Improving the simulation of diurnal and sub-diurnal precipitation over different climate regimes

(A white paper for a potential GASS project)

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1. Motivation

General Circulation Models (GCMs) for weather forecasts and climate simulations continue having difficulties in modeling the diurnal and sub-diurnal precipitation particularly over land. The issue is related to inappropriate representation of the processes that control sub-diurnal phenomenon like convection, and phenomena with timescales around the order of diurnal, like mesoscale systems. Over mid-latitude lands, such as warm seasons at the Southern Great Plains (SGP), there are two diurnal peaks of precipitation from observations: a predominant nocturnal peak of precipitation associated with eastward propagating mesoscale convective systems which usually originate over the Rocky Mountains and are often elevated and decoupled from the local surface, and a secondary late-afternoon peak associated with the transition from shallow to deep convection which is strongly coupled with the local surface forcing. Most GCMs often fail to capture the observed nocturnal peak and instead tend to simulate a diurnal peak of precipitation around noon, much earlier than the observed late-afternoon peak. Over tropical lands, such as over the Amazon and Darwin, Australia regions, the diurnal and sub-diurnal variability of precipitation are strongly influenced by different large-scale environments (e.g., dry versus wet seasons over the Amazon, or active versus break periods of monsoon at Darwin), adding difficulty for GCMs to capture the distinguishable behaviors. Moreover, difficulties facing the modeling of diurnal and sub-diurnal convection are also some of the key issues related to the skill of modeling convectively coupled process at longer time scales. Understanding and improving the modeling of diurnal and sub-diurnal precipitation processes can therefore have broader impact on the fidelity of climate simulations.

Problems in simulating the diurnal cycle of precipitation are primarily due to shortcomings and deficiencies in representing convection initiation, evolution, and propagation, as well as the interaction between convection and its large-scale atmospheric environment and the underlying land surface. For example, the failure of capturing night-time convection may be due to the lack of convective memory and/or poor treatment of elevated convction initiation in cumulus parameterizations. It is also highly likely that certain biases in the diurnal cycle arise from errors in how convection onsets as a function of the diurnal cycle of large-scale in radiative effects, including dependence on lower free tropospheric water vapor, and mesoscale organization. It has been suggested that the interaction between water vapor in the lower free troposphere and moisture convection, mainly by way of entrainment processes (Holloway and Neelin 2009), is a primary control on the onset of deep convection. Systematically evaluating the model capability in capturing statistical relationships that describe the interaction between convection and moisture fields under various synoptic conditions against available observations would yield import insights into parameterizations of moist convection.

The highly time-resolved field data collected by the US DOE Atmospheric Radiation Measurement (ARM) program over its permanent research sites or during its major field campaigns located at different climate regimes provide crucial and comprehensive observational basis for studying diurnal and sub-diurnal precipitation. Moreover, advances in measurement techniques, data analysis approaches, and model evaluation and diagnosis tools and methods in recent years have provided more detailed and reliable observations and efficient modeling tools to facilitate process studies.

2. A potential GASS project

This white paper proposes a potential GASS project focusing on improving the model capability to simulate diurnal and sub-diurnal precipitation phenomena through a multimodel intercomparison against ARM observations. The overall goal is to understand what processes control the diurnal and sub-diurnal variation of precipitation over different climate regimes in observations and in models and identify the deficiencies and missing physics in current GCMs so as to gain insights for further improving the parameterization of convection in GCMs.

2.1 Potential research themes

1) **Interaction between convection and water vapor** Identify the processes that primarily control the diurnal and sub-diurnal variability in precipitation over different climate regimes and evaluate how well current GCMs represent these processes, and in particular the statistical relationships that describe the interaction between convection and moisture fields under various synoptic conditions against ARM observations (e.g., GoAmazon). A brainstorming thought on this research theme is
    -- *which sub-diurnal processes are most essential for the simulation of the diurnal cycle and sub-diurnal extreme events, and how can these be improved in weather and climate models?*

2) **Nocturnal convection** Identify the processes that primarily control nocturnal elevated convection at SGP and evaluate how well current GCMs represent these processes. The MC3E (Xie et al. 2014), PECAN (Greets et al. 2016) field campaigns, as well as ARM long-term observations will provide observational insights into this issue, and support for modeling investigations.
    -- *What is the role of convective memory (advection)?*
    -- *What is the rold of the night-time boundary-layer and elevated convection initiation?*
    -- *What maintains the convection? (Is spatial separation of up- and downdraughts important or is it upper level heating and interaction with dynamics?)*

3) **Convection transition** Identify the processes that primarily control the transition from shallow to deep convection at SGP and evaluate how well current GCMs represent these processes. A few cases can be selected from those identified in Zhang and Klein (2010 and 2013) and Zhang et al. (2017), which also provided the observational basis for modeling studies.

2.2 A hierarchy modeling approach

A hierarchy of models including SCMs, CRMs, and GCMs is proposed to be used in the multimodel intercomparison study to diagnose and investigate the associated processes and model biases in depth. This modeling approach has been proven very useful to identify strengths and weaknesses of model parameterizations by comparing results among different models and with observations over different climate regimes in earlier GASS (GCSS) studies. Both SCMs and CRMs will be driven with the same large-scale forcing derived from the field campaign data. GCMs can be run in hindcast mode with initial conditions from NWP analyses so that output can be directly compared to the observations. GCMs are also recommended to run at higher resolution over the selected regions if they can run at variable resolutions.

GCMs in climate simulation mode are expected to have similar diurnal characteristics as that in short-term hindcast mode.

2.3 Suggested cases

- The SGP Midlatitude Continental Convective Clouds Experiment (MC3E) (22 April 2011 to 6 June 2011)
- The 2015 Plains Elevated Convection At Night (PECAN) (1 June 2015 – 15 July 2015)
- The Green Ocean Amazon (GOAmazon) (January 2014 - December 2015).
- Long-term ARM data at its SGP and TWP sites

2.4 Diagnostics

- Metrics for the diurnal cycle of precipitation (Covey et al. 2016)
- Convecion onset diagnostics (Bretherton et al. 2004, Holloway and Neelin 2009)
- ……

3. Timelines, participants, and publication plan

This could be a three-year project containing several sub-projects or stages. The scope of the study could be narrowed down and detailed timeline will be determined based on feedbacks from the breakout session in the upcoming Pan-GASS meeting. Both major weather prediction and climate modeling centers and individual groups are welcome to participate in the study by contributing model results, observational data, and/or analyses. Results can be summarized in papers in regular journals.

4. References

Bretherton, C. S., M. E. Peters, and L. E. Back, 2004: Relationships between water vapor path and precipitation over the tropical oceans. Journal of Climate, 17, 1517–1528.

Covey C., et al. 2016: Metrics for the Diurnal Cycle of Precipitation: Toward Routine Benchmarks for Climate Models. https://doi.org/10.1175/JCLI-D-15-0664.1.

Greets B. et al. 2017. The 2015 Plain Elevated Convection At Night field project. *Bull. Amer. Meteor. Soc.,* 98, 767–786, https://doi.org/10.1175/BAMS-D-15-00257.1.

Holloway, C. E., and J. D. Neelin, 2009: Moisture Vertical Structure, Column Water Vapor, and Tropical Deep Convection. Journal of the Atmospheric Sciences, 66, 1665–1683.

Tang, S., S. Xie, et al. 2016: Large-Scale Vertical Velocity, Diabatic Heating and Drying Profiles Associated with Seasonal and Diurnal Variations of Convective Systems Observed in the GoAmazon2014/5 Experiment, Atmos. Chem. Phys. Discuss., 2016, 1-39, doi: 10.5194/acp-2016-644.

Xie, S., T. Hume, C. Jakob, S. Klein, R. McCoy, and M. Zhang, 2010: Observed large-scale structures and diabatic heating and drying profiles during TWP-ICE, J. climate, 23, 57-79, doi:10.1175/2009JCLI3071.1.

Xie, S., Y. Zhang, S. E. Giangrande, M. P. Jensen, R. McCoy, and M. Zhang, 2014: Interactions between Cumulus Convection and Its Environment as Revealed by the MC3E Sounding Array. J. Geophys. Res. Atmos., 119, 11784–11808, doi: 10.1002/2014JD022011.

Zhang Y., and Klein, 2010: Mechanisms affecting the transition from shallow to deep convection over land: Inferences from observations of the diurnal cycle collected at the ARM Southern Great Plains site. J. Atmos. Sci., 67, 2943–2959, https://doi.org/10.1175/2010JAS3366.1.

Zhang Y., and Klein 2013: Factors controlling the vertical extent of fair weather shallow cumulus clouds over land: Investigation of diurnal-cycle observations collected at the ARM Southern Great Plains site. J. Atmos. Sci., 70, 1297–1315, https://doi.org/10.1175/JAS-D-12-0131.1.

Zhang, Y., S. A. Klein, J. Fan, A. Chundra, P. Kollias, S. Xie and S. Tang, 2017: Large-eddy simulation of shallow cumulus clouds over land: A composite case based on ARM long-term observations at its Southern Great Plains site. J. Atmos. Sci., 74, 3229-3251, DOI: 10.1175/JAS-D-16-0317.1.