DOE ASR Final Report

Project Title "Improving GCM Representation of Convective Cloud Microphysics by Using ARM Raman Lidar and Cloud Radar Observations"

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Major goals of the project

The overall objective of this Department of Energy (DOE) Atmospheric System Research (ASR) funded project is to improve the representation of convective cloud microphysics in global climate models (GCMs) and check it by comparing the model simulations with observations. We have derived the cloud ice water content by synthesizing ARM Raman lidar (RL) and cloud radar observations at the Atmospheric Radiation Measurement (ARM) sites. Noting that the simulated anvil clouds in terms of their macro- and micro-physical properties are sensitive to the parameterization of convective microphysical processes, observed ice water content in anvil clouds provides a useful constraint on these parameterizations. We have improved the convective microphysics parameterization scheme by (1) considering sedimentation for cloud ice crystals that do not fall in the original scheme, (2) applying a new terminal velocity parameterization that depends on the environmental conditions for convective snow, (3) adding a new hydrometeor category, "rimed ice," to the original four-class (cloud liquid, cloud ice, rain, and snow) scheme, and (4) allowing convective clouds to detrain snow particles into stratiform clouds. We have examined the impact of improved convective cloud microphysics parameterization on the simulated global climate from GCM simulations.

Main Accomplishments and Results

1.A convective microphysics parameterization was recently developed and implemented into the NCAR CAM5. By examining and testing this parameterization scheme, we found that it does not consider the convective snow detrainment, and does not consider the falling velocity of convective cloud-ice particles. Furthermore the convective snow falling velocity in the parameterization is based on that for straitiform clouds. We have improved this convective microphysics parameterization and tested it with the ARM observations.

Partitioning deep convective cloud condensates into components that sediment and detrain, known to be a challenge for global climate models, is important for cloud vertical distribution and anvil cloud formation. Here we address this issue by improving the convective microphysics scheme in the National Center for Atmospheric Research Community Atmosphere Model version 5.3 (CAM5.3). The improvements include: (1) considering sedimentation for cloud ice crystals that do not fall in the original scheme, (2) applying a new terminal velocity parameterization that depends on the environmental conditions for convective snow, (3) adding a new hydrometeor category, "rimed ice," to the original four-class (cloud liquid, cloud ice, rain, and snow) scheme, and (4) allowing convective clouds to detrain snow particles into stratiform clouds. Results from the default and modified CAM5.3 models were evaluated against observations from the U.S. Department of Energy Tropical Warm Pool International Cloud Experiment (TWP-ICE) field campaign. The default model overestimates ice amount, which is largely attributed to the underestimation of convective ice particle sedimentation. By considering cloud ice sedimentation and rimed ice particles and applying a new convective snow terminal velocity parameterization, the vertical distribution of ice amount is much improved in the mid-troposphere and upper troposphere when compared to observations. The vertical distribution of ice condensate also agrees well with observational best estimates upon considering snow detrainment. Comparison with observed convective updrafts reveals that current bulk model fails to reproduce the observed updraft magnitude and occurrence frequency, suggesting spectral distributions be required to simulate the sub-grid updraft heterogeneity.

This work was reported in Lin et al. (2021, JGR). This paper was highlighted in the ARM Annual Report.

2. We have evaluated the impacts of the improved convective microphysics parameterizations in the NCAR Community Atmosphere Model version 5.3 (CAM5.3), with a focus on the simulated cloud radiative forcing, convective cloud ice amount, and tropical precipitation.

Compared to CAM5.3 with the use of the default convective microphysics, the overestimated shortwave cloud radiative forcing due primarily to excessive convective cloud liquid is largely removed over both tropics and midlatitudes because of enhanced rain initiation and generation rate, in better agreement with the CERES-EBAF estimates. Geographic distributions of graupel occurrence frequency are well simulated over continents; whereas the graupel occurrence frequency remain uncertain over the oceanic storm track regions. The overestimation of convective ice mass is alleviated with the improvements in the convective ice microphysics parameterizations, among which adding graupel microphysics and the accompanying increase in hydrometeor fall speed play the most important role in reducing the convective ice mass overestimation in the middle and upper troposphere when evaluated against the CloudSat-CALIPSO estimates. The probability distribution function (PDF) of rainfall intensity is sensitive to warm rain processes in convective clouds and enhancement in warm rain formation shifts the PDF toward heavier precipitation, which compares better with TRMM observations. The common bias of overestimated light rain frequency and underestimated heavy rain frequency seen in GCMs is mitigated.

This work was reported in Lin et al. (2022, to be submitted to JGR).

3. We have also examined the ice clouds observed from the CALIPSO with the ground-based Raman lidar at the ARM SGP and TWP Sites, explored the optically thin ice clouds, and investigated the role of clouds in determining the tropical tropopause layer temperature structure.

Ice cloud column optical depths from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite and ground-based Raman lidars (RLs) at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) and Tropical Western Pacific (TWP) sites are compared for 8 and 4 years, respectively. The cloudy mean ice cloud column optical depths from CALIPSO Version 4 data product with a horizontal resolution of 5 km are 78% (63%) larger than those from the RLs with a resolution of 10 min/30 m at SGP (TWP) for collocated transparent profiles. The main difference at SGP is caused by the lidar ratio that for CALIPSO is related to its treatment of the multiple scattering factor. The main difference at TWP is caused by the averaging resolution. Large differences in the optical depth distribution between the CALIPSO and RL are found for small optical depths at both sites, which are due to optically very thin clouds only detectable by the RLs. The differences in ice cloud column optical depth distributions and their mean values between the CALIPSO and RL can largely be reconciled over both sites after accounting for the averaging resolutions, lidar ratios along with the CALIPSO multiple scattering factor treatment, sensitivity to optically very thin ice clouds, and definition of transparent profiles. This work also examines in detail the lidar ratios that are directly observed by the RLs, which does not support the temperature-dependent parameterizations of ice cloud lidar ratio and multiple scattering factor used in CALIPSO's Version 4 data product.

A single-column radiative-convective model (RCM) is a useful tool to investigate the physical processes that determine the tropical tropopause layer (TTL) temperature structures. Previous studies on the TTL using the RCMs, however, omitted the cloud radiative effects. In this study, we examine the impact of cloud radiative effects on the simulated TTL temperatures using an RCM. We derive the cloud radiative effects based on satellite observations, which show heating rates in the troposphere but cooling rates in the stratosphere. We find that the cloud radiative effect warms the TTL by as much as 2 K but cools the lower stratosphere by as much as -1.5 K, resulting in a thicker TTL. With (without) considering cloud radiative effects, we obtain a convection top of 167 hPa (150 hPa) with a temperature of 213 K (209 K), and a cold point at 87 hPa (94 hPa) with a temperature of 204 K (204 K). Therefore, the cloud radiative effects widen the TTL by both lowering the convection-top height and enhancing the cold-point height. We also examine the impact of TTL cirrus radiative effects on the RCM-simulated temperatures. We find that the TTL cirrus warms the TTL with a maximum temperature increase of 1.3 K near 110 hPa.

Optically very thin ice clouds from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and ground-based Raman lidars (RL) at the atmospheric radiation measurement (ARM) sites of the Southern Great Plains (SGP) and Tropical Western Pacific (TWP) are analyzed. The optically very thin ice clouds, with ice cloud column optical depths below 0.01, are about 23% of the transparent ice-cloudy profiles from the RL, compared to 4–7% from CALIPSO. The majority (66–76%) of optically very thin ice clouds from the RLs are found to be adjacent to ice clouds with ice cloud column optical depths greater than 0.01. The temporal structure of RL-observed optically very thin ice clouds indicates a clear sky–cloud continuum. Global cloudiness estimates from CALIPSO observations leveraged with high-sensitivity RL observations suggest that CALIPSO may underestimate the global cloud fraction when considering optically very thin ice clouds.

The above efforts were reported in Balmes et al. (2019, JGR), Fu et al. (2018, Atmsophere), and Balmes and Fu (2018, Atmosphere).

Opportunities for training and professional development that the project has provided

This project supported three graduate students who received rigorous training on the convective cloud microphysics parameterization, and retrievals of ice cloud water content by using ground-based cloud radar and Raman lidar observations. Lin Lin, who is scheduled to defend her Ph.D. in early 2022, was fully supported by this project, and Wei Zhao and Kelly Balmes, who received their Ph.D. in 2020 and 2021, respectively, were in part supported by this project.

How have the results been disseminated to communities of interest

The results have been disseminated to communities of interest mainly through the scientific journal publications and presentations in the scientific conferences.

1) Publications Acknowledging *the Office of Science (BER), U.S. Department of Energy: Grant DE-SC0018190*

Lin, L., Q. Fu, X. Liu, and Y. Shan, 2022: Global climate impacts of improved convective cloud microphysics parameterizations in the NCAR CAM5. J. Geophys. Res. Atmos., 126 (to be submitted).

Lin, L., Q. Fu, X. Liu, Y. Shan, S. E. Giangrande, G. S. Elsaesser, K. Yang, and D. Wang, 2021: Improved convective ice microphysics parameterization in the NCAR CAM model. J. Geophys. Res. Atmos., 126, doi:10.1029/2020JD034157.

Na, Y., R. Lu, Q. Fu, and C. Kodama, 2021: Precipitation Characteristics and Future Changes Over the Southern Slope of Tibetan Plateau Simulated by a High-Resolution Global Nonhydrostatic Model. J. Geophys. Res. Atmos., 126, 3, doi:10.1029/2020JD033630.

Balmes, K. A., and Q. Fu, 2020: The diurnally-averaged aerosol direct radiative effect and the use of the daytime-mean and insolation-weighted-mean solar zenith angles. J. Quant. Spectrosc. Radiat. Transfer, 257, doi:10.1016/j.jqsrt.2020.107363.

Na, Y., Q. Fu, and C. Kodama, 2020: Precipitation Probability and Its Future Changes From a Global Cloud-Resolving Model and CMIP6 Simulations. J. Geophys. Res. Atmos., 125, 5, doi:10.1029/2019JD031926.

Balmes, K. A., Q. Fu, and T. J. Thorsen, 2019: Differences in Ice Cloud Optical Depth From CALIPSO and Ground-Based Raman Lidar at the ARM SGP and TWP Sites. J. Geophys. Res. Atmos., 124, 1755-1778, doi:10.1029/2018JD028321.

Fu, Q., M. Smith, and Q. Yang, 2018: The Impact of Cloud Radiative Effects on the Tropical Tropopause Layer Temperatures. Atmosphere, 9, 377, doi:10.3390/atmos9100377.

Balmes, K. A., and Q. Fu, 2018: An Investigation of Optically Very Thin Ice Clouds from Ground-Based ARM Raman Lidars. Atmosphere, 9, 445, doi:10.3390/atmos9110445.

2) ARS STM Presentations

Lin, L., Q. Fu, X. Liu, Y. Shan, S. Giangrande, G. S. Elsaesser, K. Yang and D. Wang: Improved convective ice microphysics parameterization for GCMs. ARM/ASR Joint User Facility/Principal Investigator Meeting. June 21-24, 2021 (virtual).

Lin, L., Q. Fu, X. Liu, Y. Shan, S. Giangrande, G. S. Elsaesser, K. Yang and D. Wang: Improved convective ice microphysics parameterization in the NCAR CAM model. ARM/ASR Joint User Facility/Principal Investigator Meeting. June 23-26, 2020 (virtual).

Lin, L., Q. Fu, X. Liu, and Y. Shan, 2019: Effects of Convective Ice Fall Velocity and Detrainment on Anvil Clouds: Single-Column Model Testing with NCAR CAM6 Evaluated with the ARM TWP-ICE and MC3E Data. The 2019 ARM/ASR Joint User Facility/PI Meeting, June 10-13, 2019, Rockville, MD.

Zhao, W., R. Marchand, Q. Fu, 2019: The Effect of Spatial Variability on Autoconversion and Accretion rate in Eastern North Atlantic Boundary Layer Clouds. The 2019 ARM/ASR Joint User Facility/PI Meeting, June 10-13, 2019, Rockville, MD.

Zhao, W., K.A. Balmes, Q. Fu, R. Marchard and J.M. Comstock, 2018: Retrieval of Ice Water Content in Convective Outflow Anvil Clouds Using Raman Lidar and Cloud Radar. 2018 ARM/ASR Joint User Facility/PI Meeting, March 19 to 23, 2018, Tysons, Virginia**.**

Zhao, W., R. Marchand, Q. Fu, E. Luke and P. Kollias, 2018: Spatial Covariance of Cloud and Precipitation Liquid Water Content at the ARM ENA Site. 2018 ARM/ASR Joint User Facility/PI Meeting, March 19 to 23, 2018, Tysons, Virginia**.**