Improving Convection and Cloud Parameterization Using ARM Observations and NCAR Community Atmosphere Model CAM5

Final Technical Report for DOE Award DE-SC0008880

Principal Investigator: Guang Zhang
University of California San Diego
09/01/2012 through 08/31/2016

The fundamental scientific objectives of our research are to use ARM observations and the NCAR CAM5 to understand the large-scale control on convection, and to develop improved convection and cloud parameterizations for use in GCMs. We are very successful in achieving our objectives. The following is a list of our accomplishments:

- Our ASR supported research resulted in 16 refereed journal publications and 1 book chapter.
- We evaluated convective trigger functions and closures used in major GCMs using ARM data and CRM simulation.
- We evaluated the effects of convective microphysics parameterization on simulation of clouds and hydrological cycle
- We used the improved Zhang-McFarlane convection scheme to investigate its effect on MJO simulation in CAM5.
- We estimated convective entrainment rates and entrained properties for use in convective parameterization using CRM and LES simulations of convection for TWP-ICE.
- We have actively participated in the ASR Science Team meetings and Cloud Lifecycle Working Group activities.

Below is a summary of our research results:

1. We evaluated convective trigger functions using ARM data (Suhas and Zhang 2014)

Realistic simulation of different modes of atmospheric variability ranging from diurnal cycle to inter-annual variability in GCMs depends crucially on the convection trigger criteria. In this work, we used the ARM single column model forcing data to evaluate the performance of the commonly used convective trigger functions in major GCMs in the world. Using a statistical skill score, three consistently better performing trigger functions were identified. They are based on dilute and undilute convective available potential energy (CAPE) generation rate from large-scale forcing in the free troposphere (hereafter dCAPE), and parcel buoyancy at the lifting condensation level (Bechtold scheme). The key variables used to define these trigger functions are examined in detail. It is found that the dilute dCAPE trigger function performs the best consistently in both tropical and midlatitude convection environment. Composite fields and probability distributions of key variables of the trigger functions, based on the correct-prediction, over-prediction, under-prediction of convection and correct prediction of no-convection cases for convection onset are examined.

2. We developed a diagnostics method to relate model simulation biases to model physics deficiencies and tested it on MJO simulation using AMIE/DYNAMO observations (Subramanian and Zhang 2014)

In this work, we developed a diagnostic method to understand model physics deficiencies from model simulation biases using a nudging technique. We showed that by nudging the model-simulated fields to reanalysis or observational data the nudging tendencies can be used to measure model physics parameterization errors. The diagnosis of such nudging tendencies provides an efficient and objective way to identify model biases, which can be used to guide the model physics parameterization development. We ran a series of numerical hindcast experiments using the NCAR CAM3 and compared with AMIE/DYNAMO IOP observations. Our nudging experiments indicate that getting the circulation fields right is the most important to MJO simulation, followed by the moisture field, while biases in temperature field appear to be the least important.

3. We evaluated convective closures using cloud-resolving model simulation of TWP-ICE convection (Suhas and Zhang 2015)

Closure is an important component of a mass flux-based convective parameterization scheme and it determines the amount of convection with the aid of a large-scale variable (closure variable) that is sensitive to convection. In this study, we have evaluated and quantified the relationship between commonly used closure variables and convection for a range of global climate model (GCM) horizontal resolutions. We have used cloud resolving model simulation data to create domain averages representing different GCM horizontal resolutions down to the grey-zone (<10 km) scale. Lead-lag correlation analysis shows that except moisture convergence and turbulent kinetic energy (TKE), none of the other closure variables evaluated in this study show any relationship with convection for the six subdomain sizes. It is found that the correlation between moisture convergence and convective precipitation is largest when moisture convergence leads convection. This correlation weakens as the subdomain size decreases to 8 km or smaller. Although convective precipitation and mass flux increase with moisture convergence at a given subdomain size, as the subdomain size increases, the rate at which they increase becomes smaller. This suggests that moisture convergence-based closure should scale down the predicted convective precipitation for given moisture convergence as GCM resolution increases.

4. We evaluated the effects of convective microphysics parameterization on simulation of clouds and hydrological cycle (Storer et al. 2015)

The two-moment microphysics scheme for deep convection that we developed for CAM5 (Song et al. 2012) improved hydrometeor profiles in deep convective clouds and increased deep convective detrainment, reducing the negative biases in low and mid-level cloud fraction and liquid water path compared to observations. In this work, we examine in more detail the impacts of this improved microphysical representation on regional scale water and radiation budgets. As a primary source of cloud water for stratiform clouds is detrainment from deep and shallow convection, the enhanced detrainment leads to larger stratiform cloud fractions, higher cloud water content, and more stratiform precipitation over the ocean. This leads to an increased net cloud radiative forcing. Over land regions, cloud amounts are reduced due to lower relative humidity, leading to weaker cloud forcing and increased OLR. Comparing the water budgets to cloud resolving model simulations shows improvement in the partitioning between convective and stratiform precipitation, though the deep convection is still too active in the GCM. The addition of convective microphysics leads to an overall improvement in the regional cloud water budgets.

5. We investigated the dependence of convective transport on GCM resolution using WRF simulations of MC3E and TWP-ICE convection (Liu et al. 2015)

We examined the scale dependence of eddy transport of water vapor to improve the representation of convective transport across all scales. Results show that there are strong grid-spacing dependencies of updraft and downdraft fractions regardless of altitudes, cloud life stage, and geographical location. As for the eddy transport of water vapor, updraft eddy flux is a major contributor to total eddy flux in the lower and middle troposphere. However, downdraft eddy transport can be as large as updraft eddy transport in the lower atmosphere especially at the mature stage of midlatitude continental convection. We show that the single-updraft approach significantly underestimates updraft eddy transport of water vapor because it fails to account for the large internal variability of updrafts, while a single downdraft represents the downdraft eddy transport of water vapor well. We find that using as few as three updrafts can account for the internal variability of updrafts well.

6. We tested the effect of convective microphysics parameterization scheme on MJO hindcasts in CAM5 (Klingaman et al. 2015)

Diabatic heating through microphysical processes is known to be important to MJO evolution. We investigated how condensational heating from microphysical processes in convection affects MJO hindcast in CAM5 in an MJO intercomparison project that we participated in. The short-term MJO hindcasts indicate that with the inclusion of convective microphysics the hindcast skills are improved considerably. Fig. 1 shows the hindcast lead-time for different models participating in the comparison. The NCAR CAM5 that incorporates convective microphysics (blue line labeled CZ) has the longest forecast lead-time, about 20 days.

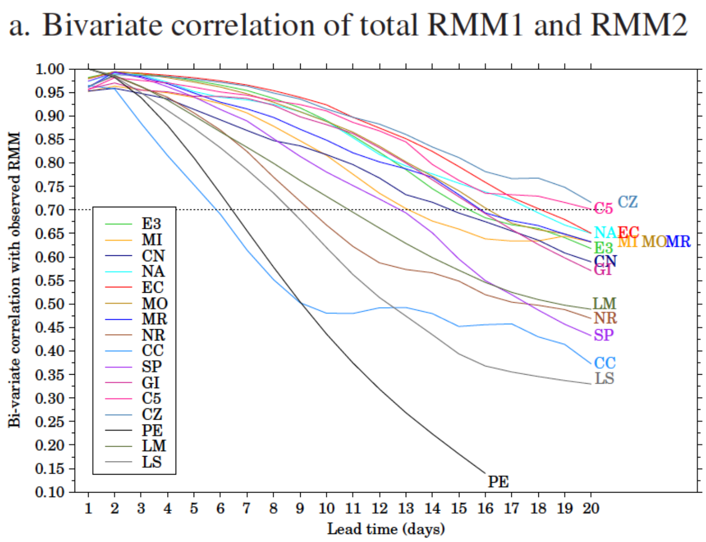

Fig. 1: Hindcast lead time of Wheeler-Hendon MJO index (RMM1 and RMM2) for different models participating in the diabatic heating intercomparison project. The NCAR CAM5 with Song and Zhang (2011) convective microphysics scheme is the blue line labeled CZ (from Klingaman et al. 2015). It has the best performance among the participating models in terms of forecast lead-time.

7. We estimated the entrainment rates and entrained thermodynamic properties for convective parameterization using CRM and LES simulations for TWP-ICE (Zhang et al. 2015)

Entrainment of air into convective clouds is very important to convection simulation in GCMs. Current convective parameterization schemes assume a variety of entrainment profiles. Furthermore, entrained air is assumed to carry environmental mean thermodynamic properties. Since these assumptions are critical to sensitivity of simulated convection to environmental moisture, in this work we estimated the entrainment rates using a 1-km-resolution cloud-resolving model (CRM) simulation of convective clouds from TWP-ICE. High-resolution (100 m) large-eddy simulation of TWP-ICE convection was also analyzed. The clouds are divided into different types, characterized by cloud-top heights. We analyzed the output of a cloud-resolving model simulation of convective clouds during TWP-ICE to estimate convective entrainment rates and entrained properties. We found that the entrained air is a mixture of approximately equal amount of cloud air and environmental air, and the detrained air is a mixture of ~ 80% of cloud air and 20% of the air with saturation moist static energy at the environmental temperature. Further, entrainment rate is much larger than often used in bulk-plume models and decreases with height for each cloud type.

8. We coupled a stochastic convective parameterization scheme with the Zhang-McFarlane scheme and incorporated it into the NCAR CAM5 to improve precipitation simulation (Wang et al. 2016)

As climate model resolutions increase, the stochasticity of convection in a GCM gridbox at a given time becomes more prominent, conventional, deterministic convective parameterization schemes will become inadequate. With this in mind, we coupled a stochastic convection scheme with the Zhang-McFarlane deterministic convection scheme and implemented it into the NCAR CAM5. Results show that the stochastic parameterization decreases the frequency of weak precipitation and increases the frequency of intense precipitation, largely eliminating the well known too-much-drizzle problem in CAM5. In the global tropical belt, the precipitation intensity PDF from the simulation incorporating stochastic convection parameterization agrees remarkably well with that of TRMM observations.

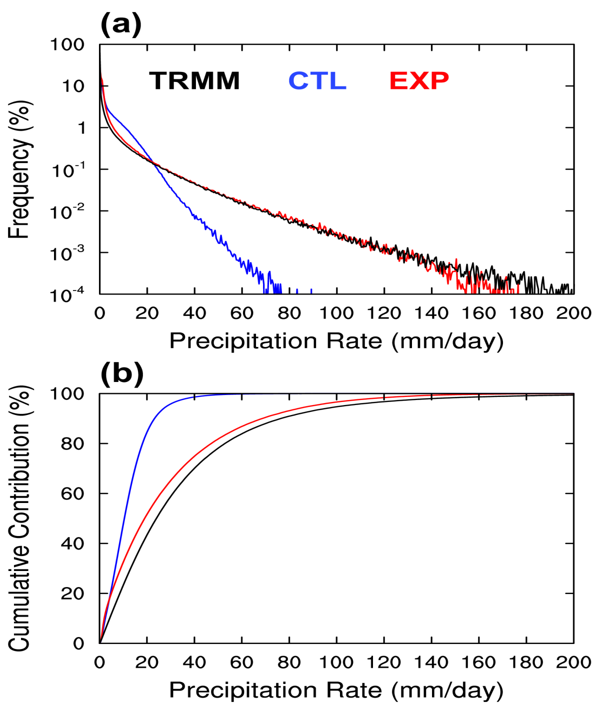

Fig. 2: (a) Frequency distribution of precipitation rates and (b) cumulative contribution from each binned precipitation rate based on daily mean precipitation data. The results are for the global belt of 20°S-20°N from the Tropical Rainfall Measurement Mission (TRMM) observation (black line), the standard CAM5 simulation (blue line) and the CAM5 simulation with stochastic convective scheme (EXP, red line). In both pdf (a) and cumulative distribution (b) EXP simulation is in excellent agreement with TRMM observations.

Refereed journal and book chapter publications resulting from ASR funded research:

1. Davies, L. C. Jakob, K. Cheung, A. Del Genio, A. Hill, T. Hume, R.J. Keane, T. Komori, V. E. Larson, Y. Lin, X. Liu, B. J. Nielsen, J. Petch, R. S. Plant, M. S. Singh, X. Shi, X. Song, W. Wang, M. A. Whitall, A. Wolf, S. Xie, G. Zhang, 2013: A single column model ensemble approach applied to the TWP-ICE experiment. *J. Geophys. Res*., *118*, 6544–6563, doi:10.1002/jgrd.50450.
2. Zhang, G.J., M. Cai, and A. Hu, 2013: Energy consumption and the unexplained winter warming over northern Asia and North America. *Nature Climate Change*, **3**, 466-470, DOI:10.1038/NCLIMATE1803.

3. Song, X., G. J. Zhang, and M. Cai, 2014: Characterizing the climate feedback pattern in the NCAR CCSM3-SOM using hourly data. *J. Climate*, **27**, 2912- 2930, DOI: 10.1175/JCLI-D-13-00567.1.
4. Lim, K.-S., J. Fan, L. R. Leung, P.-L. Ma, B. Singh, C. Zhao, Y. Zhang, G. J. Zhang, and X. Song, 2014: Investigation of aerosol indirect effects using a cumulus microphysics parameterization in a regional climate model, *J. Geophys. Res*., **119**, 906–926, doi:10.1002/2013JD020958.
5. Subramanian, A., and G. J. Zhang, 2014: Diagnosing MJO Hindcast Biases in NCAR CAM3 Using Nudging During the DYNAMO Field Campaign. *J. Geophys. Res. Atmos*., **119**, doi:10.1002/2013JD021370.
6. Song, X. and G. J. Zhang, 2014: Role of Climate Feedback in El Niño-like SST Response to Global Warming, *J. Climate*, 27, 7301-7318, DOI: 10.1175/JCLI-D-14-00071.1.
7. Suhas, E., and G. J. Zhang, 2014: Evaluation of trigger functions for convective parameterization schemes using observations. *J. Climate*, **27**, 7647-7666, DOI: 10.1175/JCLI-D-13-00718.1.
8. Suhas, E., and G. J. Zhang, 2015: Evaluating convective parameterization closures using cloud-resolving model simulation of tropical deep convection, *J. Geophys. Res. Atmos*., **120**, doi:10.1002/2014JD022246.
9. Fan, J. Y.-C. Liu, K.-M. Xu, K. North, S. Collis, X. Dong, G. J. Zhang, Q. Chen, P. Kollias, and S. Ghan, 2015: Improving representation of convective transport for scale-aware parameterization: 1. Convective and cloud properties simulated with spectral bin and bulk microphysics, *J. Geophys. Res. Atmos*., 120, doi:10.1002/2014JD022142.
10. Liu, Y.-C., J. Fan, G. J. Zhang, K.-M. Xu, and S. Ghan, 2015: Improving representation of convective transport for scale-aware parameterization: 2. Analysis of cloud-resolving model simulations. *J. Geophys. Res. Atmos*., 120, doi:10.1002/2014JD022145.
11. Klingaman, N. P., S. J. Woolnough, X. Jiang, et al. (G. J. Zhang), 2015: Vertical structure and physical processes of the Madden–Julian oscillation: Linking hindcast fidelity to simulated diabatic heating and moistening. *J. Geophys. Res. Atmos.*, 120, doi:10.1002/2014JD022374.
12. Zhang, G. J., J. Fan, K.-M. Xu, 2015: Comments on "A unified representation of deep moist convection in numerical modeling of the atmosphere. Part I". *J. Atmos. Sci*., **72**, 2562-2565.
13. Zhang, G. J., and X. Song, 2015: Parameterization of Microphysical Processes in Convective Clouds in Global Climate Models, *Amer. Met. Soc. Monograph* Eds. R. Fovell and W.-W. Tung, 56, 12.1-12.18, DOI: 10.1175/AMSMONOGRAPHS-D-15-0015.1.
14. Storer, R., G. J. Zhang, and X. Song, 2015: Effects of Convective Microphysics Parameterization on Large-scale Cloud Hydrological Cycle and Radiative Budget in Tropical and Midlatitude Convective Regions, *J. Climate*, **28**, 9277-9297. doi: http://dx.doi.org/10.1175/JCLI-D-15-0064.1.
15. Zhang, G. J., X. Wu, X. Zeng, and T. Mitovski, 2015: Estimation of convective entrainment properties from a cloud-resolving model simulation during TWP-ICE. *Clim. Dyn*., DOI 10.1007/s00382-015-2957-7.
16. Lu, C. Y. Liu, G. J. Zhang, X. Wu, S. Endo, L. Cao, Y. Li, and X. Guo, 2015: Improving parameterization of entrainment rate for shallow convection with aircraft measurements and large-eddy simulations. *J. Atmos. Sci*., doi: http://dx.doi.org/10.1175/JAS-D-15-0050.1.
17. Wang, Y., G. J. Zhang, and G. Craig, 2016: Stochastic convective parameterization improving the simulation of tropical precipitation variability in the NCAR CAM5, Geophys. Res. Lett., 43, doi:10.1002/2016GL069818.