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Leveraging the MJO for Predicting Envelopes of Tropical Wave and Synoptic Activity at Multi-Week Lead Times

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1. LONG-TERM GOALS

The Madden-Julian Oscillation (MJO) is the dominant mode of tropical variability on the intraseasonal time scale, and it extensively interacts with other components of the climate and weather systems. In this project, we will focus on its interactions with the major modes of the tropical variability on the synoptic time scale - the convectively coupled equtorial waves (CCEWs), which include Kelvin, equatorial Rossby (ER), mixed Rossby-gravity (MRG), eastward and westward Inertio-gravity (EIG and WIG) waves. The long-term goals are to explore the possible relationships between the MJO and the CCEWs, the physical mechanisms behind these relationships, and the predictability and prediction skill of the envelopes of the CCEWs in accociation with the MJO, thus contributing to forming a seamless bridge between weather and climate prediction.

2. OBJECTIVES

The main objectives of this project are listed below.

A. Explore and characterize the observed relationships between the MJO and organized synoptic variability in the tropics, including lead-lag relationships and implied predictability as well as characterizing the physical mechanisms behind these relationships.

B. Utilize two state-of-the-art multi-model experimental archives[1] to assess the capabilities of present-day forecast models and GCMs to simulate and forecast the MJO, tropical synoptic variability, and the relationships between them.

C. Conduct more comprehensive analysis on the NOAA/GFDL HiRAM (climate) and NAVGEM (weather forecast) GCMs to more fully characterize these models' fidelity in simulating and forecasting MJO – synoptic variability relationships and their depiction of the intrinsic predictability of tropical transient wave activity on intraseasonal time scales.

[1] *1) MJO Task Force & GEWEX GASS MJO Diabatic Heating Experiment, 2) Intraseasonal Variability Hindcast Experiment (ISVHE)*

Our focus to date has been on objectives A and B. For objective C, we note that NAVGEM is included in our analyses associated with objective B and the analysis of HiRAM is being supported through other NOAA-related funding PI'd by X.Jiang.

3. APPROACH

In order to achieve the goals listed above, we are analyzing various datasets including satellite observations such as the TRMM rainfall, reanalysis datasets such as the ERA-Interim reanalysis, and two state-of-the-art multi-model experiment archives, one of which includes NAVGEM. We have compare the results based on the observations with the model simulations to quantify current generation model performance in capturing the observed relationships between the MJO and the tropical synoptic variability. The project has been led by D. Waliser and X. Jiang with project postdoc Y.Guo carryong out much of the analysis, synthesis and writing.

4. WORK COMPLETED

Since the start of the project, we have acquired the substantial observational and modeling data needed to carry out this project, including satellite observations (e.g., TRMM3B42 rainfall), reanalysis datasets (e.g., various ERA-Interim variables), and precipitation and other model variables from 20-year simulations with 6-hourly output from 26 GCM simulations that contributed to the MJO Task Force & GEWEX GASS MJO multi-model MJO physics experiment. We are continuing retrieving data needed for research in Year 3, such as various dynamic and thermodynamic variables at significant pressure levels from those GCM simulations.

1. We have conducted analysis on the observed relationship between the MJO and the CCEWs, focusing on the modulation of the Kelvin wave activity by the MJO over the South America and tropical Atlantic region. The major results have been summarized in a journal paper, which appeared in the Journal of the Atmospheric Sciences (Guo, Jiang and Waliser, 2014).

2. We have further explored the relationships between the MJO and the CCEWs using both observations and 26 GCM simulations, and found that a model's ability to simulate realistic MJO is strongly linked to its ability to capture the realistic climatology of the CCEWs as well as their interactions with the MJO. These results have been written up to a journal paper, which has been submitted to the Journal of Climate (Guo, Waliser and Jiang, 2014, under minor revision).

3. In addition, we have utilized the two model archives to do foundational work on MJO model evaluation (Jiang et al. 2014) and MJO/ISV prediction/predictability studies (Mani et al. 2014a,b). The results of these are discussed in Section 7 as they are also partially supported by other synergistic awards/sponsors.

Item 1 was completed in Year 1 and so the results reported in Section 4 and 7 mainly focus on items 2 and 3.

4. RESULTS

Our research activity during Year 2 focuses on examining the possible systematic relationships between the MJO and the CCEW activity based on the TRMM rainfall and simulated precipitation by 26 GCM simulations participating in the MJO Task Force & GEWEX GASS MJO intercomparison

project. Important results are highlighted below and a summary schematic of the findings is shown in Figure. 3.

First, the convective anomalies of each CCEW mode were isolated by filtering the precipitation data according to specific spectra of the wavenumber-frequency domain that corresponds to that particular wave mode. The time period for filtering is 14 years (1998-2012) for the TRMM and 20 years (1991-2010) for the GCM simulations. The anomalies of intraseasonal variability (ISV) were also obtained by applying a 20-100-day temporal filtering to the precipitation.

Then, an MJO score was determined for each of the GCMs following below approach: firstly, the equatorially averaged (10°S-10°N) ISV anomalies from 50°-180°E based on the TRMM observation were lag-regressed against an Indian Ocean ISV index from lag day -20 to day 20 such that the large-scale, eastward propagation of the ISV, which is the key characteristics of the MJO, was revealed. The same lag-longitude regression was applied to a GCM simulation, and the resulting pattern was correlated to that based on the TRMM to assess how well the GCM result resembled the observation. The correlated coefficient is therefore designated as the MJO score for that mode: "1" for perfect MJO model, while "0" for model with no MJO skill at all.

The possible linkages between a model's ability to simulate the MJO and how well they simulate the CCEWs are examined from two perspectives: one focuses on the climatological behavior of the CCEW activity, and the other focuses on the variation of the CCEW activity in association with the MJO, or in other words, the multiscale interactions between the MJO and the CCEWs.

i) Climatology of the CCEW activity

A quantity to represent the climatological CCEW activity was obtained by averaging the CCEW variances over the Indo-Pacific warm pool region (50º -180 ºE, 15ºS-15ºN) in which the MJO is most active. This was done for each CCEW mode and each GCM. It is found that the magnitudes of CCEW variances for a GCM are highly dependent on the magnitude of the variance of the "total" mode in that model. Here, the "total" mode corresponds to the anomalous precipitation that retains all time-scale variabilities except the annual cycle. Because the magnitudes of the "total" variances vary largely from model to model, we further calculated the so-called fractional variances of the CCEWs, which are the absolute CCEW variances relative to the "total" variance, to eliminate the impact of model-to-model difference in the background variance.

The examination of the fractional CCEW variances and the models' MJO scores revealed that better MJO models tend to simulate larger Kelvin, MRG, WIG, and EIG fractional variances (Fig. 1b-e), and smaller fractional variances for the low-frequency variability indicated by the ">100d" mode (Fig. 1g). Note that the Kelvin, MRG, WIG and EIG waves reside in the high-frequency end of the precipitation spectrum. Previous studies have discovered a longstanding problem in GCMs' simulating tropical convection: they generally simulated inadequate variances for the high-frequency variabilities, the CCEWs here, and at the same time accumulated too much low-frequency variability. Thus, our results that better MJO models tend to have larger/smaller variances for the high-frequency/low-frequency modes correspond to the alleviation of the above longstanding problem in simulating the tropical convection, which likely contributes to the improved MJO simulation.

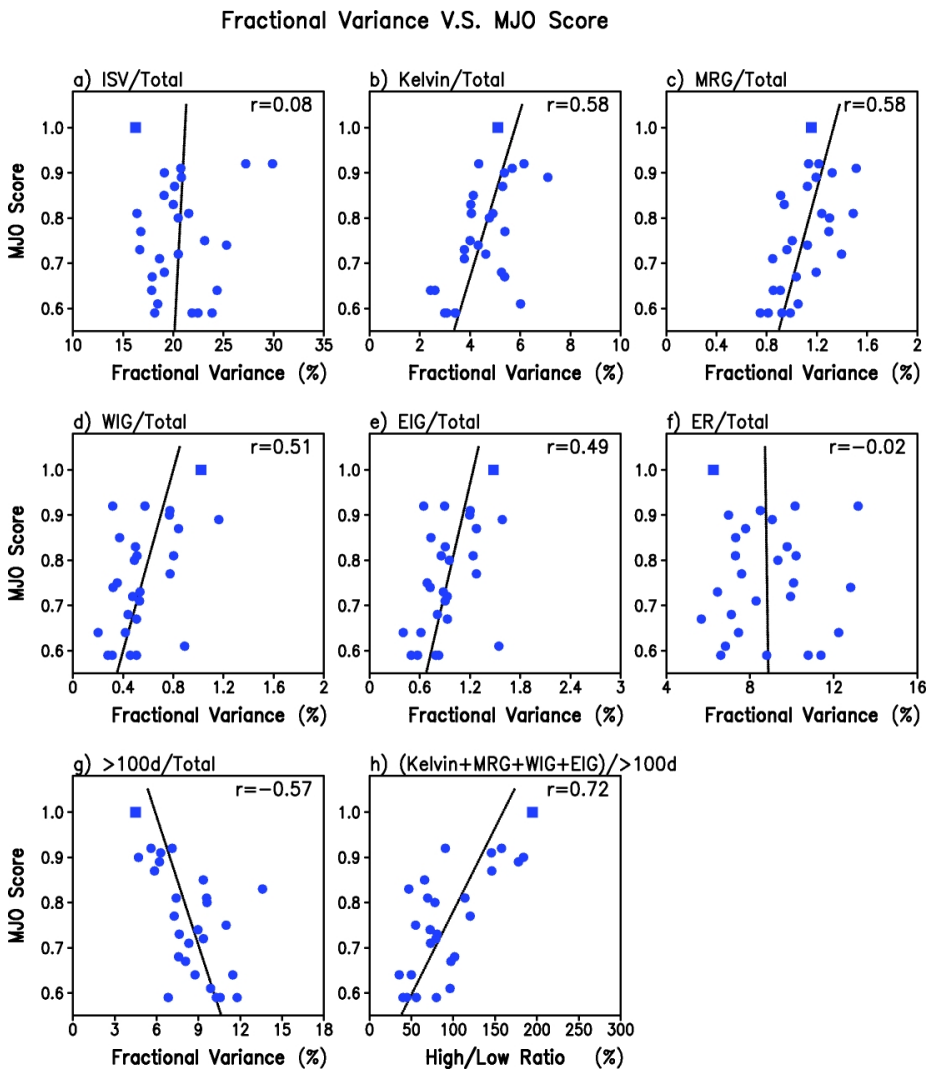

Figure 1: Scatter plots of the MJO score and the fraction of (a) ISV, (b) Kelvin, (c) MRG, (d) WIG, (e) EIG, (f) ER, (g) low-frequency (period >100 day) mode variance relative to the "total" variance, and (h) summed Kelvin, MRG, WIG, and EIG variances relative to the low frequency mode variance. Closed circles represent individual GCM simulations, while closed square represents the TRMM observation. The correlation coefficient of each scatter plot is indicated by the number at the right upper corner of the panel.

ii) Multi-scale interactions between the MJO and CCEWs

The multi-scale interactions between the MJO and the CCEWs have been examined using the lag regression analysis in which the time series of the squared CCEW anomalies during the entire period were regressed onto the Indian Ocean ISV index, and larger regression coefficients suggest stronger interactions between the MJO and the CCEWs. The strength of the multi-scale interaction is thus quantified by averaging the regression coefficients over a region (75º-85ºE and 5ºS-5ºN) around the ISV index at lag day 0. Comparing the strength of the multi-scale interaction and the MJO performance across the GCMs, we found that better MJO models tend to have stronger and more coherent interactions between the MJO and the Kelvin, MRG, WIG and EIG waves, which is likely another reason why these models simulate better MJO (Fig. 2).

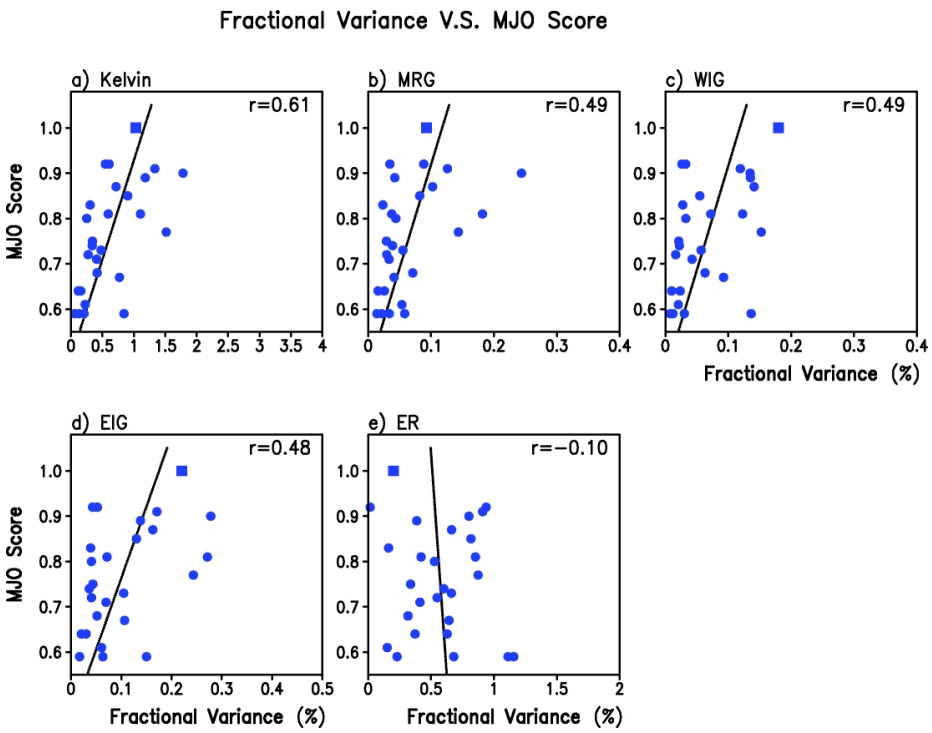

Figure 2. Scatter plots of the MJO score and the ISV associated variances of (a) Kelvin, (b) MRG, (c) WIG, (d) EIG, and (f) ER wave modes. Here, the values of the ISV associated CCEW variances are computed by averaging the CCEW variances in the concurrent regression maps over 75°E-85°E and 5°S-5°N. For example, values of the Kelvin case come from the averages of the Kelvin variances in Fig. 6 over the averaging domain. Closed circles represent individual GCM simulation, while closed square represents the TRMM observation. The correlation coefficient of each scatter plot is indicated by the number at the right upper corner of the panel.

The major results from the above two perspectives were summarized in the schematic plots in Fig. 3. In the "good" MJO group, the high-frequency CCEWs, or synoptic waves, (i.e., Kelvin, MRG, WIG and EIG) are more realistically simulated, and this is illustrated as a stronger climatological variance (in terms of fraction to the "total" anomalies). In addition, the CCEWs in these models exhibit better coherence with the MJO, illustrated as enhanced CCEW activity within the active MJO convection envelope in contrast to the less coincidence between the CCEW enhancement and the MJO envelope in the "bad" MJO group.

The finding that better MJO models tend to simulate stronger climatological wave variances (in terms of fraction of the "total" variance) corresponds to the alleviation of longstanding problem in simulating tropical precipitation in climate models, i.e., too weak (strong) variance in the high-frequency (low-frequency) spectrum of the precipitation. The finding that better MJO models tend to show better coherence and stronger interactions between the synoptic waves and the MJO is also reasonable since the multi-scale interactions have been thought to play critical roles in the existence and propagation of the MJO. It is likely that these two conditions have some bearing on the improved MJO performance that has been achieved in the good MJO models.

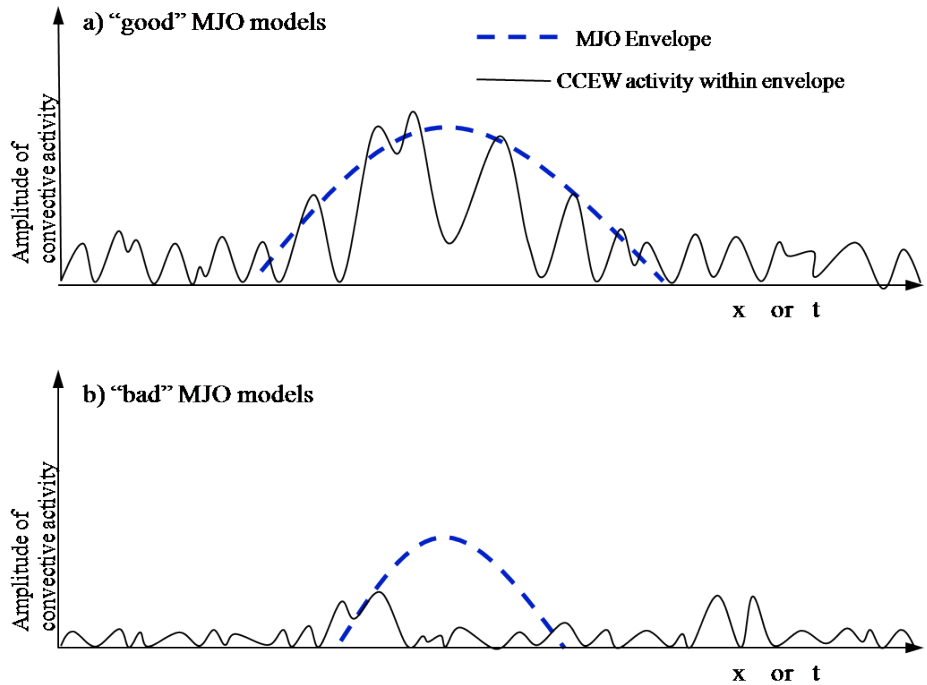

Figure 3. Schematic illustration of the* multi-scale *structure of the MJO and the embedded higher-frequency CCEWs (i.e. namely Kelvin, MRG, WIG and EIG) simulated in the (a) "good" and (b) "bad" MJO models.

5. IMPACT/APPLICATIONS

The MJO can be regarded as the slowly eastward propagating, planetary-scale convective envelope of embedded CCEW waves, and two-way interactions between them have been observed. Therefore, a climate model's faithful representation of CCEWs as well as their interactions with the MJO is hypothesized to be strongly linked to the model's ability to simulate the MJO. However, such efforts on examining the relationships between the representation of the CCEWs and the representation of the MJO in the GCMs have rarely been made. In this sense, our research is novel as it proves that there does exist systematic relationships between the simulation of the MJO and the simulation of CCEWs based on a diverse set of 26 independent GCMs, and suggests that improved representation of one is likely accompanied by (or due to) better representation of the other in the climate models, thus providing valuable insights to the climate dynamics and modeling communities.

Furthermore, given the symbiotic relation between the MJO and the CCEWs, as well as the synoptic feature of the CCEWs, our results suggest that improved prediction skill from the intraseasonal to the synoptic time scales might be achieved at the same time as the consequence of better representations of the CCEWs as well as their interactions with the MJO, thus contributing to bridging the prediction between weather and subseasonal time scales.

6. RELATED PROJECTS

Two very closely related efforts are worth mentioning, each involving one of the community modeling activitites mentioned in Section 2, Objective B and highlitghted in the proposal. Each of these studies

has benefited from the study and discussions associated with the above results and vice versa. This occurs through the joint supervision of these projects by Dr. Waliser and Dr. Jiang and through weekly group meetings where these topics are jointly discussed.

The first is analysis already being carried out on the ISV Hindcast Experiment (ISVHE). Under the guidance of co-PIs Waliser and Jiang, and consultations with Dr. Guo, our colleague/postdoc Dr. Neena Mani has carried out a predictability study on the MJO using ISVHE. Figure 4 highlights a summary of the results, illustraing a comparison between MJO model hindcast skill (model compared to obervations) for single hindcast members (black bars), the improvement when using the model ensemble (hatched), then the estimate of predictability (twin idealized predictions, i.e. model compared to model) for single members (tan bars), and the predictability when using the ensemble compared to a member (gray bars). This illustrates that for the most part there is significant room for improvement in our forecast models of the MJO. The results of this study are published in Mani et al (2014a). A pararllel study has been performed for the eastern Pacific ISV, known to influence TC variability in this region as well asa the local monsoon variabilityuy, and these results are publsihed in Mani et al. (2014b).

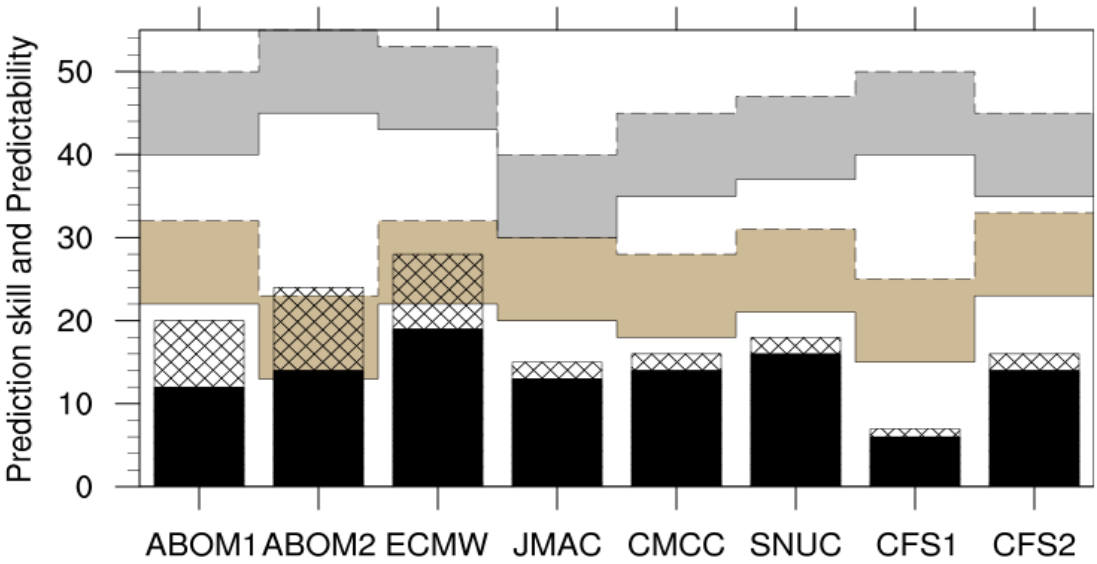

Figure 4: Average prediction skill (black bar) and ensemble mean prediction skill (hatched bar) estimates for MJO for the eight models are shown along with the respective, deterministic (wheat shaded area) and ensemble (grey shaded area) estimates of MJO predictability (+/-5 range).

The second is the initial analyses being carried out on the MJO TF and GEWEX GASS MJO Diabatic Heating Experiment – or more generally the Multi-model Physics Experiment. This work is being led by Dr. Waliser and Dr. Jiang, with the analysis being mainly carried out by Dr. Jiang. Figure 5 highlights a summary of the multi-model comparison of the MJO, which is just one comparison and analysis in a wide spectrum of analyses that includes analyses of 2-day and 20-day hindcasts, and 20 year simulations. The results of this study have been submitted (Jian et al. 2014) with two others studies (led by UKMO, U. Reading), the three of which form the initial foundational results from this international community activity. Note NRL provided NAVGEM simulations for this activity.

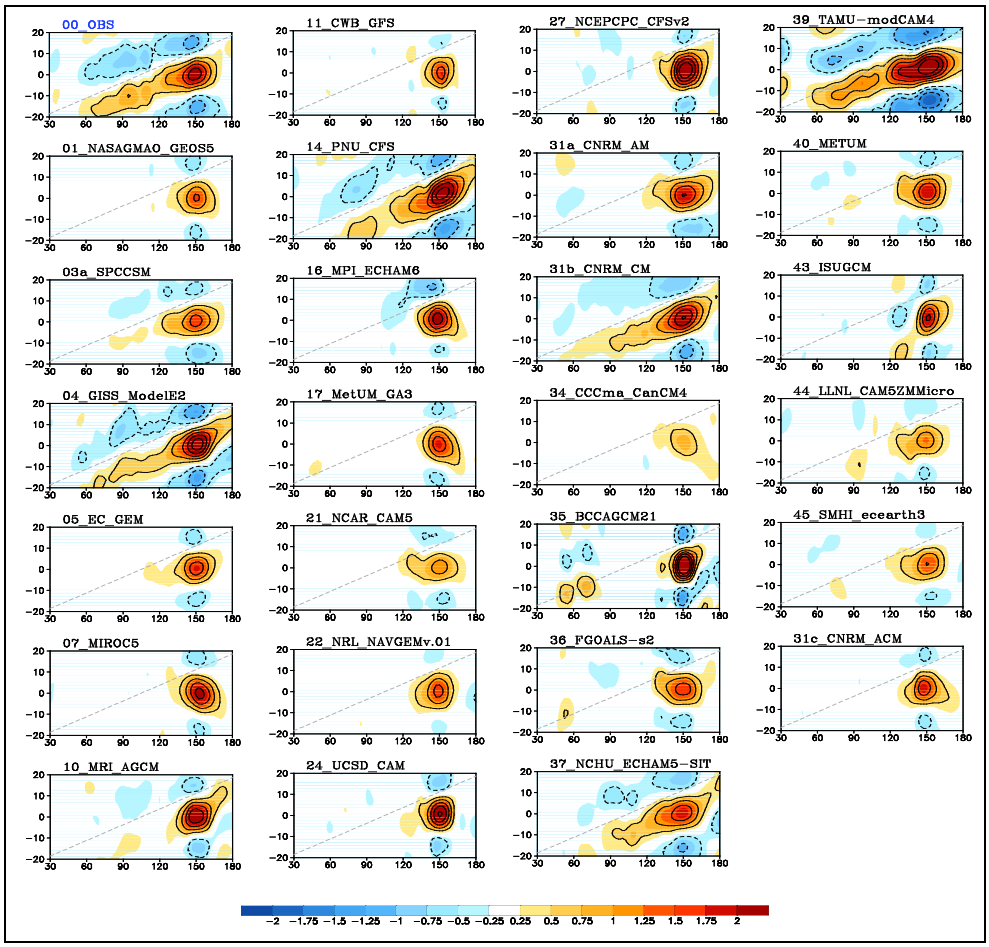

Figure 5 : Time-lag precipitation diagrams using a base point in the western Pacific on the equator and 150E for 20-year simulations for the models that contributed 20-year simulations to the MJO TF – GEWEX GASS multi-model MJO physics comparison project.

7. PUBLICATIONS

Guo, Y, D. E. Waliser, and X. Jiang, 2014: A Systematic Relationship between Convectively Coupled Equatorial Wave Activity and the Performance of the Madden-Julian Oscillation in Climate Model Simulations. J. Clim., under revision.

Guo, Y, X. Jiang, and D. E. Waliser, 2014: Modulation of the Convectively Coupled Kelvin Waves over South America and the Tropical Atlantic Ocean in Association with the Madden-Julian Oscillation. J. Atmos. Sci., 71, 1371–1388. doi: http://dx.doi.org/10.1175/JAS-D-13-0215.1

Jiang, X., Waliser, D. E. and 30 more authors, 2014: Exploring Key Processes of the Madden-Julian Oscillation (MJO): A Joint WGNE MJO Task Force / GEWEX GASS Project on the Vertical Structure and Diabatic Processes of the MJO - Part I. Climate Simulations, JGR, submitted.

This is part of a 3-paper set - with the other two led by our UKMO and U. Reading colleagues.

Mani, N. J., J. Y. Lee, D.E. Waliser, B. Wang, and X. Jiang, 2014a: Predictability of the Madden-Julian Oscillation in the Intraseasonal Variability Hindcast Experiment (ISVHE). J. Clim., 10.1175/JCLI-D-13-00624.1

Mani, N. J., X. Jiang, D.E. Waliser, J. Y. Lee, and B. Wang, 2014b: Eastern Pacific Intraseasonal Variability: A predictability perspective. J. Clim., in press.