Cracking the MJO nut

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[1] The Madden-Julian oscillation poses great challenges to our understanding and prediction of tropical convection and the large-scale circulation. Several internationally coordinated activities were recently formed to meet the challenges from the perspectives of numerical simulations, prediction, diagnostics, and virtual and actual field campaigns. This article provides a brief description of these activities and their connections, with the motivation in part to encourage the next generation of physical scientists to help solve the grand challenging problem of the Madden-Julian oscillation.
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1. Introduction

[2] The Madden-Julian oscillation (MJO) exerts pronounced influences on global climate and weather systems [*Zhang* 2005; *Lau and Waliser*, 2011]. It represents a major source of predictability on intraseasonal time scales [*Waliser et al*., 2003; *Waliser*, 2011; *Pegion and Kirtman*, 2008; *Gottschalck et al*., 2010; *NAS*, 2010]. It challenges our understanding of tropical convection and its interaction with the large-scale environment [*Wang*, 2011; *Khouider et al*., 2013], and global climate models have particular difficulties in reproducing this phenomenon [*Slingo et al*., 1996, 2005; *Lin et al*., 2006; *Kim et al*., 2009; *Sperber et al*., 2011; *Hung et al*., 2012].

[3] Tropical convection commonly organizes into larger systems, such as mesoscale convective systems or MCSs [*Houze*, 2004] to convectively coupled waves [*Takayabu*, 1994; *Wheeler and Kiladis*, 1999], including superclusters or Kelvin waves [*Nakazawa*, 1988], which are key dynamical elements of the MJO [*Moncrieff*, 2010]. Rather than being controlled by the large-scale motion, as in midlatitudes, tropical convection is an integral part of that motion, with cross-scale organization and interaction with other tropical perturbations through its diabatic heating and momentum transport.

[4] Representation of cumulus convection is one of the primary limiting factors in MJO simulation and prediction. Traditional convective parameterization schemes fail to represent organized convection, such as MCSs. Most global models do not have sufficient resolution to simulate mesoscale circulations and MCSs. Progress has recently been made by constructing global models with cloud-system resolving resolution [*Miura et al*., 2007] and superparameterization [*Grabowski*, 2001; *Khairoutdinov et al*., 2005]. These new tools shed light on dynamical processes in global models, such as mesoscale momentum transport [*Moncrieff*, 1992; *Moncrieff and Klinker*, 1997]. However, in the foreseeable future, cumulus parameterization will remain unavoidable in most global weather and climate models. Parameterization improvement and development depend critically on in situ observations, innovative diagnostics, and advances in the theoretical understanding of tropical convection and its interaction with the large-scale environment.

[5] The MJO has been intensively studied (see summaries in *Zhang* [2005] and *Lau and Waliser* [2011]) since its first documentation by *Madden and Julian* [1971, 1972]. However, our understanding of the MJO is still limited. An international workshop on organized tropical convection and the MJO held in Trieste, Italy [*Moncrieff et al*., 2007] recommended projects focused on MJO physics and dynamics. These projects have developed into an Intraseasonal Variability Hindcast Experiment (section 4), the Year of Tropical Convection (YOTC) virtual field campaign (section 5), an actual, focused field campaign in the tropical Indian Ocean where MJO convection is often initiated (section 6), and the MJO Vertical Structure and Physical Processes Project (section 7). In addition, an MJO Task Force (MJOTF) was formed to address specific issues related to MJO model improvement and prediction (section 2), an international operational MJO forecast effort was formed (section 3), and an international subseasonal to seasonal prediction project has recently commenced (section 8). Some of these efforts are joint projects of the World Weather Research Program (WWRP), the Observing System Research and Predictability Experiment (THORPEX), the World Climate Research Program (WCRP), and are endorsed by International and US CLIVAR (Climate Variability and Predictability). This article provides a synthesized description of these efforts.

2. Madden-Julian Oscillation Task Force

[6] The YOTC (section 5) MJOTF of WWRP and WCRP started in 2009 with the purpose of improving MJO representation in weather and climate models, and enabling more skillful predictions of the MJO and related phenomena. The MJOTF consists of 15 members from 5 countries. Its major research thrusts along with its tangible research accomplishments are described below.

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[7] Building upon the climate model diagnostics designed earlier to assess whether a climate model produces realistic MJO signals [*CLIVAR Madden Julian Oscillation Working Group*, 2009; *Kim et al*., 2009], the MJOTF is developing advanced process-oriented diagnostics of MJO simulation and prediction. The diagnostics developed so far include those based on relative humidity, vertical velocity, and vertical structure of diabatic heating relative to precipitation [*Kim et al*., 2012], and the vertically integrated moist static energy budget. Figure 1 shows an example of a moist static energy budget diagnostic applied to three model pairs, each including a poor and improved MJO simulation. The *y* axis measures MJO strength, and the *x* axis shows Indo-Pacific warm pool gross moist stability, which approximates how efficiently convection and the associated large-scale circulations discharge moisture from the atmospheric column. Gross moist stability is lower or negative for models with superior MJO performance (i.e., with a higher ratio of eastward to westward propagating spectral power, as observed), consistent with results from theory and previous modeling studies [*Raymond and Fuchs*, 2009; *Hannah and Maloney*, 2011].

[8] Evaluation of real-time MJO forecasts (section 3) and development of a metric for boreal summer intraseasonal forecast are ongoing MJOTF activities. A forecast metric for the boreal summer variability that explicitly captures northward propagation has been developed and is being made operational [*Lee et al*., 2012]. The MJOTF also developed an experimental modeling framework to assess MJO predictability and forecast skill in state-of-the-art models, which contributed to the Intraseasonal Variability Hindcast Experiment (ISVHE) project (section 4). The MJOTF is currently pursuing activities relating to the analysis of multiscale interactions in models, including high-resolution models, with a focus on vertical profiles of diabatic heating [*Petch et al*., 2011; section 7].

[9] In addition, the MJOTF has produced a simple metric for the climate model metrics panel of the Working Group on Numerical Experimentation (WGNE) and the Working Group on Coupled Modeling (WGCM) that assesses climate model MJO performance [*Sperber and Kim*, 2012], and has contributed to the assessment of MJO performance in the Coupled Model Intercomparison Project 5 models [*Hung et al*., 2012]. During the next three years, the MJOTF plans to expand its research activities, including intraseasonal air-sea interaction and support for activities of the WMO Subseasonal to Seasonal (S2S) Prediction Project (section 8).

3. Madden-Julian Oscillation Prediction

[10] The MJO is a critical component of extended-range (weeks 2 to 4) forecasts [*Waliser*, 2011] because of its prominent role in global short-term climate. Real-time forecasts of the MJO are becoming increasingly important for subseasonal prediction because of the rapid increase in user requests for such information.

[11] Madden-Julian oscillation prediction studies using operational dynamical models have increased in recent years [*Savage and Milton*, 2007; *Vitart et al*., 2007; *Lin et al*., 2008; *Seo*, 2009; *Seo et al*., 2009; *Rashid et al*. 2011]. The WGNE and the CLIVAR MJO Working Group (now the MJOTF) jointly facilitated an activity to apply a uniform diagnostic for MJO identification in real-time dynamical model forecasts and corresponding skill metrics [*Gottschalck et al*., 2008; *Sperber and Waliser*, 2008; *Gottschalck et al*., 2010]. This enables a consistent time-dependent evaluation of MJO forecasts from multiple sources to assess skill as a function of model and data assimilation improvements. An international MJO forecast activity involving nine operational centers has been in place since 2010 using the uniform skill metrics [*Gottschalck et al*., 2010]. The Climate Prediction Center (CPC) of National Centers for

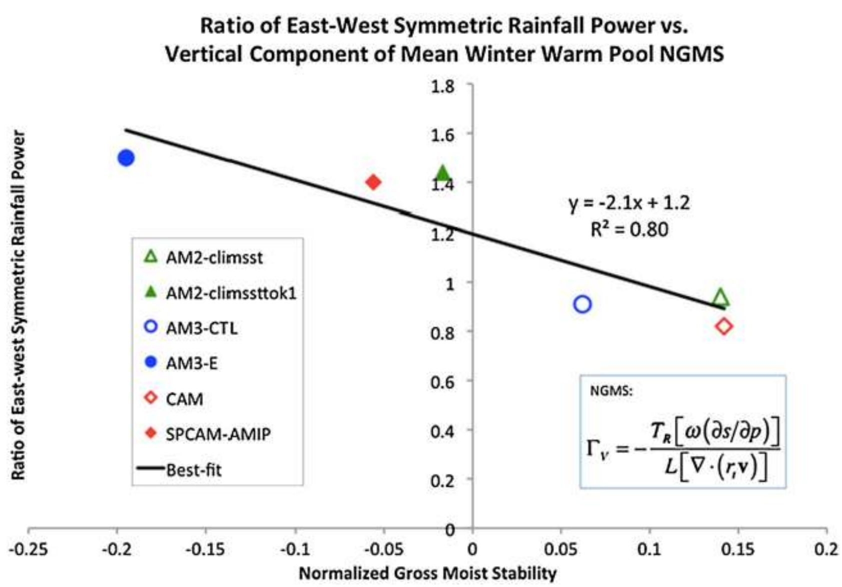

Figure 1. Ratio of east/west symmetric (with respect to the equator) rainfall power in the MJO band (30–96 days, wave numbers 1–3) versus the vertical component of normalized gross moist stability averaged over the Indo-Pacific warm pool during boreal winter for six climate models. The definition of NGMS is shown at the lower right, where *s* is moist entropy, r_t is the water vapor mixing ratio, and T_R is a reference temperature. The observed ratio of east-west rainfall power is 2.4 estimated from TRMM data. (Courtesy of Jim Benedict)

Environmental Prediction is hosting the acquisition of the forecast data, application of the MJO diagnostic, and real-time display (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/CLIVAR/clivar_wh.shtml).

[12] Figure 2a shows an example of 40 day observations for the Realtime Multivariate MJO (RMM) index [*Wheeler and Hendon*, 2004] and its ensemble forecast for the next 15 days. The RMM index is a commonly used metric for the observed and simulated/forecasted MJO. The forecast skill of many participating models, as represented by bivariate correlation (r) between the observed and forecast RMM indices, is shown in Figure 2b for all daily forecasts from 1 September 2011 to 31 March 2012 [i.e., the DYNAMO field campaign period (section 6)]. The majority of the forecast models showed useful skill ($r \geq 0.5$) throughout the first 15 days, with several maintaining above $r = 0.7$, indicating skillful forecasts through and beyond two weeks.

[13] This activity is already applied in an operational setting to aid in the production of the CPC Weekly MJO update (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/mjoupdate.pdf), ABOM Weekly Tropical Climate Note (http://www.bom.gov.au/climate/tropnote/tropnote.shtml) and the weekly CPC Global Tropics Hazards and Benefits Outlook (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/ghazards/index.php), which highlights expected areas of persistent rainfall anomalies, and regions favorable/unfavorable for tropical cyclogenesis for two weeks ahead. The MJO forecasts were used extensively by the DYNAMO extended range MJO forecast team during the field campaign (section 6) where active MJO events with varying characteristics occurred.

4. Intraseasonal Variability Hindcast Experiment

[14] Motivated by significant societal demands for accurate monsoon subseasonal prediction, the ISVHE was launched in 2009. It concentrates on all modes of tropical intraseasonal variability (ISV). The MJO and other ISV modes are important sources of predictability in the World's most populous monsoon regions [*Webster, et al.*, 1998; *Wang*, 2005]. The ISVHE is supported by the Asia-Pacific Economic Cooperation Climate Center, and National Oceanic and Atmospheric Administration Climate Test Bed, and is endorsed by the CLIVAR Asian-Australian Monsoon Panel, YOTC/MJOTF (sections 2 and 5), and the Scientific Steering Committee of Asian Monsoon Years (2007–2012).

[15] The multimodel ensemble (MME) approach has proven to be one of the most effective ways to improve seasonal prediction by reducing model errors and better quantifying forecast uncertainties [*Krishnamurti et al.*, 1999; *Doblas-Reyes et al.*, 2000; *Shukla et al.*, 2000; *Palmer et al.*, 2000; *Wang et al.*, 2009]. Given the expected benefits in intraseasonal prediction, the development of MME techniques has been an integral part of the ISVHE project, with expected follow-on benefits to the operational MJO prediction (section 3). Underlying the development of an MME is the intrinsic need for model multidecade hindcast data sets to properly quantify and combine the independent skill of each model as a function of lead-time and season. Moreover, great uncertainties still exist regarding the level of predictability that can be ascribed to the MJO, other subseasonal phenomena, and the weather/climate components they interact with [*Sperber and Waliser*, 2008]. The ISVHE project is the first attempt to produce a long-term hindcast data set that specifically targets the needs and themes associated with intraseaonal prediction research.

[16] The objectives of the ISVHE are to:

(1) Better understand the physical basis for intraseasonal prediction and estimate the potential and practical predictability of ISV, including the MJO, in a multimodel framework;

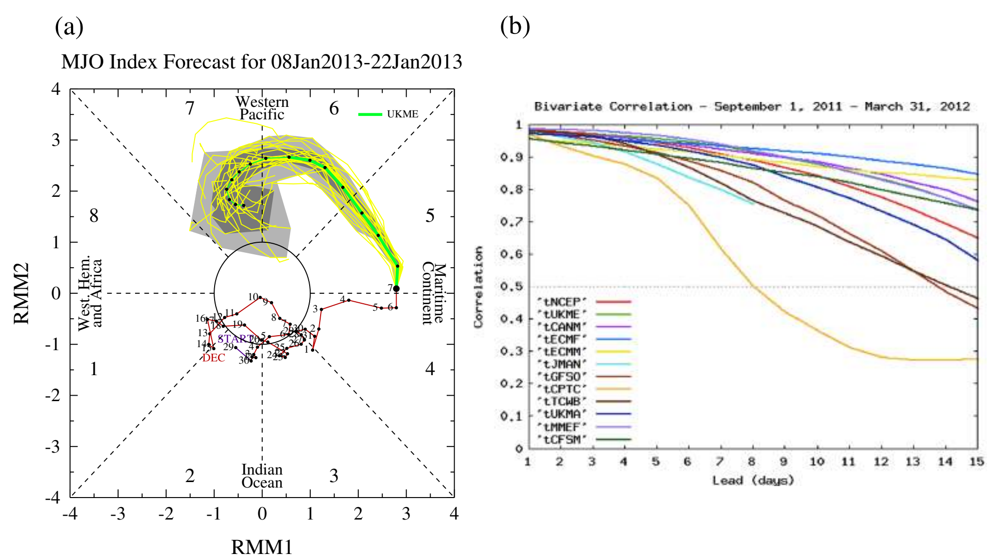

Figure 2. (a) An example of an RMM index forecast. Recent observations of the index are shown in red with annotated numbers representing the date (29 November 2012 to 7 January 2013). Forecasts for the next 15 days (ensemble mean, green line; ensemble members, yellow lines) are appended from the last observation date. A measure of forecast confidence is provided by displaying areas in which 50% (dark gray) and 90% (light gray) of ensemble members, respectively, reside. Counterclockwise movement of daily points in the phase space is indicative of eastward propagation and the strength of the MJO is proportional to the distance from the origin. (b) Bivariate correlation between the observed and forecast RMM indices using the method by *Lin et al*. [2008] for all daily forecasts from 1 September 2011.

(2) Develop optimal strategies for an MME ISV prediction system, including optimal initialization schemes and quantification of prediction skill with forecast metrics under operational conditions;
(3) Discover new physical mechanisms associated with ISV that cannot be obtained from analyses of a single model;
(4) Identify model deficiencies in prediction of ISV in a multimodel framework and suggest ways to improve models.

[17] Two experiments have been made: 20 year control simulations and 21 year hindcasts. The control simulations characterize the models' intrinsic ISV, its interactions with related phenomena of interest, and the models' shortcomings in representing them. The hindcasts characterize the model forecast skill and explore approaches to ensemble forecasting of the MJO. The 21 year hindcast experiment is based on a set of retrospective forecasts, covering the period from January 1989 to October 2009, including the YOTC period (section 5). The hindcasts are initiated either every 10 days in each calendar month or every first day of each month for at least a 45 day integration with at least five ensemble members. Currently, hindcast data sets produced by 12 models have been collected from six operational centers and six research groups.

[18] Preliminary analysis has shown that MME produces significantly improved MJO forecast skill (Figure 3). Predictions were made from the first day of each month from October to March for the period of 1989–2008. Prediction skill is measured by the two leading RMM modes [*Wheeler and Hendon*, 2004]. The independent forecast (1999–2006) skill using MME with weighting (MME_MLRM) is not an improvement on the simple MME skill, which is much higher than the averaged skill of all the individual models. The best three-model MME shows significantly better skill than any simple all-model composite, suggesting the importance of individual model quality and relative independence among the models hold the key for improvement of MME skill.

5. YOTC: A Virtual Global Field Campaign

[19] For logistical and financial reasons, actual field campaigns on the global scale are not possible. Therefore, observations of dynamical interactions between MJO convection and the large-scale circulation (e.g., convective momentum transport), or more broadly across scales extending from planetary to synoptic and smaller, are very difficult and next to impossible to obtain unambiguously. To address such formidable problems, the WCRP and WWRP/THORPEX jointly sponsor the YOTC framed as a "virtual global field campaign" [*Moncrieff et al.*, 2012; *Waliser et al.*, 2012]. In this framework of a virtual field campaign, the planetary to subsynoptic scale "observations" are obtained, not from actual field campaign, but from high-resolution global weather model analysis and forecasts that assimilate tens of millions pieces of observational data each day, mostly from satellites. This framework is a fertile basis for breaking the deadlock in modeling and predicting tropical convection and studying its global effects. The fidelity of this framework will increase as global models attain even higher resolution and as data assimilation methods continue to improve and incorporate a wider range of satellite and other data streams.

[20] The weather-climate intersection (weeks to months) is where the framework of a virtual global field campaign can be used to best advantage, for example, to examine and refine weather processes and events in climate models, and to identify and reduce "climate drifts" in long-range weather forecasts. With that in mind, the YOTC project has delivered a unique virtual atmospheric database in the form of a complete (four times per day) global analysis, 10 day forecasts, and subgrid physical tendencies from the European Centre for Medium-Range Weather Forecasts Integrated Forecast System with a 25 km mesh (16 km from January 2010) for the 2 year period of May 2008 to April 2010. The YOTC-European Centre for Medium-Range Weather Forecasts database has been used in a number of internationally coordinated projects. They include the MJO vertical structure and physical processes modeling study (section 7), the "Transpose-AMIP" project (www.metoffice.gov.uk/hadobs/tamip) endorsed by WGNE and WGCM, and related efforts [e.g., *Boyle et al.*, 2006; *Xie et al.*, 2012] in which global climate models are run in weather forecast mode. Also, very high-resolution regional-scale simulations of tropical convection (i.e., the Cloud System Resolving Modeling of the Tropical

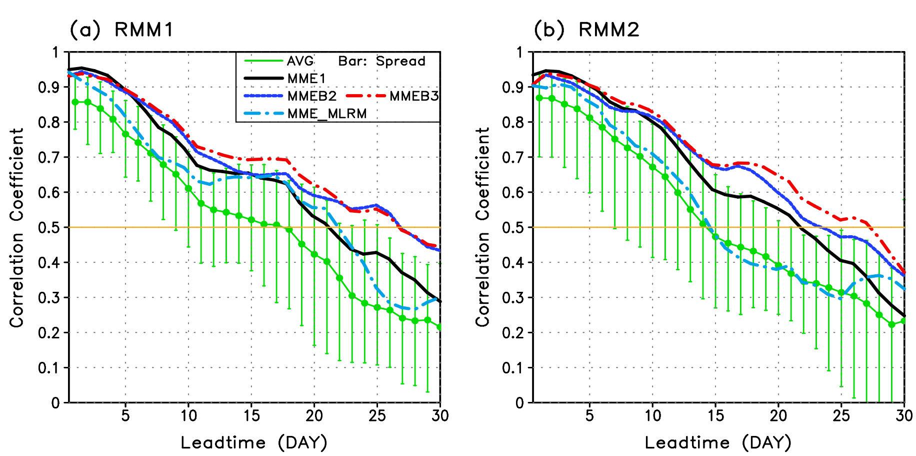

Figure 3. Hindcast skill of the MJO in ISVHE models. MME1 was made by simple composite with all models. MMEB2 represents the simple composite using the best two models. MMEB3 denotes simple composite using the best three models, and MME_MLRM denotes the MME with weighting.

Atmosphere project; *Holloway et al*., 2013) have been completed.

[21] In addition to the virtual atmospheric database, a satellite data set well suited to the study of clouds/convection, composed of A-Train sensors collocated to CloudSat footprints, has been developed for the YOTC period. Another development is the YOTC-Giovanni satellite data dissemination and analysis system. More information on all of the above is available on the YOTC website, www.ucar.edu/yotc.

6. CINDY/DYNAMO Field Campaign

[22] The CINDY/DYNAMO (CINDY2011 (*Cooperative Indian Ocean Experiment on Intraseasonal Variability in Year 2011*) is the international umbrella of the field campaign. DYNAMO (*Dynamics of the MJO*) represents the US participation in the field campaign, which included contributions from AMIE (*ARM MJO Investigation Experiment*) and LASP (*Littoral Air-Sea Process*)) field campaign was designed to collect in situ observations in the tropical Indian Ocean region to aid development of numerical models and advance understanding of the structure and statistics of convective clouds, their interaction with the large-scale environment, and air-sea interaction during MJO initiation. A brief summary is provided below (An overview is provided in K. Yoneyama, C. Zhang, and C. Long, Tracking pulses of the Madden-Julian Oscillation, submitted to *Bulletin of the American Meteorological Society*, 2013).

[23] The overarching goal of the CINDY/DYNAMO field campaign is to expedite our understanding of processes key to MJO initiation over the Indian Ocean and to improve simulation and prediction of the MJO. Three hypotheses on MJO initiation are being tested that involve the structure and evolution of cloud populations, their interaction with the large-scale environment, especially the low-level moist layer, and air-sea interaction. The field campaign took place in the tropical Indian Ocean and the surrounding regions during October 2011 to March 2012. Its main components included an atmospheric sounding network including two intensive sounding arrays, a multiple wavelength (W, Ka, C, and S bands) radar network, a ship/mooring network to measure air-sea fluxes, the marine atmospheric boundary layer, and upper-ocean large-scale and turbulent mixing structures, and aircraft operations to measure the atmospheric boundary layer, upper ocean, and troposphere over large-scale areas in between fixed atoll and ship sites.

[24] These observing platforms targeted processes deemed critical for MJO initiation but poorly observed and understood, including shallow cloud moistening, convective sensitivity to environmental moisture, low- versus upper-level diabatic heating, cloud microphysics, convective organization, large-scale moisture advection and convergence, surface evaporation, the ocean barrier layer, and upper-ocean mixing and entrainment. A better understanding of these processes is essential for improving their representation in numerical models and improving MJO simulation and prediction. The field campaign collected unprecedented data of the atmosphere, ocean, and their interface during multiple MJO events (A review of the MJO events during the field campaign is given in J. Gottschalck, P. Roundy, C. Schreck, A. Vintzileos, and C. Zhang, Large-Scale Atmospheric and Oceanic Conditions During the 2011–12 DYNAMO Field Campaign, submitted to *Monthly Weather Review*, 2013). One MJO event will be an additional case study for the MJO Vertical Structure and Physical Processes Project (section 7).

7. MJO Vertical Structure and Physical Processes Project

[25] A wide range of studies have suggested important roles for a number of various diabatic heating components in initiation and maintenance of the MJO, including shallow convective heating [*Zhang and Mu*, 2005; *Benedict and Randall*, 2009; *Li et al*., 2009; *Zhang and Song*, 2009], stratiform heating [*Fu and Wang*, 2009; *Seo and Wang*, 2010], and radiative heating [*Lee et al*., 2001; *Lin et al*., 2007]. A transition in the vertical heating structure during MJO evolution, namely, from shallow, to deep, and then to stratiform, results in a westward vertical tilt that has been found in observations [*Lin et al*., 2004; *Kiladis et al*., 2005; cf. *Katsumata et al*., 2009] and recent reanalysis data sets (ERA-Interim, CFS-R, MERRA, JRA-25) over both the eastern equatorial Indian Ocean and western Pacific [*Jiang et al*., 2011; *Ling and Zhang*, 2011]. Satellite-based estimates of latent heating profiles [*Tao et al*., 2006] also exhibit the vertical tilt in the MJO heating structure, although the magnitude and character of the tilt is not as consistent across products as those based on sounding and reanalysis data [*Morita et al*., 2006; *Jiang et al*., 2009; *Zhang et al*., 2010; *Jiang et al*., 2011; *Ling and Zhang*, 2011].

[26] Given the central role of diabatic heating and related processes (e.g., convection, clouds, boundary layer) in MJO physics, and the demands for reducing the model deficiencies in simulating the MJO, it is of great interest and an urgent need to examine vertical structures of diabatic heating and related processes of the MJO in current GCMs, compare them with observations, and explore how their structures and fidelity relate to models' MJO representation and forecast skill. With this in mind, the MJOTF (section 2) and GEWEX Atmospheric System Study (GASS) (GASS is a reorganized combination of the previous GEWEX Cloud System Study and GEWEX Atmospheric Boundary Layer Study (www.gewex.org)) have joined forces to develop a modeling experiment to help address the above objectives [*Petch et al*., 2011]. The MJOTF strengths in MJO diagnostic, simulation, and forecasting expertise, partnered with the GASS strengths in clouds and convection modeling and parameterization, has forged a unique expertise to make additional headway with the MJO.

[27] The overall experimental design (www.ucar.edu/yotc/mjodiab.html) takes advantage of the known links between biases in short-range forecasts and long-term climate simulations [*Boyle et al*., 2006] and evaluates these in the context of the MJO. It is composed of the following components:

I. Twenty-year climate simulations, with 6 h global output. They characterize the intrinsic capabilities of a model for representing MJO variability and for exploring multiscale interactions with the MJO (e.g., TCs, monsoon, ENSO). Simulations will be evaluated with metrics that broadly describe the model's performance in terms of the MJO (section 2) and the associated vertical heating and moistening structures.

II. Daily initialized 2 day hindcasts for two MJO events within the YOTC period during boreal winter 2009–2010 (see events and start dates in Figure 4). A principal focus of this component is to provide highly detailed and comprehensive (e.g., every time step) model output over a select near-equatorial Indian and Western Pacific Ocean domain (Figure 4) to investigate heat, moisture, and momentum budgets and the roles of various physical processes.

III. Hindcasts with lead-time up to 20 days for the same two MJO events in II but with a wider range of start dates to account for the full MJO cycle (Figure 4). Model analyses (3 hourly global output) will reveal model forecast performance and its evolution from observed (initial) conditions to the model's intrinsic mode(s) of variability.

[28] All three components include vertical structure information on all diabatic and momentum source and sink processes. Hindcast components II and III provide the framework for examining an MJO event from the CINDY/DYNAMO field program (section 5) that occurred in November–December 2011. Unlike previous GASS projects, the initial emphasis is not on process modeling per se but on the analysis of the global models to determine suitable follow-on process studies. These studies will likely be based on the well-observed CINDY/DYNAMO period, and will possibly inform the need for future field experiments and observing systems.

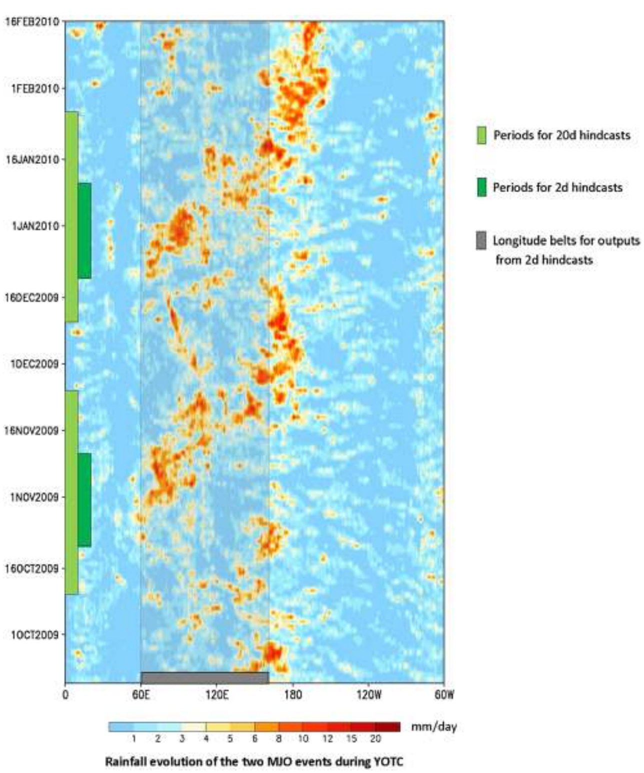

Figure 4. Time-longitude diagram (10°N–10°S) of TRMM 3B42 precipitation highlighting the two selected MJO events (YOTC events) for the MJOTF and GASS model hindcast experiments. Dark green and gray bars highlight periods of start days and the reduced longitude domain of the 2 day hindcast component (II) and light green bars indicate periods of the start days for the 20 day hindcast component (III).

8. Subseasonal to Seasonal Prediction Project

[29] The S2S project (http://www.wmo.int/pages/prog/arep/wwrp/new/documents/Implementation_plan_V6.4_nolinenos.pdf) is a joint research project of WWRP/THORPEX and WCRP, started in 2013 for an initial period of 5 years. Its main goals are to improve forecast skill and understanding of subseasonal to seasonal variability, and to promote its uptake by operational centers and exploitation by the applications community.

[30] The research priorities of the S2S project are to (i) evaluate the potential predictability of subseasonal events, with a special emphasis on the risk of high-impact extreme weather events; (ii) understand systematic errors and biases in the subseasonal to seasonal time range, and compare, verify and test multimodel combinations of subseasonal forecasts; (iii) set up demonstration projects; and (iv) set up a subseasonal database including operational forecasts a few weeks behind real-time.

[31] The establishment of an extensive database of subseasonal (up to 60 days) near real-time forecasts and reforecasts (hindcasts) will be modeled in part on the THORPEX Interactive Grand Global Ensemble database for medium-range forecasts (up to 15 days) and the Climate-System Historical Forecast project for seasonal forecasts. The database will also be open to reforecasts produced by high-resolution climate models to compare the subseasonal prediction skills in climate and Numerical Weather Prediction (NWP) models.

[32] An important aspect is to promote use of these forecasts and their uncertainty estimates by the applications community. The project will focus on some specific case studies, which will provide the basis to better quantify benefits through links with the WWRP Societal and Economic Research and Applications working group and relevant WCRP activities.

[33] The MJO will be a major focus of the S2S project. S2S activities related to the MJO will be coordinated with the MJOTF (section 2) and YOTC (section 4). The involvement of S2S in MJO research activities will have the following attributes:

(1) The S2S subseasonal database will be an excellent resource for the MJOTF to develop and apply monitoring and forecasting metrics for the MJO. It will also be useful for testing multimodel MJO ensemble forecasts.
(2) S2S will have an interest in model biases and errors associated with forecast of the MJO and related ISV. For instance, the difficulty of the MJO to cross the Maritime Continent in models, known as the MJO "Maritime Continent Prediction Barrier" problem [*Vitart et al.*, 2007; *Weaver et al.*, 2011; *Fu et al.*, 2011], will be investigated.
(3) The S2S database will also be an excellent resource for evaluating the ability of operational subseasonal forecasting models to simulate and predict teleconnections associated with the MJO. This would include investigating the ability of models to simulate the impact of the MJO on high-latitude weather regimes, especially the North Atlantic Oscillation, and on tropical cyclones.
(4) Keen interest exists in exploring the utility of MJO and ISV forecasts to application and decision support areas. Numerous studies have highlighted the modulation by the MJO/ISV of a number of quantities closely related

to application and decision support. The S2S database and demonstration cases will be helpful in determining the utility of the MJO forecasts for applications such as ocean chlorophyll, river discharge, flood, aerosol, ozone, and snowpack [e.g., *Tian and Walliser*, 2011].

(5) S2S will have an interest in connecting subseasonal and seasonal predictability, for instance the MJO-ENSO covariability that may lead to high (more useful) levels of skill.

9. Concluding Remarks

[34] Cracking the hard nut of the MJO needs persistent and coordinated efforts of observations, modeling, diagnostics, and forecasts, some of which are already in place. Their motivations, objectives, designs, preliminary results, and connection to each other were briefly described in this article. With these efforts in progress simultaneously, the MJO research and prediction communities, particularly with the contributions from a new generation of talent, are poised to make unprecedented advancement in our understanding of fundamental MJO dynamics and physical processes, its global impact, its predictability, and in improvement of our ability to predict the MJO. Through the multitude of interactions of the MJO and various weather, climate, and environmental components of the Earth system, better MJO predictions will provide valuable information for hazard response, resource managers and other decision makers.

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