Project Title: Development of a Framework for Process-Oriented Diagnosis of Global Models
Project Number: GC15-106 (NA15OAR4310099)
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Report Type: Final Report

Main Goals of the Project

A. Develop a common and extensible mechanism for rapid dissemination of process-oriented diagnostics across modeling centers

B. Development of model diagnostics related to tropical convection and tropical variability

C. Implementation of these critical diagnostics for tropical convection and its variability into the framework developed in A.

Results and Accomplishments

A. NOAA MAPP Model Diagnostics Task Force (MDTF) Activities

1) General Task Force Activities
The NOAA MAPP MDTF was initiated in Fall of 2015, led by chair Maloney, and co-chairs Gettelman, Ming, and Aiguo Dai. Regular telecons have been conducted on the first Monday of each month. The task force activities that have been initiated and are ongoing are described below. In Fall of 2018, the MDTF was renewed and entered its second phase, led by David Neelin of UCLA, with Maloney as co-chair along with Andrew Gettelman of NCAR, Allison Wing of FSU, and John Krasting of GFDL.

2) Development of Diagnostics Software Framework/Application Programming Interface (API)
Based on discussions among our Type 1 team and the task force, and given input from others external to the task force including V. Balaji and Erik Mason at GFDL, and members of the WGCM community, we developed an Application Programming Interface (API), or guidance for use of diagnostics in the model workflows including NCAR and GFDL. We refer to this framework as the MDTF Process Oriented Diagnostics (PODs) framework. Each "POD" shown in **Figure 1** below is an individual process-oriented diagnostic supplied by a member of the task force or outside community. A Python-based code infrastructure for implementation and output of these diagnostics has been developed. The basic structure uses a Python driver to call a series of diagnostic packages or modules to develop graphics and then output them to a common website. The prototype shell script in Python works with diagnostics code developed in NCL, Python, Fortran or any other open source graphics package. The diagnostic modules have access to data structures and arguments from Python, and outputs a standard plot type to a location where it can be used to construct web pages by the driver.

A schematic of the MDTF PODs framework (mdtf.py) is shown below, including an example web page of a particular diagnostic implemented into this workflow. We note that we have also incorporated other process-oriented teleconnection diagnostics generated by the broader task force into this framework (e.g. Henderson et al. 2017). The website for the latest implementation of this framework is found here:
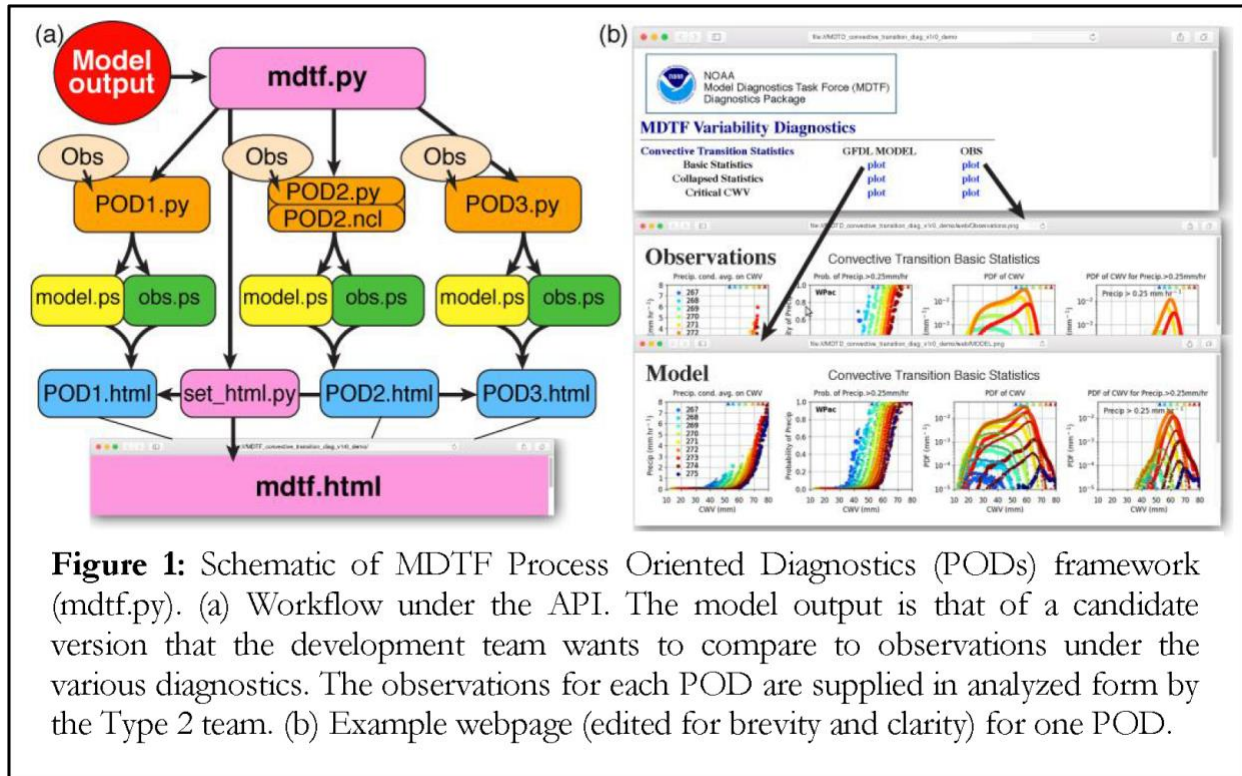http://www.cesm.ucar.edu/working_groups/Atmosphere/mdtf-diagnostics-package/

Figure 1: Schematic of MDTF Process Oriented Diagnostics (PODs) framework (mdtf.py). (a) Workflow under the API. The model output is that of a candidate version that the development team wants to compare to observations under the various diagnostics. The observations for each POD are supplied in analyzed form by the Type 2 team. (b) Example webpage (edited for brevity and clarity) for one POD.

3) Release and revision of MDTF diagnostic code to the community
In December 2017, we released version 3 of the MDTF diagnostic code to the community. We recently (March 11, 2019) released the most recent revised version of this code (http://www.cesm.ucar.edu/working_groups/Atmosphere/mdtf-diagnostics-package/). The revision of the software framework and associated webpage has included detailed specification of documentation protocols for process-oriented diagnostics modules (PODs). The Template for POD documentation specifies a uniform format to provide a consistent user experience, including contact information for technical person and a long-term contact, open source copyright agreement (LGPLv3 license), functionality, technical information, published references and a brief user-oriented description. Focused outreach to groups to complete delivery and documentation has had an excellent response with release timing coordinated with revision and acceptance of a BAMS article elaborated below. Software framework documentation has been completed including a Developers Walk-through and a user-oriented Getting Started document. The code, with data and this documentation is available from the package webpage.

The code currently contains 10 different diagnostic 'packages' from 7 groups:

Convective Transition Diagnostics	J. David Neelin (UCLA)
MJO Teleconnections	Eric Maloney (CSU)
Extratropical Variance (EOF 500hPa Height)	CESM/AMWG (NCAR)
Wavenumber-Frequency Spectra	CESM/AMWG (NCAR)
MJO Spectra and Phasing	CESM/AMWG (NCAR)
Diurnal Cycle of Precipitation	Rich Neale (NCAR)
MJO Propagation and Amplitude	Xianan Jiang, UCLA
AMOC 3D structure	Xiaobiao Xu (FSU/COAPS)
ENSO Moist Static Energy	Hariharasubramanian Annamalai, U. Hawaii
Warm Rain Microphysics	Kentaroh Suzuki (AORI, U. Tokyo)

More diagnostics will be continually implemented into this framework, especially as more diagnostic development teams have joined the MDTF since its renewal in 2018.

4) NOAA MDTF Timeslice Experiments
Time slice experiments have been completed with the NCAR and GFDL models to provide high time and space frequency resolution output to kick start task force diagnostics efforts. The specifications of this design are:

Timeslices of free running models
Specified SSTs: 1993-2012 with limited output, 2008-2012 with high frequency output

Models
NCAR (1 deg, possible short run of 0.25 deg)
GFDL (1 deg, possible short 0.5 deg run)

Output schemes
1. 20-year (1993-2012) simulation: Daily, a handful set of 2D variables
2. 5-year (2008-2012) sub period: 6-hourly, comprehensive list
3. 2-year (2011-2012) sub period: hourly, variables for diurnal cycle study

Both NCAR and GFDL have completed these experiments.

5) Session at 2016 AGU Meeting and other Meetings
A session on process-oriented diagnostics was conducted at the 2016 AGU meeting in San Francisco. PI Maloney submitted the proposal in April. This meeting served as a venue for a face-to-face meeting of the entire MDTF, including a Monday evening dinner. The PIs on the Type 1 team also visited to GFDL in November in association with the WCRP Model Hierarchies workshop, and PI Maloney visited GFDL in February to give a seminar and have discussions with co-PI Ming and GFDL scientist Ming Zhao.

6) AMS Special Collection

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Process-Oriented Model Diagnostics

Description of the collection:

This special collection is devoted to process-oriented evaluation of climate and Earth system models, and spans several American Meteorological Society journals. The Model Diagnostics Force (MDTF) of the NOAA Modeling, Analysis, Predictions, and Projections Program (MAPP) has organized this special collection. The collection is motivated by community interest in moving beyond performance-oriented metrics toward process-oriented metrics of models, current efforts to develop the next generation of climate and Earth system models including those related to the Coupled Model Intercomparison Project (CMIP), and a need to link model development and evaluation efforts across modeling centers. Assessing processes in climate and Earth system models is essential for understanding model biases, identifying model error origins, and developing next-generation models.

SPECIAL
Process-Oriented Model Diagnostics
COLLECTION

The papers detail studies not only by MDTF members, but also those contributed by the broader community.

Names and Affiliations of Collection Organizers:
Eric Maloney, Colorado State University
Daniel Barrie, NOAA MAPP Program
Aiguo Dai, University at Albany
Andrew Gettelman, National Center for Atmospheric Research
Yi Ming, NOAA Geophysical Fluid Dynamics Laboratory

Abstracts for all AMS articles are available to everyone, as is the full text of Bulletin articles. Access to full-text HTML and PDF articles in the technical journals is limited to paid subscribers.

A special collection on process-oriented diagnostics is included in AMS journals that reports on and synthesizes the work of our task force (https://journals.ametsoc.org/topic/process_oriented_model_diagnostics). The special collection description is included here:

This special collection is devoted to process-oriented evaluation of climate and Earth system models, and spans American Meteorological Society journals including *Bulletin of the American Meteorological Society (AMS)*, *Journal of Climate, Journal of the Atmospheric Sciences*, and *Journal of Hydrometeorology*. The Model Diagnostics Force (MDTF) of the NOAA Modeling, Analysis, Predictions, and Projections Program (MAPP) has organized this special collection. The collection is motivated by community interest in moving beyond performance-oriented metrics toward process-oriented metrics of models, current efforts to develop the next generation of climate and Earth system models including those related to the Coupled Model Intercomparison Project (CMIP), and a need to link model development and evaluation efforts across modeling centers. Assessing processes in climate and Earth system models is essential for understanding model biases, identifying model error origins, and developing next-generation models.

The centerpiece of the special collection is a comprehensive article in the *AMS Bulletin* that gives background on the concept of process-oriented model diagnosis, provides a partial summary of previous efforts at process-oriented diagnosis including both individual and organized efforts, highlights key diagnostics developed by the MDTF, and describes an integrative process-oriented metrics framework serving multiple modeling centers that is being developed under the NOAA MAPP MDTF (Maloney et al. 2019, described immediately below). Papers in *Journal of Climate*, *Journal of the Atmospheric Sciences*, and *Journal of Hydrometeorology* provide the scientific details of specific process-oriented diagnostics to accompany this core study. These papers detail studies not only by MDTF members, but also those contributed by the broader community. The collection currently has 17 papers.

7) Overview BAMS article
A *Bulletin of the American Meteorological Society* (BAMS) overview article (Maloney et al. 2019) of the process-oriented diagnostics effort has been coordinated between this grant and the successor grant lead by PI Neelin.   The *BAMS* paper provides a summary of PODs being

developed by the MDTF and the initial stage of the software framework that aids modeling centers to easily use these diagnostics, as well as the motivations and aims of the process-oriented diagnostics effort. Figure 1 from the BAMS article is included above to provide both a current sense of the framework and a condensed example of the output from one of the PODs. As mentioned above, this is the centerpiece of the AMS special collection.

8) 2017 WGNE Systematic Errors Workshop
The MDTF co-organized the 5th WGNE workshop on systematic errors in weather and climate models to held 19-23 June, 2017 in Montreal, Canada. A dedicated session on model metrics and diagnostics took place at this meeting, including a substantial number of contributions from the MDTF. The MDTF had a dedicated side meeting on June 23, part of which was held coincident with the WGNE MJO Task Force.

B. Research Activities

For brevity, only the papers for 2018-2019 are described in detail, although a total of 25 publications are included in the reference list below. Figures are displayed for the first four publications.

Process-Oriented Evaluation of Climate and Weather Forecasting Models (Maloney et al. 2019)
The is the lead paper of the AMS Special Collection on Process-Oriented Diagnostics and is listed here again for completeness. Realistic climate and weather prediction models are necessary to produce confidence in projections of future climate over many decades and predictions for days to seasons. These models must be physically justified and validated for multiple weather and climate processes. A key opportunity to accelerate model improvement is greater incorporation of process-oriented diagnostics (PODs) into standard packages that can be applied during the model development process, allowing the application of diagnostics to be repeatable across multiple model versions and used as a benchmark for model improvement. A POD characterizes a specific physical process or emergent behavior that is related to the ability to simulate an observed phenomenon. This paper describes the outcomes of activities by the Model Diagnostics Task Force (MDTF) under the NOAA Climate Program Office (CPO) Modeling, Analysis, Predictions and Projections (MAPP) program to promote development of PODs and their application to climate and weather prediction models. MDTF and modeling center perspectives on the need for expanded process-oriented diagnosis of models are presented. Multiple PODs developed by the MDTF are summarized, and an open-source software framework developed by the MDTF to aid application of PODs to centers' model development is presented in the context of other relevant community activities. The paper closes by discussing paths forward for the MDTF effort and for community process-oriented diagnosis. See **Figure 1** above.

Madden–Julian oscillation changes under anthropogenic warming (Maloney et al. 2019)
The Madden–Julian oscillation (MJO) produces a region of enhanced precipitation that travels eastwards along the Equator in a 40–50 day cycle, perturbing tropical and high-latitude winds, and thereby modulating extreme weather events such as flooding, hurricanes and heat waves. Here, we synthesize current understanding on projected changes in the MJO under anthropogenic

warming, demonstrating that MJO-related precipitation variations are likely to increase in intensity, whereas wind variations are likely to increase at a slower rate or even decrease. Nevertheless, future work should address uncertainties in the amplitude of precipitation and wind changes and the impacts of projected SST patterns, with the aim of improving predictions of the MJO and its associated extreme weather. Figure 2 summarizes the processes and anticipated changes to the MJO in a future warmer climate as exposed by this study.
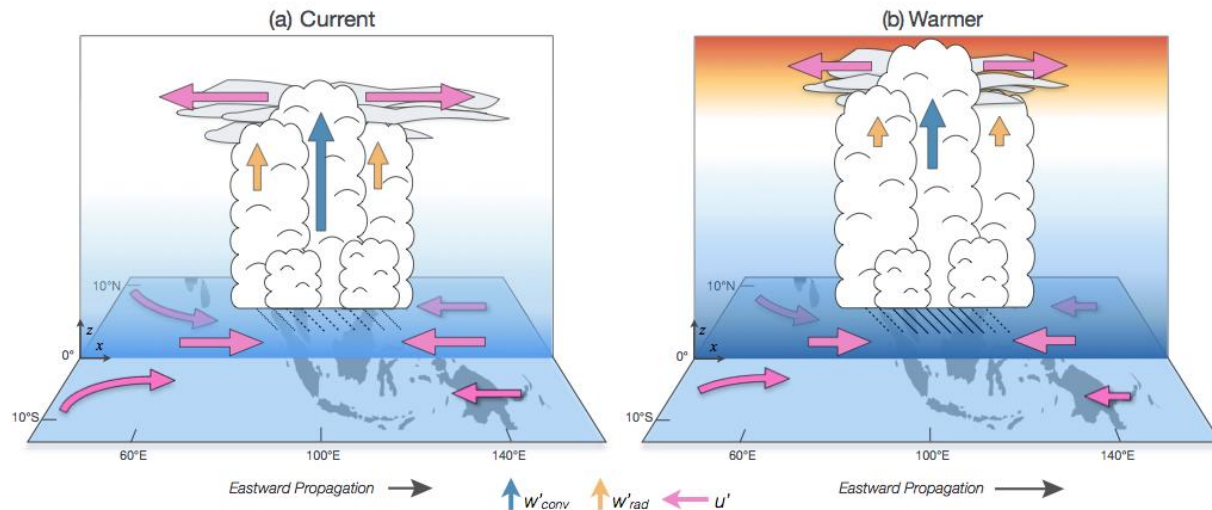

Figure 2. Schematic summarizing our best understanding of changes in MJO convective anomalies and the anomalous large-scale circulation. Current climate is represented in (a), and a warmer climate in (b). As the climate warms, the mean vertical gradient in water vapor (blue shading) increases. Tropospheric temperature (orange shading) will also increase, with the largest increments occurring in the upper troposphere, resulting in increased static stability. The increased static stability will result in weaker anomalous horizontal (u') and vertical (w') motions and less extensive upper-level clouds[73]. The subscripts *conv* and *rad* indicate vertical motions balancing convective and radiative heating anomalies, respectively. The stronger moisture gradient will likely outstrip the stronger static stability to result in more efficient moistening of the troposphere by heating in a warmer climate, fostering stronger MJO convection. A warmer climate will also result in a deeper troposphere, deeper convection, weaker anomalies in longwave radiative heating, and faster propagation.

Mechanisms for global warming impacts on Madden-Julian Oscillation precipitation amplitude (Bui and Maloney 2019)

In a paper published in *J. Climate*, process-oriented MJO diagnostics are applied to understand MJO precipitation amplitude change in a warming climate. In particular, mechanisms that cause changes in Madden-Julian Oscillation (MJO) precipitation amplitude under global warming are examined in Coupled Model Intercomparison Project phase 5 models. Under global warming in the Representative Concentration Pathway 8.5, MJO precipitation intensifies in most models relative to current climate while MJO wind circulations increase at a slower rate or weaken. Changes in MJO precipitation intensity are partially controlled by changes in moisture profiles and static stability. The vertical moisture gradient increases in the lower half of the troposphere in response to the surface warming, while the vertical static stability gradient increases due to preferential warming in the upper troposphere. A non-dimensional quantity called α has been

defined that gives the efficiency of vertical advective moistening associated with diabatic processes in the free troposphere, and has been hypothesized by previous studies to regulate MJO amplitude. α is proportional to the vertical moisture gradient and inversely proportional to static stability. Under global warming, the increased vertical moisture gradient makes a larger in models, despite increased static stability. Although α increases in all models, MJO precipitation amplitude decreases in some models, contrary to expectations. It is demonstrated that in these models more top-heavy MJO diabatic heating with warming overwhelms the effect of increased α to make vertical moisture advection less efficient (**Figure 3**).
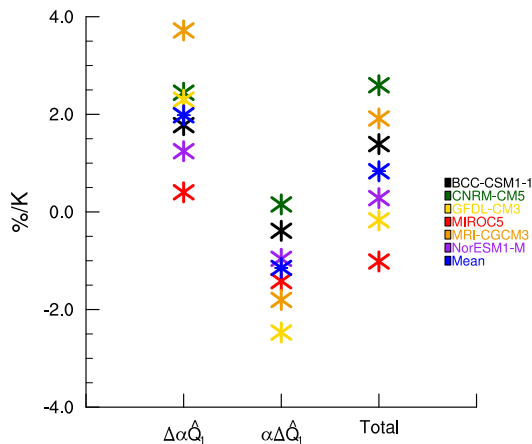

Figure 3. Changes in the column integrated (from 850 to 500 hPa) $\hat{Q}_1 \Delta \bar{\alpha}$ (left), $\bar{\alpha} \Delta \hat{Q}_1$ (middle) and sum of the two terms (right) from (8) averaged between lags of -5 to 5 days over the warm pool. Units are % K^{-1}.

Convective transition statistics over tropical oceans for climate model diagnostics: GCM evaluation (Kuo et al. 2019)

A multi-author paper (Kuo et al. 2019) has been submitted using the Convective Transition Diagnostics module to analyze multiple model simulations including the MDTF time-slice runs. These time slice runs with the NCAR and GFDL models, undertaken as an activity of the initial phase of the MDTF, include high-frequency output with additional variables for advanced diagnostics. time slice experiments and the Madden-Julian Oscillation (MJO) Task Force ensemble. Examples of results are illustrated in Figure 4, which focuses on one of the measures of deep convection, the precipitation conditionally averaged as a function of the water vapor and temperature. Although models tend to qualitatively match the observations in this and a number of similar measures, quantitative discrepancies are common even among models that are performing well. The National Center for Atmospheric Research and Geophysical Fluid Dynamics Laboratory models do well by these measures but in the MJOTF ensemble, there are some models that fare poorly. This points to issues in the representation of conditional instability for deep convective plumes interacting with the temperature-moisture environment in these schemes.
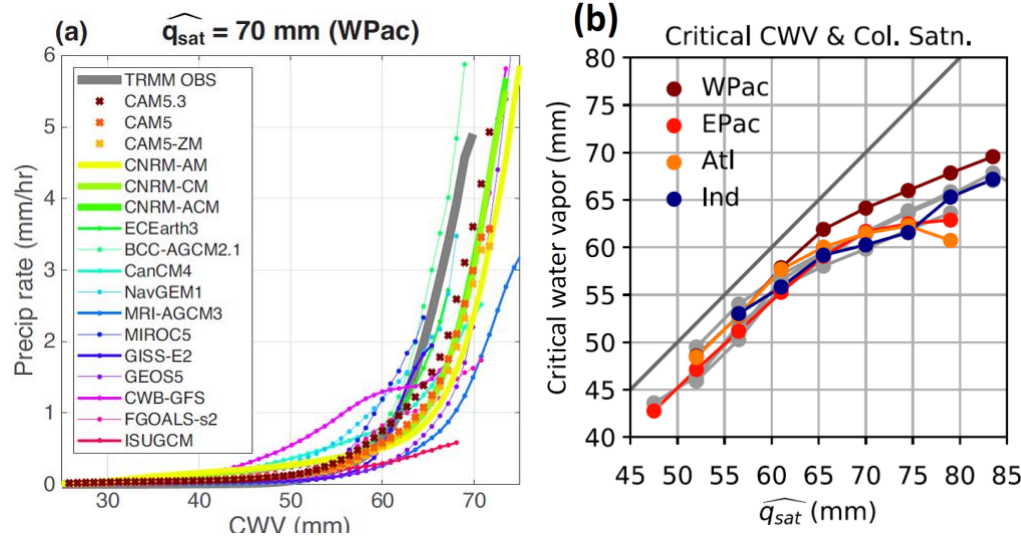
Figure 4. (a) Conditionally averaged precipitation rate for a common temperature, as measured by column water vapor saturation value (= 70 mm) in the tropical western Pacific for models from the MJO task force ensemble and MDTF time slice runs, with comparison to TRMM observations. The rapid pickup of precipitation associated with the onset of conditional instability and deep convection is captured qualitatively by most models, but with significant discrepancies in the water vapor at which the onset occurs. The Community Atmosphere Model does quite well by this measure. (b) The critical water vapor value at which this rapid pickup begins, displayed as a function of temperature for a version of the GFDL model that performs very well by this measure.

The Global Teleconnection Signature of the Madden-Julian Oscillation and its Modulation by the Quasi-Biennial Oscillation (Toms et al. 2019)

Recent research has suggested that the tropical and extratropical character of the Madden-Julian Oscillation (MJO) depends on the state of the stratospheric Quasi-Biennial Osillation (QBO). With this in mind, we use both reanalysis and a global climate model (CESM2-WACCM) to analyze the global character of upper tropospheric-lower stratospheric geopotential height anomalies connected with the MJO and quantify dependencies of these teleconnections on the state of the QBO. We find that the global teleconnection signature of the MJO depends upon the state of the QBO. Globally, within reanalysis the fraction of 20 to 90 day 250-hPa geopotential height variance linked to the MJO is largest during boreal winter and summer for easterly QBO phases and smallest during westerly QBO phases of boreal winter. The difference between QBO phases is mostly driven by changes in the tropical signature of the MJO, although during boreal winter the Northern Hemispheric teleconnections are particularly more prominent during easterly QBO phases. Otherwise, the QBO modulation of extratropical MJO teleconnections is mainly realized through changes in the locations of the teleconnections. A QBO-MJO relationship is also apparent within CESM2-WACCM, but is weaker than that observed. This extratropical modulation implies that the regions that benefit from increased subseasonal predictability due to the MJO may also change as a function of the QBO. In a broader sense, these findings emphasize that knowledge of the tropical stratospheric state, particularly as it relates to the QBO, is important for understanding the connections between the MJO and the extratropics. This paper is accepted pending revisions in *JGR*.

Dynamics-oriented diagnostics for the Madden-Julian Oscillation (Wang et al. 2018)

Realistic simulations of the Madden-Julian Oscillation (MJO) by global climate models (GCMs) remain a great challenge. To evaluate GCM simulations of the MJO, the U.S. CLIVAR MJO Working Group developed a standardized set of diagnostics, providing a comprehensive assessment of statistical properties of the MJO. Here, we develop a suite of complementary diagnostics that provide discrimination and assessment of MJO simulations based on the perception that the MJO propagation has characteristic dynamic and thermodynamic structures. The new dynamics-oriented diagnostics help to evaluate whether a model produces eastward propagating MJO for the right reasons. The diagnostics include (1) the horizontal structure of boundary layer moisture convergence (BLMC) that moistens the lower troposphere to the east of convection center; (2) the preluding eastward propagation of BLMC that leads the propagation of MJO precipitation by about 5 days; (3) the horizontal structure of 850 hPa zonal wind and its equatorial asymmetry (Kelvin easterly vs. Rossby westerly intensity); (4) the equatorial vertical longitudinal structure of equivalent potential temperature and convective instability index that reflect the pre-moistening and pre-destabilization processes; (5) the equatorial vertical longitudinal distribution of diabatic heating that reflects the multi-cloud structure of the MJO; (6) the upper-level divergence that reflects the influence of stratiform cloud heating; and (7) the MJO available potential energy generation that reflects the amplification and propagation of MJO. The models that simulate better three-dimensional dynamic and thermodynamic structures of MJO generally reproduce better eastward propagations. This evaluation identifies a number of shortcomings in representing dynamical and heating processes relevant to the MJO simulation and reveals potential sources of the shortcomings.

A Unified Moisture Mode Framework for Seasonality of the Madden-Julian Oscillation (Jiang et al. 2018)
The Madden-Julian Oscillation (MJO) exhibits pronounced seasonality. 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 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 mechanism based on the moisture mode framework is provided to interpret seasonality of MJO propagation characteristics. The process that was recently found to be critical for the eastward propagation of the winter MJO, i.e., moistening and drying due to horizontal advection of the lower-tropospheric mean moisture by MJO winds, is also shown to play a dominant role in 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 seasonal mean moisture pattern for MJO propagation is further supported by close association between model skill in representing 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.

The impact of the Madden-Julian Oscillation on high-latitude winter blocking during El Niño-Southern Oscillation Events (Henderson and Maloney 2018)
          Wintertime high-latitude blocking is associated with persistent changes in temperature and precipitation over much of the Northern Hemisphere. Studies have shown that the Madden-

Julian Oscillation (MJO), the primary form of intraseasonal tropical variability, significantly modulates the frequency of high-latitude blocking through large-scale Rossby waves that alter the global circulation. However, the characteristics of MJO teleconnections are altered by the El Niño-Southern Oscillation (ENSO), which modifies the global flow on interannual timescales, suggesting that the MJO influence on blocking may depend on ENSO phase.

The characteristics of MJO Rossby waves and blocking during ENSO events are examined using composite analysis and a nonlinear baroclinic model. The ENSO phase-dependent teleconnection patterns are found to significantly impact Pacific and Atlantic high-latitude blocking. During El Niño, a significant persistent increase in Pacific and Atlantic blocking follows MJO RMM phase 7, characterized by anomalous enhanced tropical convection over the East Indian Ocean and suppressed west Pacific convection. The maximum Atlantic blocking increase is triple the climatological winter mean. Results suggest that the MJO provides the initial dipole anomaly associated with the Atlantic blocking increase, and transient eddy activity aids in its persistence. However, during La Niña significant blocking anomalies are primarily observed during the first half of an MJO event. Significant suppression of Pacific and Atlantic blocking follows RMM phase 3, when east Indian Ocean MJO convection is suppressed and west Pacific convection is enhanced. The physical basis for these results is explained.

Convective transition statistics over tropical oceans for climate model diagnostics: Observational baseline (Kuo et al. 2018)

Convective transition statistics, which describe the relation between column-integrated water vapor (CWV) and precipitation, are compiled over tropical oceans using satellite and ARM site measurements to quantify the temperature and resolution dependence of the precipitation-CWV relation at fast timescales relevant to convection. At these timescales, and for precipitation especially, uncertainties associated with observational systems must be addressed by examining features with a variety of instrumentation, and identifying robust behaviors versus instrument sensitivity at high rain rates. Here the sharp pickup in precipitation as CWV exceeds a certain critical threshold is found to be insensitive to spatial resolution, with convective onset occurring at higher CWV but at lower column relative humidity as bulk tropospheric temperature increases. Mean tropospheric temperature profiles conditioned on precipitation show vertically coherent structure across a wide range of temperature, reaffirming the use of a bulk temperature measure in defining the convective transition statistics. The joint probability distribution of CWV and precipitation develops a peak probability at low precipitation for CWV above critical, with rapid decreasing probability of high precipitation below and near critical, and exhibits systematic changes under spatial-averaging. The precipitation pickup with CWV is reasonably insensitive to time-averaging up to several hours but is smoothed at daily timescales. This work demonstrates that CWV relative to critical serves as an effective predictor of precipitation with only minor geographic variations in the tropics, quantifies precipitation-related statistics subject to different spatial-temporal resolution, and provides a baseline for model comparison to apply these statistics as observational constraints on precipitation processes.

Toward next-generation precipitation diagnostics (Quinn and Neelin 2017a,b; Ahmed and Neelin 2018, Martinez-Villalobos & Neelin 2018)

These studies explore further diagnostics for convection and tropical precipitation clusters, leveraging other funding for basic development, and coordinating with this project in examining potential future inclusion in the process-oriented diagnostics package. Quinn and Neelin 2017a,b

examine the probability distribution of the sizes of contiguous clusters of precipitating points, as measured by the precipitation integrated over the cluster (cluster power, which can be expressed either as a latent heat in gigawatt, or as water loss from the atmosphere in gigaton/hour). Tropical distributions are shown to obey power law followed by an approximately exponential cut off that limits the probabilities of the largest clusters. The GFDL HIRAM model is shown to reproduce observed statistics for the tropics reasonably well at both high and moderately high resolution. Coupled Model Intercomparison Project Phase 5 (CMIP5) models yield plausible approximations to this in several respects, with some quantitative differences. Martinez-Villalobos and Neelin (2018) analyzes similar considerations for precipitation accumulations in US hourly observations, finding a shift in the exponential cutoff in certain US regions. Ahmed and Neelin (2018) takes convective transition statistics in a direction that is even more directly comparable to ill-constrained aspects of convective parameterizations. Using European Center for Medium-Range Weather Forecasting reanalysis for temperature and water vapor (after validation against instantaneous observations of column water vapor) with observed precipitation, the convective onset is studied as a function of contributions to equivalent potential temperature through lower tropospheric layers. An influence function for each layer is determined that should provide a strong constraint on convective parameterizations when applied to models.

Understanding the dynamics of monsoon depressions (Adames and Ming 2018 a,b)
The tropics are characterized by synoptic-scale scale disturbances that play an important role in precipitation variability. Of these systems, south Asian monsoon low pressure systems, referred to as synoptic-scale monsoonal disturbances (SMDs), have remained elusive. It has long been thought that these systems grow due to a variant of baroclinic instability that includes the effects of convection. Recent work, however, has shown that this framework is inconsistent with the observed structure and dynamics of SMDs. Here we present an alternative framework that may explain the growth of SMDs and may also be applicable to other modes of tropical variability. Moisture is prognostic and is coupled to precipitation through a simplified Betts-Miller scheme. Interactions between moisture and potential vorticity (PV) in the presence of a moist static energy gradient can be understood in terms of a "gross" PV (q_G) equation. q_G summarizes the dynamics of SMDs and reveals the relative role that moist and dry dynamics play in these disturbances, which is largely determined by the gross moist stability. Linear solutions to the coupled PV and moisture equations reveal Rossby-like modes that grow due to a moisture-vortex instability. Meridional temperature and moisture advection to the west of the PV maximum moisten and destabilize the column, which results in enhanced convection and SMD intensification through vortex stretching. This instability occurs only if the moistening is in the direction of propagation of the SMD and is strongest at the synoptic scale.

Changes in Madden-Julian Oscillation Precipitation and Wind Variance Under Global Warming (Bui and Maloney 2018)
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 using the multimodel Coupled Model Intercomparison Project phase 5 data set. 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 multimodel mean shows a 20% increase in both the 500-hPa vertical tropical dry static energy gradient and the ratio of intraseasonal precipitation to 500 hPa 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.

C. Highlights of Accomplishments

- Accomplishments of the MDTF task force relevant to this project include:
  - We have developed an open source MDTF Process Oriented Diagnostic (POD) framework that enables expanded process-oriented evaluation of models
  - Seven groups have thus far implemented their process-oriented diagnostics into the POD framework, including the convective onset diagnostics and teleconnection diagnostics developed by members of our lead team.
  - We have successfully implemented an AMS special collection on process-oriented diagnostics
  - A *Bulletin of the American Meteorological Society* overview article (Maloney et al. 2019) of the process-oriented diagnostics effort is published in the September 2019 issue, coordinated with the new activity of the successor grant
  - The MDTF co-organized the 5th WGNE workshop on systematic errors in weather and climate models held 19-23 June, 2017 in Montreal, Canada.
- The MDTF has been renewed for a second 3-year term in Fall of 2018 given the success of the previous iteration of the task force.
- A key process-oriented diagnostic was developed indicating column water vapor relative to a critical threshold provides a baseline for model comparison and provide an observational constraint on precipitation processes.
- 3-D process-oriented diagnostics to understand MJO moistening processes based on weak tropical temperature gradients (WTG) have been developed and successfully applied to SP-CESM and other models.
- Process-oriented diagnostics have been developed to document and understand reasons for poor MJO teleconnections in CMIP models
- Modeling diagnostics suggest that the MJO teleconnection to the extratropics may weaken in future climate, and these changes have been interpreted through the WTG diagnostics noted two bullets above and described in a *Nature Climate Change* paper.

D. Transitions to Operations
No developments have transitioned into operational or applied use

E. Estimate of current technical readiness level of work

The overall technical readiness level is chosen as RL4 (i.e.: Successful evaluation of system, subsystem, process, product, service, or tool in a laboratory or other experimental environment; this can be considered an intermediate phase of development*.) Different aspects of the project would be at different readiness levels, for instance, the released software framework with current PODs evaluated on its own would be at a higher level.

[*following RL definitions at https://cpo.noaa.gov/Meet-the-Divisions/Earth-System-Science-and-Modeling/MAPP/MAPP-PI-Handbook]

F. Publications from the Project

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H. Budget for the Coming Year
N/A

I. Future Work
This project is closing. Work under this project is continuing under a new NOAA grant. These results will be reported separately.