Title of Grant:

Use of Remote Sensing and In-Situ Observations to Develop and Evaluate Improved Representations of Convection and Clouds for the ACME Model

Grant number:

Award No. DE-SC0016304

Type of report:

Final Technical Report

Name of the principal investigator:

Dr. Xiaohong Liu
University of Wyoming

Name and address of the recipient's institution:

Prof. Xiaohong Liu
Department of Atmospheric Science
University of Wyoming
Laramie, WY 82071
Tel: 307-766-3225
Email: xliu6@uwyo.edu

Sponsoring program office:

Dr. Shaima Nasiri, Program Manager, Office of Biological & Environmental Research, Atmospheric System Research Program

Executive Summary

The overachieving goal of the whole CMDV-MCS project is to improve understanding of warm season continental convection and to develop treatments of convection and microphysics capable of representing mesoscale convective systems (MCSs) features in large-scale models. Our tasks for this project contributing to the overachieving goal include: (1) Improve the ice nucleation formulation for MG2 and P3 cloud microphysics schemes; (2) Improve the treatment of subgrid dynamics and thermodynamics driving the ice nucleation in E3SM; and (3) Test the performance of improved ice microphysics in E3SM with observation data. In this project, we have

(1) *Improved the ice nucleation parameterization for MG2 and P3 in E3SM* by implementing two advanced empirical parameterizations with connection to aerosols. The two deterministic heterogeneous ice nucleation parameterizations (i.e., DeMott et al., 2015; Niemand et al., 2012) were merged with the MG2 and P3 cloud microphysics schemes in E3SM. Long-term simulations were conducted to examine the impacts of these new parameterizations on simulated cloud properties;

(2) *Improved the treatment of subgrid dynamics and thermodynamics driving the ice nucleation in E3SM*. We evaluated the double Gaussian PDF of vertical velocity simulated by the Cloud Layers Unified By Binormals (CLUBB) and the sub-column vertical velocity sampled from the Subgrid Importance Latin Hypercube Sampler (SILHS) in E3SM. We introduced the vertical velocity variance induced by topographic gravity waves for ice nucleation and droplet activation; and

(3) *Tested the performance of improved ice microphysics in E3SM with observation data*. We tested the new treatments of ice nucleation in the single column model (SCM) mode for the stratiform mixed-phase clouds observed during 9-10 October 2004 in the DOE ARM Mixed-Phase Arctic Cloud Experiment (M-PACE) and for the convective clouds observed on 20 May 2011 in the Midlatitude Continental Convective Clouds Experiment (MC3E). Modeled ice nucleating particles (INPs) concentrations were compared against observations collected around the globe.

Project Accomplishments:

(1) Improve the ice nucleation formulation for MG2 and P3

We have improved the current stochastic ice nucleation parameterization in mixed-phase clouds (CNT) in E3SM by implementing two advanced empirical parameterizations with connection to aerosols. The two deterministic heterogeneous ice nucleation parameterizations (i.e., DeMott et al., 2015; Niemand et al., 2012) were merged with the MG2 and P3 cloud microphysics schemes in E3SM.

We have conducted multi-year simulations using CNT (default scheme in E3SM version 1) and the two new parameterizations in E3SM version 1 (v1) and E3SM version 0 (v0) to examine the influence of these new schemes on model clouds and global climate. Because of the efficient dust transport to northern hemispheric (NH) high latitudes in E3SM v1, this model presents significantly higher (by nearly 50 times) ice nucleating particle (INP) concentrations than E3SM v0 in the Arctic regions. As a result, the Arctic regions show a 20% difference in liquid water path (LWP) and a 10% difference in cloud

radiative forcing between the three ice schemes in E3SM v1, which are not seen in E3SM v0. This was also the case when we nudged the two model versions' winds toward MERRA2 reanalysis. The global impacts on LWP and cloud radiative forcing were also assessed. Since P3 will be the default scheme for E3SM v3 and v4, quantifications of these impacts on clouds, precipitation and climate are important for the future E3SM model developments.

(2) Improved the treatment of subgrid dynamics and thermodynamics driving the ice nucleation in E3SM

We evaluated the double Gaussian PDF of vertical velocity simulated by the Cloud Layers Unified By Binormals (CLUBB) in E3SM v1. The estimated vertical velocity variance in CLUBB is generally smaller than that predicted by the Univ. Washington (Bretherton and Park) turbulence scheme used in E3SM v0. Without applying an artificial lower bound value, the simulated updraft velocity PDF gives a lower estimate of ice nucleate rate for cirrus clouds.

The sub-column values sampled from the Subgrid Importance Latin Hypercube Sampler (SILHS) were also evaluated. Results show that SILHS sampled values have some numerical noises and sometimes the solution doesn't converge with increasing number of sub-columns due to the sampling noise. Based on this result, we decided to use the explicit numerical integration or the quadrature method based on the predicted vertical velocity-variances by CLUBB.

We collaborated with Dr. Julio Bacmeister at NCAR to introduce the vertical velocity-variance induced by topographic gravity waves for cloud formation (i.e., ice nucleation and droplet activation). The model implementation was finished. Impacts on the model performance were evaluated by comparison with observations of ice cloud properties.

(3) Tested the performance of improved ice microphysics in E3SM with Observation data

Since the understanding of aerosols (dust) transport is crucial to the new treatments of ice nucleation, we tested the simulated dust distribution with ground-based observations at high latitudes and the NASA CALIPSO data. Although E3SM v1 still underestimates the dust burden at the Arctic regions, it agrees much better with both surface and CALIPSO observations than E3SM v0. This provides a more realistic aerosol background to the heterogeneous ice nucleation parameterizations in E3SM v1.

In addition, we tested the new treatments of ice nucleation in the single column model (SCM) mode for the stratiform mixed-phase clouds observed during 9-10 October 2004 in the DOE ARM Mixed-Phase Arctic Cloud Experiment (M-PACE) and for the convective clouds observed on 20 May 2011 in the Midlatitude Continental Convective Clouds Experiment (MC3E). The new ice nucleation parameterizations substantially increase LWC and agree much better with ARM ground-based remote sensing observations than the default treatment. The model can well simulate the phase partitioning in these clouds.

We collected the INP observation data from all over the globe, especially in the high latitude regions, to test the performance of the new parameterizations in E3SM v1. We

have run the E3SM model with the high frequency output of INP concentrations near the Storm Peak Laboratory for the comparison with INP data obtained during the Fifth International Workshop on Ice Nucleation-Phase 3 (FIN-3).

Peer-Reviewed Publications Acknowledging the Funding Support from This Project (project members are highlighted in bold fond)

1. **Shi, Y., and X. Liu** (2019), Dust radiative effects on climate by glaciating mixed-phase clouds, *Geophysical Research Letters*, *46*, 6128–6137, https://doi.org/10.1029/2019GL082504.

2. **Liu, X., and X. Shi**, 2018: Sensitivity of ice crystal number from homogeneous nucleation to aerosol perturbation and implications for aerosol indirect effects through cirrus clouds, *Geophysical Research Letter*, *45*, 1684–1691, https://doi.org/10.1002/2017GL076721.

3. Zhao, B., K.-N. Liou, Y. Gu, Q. Li, J. H. Jiang, L. Huang, **X. Liu, X. Shi**, H. Su, and C. He, 2018: Impact of aerosols on ice crystal size, *Atmospheric Chemistry and Physics*, 18, 1065–1078, https://doi.org/10.5194/acp-2017-548.

4. **Shi, X., and X. Liu**, Sensitivity study of anthropogenic aerosol indirect forcing through cirrus clouds with Community Atmosphere Model version 5, *Journal of Meteorological Research*, 32(5), 693–706, doi: 10.1007/s13351-018-8011-z.

Presentations Acknowledging the Funding Support from This Project (project members are highlighted in bold fond)

1. Liu, X., Shi, Y., Wu, M., Wang, Z., Zhang, D., and Vogelmann, A. M., "Dust glaciation effects on mixed-phase clouds with a global climate model constrained by observations". AMS 99th annual meeting, Phoenix, Jan. 6-10, 2019.

2. Liu, X., "Simulating mixed-phase clouds at high latitudes: model evaluation, improvement, and interactions with aerosol", seminar at Brookhaven National Laboratory (BNL), Upton, NY, Apr. 11, 2019.

3. Liu, X. and Y. Shi, "Dust transport in E3SM version1 and version0 and impacts on clouds properties", 2018 ARM/ASR PI Meeting, March 19-23, 2018.

4. Liu, X., Y. Shi, M. Wu, and K. Zhang, "Responses of mixed-phase cloud condensates and cloud radiative effects to ice nucleating particle concentration in NCAR CAM5 and DOE ACME climate models", 2017 AGU Fall Meeting, December 11-15, 2017.

5. Jiwen Fan, X. Liu, M. Paukert, P. Rasch, and K. Zhang, "Cloud microphysics developments under CMDV-MCS", 2017 ARM/ASR PI Meeting, March 13-17, 2017.

6. Yang Shi, Xiaohong Liu, Mingxuan Wu, and Kai Zhang, "Responses of Mixed-phase Cloud Condensates and Cloud Radiative Effects to Ice Nucleation Parameterizations and Dust Concentrations in E3SM", AGU Fall Meeting, December 10-14, 2018.

7. Yang Shi, Xiaohong Liu, "Ice nucleation parameterizations in ACME and CAM", CMDV-MCS monthly seminar in October 2017.

8. Kai Zhang, Hui Wan, Hailong Wang, Po-Lun Ma, Xiaohong Liu, and Philip J. Rasch, "Macrophysical and microphysical processes of ice clouds and their interactions with aerosols in EAMv1", AGU Fall Meeting, December 10-14, 2018.