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Executive Summary

The overachieving goal of this project is to improve the predictability of mixed-phase clouds and aerosol interactions in the Community Atmosphere Model version 6 (CAM6) through comparison with the ARM observations. There are three main objectives of the proposed study: (1) Improve the representation of ice microphysical processes in mixed-phase clouds; (2) Test the performance of ice microphysics in CESM-CAM6 with the ARM observations in northern and southern high latitudes; and (3) Examine mixed-phase cloud microphysics-aerosol-turbulence-radiation interactions in CESM-CAM6. In this project, we have

(1) *Improved the representation of ice microphysical processes in mixed-phase clouds* in CESM-CAM6 by implementing the marine organic aerosol (MOA) and treating the ice nucleating particles (INPs) from MOA and its impacts on mixed-phase clouds. We improved the treatment of ice depositional growth through the Wegener–Bergeron–Findeisen (WBF) process by considering the subgrid heterogeneous distributions between liquid droplets and ice crystals in mixed-phase clouds;

(2) *Tested the performance of ice microphysics in CESM-CAM6 with the ARM observations at high latitudes*. We compared the simulated INP concentrations with the ARM observations, e.g., from M-PACE, ISDAC, INPOP, and other data (Mace Head, Zeppelin, CAPRICORN). We examined the impact of improved WBF treatment on model simulated Arctic mixed-phase clouds observed in the M-PACE field campaign. Seasonal variations of modeled mixed-phase cloud properties (LWO, IWP) are compared with the ground-based remote sensing retrievals at the ARM's NSA Utqiaġvik site; and

(3) *Examined mixed-phase cloud microphysics-aerosol-dynamics-radiation interactions* in CESM-CAM6 that include the impacts of MOA INPs, and impacts of different model parameterizations (CLUBB versus UW turbulence & shallow convection schemes, MG2 versus MG1) on high-latitude mixed-phase cloud properties. Aerosol indirect effects of MOA through the liquid phase (droplet activation) and ice phase processes (e.g., the glaciation indirect effect) were investigated.

Project Accomplishments:

(1) Improve the representation of ice microphysical processes in mixed-phase clouds in CAM6

We have implemented marine organic aerosol (MOA) as a new aerosol species into the CESM2-CAM6. The MOA species represents three macromolecules including proteins, polysaccharides, and lipids. MOA is emitted into the atmosphere either externally or internally mixed with sea salt based on the OCEANFILMS (Burrows et al., 2014) emission scheme, which models the relationship between mass fraction of MOA in sea spray aerosol (SSA) and ocean biogeochemistry. Based on modeled MOA, we further implemented two heterogeneous ice nucleation parameterizations (Wilson et al., 2015; McCluskey et al., 2018) for MOA as INPs in CAM6.

We improved the treatment of ice depositional growth at the expense of liquid water through the Wegner-Bergeron-Findeisen (WBF) process in CESM-CAM5 by accounting for the subgrid heterogeneous distribution between liquid droplets and ice crystals in mixed-phase clouds. Two methods were tested. For the first method, the default saturation water vapor mixing ratio in the WBF calculation was replaced with a water vapor mixing ratio weighted by liquid and ice mass mixing ratios. For the second method, a perturbation to the supersaturation relaxation time scale associated with the WBF process was applied based on the assumption that liquid droplets and ice crystals in mixed-phase clouds are distributed in pocket structures following Tan and Storelvmo (2016).

(2) Developed mixed-phase cloud and aerosol observation data

We applied the multi-sensor algorithm to the ARM West Antarctic Radiation Experiment (AWARE) data, which allow us to compare stratiform mixed-phase cloud properties between the two Polar regions (i.e., NSA site and McMurdo station) using ARM ground-based data (Zhang et al., 2019) in addition to satellite measurements (Zhang et al., 2018). In general, ground-based and satellite measurements show consistent results. However, there are differences in seasonal variations of mixed-phase cloud properties, which requires further explorations.

We worked on the ground-based aerosol characterizations. We corrected the MPL data (overlap and after pulse) for both parallel and perpendicular channels to provide reliable depolarization ratio measurements in order to reliably separate dust from other types of aerosols. We finalized the approach and applied it to multi-year ARM data with the next step to study aerosol interactions with polar stratiform mixed-phase clouds.

(3) Test the performance of ice microphysics in CESM-CAM6 with the ARM observations in northern and southern high latitudes

We examined CAM6 simulations with the added MOA internally mixed with sea salt. We found that MOA in the model simulations comprises up to 50% and 70% of sea spray aerosol (SSA) in the accumulation and Aitken mode, respectively. The accumulation mode number concentrations are increased by 80% in some regions of the Southern Ocean and the Arctic, and annual mean CCN concentrations (at supersaturation of 0.1%) are increased by 15%–50% over much of the oceans from 30°S to 70°S. We evaluated simulated MOA concentrations with observations at Mace Head, Ireland and Amsterdam Island. Generally, CAM6 has the ability to capture the observed MOA in terms of seasonal variations, and the model simulates a reasonable magnitude observed at Mace Head. However, the model overestimates the MOA concentrations observed at Amsterdam Island.

Moreover, we examined the contribution of MOA to the global INP distribution. Our results indicate that the marine organic INPs are much more important than dust INPs over the Southern Ocean, and thus may contribute significantly to cloud glaciation at high latitudes. We evaluated model simulated INPs concentrations with ARM observations, e.g., from M-PACE, Ice Nucleating Particles at Oliktok Point (INPOP) campaign, and other data (Mace Head, Zeppelin, CAPRICORN).

We ran the CESM-CAM5 in the single column mode (SCM) for the M-PACE field campaign case to examine the impact of improved WBF treatment on the simulated Arctic mixed-phase clouds. Additionally, global simulations of CAM5 were conducted for the analysis of seasonal variations of the Arctic stratiform mixed-phase clouds at the ARM's NSA Utqiaġvik site. Model results were evaluated against the multi-year ground-based retrievals of cloud occurrence frequency, cloud liquid water path (LWP), ice water path (IWP), and cloud phase partitioning for stratiform mixed-phase clouds. Generally, the default CAM5 model significantly underestimates the LWP but slightly overestimated IWP compared to the observation. The phase partition of simulated mixed-phase clouds was remarkably improved with the improved WBF treatment. A paper was published based on these results (Zhang, Liu et al., 2019).

(4) Examine mixed-phase cloud microphysics-aerosol-turbulence-radiation interactions in CESM-CAM6

We examined the impacts of different ice nucleation parameterizations for MOA on mixed-phase clouds (e.g., LWP, IWP, cloud fraction, shortwave and longwave cloud forcings), using CAM6. The impacts of MOA on cloud properties and cloud forcings vary with time and region with the maximum in the austral summer over the Southern Ocean. MOA enhances the shortwave cloud forcing by up to 4.2 W m^{-2} while weakens the shortwave cloud forcing by 0.36 W m^{-2} over the Southern Ocean in the austral summer by the CCN and INPs effect, respectively.

We examined the impacts of the high-order turbulence closure scheme CLUBB (Cloud Layers Unified By Binormals) and the Morrison and Gettelman (MG) cloud microphysics scheme on the simulated mixed-phase clouds utilizing the CAPT framework. In addition, we tested the sensitivities of modeled mixed-phase clouds to the University of Washington (UW) turbulence and shallow convection schemes, and to the Meyers et al. (1992) ice nucleation scheme. We found that the insufficient heterogeneous ice nucleation at temperatures warmer than -15℃ in the classical nucleation theory (CNT) versus Meyers et al. (1992) and the negligible ice processes in CLUBB versus UW schemes are primarily responsible for the significant underestimation of cloud ice water content in the Arctic single-layer mixed-phase clouds in the model. The paper based on these results have been submitted for publication (Zhang et al., 2020).

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. **Zhang, M.**, S. Xie, **X. Liu**, W. Lin, K. Zhang, H.-Y. Ma, X. Zheng, and Y. Zhang (2020), Toward understanding the phase partitioning of Arctic mixed-phase clouds simulated in E3SM with ARM M-PACE observations, *Earth and Space Science*, in revision.

3. **Zhang, M., X. Liu**, M. Diao, J. D'Alessandro, Y. Wang, C. Wu, **D. Zhang, Z. Wang**, and S. Xie (2019), Impacts of representing heterogeneous distribution of cloud liquid and ice on phase partitioning of Arctic mixed-phase clouds with NCAR CAM5, *Journal of Geophysical Research*, *124*, 13,071–13,090. https://doi.org/10.1029/2019JD030502.

4. D'Alessandro, J., M. Diao, **C. Wu**, **X. Liu**, J. B. Jensen, and B. Stephens (2019), Cloud phase and relative humidity distributions over the Southern Ocean in austral summer based on in situ observations and CAM5 simulations, *Journal of Climate*, *32*, 2781–2805. DOI: 10.1175/JCLI-D-18-0232.1.

5. Zhao, B., Y. Wang, Y. Gu, K.-N. Liou, J. H. Jiang, J. Fan, **X. Liu**, L. Huang, and Y. L. Yung, Evidence for the ice nucleation ability of anthropogenic aerosols, *Nature Geosciences*, 12, 602–607, https://doi.org/10.1038/s41561-019-0389-4.

6. Zhang, D. A. Vogelmann, P. Kollias, E. Luke, F. Yang, D. Lubin, **Z. Wang**, 2019: Comparison of Antarctic and Arctic Stratiform Mixed-phase Cloud Properties Using Ground-based Remote Sensing Measurements**,** *Journal of Geophysical Research*, 124, 10,186–10,204. https://doi.org/10.1029/2019JD030673.

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 99_{th} 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., Keynote "Aerosol Effects on Cold Clouds", Chinese Meteorological Society (CMS) the 35th Annual Meeting, Hefei, October 24, 2018.

4. Liu, X., X. Zhao, S. M. Burrows, C. S. McCluskey, and P. J. DeMott, Effects of Marine Organic Aerosol as Sources of Ice Nucleating Particles on Mixed-Phase Clouds at High Latitudes, 2019 ARM/ASR joint PI meeting, Rockville, Maryland, 10-13 June, 2019 (poster).

5. Burrows, S. M., C. McCluskey, S. Elliott, X. Liu, P. DeMott, Understanding and modelling sources of ice nucleating particles in the Energy Exascale Earth System Model (E3SM), 2019 ARM/ASR joint PI meeting, Rockville, Maryland, 10-13 June, 2019 (poster).

6. Zhao, X., and X. Liu, Implementing marine organic aerosol and ice nucleation in CESM2: Description, evaluation, and impacts on clouds (talk), 2019 NCAR AMWG meeting, Boulder, CO, 19-21 February, 2019.

7. Zhang M., Liu. X, Xie. S., Lin. W., Diao. M., Ma. H., Zheng. X., D'Alessandro. J., Testing heterogeneous mixing between cloud liquid and ice in mixed-phase clouds using E3SM with short-term hindcast approach, AGU Fall Meeting, 10-14 December, 2018 (Poster).

8. Zhang M., S. Xie, X. Liu, W. Lin, K. Zhang, H.-Y. Ma, X. Zheng, Y. Zhang, Toward Understanding the Characteristics of Mixed-Phase Clouds Simulated in E3SM with ARM M-PACE Observations, AGU Fall Meeting, 9-13 December, San Francisco, 2019 (oral).