop, i.e, Friday morning. There were asked to break up their discussion into the following three themes.

I. Scientific and practical issues associated with their topic

II. State-of-art and recent advances

III. Challenges and recommendations

All the groups were asked to address the following questions as they apply to their specific topic:

a. How should convective stochasticity and organization be quantified in observations and model simulations so they can be directly compared to each other?

b. How does the perception or definition of convective stochasticity and organization depend on time and spatial scales?

c. How do convective stochasticity and organization depend on the large-scale environment?

d. How different are interactions of the large-scale environment with organized convection vs. non-organized convection?

e. To what degree can organized and non-organized convection be parameterized in global climate models?

f. Can satellite and ground radar observations provide consistent information of the degree of stochasticity of convection?

The following groups were formed and met during breakout sessions of 2 to 3 hour duration, on Monday, Wednesday and Thursday afternoons. At the end of each breakout session there was a general discussion session in the big lecture room and the groups were asked to summarize their respective group sessions and feedback was given from other groups accordingly.

The following groups were formed and their summary reports are attached in Appendix B.

I. Stochastic Modeling and Observation Tools: Gianakis, Ajayamohan, De La Chevrotirere, Ogrosky, Schumacher, C. Zhang, N. Chen, Yang, Brenowitz, Kiladis,

II. Parameterization: G. Zhang, Mukhopadhyay, Christensen, Park, Siebesma, Craig, Tung, Boing,

III. LES/CRM simulations: Austin, Waite, Moncrieff, Hagos, Bellenger, Pauluis, Khouider,

IV. MJO initiation: Shuyi Chen, Johnson, Goswami, Stachnik, Majda, Shengqian Chen, Thual, Stechmann,

4 Outcome of the Meeting

Many collaborations among individual workshop participants were forged during the workshop. Collectively, the workshop decided to pursue the following:

(a) Recommend a special issue on Stochasticity and Organization of Tropical Convection to the online open-access journal Mathematics of Climate and Weather Forecasting. The recommendation has since been accepted. The description of the special issue is posted at http://degruyteropen.com/mcwfsotc/. Nine workshop participants have expressed interest to contribute to the special issue.

(b) Write a workshop summary article for the Bulletin of the American Meteorological Society. The organizers of the workshop will draft this article.

(c) Write an article to document and compare stochasticity of the MJO and its associated perturbations using different MJO indices to assess our knowledge on this subject and the uncertainties associated with it. About 6 workshop participants will collaborate on this.

Appendix A: Workshop Agenda

Monday, May 27
8:45 9:00 Welcome remarks by BIRS manager and organizers
9:0010:30 Talks
Chair: Boualem Khouider
9:00-9:30 Mitch Moncrieff: Supercluster-like Organization & Inertial-Gravity Wave Interaction during the Year of Tropical Convection (YOTC)

9:30-10:00 Richard Johnson: MJO Initiation: Multiscale Processes Inferred from DYNAMO
10:00-10:15 Samson Hagos: Cloud Permitting Modeling of Shallow-to-Deep Convection Transitions during the Initiation and Propagation of Madden-Julian Oscillation
10:15-10:30 Hugo Bellenger: Processes of MJO Preconditionning Shallow Convection and Clear Air Turbulence
10:30-11:00 Coffee break
11:00 12:00 Talks
Chair: Boualem Khouider
11:00-11:30 Qiang Deng: The Role of Stratiform Heating in Simulating MJOs in a Stochastic Multicloud GCM
11:30-12:00 Ajaya Mohan Ravindran: MJO/MISO in a coarse resolution aquaplanet General Circulation Model
12:00 13:30 Lunch
13:00 Tour of Banff Centre Campus (May need to have quick lunch to join the tour)
14:00 Group photo
14:00–15:00 Breakout sessionsgroups will meet and start discussing their themes.
15:00–15:30 Coffee break
15:30 17:00 Breakout discussions continue (possibility short 5 min presentations within breakout sessions to put the groups up to speed)
17:00 17:30 General discussion: Remarks and comments, possible consultations across groups.

Tuesday, May 28
9:0010:30 Talks
Chair: Mitch Moncrieff
9:00-9:30 Courtney Schumacher: Mesoscale Organization from an Observational Perspective
9:30-10:00 Sam Stechmann: A Spatiotemporal Stochastic Model for Tropical Precipitation & Water Vapor Dynamics
10:00-10:15 S. Thual: A MJO Skeleton Model with Refined Vertical Structure
10:15-10:30 Nan Chen: Predicting the Cloud Patterns of the Madden-Julian Oscillation through a Low-Order Nonlinear Stochastic Model
10:30-11:00 Coffee break
11:00 12:30 Talks
Chair: Moncrieff
11:00-11:30 Phil Austin: Cloud entrainment and detrainment in high resolution simulations of convection
11:30-12:00 Pier Siebsma: Using Conditional Markov Chains (CMCs) in convection parameterizations
12:00-12:15 Michael Waite: The spectral kinetic energy budget in LES of convective turbulence
12:15-12:30 Boeing: Convective cold pools and their effects on cloud formation
12:30 13:30 Lunch
13:30–15:00 Breakout sessions
15:00–15:30 Coffee break
15:30 16:00 Breakout sessions (continue)
16:00 17:00 Group preliminary reports (10 min each)
Chair: Chidong Zhang
17:00-17:30 General discussion, comments/feedback on prelim reports
Chair: Boualem Khouider

Wednesday, May 29
8:3010:30 Talks
Chair: Chidong Zhang
8:30-9:00 Shuyi Chen: Stochastic Ensemble Modeling of Scale-Dependent Error Growth and Multiscale Interaction in Tropical Convective Systems
9:00-9:30 George Kiladis: Stochastic Aspects of Convective Organization within the MJO
9:30-9:45 Shengqian Chen: Multiscale Asymptotics for MJO Skeleton and Tropical-Extratropical Interactions

9:45-10:00 Reed Ogrosky: Identifying the MJO Using the Skeleton Model
10:00-10:15 Noah Brenowitz: Enhanced Persistence of Equatorial Waves via Convergence Coupling in the Stochastic Multicloud Model
10:15-10:45 Coffee break
10:45 12:45 Talks
Chair: Chidong Zhang
10:45-11:15 Guang Zhang: Examination of Convective Parameterization Schemes and ?Their Scale-Awareness Using Observations and Cloud-Resolving Model Simulations
11:15-11:45 P. Mukhopadhyay: Modification of Sub-grid Scale and Grid Scale Cloud and Convective Parameterization in CFSv2 and Its Impact on Organized Convection and Improving Model Fidelity
11:45-12:15 Hannah Christensen: Stochastic Parameterization: Representing Model Uncertainty in Earth-System Modelling
12:15-12:30 SeungBu Park: A unified Parameterization of Dry and Moist Convection for General Circulation Models
12:30-12:45 Joanna Slawinska: Convective Regimes as Revealed by Isentropic Analysis
12:30 14:00 Lunch
Afternoon: Free activities.

Thursday, May 30
9:0010:30 Talks
Chair: Mitch Moncrieff
9:00-9:30 Pauluis: Isentropic analysis for convective motions
9:30-10:00 George Craig: Convective Fluctuations and Stochastic Parameterization - Revisited
10:00-10:15 B. Goswami: Is SuperparameterizationCapable of Breaking The Deadlock ? - Seeking the Answer in Superparameterized CFSv2 664-Day Climate
10:15-10:30 Qiu Yang: A Multi-Scale Model for the Intraseasonal Impact of the Diurnal Cycle of Tropical Convection
10:30-11:00 Coffee break
11:00 12:30 Talks
Chair: Chidong Zhang
11:00-11:30 Dimitris Gianakis: Kernel Analog Forecasting of Intraseasonal Oscillations
11:30-12:00 Wen-Wen Tung: The Emerging States of MJO Convection Initiation
12:00-12:12:15 De La Chevrotiere: Bayesian Inference for the Stochastic Multicloud
Model Using the Giga-LES Dataset
12:15-12:30 Justin Stachnik: Sensitivities of the MJO to the Shape and Strength of the Tropical Warm Pool in the Stochastic Skeleton Model
12:30 13:30 Lunch break
13:30–15:00 Breakout sessions
15:00–15:30 Coffee break
15:30 17:00 Breakout sessions: Concluding and Report preparation

Friday, June 1
9:0010:00 Group reportsfinal (20 min each)
Chair: Chidong Zhang
10:00-10:30 Coffee break
10:30 12:30 Concluding discussion and wrap up
Chair: Boualem Khouider
12:30 13:30 Lunch break
13:30 Workshop ends

Appendix B: Group reports

Group Discussion 1

Challenges, Issues
Definition and motivation of organization: Based on existing tracking methods, you can define scales for organization. Characterize in terms of area, lifetime, structure (e.g. linear), propagating/nonpropagating, large-scale impact (Q1, Q2, Q3).Under suppressed condition, it may not be organized but can have an impact?

Two important questions:
a) what is "organization"? and
b) why do we care about organization"? Two levels of organization can be defined:

Level 1:
a) Defined by large area / long lifetime.
b) Important for the accompanying stratiform rainfall / vertical diabatic heating proles.

Level 2:
a) Defined by large area / long lifetime + linear organization (e.g. squall line);
b) Important for momentum transport (e.g. $u'w'$);

Conclusions:
a) Multiple "Levels" of organization;
b) Important for different aspects of convective parameterization;
c) Potential for more predictability, including teleconnection patterns;

To the question how to compare models to observations?":
RMM is appropriate for global MJO statistics. However, there are distinct alternatives to the RMM index that should be considered to be used in different contexts.

Here are some recommendations:
OMI: Convection only;
MJOSA: Convection and circulation, including off-equatorial circulation; No temporal filtering or empirical orthogonal functions; There are two outcome to the MJOSA, one form which gives an amplitude in every longitude in time, and another form which provides two indices. Because of the absence of temporal ltering, monitoring is in real-time.
NLSA: Convection only; It requires minimal preprocessing, no spatial-time pre-filtering or seasonal partition; It provides clean separation of Summer boreal ISO and MJO with favourable predictability; No spatial orthogonality required.

Revisit MJO metrics. Examples of MJO metrics that are of interest for organization: Rain rate on the 10E-10W band (comes in response to the fact that the RMM is circulation based), Longitude/propagation speed. Desired statistics: mean, variance, decorrelation should be included in standard diagnostics.

Recommendations:
How can the SMCM be leveraged to get more information? How realistically can it be used in operational GCM? Calibrate the SMCM for the cloud areas equilibrium distribution or transition time scales from data. Geographic and scale dependence is important. Dataset suggested: DYNAMO (Indian), DARWIN (Australia), KWAJEX (Central Pacific), TRMMVGPM.

Improve the stratiform representation: couple the stratiform formation from to the large-scale environment: important indicators are upper level shear, middle level relative humidity. (Add non-precipitating envelope?). Include local interactions between the microscopic convective elements;

Develop dynamical diagnostics/criteria for the SMCM to compare against observations: e.g. a localized Wheeler-Kiladis"-like criteria for the cloud area fractions that helps to validate and/or retune the SMCM.

Low order model: Use multiplicative noise or hidden Markov processes to approximate the cloud transitions. Generally, further development and applications of space-time localized spectra, indices, and conditional statistics for other models and observational studies;

We strongly suggest that codes, diagnostic tools, and actual indices be made available to the community.

Group 2: Report of the Parameterization Group.

State of the art. Problems with variability in deterministic parameterizations.

Deterministic convection parametrisation schemes aim to represent the average of the possible effects of unresolved, subgrid-scale convective clouds on the resolved scale state. This is a good approximation for large grid boxes, since the average is taken over many convective plumes, so the statistical relationship encoded in the parametrisation scheme will hold. However as model resolution increases, the validity of this approach is compromised. For smaller grid boxes, the issue of sampling becomes more important, and the variability in the unresolved forcing for a given resolved-scale state is expected to increase. There is therefore much interest in developing stochastic parametrisation schemes that represent the variability of unresolved convective processes and the impact that this unresolved variability has on the large scale state.

Approaches to stochastic parameterization

Pragmatic Approaches, Not scale aware, not related to physics

Two operational stochastic schemes have been developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) that have been adapted and adopted by modelling centres worldwide. The first of these is the Stochastically Perturbed Parametrisation Tendencies scheme (SPPT), whereby a spatially and temporally correlated random number field is used to perturb the parametrisation tendencies from the models physics package. This pragmatic approach to representing uncertainty was initially proposed to improve the reliability of the Centres medium range forecasts by correcting the under-dispersive nature of the ensemble. The imposed spatial and temporal correlation scales have no physical basis, though coarse graining studies have been used to retrospectively justify the multiplicative nature of the noise and its magnitude. Despite the ad hoc choices in the formulation of the scheme, SPPT is surprisingly effective at improving ensemble reliability, reducing forecast error, and improving biases in the mean and variability of the models climate. However, the scheme comes under much criticism for the lack of physical justification in its approach.

The second scheme is the Stochastic Kinetic Energy Backscatter scheme (SKEB). This scheme represents a process that is otherwise missing due to the truncation of the model equations, namely the upscale transfer of kinetic energy from small to large scales. This is achieved by perturbing the stream function to inject energy directly into the largest scales. Despite being physically motivated, the scientific basis of the scheme is weak, as is reflected in the wide variety of implementations used in different weather centres. In addition, the scheme is not scale aware: the backscatter ratio must be re-tuned for each new model resolution. Recent work by Shutts (2015) suggests a physically motivated improvement to the scheme, whereby the interaction of convection with model dynamics near the grid scale is recognised as the principle source of model error represented by SKEB style schemes.

Stochastic multiplume, Scale-aware across

A physically motivated model, which has gained much attention in recent years, is the stochastic multi-plume model (Plant and Craig 2008). Convective variability is first characterised mathematically. With the assumptions of convective equilibrium and non-interacting plumes, an expression for the distribution of individual mass fluxes, and for the probability distribution of total mass flux, can be derived, where the large scale state is used to constrain the mean total convective mass flux. The variance of the convective mass flux scales inversely with the number of convective clouds in the ensemble, and the variability about the mean becomes increasingly important as the grid box size is reduced or in cases of weak forcing. The first step in implementing a parametrisation scheme based on this theory is estimating the large-scale environmental properties necessary for the convective equilibrium assumption: the atmospheric state is first averaged over neighbouring grid boxes within a specified area such that this region will contain many clouds. Importantly, this enables the scheme to scale well across model resolutions, with no retuning required, up until resolutions where the grid scale becomes comparable with the scales of convective clouds. Temporal correlations are introduced into the scheme by assuming that clouds have a finite lifetime.

Multicloud model, Temporal organisation, self-similar?

A second physically motivated model is the stochastic multi-cloud model, based on analysis of observations and theoretical understanding of tropical dynamics (Khouider et al. 2010). The parametrisation is centred around three cloud types observed over the warm pool and in convectively coupled waves, shallow congestus, stratiform and deep cumulus clouds, emphasizing the dynamic role of each of these cloud types.

Each GCM grid box is first divided into a number of lattice sites, spaced 1-10km apart. As in the multi-plume model, this introduces a degree of scale awareness to the multi-cloud model, which subsequently performs well at a variety of resolutions. The scheme avoids introducing ad hoc parameters, as in other parametrisation schemes. Each lattice site switches from cloud type to cloud type following a set of probabilistic rules, conditioned on the large-scale state. The transition timescales can be estimated from observational data or LES simulations. The order of the transitions introduces temporal organisation to the system, which is important for simulating the MJO.

Issues

Stochastic parameterizations aim to take into account temporal and spatial organisation of clouds in a stochastic matter. In doing this a number of issues should be taken into consideration:

Upscale influence of small scale processes.

It is not a priori clear which processes and structures on the subgrid scale are relevant in the sense that they have implications on the larger resolved scale. Care should therefore be taken to i) only develop stochastic parameterizations for those subgrid phenomena that actually influence the larger scale dynamics and ii) make sure that the stochastic parameterization descriptions actually generates realistic perturbations on the resolved scales

Spatial versus temporal subgrid organisation

Most current schemes for stochastic convection parameterizations (.e. multicloud model, multiplume model, conditional markov chain (CMC) approaches) do introduce temporal correlations but have a lack of spatial organization. It is unclear to what extend it is necessary to introduce spatial correlation which would turn CMC type of parameterizations more into cellular automata type of descriptions. This would introduce new complexity but will also allow for explicit spatial organization on the subgrid scale.

Scale awareness

Stochastic parameterizations become increasingly important if the resolution is becoming comparable with the size of the phenomenon that requires parameterization. This implies that a stochastic parameterization should be scale aware since the variability should increase with higher resolution in a realistic manner. If the resolution becomes even higher than the phenomenon (i.e. convective plume) but is still not high enough that it resolves the process most of the presently presented new stochastic frameworks break down (multicloud model, multiplume model). The range of validity of a stochastic parameterization needs to be explicity recognized, and approaches that represent only the smaller clouds or convective motions could be explored.

Stochastic perturbations across different parameterizations

It is quite likely that when existing stochastic cloud models (i.e. the multicloud model) are implemented in existing operational GCMs it will not be possible to incorporate these into one single (i.e convection) parameterization. For instance the stratiform part of the multicloud model is in most GCMs (at least in part) represented in the cloud scheme. This creates the problem of how to practically implement recently developed off-line stochastic models in present day numerical weather prediction (NWP) and climate models.

Determination of parameters in stochastic parameterizations

At present many of the parameters in stochastic parameterizations (i.e. the multicloud model) are only beginning to be constrained by observations and turbulence resolving models. Especially if these models are to be used in operational models thay need to behave in a realistic manner over the whole phase space of possible realisations. This requires a serious investment in the training and optimalisation of the used parameters in these parametrizations. A further issue is the dependence of stochastic variability on weather regime, which has been found in mid-latitudes and may occur in the tropics as well, and needs to be accounted for in the choice of parameters or even the formulation of the scheme.

Trigger of convection

The rigger function for convection is mostly still done in a deterministic fashion. It may be more appropriate to incorporate the trigger function as an integral part of a stochastic convection framework.

Stochastic vs Numerical noise

Even when using deterministic parameterizations there is numerical noise at the grid scale. When introducing stochastic parameterizations one needs to keep track of the intended variability originating form stochastic parameterization vs the unintended numerical noise due to numerics, including potential interactions between the two.

Opportunities and recommendations:

Systematic analysis of coarse-graining CRMs/ LES

One prime opportunity is to make use of large-domain turbulence resolving simulations. By systematic coarse graining the simulation results as well as systematically varying the imposed resolution it will be possible to inform parameterizations on relationships between resolved and subgrid processes, the degree of stochasticity and scale-awareness, all as a function of the used resolution. Ideally such simulation studies could be based on recent tropical field experiments such as Cindy-Dynamo or upcoming programs such as YMC and could be organized in collaboration with the WGNEs Grey Zone Project.

Use Hierarchy of models in a consistent way: from cellular automata to GCMs

The use of hierarchy of models in terms of complexity is encouraged, starting from exploring new approaches in simplified models (Lorentz96) and test basic principles, further exploiting it in models of intermediate complexity and finally using it in operational models with the full operational complexity.

LES as convergence test

Operational mesoscale models should all have the option to be able to run in a LES-mode. This will allow more systematic exploitation of simulating periods during field campaigns are various resolutions. It also makes it easy to evaluate parameterizations in such models and investigate how/whether their behaviour is converging when approaching turbulence resolving resolutions.

Common metric to test and evaluate parameterizations in general.

We hope to see recommendation along these lines from WG1 and would certainly support those. In particular, process-oriented metrics relating to structure and organization of convective play an important role between bulk indices for large-scale phenomena such as MJO and direct measures of parameterization output such as Q1, Q2 and Q3.

Testing the stochastized versions in an ensemble environment

Stochastic parametrization represents a paradigm shift when compared to deterministic parametrization: a stochastic model represents one possible realization of the system, as opposed to the most likely evolution represented by a deterministic scheme. It is therefore important to assess stochastic schemes in an ensemble setting. How well does the scheme represent model uncertainty? What can be learned from the ensemble about predictability of the process in question? How does the ensemble mean compare to traditional deterministic forecasts?

How to incorporate existing stochastic parameterizations into current parameterizations in operational models?

An area of active research should be investigating ways of including state-of-the-art stochastic schemes into operational models. It is not necessarily obvious how new schemes should interact with the other physics schemes or, in the case of the multi-cloud model, how well the scheme will perform in mid-latitudes. Nevertheless, this is an important step to take to allow these schemes to be evaluated against existing forecast models and observations.

Determine Upscale Growth from CRMs

In order for a stochastic parametrisation to be useful, the stochasticity must have an impact on the resolved scale flow. An interesting area of research is determining exactly how stochastic parametrisations can have this impact. Determining upscale error growth using CRM simulations can inform the community as to which uncertain processes should be made stochastic, and which are unimportant in this respect.

Group III: LES/CRM Simulations

ISSUES

- Measurements of evaporation and fine-scale humidity for evaluation of LES/CRM simulations cold pools, PBL structure (ML depth evolution)
- Limitations of periodic boundary conditions; coupling of CRM/LES to large scales; validity of the weak-temperature gradient approximation.
- Cross-grid interaction in super-parameterized models: Periodic boundary conditions preclude propagation of organized convection (e.g., MCS) across the parent climate model grids. Propagation across climate grids requires interaction between vertical shear on the low-resolution climate grid with latent heating on high-resolution CRM grids. This can result in structural bias, e.g., absence of mesoscale downdrafts. A better understanding of the spatio-temporal evolution of convective activity and, in particular, of the nature of scale interactions.

- Microphysical parameters that are significant drivers for CRM/LES simulations.

B. STATE-OF-THE-ART

- 1-km-grid models are positioned to evaluate the statistics (e.g., clustering, isentropic analysis, mass flux) and stochastic aspects (e.g. conditional pdf, time-lag correlation) of organized convection in large computational domains.
- Use of high-res global NWP virtual global field campaign analysis for initial conditions and/or evaluation of MJO and convectively coupled equatorial wave simulations. Development of scaling laws for convection (Giannakis, Peters and Neelin, Stechman, Craig) that can be tested and evaluated in CRM/LES.
- New methods for analyzing thermodynamic cycles in numerical models can be used to assess the interactions between thermodynamics and dynamics in convection.
- Momentum transport by organized convection is distinct from CMT by unorganized cumulus, i.e., counter gradient momentum transport and upscale kinetic energy tendencies. Theory and simulation show significant effects on the MJO and convectively coupled equatorial waves. (few convective scheme taking this into account: Wu et al. discussion about super parameterization that do not re-inject CMT to the large-scale)
- Organized convection in shear has been approximated as Lagrangian multiscale coherent structures and has been represented in simplified global models by multicloud parameterization. It timely to examine aspects such as organized momentum transport in full GCMs (e.g., CSM and CCSM). (e.g., It has been shown that all CMIP5 models fail to represent the Tropical Easterly jet because they significantly underestimate upper-tropospheric shear.)
- The Vertical Structure and Diabatic Process intercomparison is an example of a multimodel intercomparison of MJO that compares models across time and space scales and could be employed for the Year of the Maritime Continent[1].

Four papers on a collaborative project between GASS, YOTC and the MJO Task Force Vertical Structure and Diabatic Processes of the MJO have been accepted for publication in JGR.
a) 20-year climate simulations;
b) 20-day hindcasts;
c) 2-day hindcasts;
d) analysis of the GCMs that contributed to all 3 projects.

C) RECOMMENDATIONS

- Employ virtual global field campaign data (10 km grid ECMWF IFS) to evaluate large-domain 1-km-grid CRMs, as a supplement to actual field-campaign data. (for example model precipitation and organized convection and momentum transport following Praveen et al. (2015) 10.1175/JCLI-D-14-00415.1) also cf. parameterization development
- Contribute to the Year of the Maritime Continent (YMC) actual and virtual field campaign for (2017 2019) Design a YMC Grey Zone project on organized tropical convection resembling the giga-EUCLIPSE cold-air outbreak study. CRM O(1km) vs LES . how good is 100m resolution?
- Use CRMs to inform convection initiation, stratiform/convective fraction. Suggest CRM modellers archive variables from simulations for standard diagnostics (isentropic analysis, cloud transitions).
- Adoption of new diagnostics to address the statistical behavior of convection (NLSA, isentropic analysis, lagrangian trajectories, information theory, Hidden Markov Model (Crommelin and Vanden-Eijnden) that could be systematically for model intercomparison

[1] https://usclivar.org/sites/default/files/meetings/2014/summit-presentations/Zhang_Summit2014.pdf

- The use of CRMs to quantify transitions between cloud types may be enhanced by the use of simplified microphysics parameterizations that could be more easily explored. The microphysics of evaporation is of particular interest. Comparison with disdrometers and dual-polarization radars measurements from field campaigns could provide an observational constraint. Need simple microphysics, easy to tune and compare in particular in terms of precipitation efficiency (). Test the sensitivity of microphysics to subgrid turbulence, vertical velocity
- Coupling CRM/LES with the ocean.
  (1) Precipitation leads to fresh water lenses. Convection initiates on their edge (Carbone et al.? link with cold pools?).
  (2) During calm weather (shallow convection, congestus) strong stratifications appear in the first tens cm of the ocean making it reactive on the scale of 1 hour. Impacts PBL and convection triggering (Bellenger et al 2010, Ruppert and Johnson 2015, Johnson et al 2015).

Response to Questions

a) and b): Whats the physical interpretation of the theoretical variables in multicloud parameterization, what do we need from CRM/LES and observations, e.g., cold-pool aspects, evaporation. Mesoscale scale-selection multicloud parmeterization/ multiscale coherent structures context need to be evaluated against large-domain LES/CRM and observations, including geostationary satellite observations.

d) and e): The effects of vertical shear on moist convection is given little attention compared to moistening/drying/heating contrary to results of theoretical, numerical and observational studies.

f): Forward operator (radar simulator) development for LES/CRM would facilitate comparison of models with radar measurements.

Group 4: Initiation and Dynamics of MJO/Physical Processes

Summary and Report

One of the most challenging aspects of identifying the initiation of a primary Madden-Julian oscillation (MJO) event is first defining the MJO. The MJO is highly stochastic and may initiate from any number (or combination) of mechanisms such as stochastic convection and internal atmospheric variability, recharge-discharge, air-sea coupling, upscale energy transport, moisture modes and cloud-radiation interactions, extratropical forcing (e.g., Rossby waves or equatorially propagating cold air outbreaks), among others that are documented in recent and historical literature. The MJO also displays a strong seasonality and interannual variability; each MJO event is different and unique.

Nevertheless, we see a need for a more unified definition of the MJO. Likewise, there is the pressing challenge for the development of revised MJO indices that can better identify local MJO activity and event initiation. Such an index would be most successful if it could be computed from both observational and model data. Current popular indices such as the Real-time Multivariate MJO (RMM) index (Wheeler and Hendon 2004) struggle with identifying the initiation of primary MJO events when occurring at scales smaller than the zonal wavenumber-1 modes that comprise the leading EOFs of this index. Similarly, the RMM requires global wind data and thus cannot be computed from limited domain simulations such as regional climate or cloud resolving models (CRMs). Global climate models (GCMs) will be largely unsuccessful at tracking the MJO via precipitation or simulated OLR anomalies while low-order models may be limited to a few variables like convective heating. As such, we recommend the development of an MJO index for initiation based on our identifying and characteristic traits of the phenomenon, potentially including the following qualities:

- The presence of large-scale convective anomalies along or near the equator and grouped within 1000 km (i.e., the convective envelope)
- The development of mesoscale organization within the convective envelope and the appearance of multiscale interactions
- The start and maintenance of eastward propagation at 5 m s-1 item The onset of zonal circulation anomalies that eventually grow to scales of wavenumber-1 to wavenumber-3

To better elucidate the dynamics and mechanisms responsible for MJO initiation, we also recommend additional research that attempts the following:

- Synthesis and climatology research that documents the distribution of mechanisms considered most important for observed and modeled MJOs (i.e., statistical analysis of mechanisms associated with MJO initiation)
- Model intercomparison studies for all scales of numerical analysis (i.e., GCMs, CRMs, LES, and low-order analytic models) that focus on the successful initiation of primary MJO events rather than maintenance or propagation (similar to the second objective of the GASS-YoTC Vertical Structure and Physical Processes model evaluation project with high-frequency model output)
- Additional studies examining the failure of large-scale MJO initiation
- Improved understanding of MJO event termination and/or the corresponding initiation of long-term quiescent periods (e.g., why do some years have little to no MJO activity?)
- Better understanding the continuum of Kelvin waves and the MJO in addition to the role of wave interactions on influencing MJO organization and event initiation
- Discovering the role of stochasticity, organization, and multiscale processes that contribute towards MJO initiation

Additional work is needed to incorporate these findings into numerical models. For example, recent work has shown that the mid-level moistening in models is often insufficient compared to observations and provides a reference for tuning multiscale interactions and accounting for the upscale effects of clouds and convection in convective parameterizations. It is our hope that the above work may help identify those large-scale environmental conditions and dynamical mechanisms that are considered necessary and sufficient for MJO initiation over the Indian Ocean and other locations in addition to improving mid-range global weather forecasts.

CLIFF's NOTES:

1. Scientific and practical issues associated with MJO initiation

a. What is the MJO/How to define the MJO?

b. The MJO experiences strong seasonality and interannual variability

c. Challenges associated with common MJO indices
   i. Do we use regional or global indices?
   ii. What metrics best describe the local onset of an MJO? Convective organization, or just any sort of OLR and energetic anomaly?

d. Can we list different conditions and situations that initiate MJOs in the Indian Ocean?

2. Quantifying stochasticity and organization

a. What is organization?

b. What is stochasticity?

c. Stochasticity and organization are both scale-dependent in models and observations

3. Merging stochasticity and organization

a. What are the large-scale environmental effects on stochasticity?

b. Do we need an index to measure convective organization for the MJO?
   i. Is this useful? Would it help to better predict the initiation of primary MJOs?
   ii. What convective organizations are most common prior to the large-scale onset of an MJO?

Long Record

1. Scientific and practical issues associated with MJO initiation

a. What is the MJO/How to define the MJO?

i. Is the MJO regional or global? Do events originate solely in the Indian Ocean basin or do we consider activity that develops over the west Pacific also an MJO?
ii. Convective vs. circulation anomalies
iii. Eastward propagating vs. stationary waves
iv. Characteristic traits of an MJO event
1. We define the MJO as an equatorially envelope (grouped within 1000 km) of convective disturbances over the Indian Ocean that excites planetary scale zonal wind anomalies and travels eastward at roughly 5 m s^{-1}
2. No two MJOs are the same, it is highly stochastic unlike other mode constrained modes of tropical convection (e.g., tropical cyclones)
v. Possibility of dry modes, though question remains as to initial source of deep heating and temperature anomalies without convection
Unable to rely on SST anomalies and sensible heat fluxes; resultant heating is too shallow
vi. Do MJO events always exist in some background state or are they only present once reaching some critical amplitude?
vii. Consideration of other large-scale variability
1. Weickmann and Berry (2008) global wind oscillation
2. Straus and Lindzen (2000) growth of baroclinic modes on planetary scales

b. The MJO experiences strong seasonality and interannual variability

i. The Indian Ocean basin has strong seasonality in the zonal winds and varies with ENSO and IOD phases
ii. Do we more broadly consider monsoons and northward propagating modes in the boreal summer part of the MJO continuum?
Thual et al. (2015): The stochastic skeleton model can produce northward propagating ISO modes with a seasonally migrating warm pool, though eastward propagating mode is still preferred in the model

c. Challenges associated with common MJO indices

i. The RMM index (Wheeler and Hendon 2004) is reliable with pre-existing MJOs and MJO maintenance yet may miss the initiation of a primary event if occurring at scales smaller than the wavenumber-1 circulation component within the RMM EOFs
ii. The OMI (Kiladis) uses 2D EOFs (no meridional averaging) of OLR without consideration of circulation anomalies
iii. In short, we struggle to define local indices, especially when we consider that the MJO has global implications

d. Can we list different conditions and situations that initiate MJOs in the Indian Ocean?

i. This depends highly on you define and explain the MJO
ii. Our field campaign observations are statistically insignificant and we need a much longer record of MJOs

2. Challenges and issues associated with convective organization

a. What is organization?

i. Development of cold pools and organized momentum transport within the convective system
ii. Should appear continuously precipitating in satellite data using certain OLR thresholds, though threshold choice is subjective

b. Organization is scale-dependent

i. Typically see mesoscale organization within the active phase of the MJO

ii. Some folks may talk about coherent vortices as organization in turbulence
iii. Suppressed phase conditions, which are highly stochastic, still can self-aggregate and generate organized cold pools

c. The organization of convection will he highly driven by shear, among other environmental factors
i. Self-aggregation is likely less important than shear
ii. Should this be included in our metrics to predict MJO initiation?

3. Challenges and issues associated with quantifying stochasticity

a. What is stochasticity for tropical convection?
i. Dictionary says stochastic is random
ii. Stochasticity implies probabilistic distributions that can be analyzed statistically, though not explicitly predicted without the use of ensembles
iii. In a model, the same deterministic variables can give rise to any number of stochastic states, though the distribution should still be deterministic

b. Stochasticity is scale-dependent
i. Synoptic waves can be relatively deterministic, but downscaling to convective scales becomes more stochastic in models and observations
ii. What averaging and filtering need to be done for our context (Earth science) to bring out the stochastic and deterministic parts of our system?
iii. How many scales do we need?

c. Stochasticity in models is dependent on grid size and resolution

4.Merging stochasticity and organization

a. What are the large-scale environmental effects on stochasticity?
i. Say you have a very dry vs. moist environment. Which is more stochastic?
1. Are Bernard cells and cumulus clouds organized?
2. Will convective always self-aggregate due to radiative instabilities and interactive radiation in models?
ii. Self-aggregated shallow convection over long times may demonstrate organization, but would not call that deterministic

b. Do we need an index to measure convective organization for the MJO?
i. Is this useful? Would it help to better predict the initiation of primary MJOs?
ii. What convective organizations are most common prior to the large-scale onset of an MJO?

DISCUSSION FROM WEDNESDAY, APRIL 29, 2015

1. Scientific and Practical Issues/Statement of Problem

a. Defining the MJO
i. Each MJO (and initiation) is very different

b. Measurements
i. Indices capture different features
ii. RMM index is not well suited for the Indian Ocean
1. Cannot track active convective component over those domains (evidenced by DYNAMO data)
2. RMM is much better suited for a global index
iii. Separating primary from secondary MJOs varies by index

c. Mechanisms and Modeling
i. Tropical internal atmospheric variability
ii. Global instabilities and linear modes (both tropics and extratropics)
iii. External forcing
1. Extratropical influences
2. Upscale energy transport, waves, and aggregation
iv. Air-sea coupling
v. Role of stochastics
vi. Primary and secondary MJOs

2. State-of-Science and Recent Advances

a. Defining MJO features and characteristic traits (visual)
i. Equatorially envelope of clouds and convection (TRMM precip, OLR)
ii. Wavenumber-1 circulation anomalies
iii. Large-scale organization (multiscale)
iv. Eastward propagating at 5 m s^{-1}

b. Metrics and Indices
i. CLIVAR Working Group/Waliser et al. (2009); Gottschalk et al. (2010)
1. Variance, single variable EOFs, temporal spectrum, lag-longitude, east-west power, wavenumber-frequency filtering, etc.
ii. WH04 RMM, OMI, Skeleton index, etc.

c. Mechanisms
i. Charge-Discharge
1. Not present in DYNAMO, saw perpetual shallow convection
ii. Air-sea interactions
iii. Role of cloud populations
1. MSE increases from radiation interactions and reduced LW cooling
iv. MJO initiation mechanisms are specific to each event
v. Initiation will also be dependent on low frequency variability
vi. May have differences in winter and summer MJO events

3. Challenges and Recommendations

a. We need a new index for local aspects of the MJO and convective initiation

b. Should include and test all mechanisms in tractable models
i. Recommend a model intercomparison study of primary MJO initiation (separate for GCMs, CRMs, LES, idealized models), perhaps similar to the second objective of the GASS-YoTC Vertical Structure and Physical Processes (secondary MJOs) with high-frequency output at each timestep
ii. Synthesis study documenting frequencies of most common initiation mechanisms (climatological frequency)
1. Mechanism identifiability is a challenge in incomplete data
2. Would need to set up a hierarchy for determining primary mechanisms
iii. Studies on MJO initiation failure

c. Multiscale interactions for initiation remains a challenge

d. Need comparison observations for models of different complexities

Discussion from Thursday, April 30, 2015

1. State of the science/Potential mechanisms for MJO initiation

a. Moisture mode and cloud-radiation interactions

b. Global mode

c. Recharge/discharge

d. Air-sea coupling

e. Upscale energy transport

f. Extratropical forcing

g. High-frequency stochastic synoptic forcing

2. Concerns with indices

1. Recommend additional research into the development of initiation indices

2. Different models will have different features based on their resolution
   a. Some may have heating variables
   b. CRMs allow you to track the convection by rain rate or precipitation
   c. Regional models cannot do the RMM index because they require information on the winds and variance over a global domain
   d. GCMs will not be able to do precipitation
   e. Common observed MJO features
   i. Need to have propagation, near equator, and be based on physical data

3. Potential for future work

a. MJO initiation with several known mechanisms
   i. Comparison of relative importance
   ii. How to determine primary mechanism?
   1. Likely cannot do with observations alone (arguing over what initiated DYNAMO MJOs, which are among most well observed)
   2. Would need to do statistically in models (have controlled variables)
   iii. Use of virtual field campaigns (YOTC) and high-resolution datasets (existing and forthcoming global high resolution datasets)
   iv. Instead of determining the one mechanism that is most important, can we better synthesize all of our work and get a statistical picture of the conditions associated with MJO initiation?
   v. Do we have well-defined necessary or sufficient conditions

b. Initiation of suppressed phase and long-term quiescent MJO conditions
   i. We can detect gradual deepening of the mixed layers (from 400-500 m to 700 m) during the suppressed phase, resulting in more plumes hitting the LCL and cloud layer

c. Case studies of failed MJO event initiation
   i. Basic question: is the MJO always present or does it only organize into discrete events with significant amplitude and/or projection on our indices?
   ii. 2014: The Year without an MJO.
   iii. Saw lots of rainfall, but didnt see any propagation in precipitation features from Hovmöller plots

d. Better understanding of MJO termination
   i. Often see deeper cold pools with longer recovery time (up to 30 hrs) during suppressed phase (drier air makes cold pools even stronger)
   ii. Dependencies on large-scale environment such as cold SSTs, large-scale and long-term drying, or

even MJO strength as to whether it can maintain itself when propagating over the maritime continent

e. Continuum of Kelvin wave and MJOs needs to be realized/sorted
   i. Also have a continuum of westward moving waves
   ii. Typically only see one well-defined Rossby gyre event per year
   iii. Seasonality of the MJO means usually only one of the two Rossby waves is favored (i.e., tilted wave structures)

f. Additional comments about stochasticity and organization

4. Reviewing motivations

a. Why do we care about initiation?
   i. Operational community/forecast perspective: Models struggle most with the initiation aspect of MJO events and do ok with its maintenance and propagation once developed (similar to tropical cyclones)
   ii. If we improve MJO prediction, we improve mid-range weather forecasts
   iii. MJO generates tropical cyclones along the way in the Indian Ocean in addition to affecting TC activity in other basins (i.e., modulation of Atlantic hurricane activity)

b. How do we improve numerical models?
   i. How to implement MJO initiation mechanisms and put them into models?
   ii. Likely need to adjust multiscale interactions and parameterization (e.g., research has shown that the mid-level moistening in models is often insufficient compared to observations)
   iii. Essentially, need to better address upscaling from convection