Process-oriented Diagnosis and Metrics Development for the Madden-Julian Oscillation Based on Climate Simulations

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Final Report

1. Results and accomplishments:

The following summarizes main results from research teams of both PI (Jiang) and co-PIs (Maloney, Zhao) during the three years of this project.

1. *Process diagnoses on key physics for eastward propagation of the MJO based on multi-model simulations (Jiang, Gonzalez, UCLA)*

Key model processes responsible for realistic simulations of MJO eastward propagation were examined based on moist static energy (MSE) budget analyses by analyzing over 20 climate models participated in the MJO Task Force (MJOTF)/GEWEX GASS MJO model comparison project. Findings from this analysis lead to development of a new metric to represent eastward propagation of the MJO in climate models.

Budget analyses of MSE terms associated with MJO convection suggest that horizontal advection of MSE plays a critical role for eastward propagation of the MJO by contributing a positive (negative) MSE tendency to the east (west) of the MJO center. Further analysis indicates that this anomalous horizontal MSE advection pattern is largely due to advection of the seasonal mean MSE pattern by anomalous MJO circulation. In models that poorly capture eastward propagation of the MJO, the positive (negative) MSE anomalies by horizontal MSE advection to the east (west) of MJO convection are largely underestimated due to model biases in both mean horizontal MSE gradient over the Indo-Pacific region and anomalous circulation corresponding to the MJO convection. Total MSE tendency in these poor MJO models is dominated by surface fluxes and radiative effects, leaving stationary or even westward propagation of MJO convection. A manuscript on these analyses was published in JGR-Atmosphere (Jiang 2017).

Motivated by key funding based on the MSE budget analysis that a realistic mean MSE pattern could be critical for horizontal MSE advection, thus the eastward propagation of the MJO, also considering that vertically integrated MSE is largely dominated by the lower-tropospheric specific humidity in the Indo-Pacific warm pool, we further examined how model skill in simulating winter mean 900-650hPa specific humidity is related to model skill for the MJO eastward propagation. It is illustrated that model skill for the MJO eastward propagation is highly correlated to model fidelity in representing the mean low-tropospheric moisture over the Maritime Continent region, further supporting above-mentioned MSE budget analysis results. Based on this finding, the seasonal mean lower-tropospheric moisture (900-650hPa) could serve as an excellent metric to evaluate climate model performance in capturing the eastward propagation of the MJO. This analysis also provides an important guidance for model improvement for MJO simulations. A manuscript on this part is published in GRL (Gonzalez and Jiang 2017).

2. *Exploring key model processes in regulating the MJO amplitude in climate models (X. Jiang, UCLA)*

In addition to the eastward propagation of the MJO, another key question for the MJO research community is what controls MJO amplitude in climate models, since model MJO amplitude is largely underestimated in many present-day climate models. For this purpose, several feedback processes previously considered to be important for the MJO instability, including the gross moist stability, surface wind-evaporation, and radiative feedback are examined by analyzing the MJOTF/GASS multi-model output.

While our results tend to support previous studies that reduced export of column moist energy by circulation associated with a unit MJO precipitation could lead to stronger model MJO amplitude, it is shown that reduced energy sources, including surface fluxes and radiative heating, are evident in models with strong MJO amplitude, which is at odd with previous MJO theories in interpreting instability of the MJO. Further analyses suggest that model MJO amplitude across multi-model simulations are highly correlated to a convective adjustment time scale in the model, defined by perturbation column moisture corresponding to unit perturbation precipitation. The different convective adjustment time scales in climate models are further attributed to model differences in precipitation-water relationship as observed in Bretherton et al (2004) and amplitude of reference precipitation. It is further demonstrated that corresponding to unit intraseasonal precipitation, weaker and more bottom-heavy vertical velocity or diabatic heating, associated with a smaller organization of convective clouds, are evident in GCMs with shorter convective time scale, which is largely consistent with anti-correlation relationship between MJO amplitude and gross moist stability and energy source terms. The evidence on a strong relationship between the MJO amplitude and model convective time scale as shown in this study provides a critical understanding of MJO physics and important guidance for climate model development. A manuscript on this study is published in GRL (Jiang et al. 2016).

3. *A unified moisture mode framework for seasonality of the Madden–Julian Oscillation (Jiang, UCLA; Zhao, GFDL; Maloney, CSU)*

This study is an important extension of the work mentioned in 1) on the critical role of winter mean moisture pattern on the eastward propagation of the Madden-Julian Oscillation (MJO) during boreal winter (Jiang 2017; Gonzalez and Jiang 2017). As we know, the MJO exhibits pronounced seasonality, i.e., while it is largely characterized by equatorially eastward propagation during the boreal winter, MJO convection undergoes marked poleward movement over the Asian monsoon region during summer, producing a significant modulation of monsoon rainfall. In classical MJO theories that seek to interpret the distinct seasonality in MJO propagation features, the role of equatorial wave dynamics has been emphasized for its eastward propagation, whereas coupling between MJO convection and the mean monsoon flow is considered essential for its northward propagation. In this study, a unified physical framework based on the moisture mode theory, is offered to explain the seasonality in MJO propagation. Moistening and drying caused by horizontal advection of the lower-tropospheric mean moisture by MJO winds, which was recently found to be critical for the eastward propagation of the winter MJO, is also shown to play a dominant role in operating the northward propagation of the summer MJO. The seasonal variations in the mean moisture pattern largely shape the distinct MJO propagation in different seasons. The critical role of the seasonally varying climatological distribution of moisture for the MJO propagation is further supported by the close association between model skill in representing the MJO propagation and skill at producing the lower-tropospheric mean moisture pattern. This study thus pinpoints an important direction for climate model development for improved MJO representation during all seasons. A paper on this study has been published in the *J. Climate* special collection on development of process-oriented metrics (Jiang et al. 2018a).

4. *Development of Python/NCL codes on process-oriented diagnostic metrics for evaluation of MJO simulations in climate models, and contribution to the MDTF BAMS paper (Jiang, Gonzalez, UCLA; Maloney, CSU; Zhao, GFDL)*

During the 3rd year of this project, significant efforts have been taken on the development of Python / NCL codes for the process-oriented diagnostic metrics for evaluation of MJO simulations in climate models, built up the above mentioned findings based on multi-model analyses, i.e., 1) the seasonal mean moisture pattern plays a critical role in defining the MJO propagation (Jiang 2017; Gonzalez and Jiang 2017; Jiang et al. 2018); 2) model MJO amplitude is highly related to the model convective time scale (Jiang et al. 2016). These metric codes are finalized, and will be integrated into the open-source software package, coordinated by the MAPP's Model Diagnostic Task Force (MDTF), and be installed in modeling centers for model evaluation and diagnostic purposes.

Our project team also significantly contributed to the BAMS article in summarizing the collective efforts led by the MAPP's MDTF in developing a variety of process-oriented metrics for climate model evaluation purposes. Particularly, the co-PI (Maloney) served as co-chair of the MDTF and is the leading author of the BAMS overview article (The NOAA MDTF 2018).

5. *Identification of a westward propagating intraseasonal variability mode over the tropical western Pacific (Gonzalez and Jiang, UCLA)*

The tropical intraseasonal variability, with the Madden-Julian oscillation (MJO) as its most prominent form, exerts extensive influences on global weather extremes. In this study, in addition to the eastward propagating MJO, we present a westward propagating intraseasonal mode (WPIM) during boreal winter as a second prevailing intraseasonal mode over the tropical western Pacific (WP). Initiated over the central Pacific, the WPIM experiences slow westward propagation (3-5 m s^{-1}) near the equator with a period of about 36 days and a spatial scale of wavenumber 3-4. A strong anti-correlation is found between activity of the MJO and WPIM over the WP. A budget analysis of the moist static energy (MSE) suggests that differences in the horizontal MSE advection associated with the MJO and WPIM largely defines their distinct propagation behaviors. For the MJO, its eastward propagation is primarily driven by moistening (drying) to the east (west) of convection due to horizontal advection of background MSE by anomalous MJO circulation. While for the WPIM mode, the horizontal MSE advection by easterly mean wind advection of the intraseasonal MSE anomalies, generates moistening (drying) to the west (east) of convection, thus drives its westward propagation along with contributions by radiative effects and surface fluxes. Consistent with the MSE analysis, the WPIM (MJO) is found to be favored (suppressed) when the equatorial low-level mean easterlies between 140^{o}E-150^{o}W are enhanced, and equatorial mean moisture is reduced near the Dateline while enhanced over the off-equatorial WP between 120-160^{o}E. A manuscript on this analysis has been submitted to *JGR Atmos* (Gonzalez and Jiang 2018).

6. *Online diagnostics of moist static energy budget and an application to model simulated Madden-Julian Oscillation (Zhao, GFDL; Jiang, UCLA, et. al)*

Moist static energy (MSE) budget has long been proposed useful for understanding the modeled and observed tropical precipitation climatology and variability. Despite this notion, it has been proved challenging to fully close the MSE budget in both models and reanalysis data and this has adversely affected our understanding of the processes, especially for studies of the MJO in which a steady state cannot be assumed and accurate retrieval of the MSE budget may be most demanded. Here we demonstrate an online procedure to fully close the MSE budget and discuss issues related to this diagnostics. Furthermore, we provide an analysis of the MSE budget associated with the MJO simulated by the Geophysical Fluid Dynamics Laboratory (GFDL) new generation GCM which well reproduces many aspects of the observed MJO characteristics including its strength and eastward propagation phase speed. We illustrate the cooperated key processes leading to the charge and discharge of column integrated MSE as well as their vertical distributions, which are important to the simulated MJO life-cycle and eastward propagation. The horizontal and vertical advection plays a leading role in the initiation and eastward propagation of MJO while the longwave (LW) cloud radiative effect (CRE) plays a primary role in MJO magnitude in this model. A manuscript (Zhao et al. 2018) on this study is to be submitted shortly.

7. *New weak temperature gradient diagnostics for the MJO applied to models (Maloney, Wolding, CSU)*

The collective effects of convection can influence large-scale circulations that, in turn, act to organize convective activity. Such scale interactions may play an important role in moisture-convection feedbacks thought to be important to both convective aggregation and the Madden-Julian Oscillation, yet such interactions are not fully understood. New diagnostics based on tropical weak temperature gradient (WTG) theory have begun to make this problem more tractable, and are leveraged in this study to analyze the relationship between various apparent heating processes and large-scale vertical moisture advection in SP-CESM. WTG theory provides a framework for accurately diagnosing intraseasonal variations in large-scale vertical motion from apparent heating, allowing large-scale vertical moisture advection to be decomposed into contributions from microphysical processes, subgrid scale eddy fluxes, and radiative heating. This approach is consistent with the column moist static energy (MSE) budget approach, and has the added benefit of allowing the vertical advection term of the column MSE budget to be quantitatively partitioned into contributions from the aforementioned apparent heating processes. This decomposition is used to show that the MJO is an instability strongly supported by radiative feedbacks and damped by horizontal advection, consistent with the findings of previous studies. Periods of low, moderate, and high MJO amplitude are compared, and it is shown that changes in the vertical structure of apparent heating do not play a dominant role in limiting the amplitude of the MJO in SP-CESM. Finally, a diagnostic approach to scale analysis of tropical dynamics is used to investigate how the governing dynamics of various phenomena differ throughout wavenumber-frequency space. Findings support previous studies that suggest the governing dynamics of the MJO differ from those of strongly divergent convectively coupled equatorial waves. A paper describing these results has been published in *JAMES* (Wolding et al. 2016).

8. *Characterizing convection-radiation feedback based on DYNAMO field Observations (Johnson, Ciesielski, CSU; Jiang, UCLA)*

The relationships between radiation, clouds, and convection on an intraseasonal time scale are examined with data taken during the Dynamics of the MJO (DYNAMO) field campaign. Specifically, column-net, as well as vertical profiles of radiative heating rates, computed over Gan Island in the central Indian Ocean (IO) are used to examine three MJO events that occurred during the 3-month period (October to December 2011) over this region. Longwave and shortwave radiative heating rates exhibit tilted structures, with increasingly top-heavy anomalous radiative heating rates going into the MJO active phase. The intraseasonal variation of column-net radiative heating <Qr> enhances the convective signal in the mean by ~20% with a minimum in this enhancement ~10 days prior to peak MJO rainfall and maximum ~7 days after. This suggests that as MJO convective envelope weakens over the central IO, cloud-radiative feedbacks help maintain the mature MJO as it moves eastward. This work has been published in *JGR Atmosphere* (Ciesielski et al. 2017), and featured as a research spotlight article by the EOS Magazine (https://eos.org/research-spotlights/what-makes-the-biggest-cycle-in-tropical-weather-tick).

9. *A review article on "Progress and Status of MJO Simulation in Climate Models and Process-Oriented Diagnostics"(Jiang UCLA; Maloney, CSU)*

Supported by this project, the PI (Jiang) also led an invited article for a special collection of the Sixth International Workshop on Monsoons (IWM-6) held in Singapore, 13-17 November, 2017, on the progress and status of MJO simulation in climate models and process-oriented diagnostics (Jiang et al. 2017). In the first part of this review article, a brief overview of recent advances in modeling the MJO is provided by particularly highlighting improved MJO simulations achieved through implementations of stochastic cumulus approaches. In the second part, the most recent community efforts in the development of process-oriented diagnostics and metrics for MJO simulations are briefly reviewed. These diagnostics and metrics built upon process understanding of key MJO physics, providing important guidance to expose critical model deficiencies in simulating the MJO. These processes include convective sensitivity to environment moisture, convection-circulation interactions, cloud-radiation feedbacks, and large-scale control (e.g., the lower-tropospheric mean moisture pattern).

10. *Dynamics-oriented diagnostics for the Madden-Julian Oscillation (B. Wang, UH; Maloney, CSU; Jiang, UCLA; et al.)*

Realistic simulations of the Madden-Julian Oscillation (MJO) by current global climate models (GCMs) remain a great challenge. To evaluate GCM simulations of the MJO and identify models' shortcomings, the U.S. Climate Variability and Predictability (CLIVAR) MJO Working Group developed a standardized set of diagnostics, providing a comprehensive assessment of statistical properties of the simulated MJO. In this study, we develop a suite of complementary diagnostics that provide discrimination and assessment of MJO simulations based on the perception that the MJO has characteristic dynamic and thermodynamic structures that are intimately related to its propagation. The new diagnostics focus on large-scale dynamics and observed MJO structures, and help to evaluate whether a model produces eastward propagating MJO for the right reasons. The new dynamics-oriented diagnostics include (1) the preluding propagation of the boundary layer moisture convergence that leads precipitation propagation by about 5 days; (2) the low-level horizontal circulation structure that is intrinsically linked to MJO propagation; (3) the vertical-longitudinal distribution of diabatic heating that reflects the multi-cloud structure of the MJO convective complex and a transition from shallow cumulus-congestus clouds to deep convective-stratiform clouds; (4) the vertical structure of the equivalent potential temperature that reveals the pre-moistening and pre-destabilization processes; (5) the upper-level divergence that is a good indicator of propagation; and (6) the generation of MJO available potential energy that reflects the amplification and propagation of MJO. Objective metrics for each diagnostic quantity are applied to a suite of GCM simulations to quantitatively evaluate the GCMs' capabilities in reproducing the MJO. This evaluation identifies a number of shortcomings in representing dynamical processes relevant to MJO simulation and reveals potential sources of the shortcomings. This paper has been published in *J. Climate* (Wang et al. 2018a)

11. *Changes in Madden-Julian Oscillation precipitation and wind variance under global warming (H. Bui and E. Maloney CSU)*

The Madden-Julian oscillation (MJO) is the leading mode of tropical intraseasonal variability, having profound impacts on many weather and climate phenomena across the tropics and extratropics. Previous studies using a limited number of models have suggested complex changes in MJO activity in a warmer climate. While most studies have argued that MJO precipitation amplitude will increase in a future warmer climate, others note that this is not necessarily the case for MJO wind variability. This distinction is important since MJO wind fluctuations are responsible for producing remote impacts on extreme weather through teleconnections. In this study, we examine projected changes of MJO precipitation and wind variance at the end of the 21st Century in Representative Concentration Pathway 8.5 (RCP8.5) using the multi-model Coupled Model Intercomparison Project phase 5 (CMIP5) dataset. Under global warming, most models show an increase in MJO band precipitation variance, while wind variability decreases. The discrepancy between MJO precipitation and wind variance changes under global warming is shown to be due to increases in tropical static stability in a warmer climate. The multi-model mean shows a 20% increase in both the 500hPa vertical tropical dry static energy gradient and the ratio of intra-seasonal precipitation to 500hPa omega fluctuations, consistent with scaling by weak temperature gradient theory. These results imply that tropical static stability increases may weaken the MJO's ability to influence extreme events in future warmer climate by weakening wind teleconnections, even though MJO precipitation amplitude may increase. A manuscript on this study has been published in *Geophys. Res. Lett* (Bui and Maloney 2018).

12. *Effects of the changing heating profile associated with melting layers in a climate model. (H., Zhu, ABOM; E. Maloney, CSU, et al.)*

The impact of modifying the melting behavior at the freezing level in the GA2.0 version of the Met Office Unified Model is investigated. By allowing snow to melt over a greater depth, biases in rainfall over the Maritime Continent (MC) are found to be improved, and there is an indication of benefits to the simulation of the Madden–Julian Oscillation. Moistening diagnostics under weak temperature gradient theory are used to explain how and why changes to the treatment of melting influence tropical rainfall biases. The modified melting experiment increases the lower tropospheric diabatic heating rate per unit column-integrated convective heating in the MC, which helps to increase lower tropospheric vertical moisture advection per unit column convective heating, making conditions more favorable for convection there. Changes of the opposite sense occur in tropical ocean regions of the west Pacific and Indian Ocean. Changes in lower tropospheric radiative heating per unit convection produced by the different treatment of melting are particularly influential in engendering mean precipitation changes between the experiments. Differences in precipitation in the MC region between the control and melting experiments and opposite changes in oceanic regions to the east and west are linked through changes in the Walker circulation, making it unclear which region is most influential for forcing the improvement in the pattern of precipitation biases. Sensitivity experiments that artificially enhance convection in one region through imposition of sea-surface temperature anomalies produce a negative precipitation response in the other region. This paper has been published in *Q. J. Royal. Met. Soc.* (Zhu et al. 2017)

13. *MJO Simulation in CMIP5 Climate Models: MJO Skill Metrics and Process-Oriented Diagnosis (M.-S, Ahn, SNU; E. Maloney, CSU, et al.)*

The Madden-Julian Oscillation (MJO) simulation diagnostics developed by MJO Working Group and the process-oriented MJO simulation diagnostics developed by MJO Task Force are applied to 37 Coupled Model Intercomparison Project phase 5 (CMIP5) models in order to assess model skill in representing amplitude, period, and coherent eastward propagation of the MJO, and to establish a link between MJO simulation skill and parameterized physical processes. Process-oriented diagnostics include the Relative Humidity Composite based on Precipitation (RHCP), Normalized Gross Moist Stability (NGMS), and the Greenhouse Enhancement Factor (GEF). Numerous scalar metrics are developed to quantify the results. Most CMIP5 models underestimate MJO amplitude, especially when outgoing longwave radiation (OLR) is used in the evaluation, and exhibit too fast phase speed while lacking coherence between eastward propagation of precipitation/convection and the wind field. The RHCP-metric, indicative of the sensitivity of simulated convection to low-level environmental moisture, and the NGMS-metric, indicative of the efficiency of a convective atmosphere for exporting moist static energy out of the column, show robust correlations with a large number of MJO skill metrics. The GEF-metric, indicative of the strength of the column-integrated longwave radiative heating due to cloud-radiation interaction, is also correlated with the MJO skill metrics, but shows relatively lower correlations compared to the RHCP- and NGMS-metrics. Our results suggest that modifications to processes associated with moisture-convection coupling and the gross moist stability might be the most fruitful for improving simulations of the MJO. Though the GEF-metric exhibits lower correlations with the MJO skill metrics, the longwave radiation feedback is highly relevant for simulating the weak precipitation anomaly regime that may be important for the establishment of shallow convection and the transition to deep convection. This paper has been published in *Climate Dynamics* (Ahn et al. 2017).

14. *Role of north Indian Ocean air-sea interaction in summer monsoon intraseasonal oscillation (Zhang L. W. Han, Y. Li, UC; E. Maloney, CSU)*

Air–sea coupling processes over the north Indian Ocean associated with the Indian summer monsoon intraseasonal oscillation (MISO) are investigated. Observations show that MISO convection anomalies affect underlying sea surface temperature (SST) through changes in surface shortwave radiation and surface latent heat flux. In turn, SST anomalies may also affect the MISO precipitation tendency (dP/dt). In particular, warm (cold) SST anomalies can contribute to increasing (decreasing) precipitation rate through enhanced (suppressed) surface convergence associated with boundary layer pressure gradients.

These air–sea interaction processes are manifest in a quadrature relation between MISO precipitation and SST anomalies. A local air–sea coupling model (LACM) is formulated based on these observed physical processes. The period of the LACM is proportional to the square root of seasonal mixed layer depth H, assuming other physical parameters remain unchanged. Hence, LACM predicts a relatively short (long) MISO period over the north Indian Ocean during the May–June monsoon developing (July–August monsoon mature) phase when H is shallow (deep). This result is consistent with observed MISO characteristics. A 30-day-period oscillating external forcing is also added to the LACM, representing intraseasonal oscillations propagating from the equatorial Indian Ocean to the north Indian Ocean. It is found that resonance will occur when H is close to 25 m, which significantly enhances the MISO amplitude. This process may contribute to the higher MISO amplitude during the monsoon developing phase compared to the mature phase, which is associated with the seasonal cycle of H. A manuscript on this study has been published in J. Climate (Zhang et al. 2018).

In addition to the efforts mentioned above, the PI (Jiang) also contributed to a multi-model comparison study in exploring key processes for the northward propagating boreal summer intraseasonal variability associated with the Asian Monsoon fluctuations led by Neena Mani (Neena et al. 2017), and a diagnostic study in characterizing vertical radiative heating profiles associated with the northward propagating boreal summer MJO (Kim et al. 2018). Also partially supported by this project, the PI (Jiang) contributed to two recently published manuscripts on extended-range predictability of tropical cyclogenesis (Jiang et al. 2018b; Wang et al. 2018b). Maloney also contributed a paper in *Nature Climate Change* that summarizes our latest understanding of MO changes in future climate (Maloney et al. 2018). This paper is currently under embargo.

3. Publications from the project during the past three years

Ahn, M.-S., D. Kim, K. R. Sperber, I.-S. Kang, E. Maloney, D. Waliser, and H. Hendon, 2017: MJO simulation in CMIP5 climate models: MJO skill metrics and process-oriented diagnosis. *Climate Dyn.*, 10.1007/s00382-017-3558-4**,** 1-23.

Bui, H. X. and E. D. Maloney, 2018: Changes in Madden-Julian Oscillation Precipitation and Wind Variance Under Global Warming, **45**, doi:10.1029/2018GL078504**,** 7148-7155.

Ciesielski, P. E., R. H. Johnson, X. Jiang, Y. Zhang, and S. Xie, 2017: Relationships Between Radiation, Clouds, and Convection During DYNAMO. *Journal of Geophysical Research: Atmospheres*, 10.1002/2016JD025965.

Gonzalez, A. O. and X. Jiang, 2017: Winter Mean Lower-Tropospheric Moisture over the Maritime Continent as a Climate Model Diagnostic Metric for the Propagation of the Madden-Julian Oscillation. *Geophys. Res. Lett.*, 10.1002/2016GL072430.

Jiang, X., 2017: Key processes for the eastward propagation of the Madden-Julian Oscillation based on multimodel simulations. *Journal of Geophysical Research: Atmospheres*, 10.1002/2016JD025955.

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Jiang, X., M. Zhao, E. D. Maloney, and D. E. Waliser, 2016: Convective moisture adjustment time scale as a key factor in regulating model amplitude of the Madden-Julian Oscillation. *Geophys. Res. Lett.*, **43**, 10.1002/2016GL070898**,** 10,412-10,419.

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Kim, J., D. E. Waliser, G. V. Cesana, X. Jiang, T. L'Ecuyer, and J. M. Neena, 2018: Cloud and radiative heating profiles associated with the boreal summer intraseasonal oscillation. *Climate Dyn.*, **50**, 10.1007/s00382-017-3700-3**,** 1485-1494.

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Wang, B., S.-S. Lee, D. E. Waliser, C. Zhang, A. Sobel, E. Maloney, T. Li, X. Jiang, and K.-J. Ha, 2018a: Dynamics-Oriented Diagnostics for the Madden–Julian Oscillation. *J. Clim.*, **31**, 10.1175/jcli-d-17-0332.1**,** 3117-3135.

Wang, Z., W. Li, M. S. Peng, X. Jiang, R. McTaggart-Cowan, and C. A. Davis, 2018b: Predictive Skill and Predictability of North Atlantic Tropical Cyclogenesis in Different Synoptic Flow Regimes. *J. Atmos. Sci.*, **75**, 10.1175/jas-d-17-0094.1**,** 361-378.

Wolding, B. O., E. D. Maloney, and M. Branson, 2016: Vertically resolved weak temperature gradient analysis of the Madden-Julian Oscillation in SP-CESM. *Journal of Advances in Modeling Earth Systems*, 10.1002/2016MS000724.

Zhang, L., W. Han, Y. Li, and E. D. Maloney, 2018: Role of North Indian Ocean Air–Sea Interaction in Summer Monsoon Intraseasonal Oscillation, **31**, 10.1175/jcli-d-17-0691.1**,** 7885-7908.

Zhu, H., E. Maloney, H. Hendon, and R. Stratton, 2017: Effects of the changing heating profile

associated with melting layers in a climate model, **143**, doi:10.1002/qj.3166**,** 3110-3121.
Gonzalez, A., and X. Jiang, 2018: A westward propagating intraseasonal mode over the tropical Western Pacific, submitted to *JGR Atmos.*
Zhao M., X. Jiang, S.-J. Lin, and B. Xiang, 2018: Online diagnostics of moist static energy budget and an application to model simulated Madden-Julian Oscillation, *Geophys. Res. Lett.*, to be submitted.
Maloney, E. D., A. F. Adames, and H. X. Bui, 2018: Madden-Julian Oscillation Changes under Anthropogenic Warming. *Nature Clim. Change*, in press.
The NOAA MAPP Model Diagnostics Task Force, 2018: A Framework for Process-Oriented Evaluation of Climate and Weather Forecasting Models, *Bulletin of the American Meteorological Society*, submitted.