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Executive Summary

The objective of this project is to improve the simulation and predictability of mixed-phase clouds and aerosol interactions in the Community Earth System Model (CESM) through comparisons with the DOE ARM observations. There are four major goals of the proposed study: (1) Improve the representation of ice microphysical processes in mixed-phase clouds; (2) Develop a long-term multi-sensor mixed-phase cloud dataset; (3) Test the performance of improved ice microphysics in CESM-CAM5 with the ARM data; and (4) Examine mixed-phase cloud microphysics-aerosol-dynamics-radiation interactions in CESM-CAM5. In this project, we have

(1) *Improved the representation of ice microphysical processes in mixed-phase clouds* that include ice nucleation, ice depositional growth through the Wegener–Bergeron–Findeisen (WBF) process, feedbacks between cloud microphysics, dynamics and radiation, and provides links to aerosol properties in the Community Earth System Model (CESM)-Community Atmosphere Model version 5 (CAM5);

(2) *Developed a long-term multi-sensor mixed-phase cloud dataset*. The mixed-phase cloud retrieval algorithms are improved by refining the phase determinations and ice number concentration retrievals. A multi-year mixed-phase cloud observation dataset (1999-2004; October 2013-February 2017) is regenerated at the ARM Barrow site with the improved algorithms. The dataset has been used in the global model evaluation to improve the model parameterizations;

(3) *Tested the performance of improved ice microphysics in CESM-CAM5 with the ARM data*. CESM-CAM5 is run in the DOE Cloud-Associated Parameterizations Testbed (CAPT) and in the single-column model (SCM) mode to facilitate comparison with ARM observations. Multi-year CAPT simulations of seasonal variations of cloud microphysical properties, cloud liquid water path (LWP) and ice water path (IWP), cloud longwave and shortwave forcings, cloud occurrence frequency are evaluated against the ARM multi-sensor mixed-phase cloud retrievals; and

(4) *Examined mixed-phase cloud microphysics-aerosol-dynamics-radiation interactions* in CESM-CAM5 that include the impacts of different ice nucleation mechanisms, sensitivity to dust IN concentration, treatment of the WBF process on mixed-phase cloud properties. Aerosol effect on mixed-phase clouds through the liquid phase (droplet activation) and ice phase processes (e.g., the glaciation indirect effect) is investigated.

Project Accomplishments:

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

We have improved the current ice nucleation parameterization in mixed-phase clouds (i.e., Meyers et al. (1992) in CAM5 by implementing more advanced parameterizations with connection to aerosols. The two deterministic heterogeneous ice nucleation parameterizations (e.g., DeMott et al., 2015; Phillips et al., 2012) were implemented in CAM5. In addition, a classical-nucleation-theory (CNT) based heterogeneous ice nucleation scheme (Hoose et al., 2010; Wang et al., 2014) was implemented. The aerosol-aware ice nucleation parameterization (e.g., CNT) increases the supercooled liquid fraction in total condensed water in mixed-phase clouds especially at temperatures colder than -20°C and significantly improves the agreements of modeled phase partitioning with observations in the Polar regions (Figure 1). This work has been published in Wang et al. (2018). Because of improvement and significant reduction of some outstanding cloud biases, our implementation of advanced ice nucleation schemes (i.e., CNT) have been adopted by the latest NCAR CESM version 2 and the DOE E3SM version 1.

We have improved the treatment of Wegener–Bergeron–Findeisen (WBF) process which is critical for the conversion of liquid to ice water and thus cloud phase partitioning in mixed-phase clouds by accounting for subgrid cloud variabilities in CAM5. We applied a random number to the supersaturation relaxation time scale for ice depositional growth to represent randomly distributed sub-grid pocket structures of pure liquid and pure ice in mixed-phase clouds (Korolev et al., 2003). As a result, the mixing volume between liquid and ice and the local in-cloud deposition rate of water vapor onto ice are reduced. Additionally, we implemented two other treatments to represent subgrid cloud heterogeneity: a partially homogeneous to total cloud volume derived from the HIPPO campaign and a cloud liquid and ice mass-weighted water vapor assumption to mimic the appearance of unsaturated area in mixed-phase clouds as the result of heterogeneous distribution. We tested these three new treatments of WBF in the SCM mode for the single-layer mixed-phase clouds observed during 9-15 October 2004 in M-PACE. The new WBF treatments substantially increase LWC and agrees much better with ARM ground-based remote sensing observations than the default treatment. The model can well simulate the phase partitioning in these clouds. This work has been published in Zhang et al. (2019).

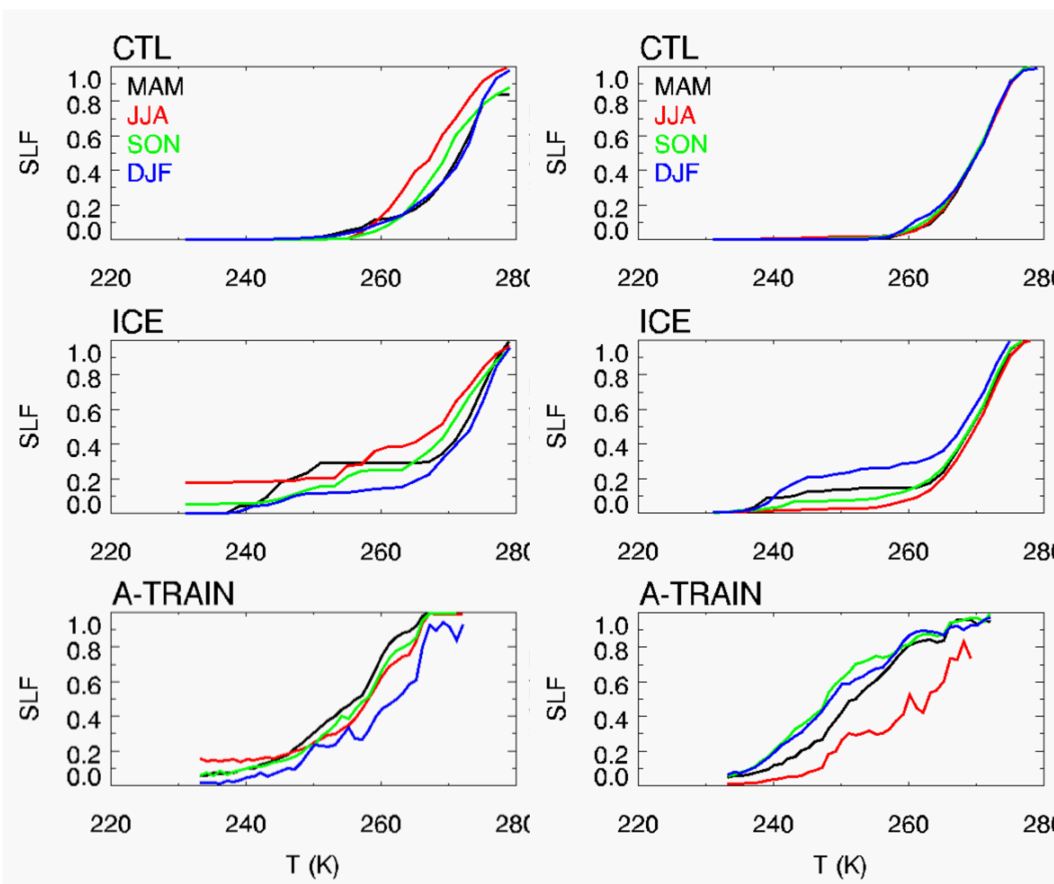

Figure 1. Modeled supercooled liquid fraction, SLF (defined as the ratio of liquid mass to total condensed water mass) as a function of air temperature in the four seasons compared with the A-Train observations in the 60°N–90°N latitude band (left column) and in the 60°S–90°S latitude band (right column). CTL is for the results from the standard CAM5 (top row), and ICE for the results from the modified CAM5 with the CNT ice nucleation parameterization (middle row). Figure modified from Wang et al. (2018).

(2) Developed a long-term multi-sensor mixed-phase cloud dataset

The dataset development efforts were focused on the two main aspects: algorithm improvements, and multi-year data processing and evaluations. We have improved the mixed-phase cloud retrieval algorithm by refining the mixed-phase determinations and ice number concentration retrievals. To better identify mixed-phase clouds at temperatures warmer than -10 °C, we have combined cloud radar Ze and Doppler velocity measurements together with lidar depolarization measurements to evaluate the phase of precipitating particles in the Arctic stratiform clouds. Results show that with cloud-top temperatures colder than -2°C, large particles falling out of the Arctic stratiform clouds are in ice phase, which is significant different from in situ measurements in mid-latitude convective clouds (Zhang et al., 2017). We have also improved the ice number concentration retrievals by considering small-scale vertical velocities and cloud layer liquid water path.

For the multi-year ARM data processing and evaluations, we have regenerated a multi-year mixed-phase cloud observation dataset for the period of 1999-2004 and October 2013 to February 2017 at the ARM Barrow site with improved algorithms. The big challenge we faced to generate a long-term dataset was the inconsistency of radar calibrations among different generations of ARM cloud radars at the Barrow site. Over 5-dBZ difference among different radar systems after 2005 was found by comparing with CloudSat radar measurements in the same region, which was reported to the radar infrastructure group. However, fixing the calibrations issues among different generation radars was a challenge. Because the ice phase retrievals are very sensitive to radar calibration, we ended the first multi-year data at 2004 when the original MMCR starting to degrade and then we processed the other three-year data (October 2013 to February 2017) based on the newest cloud radar measurements. We also applied the algorithm to the ARM AWARE measurements at McMurdo station. Due to the issue related to radar calibrations, we have not released the retrievals as a PI product because of waiting for potential radar calibration updates. However, the data are available to other researchers on requests.

We have synergized the ARM measurements with satellite measurements to improve mixed-phase cloud data availability for global model evaluations. ARM measurements of stratiform mixed-phase cloud properties at the Barrow site provided a unique dataset to evaluate and improve satellite measurements, which provide a global mixed-phase cloud dataset to improve GCM parameterizations (Wang et al., 2018).

(3) Test the performance of ice microphysics in CESM-CAM5 with observation data

We have utilized the single-column model (SCM) of CESM-CAM5 version 5.3 for testing its performance in simulating boundary layer stratiform clouds frequently observed in the Arctic. With the importance of boundary layer turbulence in the formation and maintenance of this type of clouds, in addition to the default CAM5.3, we have also tested a modified CAM5 version with the CLUBB (Cloud Layers Unified By Binormals), a higher-order turbulence closure boundary layer cloud parameterization. CLUBB replaces the shallow convection, PBL turbulence and cloud macrophysics schemes in CAM5.3. Some CLUBB parameters, which control the simulation of shallow stratocumulus clouds, were re-tuned.

We have used the "aircraft sampler" approach to output the CAM5 model simulation along the aircraft flight tracks. Model results collocated with flight tracks are directly compared with the observations. We have evaluated CAM5 simulated clouds with measurements from the HIAPER Pole-to-Pole Observations (HIPPO, 2009-2011). Generally, CAM5 is able to capture the observed specific cloud systems in terms of vertical configuration and horizontal extension. In total, the model reproduces 94.3% of observed occurrences for ice clouds (T<-40 °C), but are much lower (49.9%) for warm clouds (T >0 °C). The missing cloud occurrences in the model are primarily ascribed to the fact that the model cannot account for the high spatial variability of observed relative humidity (RH). Furthermore, model RH biases are mostly attributed to the discrepancies in water vapor, rather than temperature. These results were published (Wu et al., 2017).

Collaborating with the LLNL scientists (Shaocheng Xie and Hsi-Yen Ma), we have conducted the multi-year Cloud-Associated Parameterizations Testbed (CAPT) simulations to understand how the changes in modeled mixed-phase cloud properties (e.g., phase partitioning) are attributed to the updates made in the E3SMv1 physical parameterizations, compared to its predecessor, CAM5. Three sensitivity experiments with switching off the CNT ice nucleation scheme, the CLUBB turbulence and shallow convection scheme, and Morrison and Gettelman cloud microphysical scheme (MG2) from E3SMv1 one at a time were performed. Results were compared to the M-PACE observations (Figure 2). We found that mixed-phase clouds simulated by the default E3SMv1 are overly dominated by supercooled liquid, and cloud ice water is substantially underestimated. Such a model behavior is dramatically different from CAM5. The insufficient heterogeneous ice nucleation at temperatures warmer than -15℃ in CNT and the negligible ice processes in CLUBB are primarily responsible for the significant overestimation of cloud liquid and underestimation of cloud ice in the Arctic single-layer mixed-phase clouds simulated by E3SMv1. These results have been submitted for publication (Zhang et al., 2020).

We evaluated the CAM5 simulated cloud phase (liquid, ice and mixed-phase) and relative humidity (RH) distributions over the Southern Ocean in austral summer against in situ airborne observations. Liquid and mixed phases are seen in 1 s observation data at low temperatures (-40 to -30℃) with 3% and 4% frequencies, respectively, which are missing in the simulations. Supercooled liquid water droplets are frequently observed from -20℃ to -8℃, while the simulations show higher liquid-phase and lower mixed-phase frequencies at this temperature range. Simulations also show higher (lower) LWC in liquid (mixed) phase, higher (lower) liquid number concentration in liquid (mixed) phase, lower IWC in both ice and mixed phases, higher (lower) ice number concentration below (above) -5℃ in mixed phase, and lower (higher) liquid fractions (i.e., mass fraction of liquid water content (LWC) with respect to cloud water content (CWC), LWC/CWC) below (above) -5℃ for the total in-cloud conditions. Two sets of CAM5 simulations (nudged and free-running) show very similar results, corroborating the statistical robustness of the model–observation comparisons. The model biases are suggested to be related to the model representation of subgrid cloud heterogeneity (e.g., subgrid RH variability), and cloud microphysical processes (e.g., ice nucleation, secondary ice production and WBF). The work has been published (D'Alessandro et al., 2019).

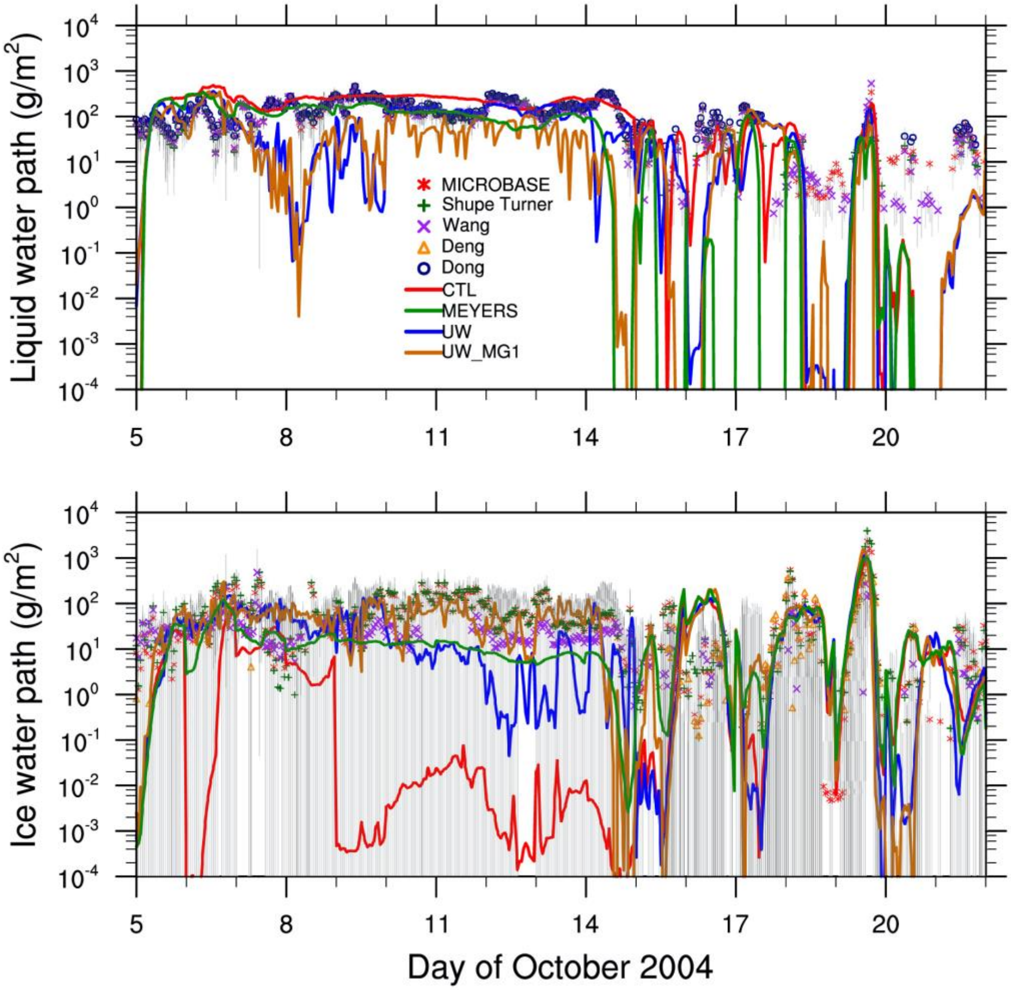

Figure 2. Time series of liquid water path (including rain; upper panel) and ice water path (including snow; lower panel) from the E3SMv1 and the M-PACE observations. CTL is the default E3SMv1 experiment in red solid line, MEYERS experiment (replacing the CNT ice nucleation scheme by Meyers et al. in E3SMv1) in green solid line, UW experiment (replacing the CLUBB turbulence and shallow convection scheme by UW schemes in E3SMv1) in blue solid line, and UW_MG1 experiment (UW schemes plus replacing MG2 by version 1 of MG cloud microphysics scheme, MG1) in brown solid. For the ARM dataset, red star is the MICROBASE observation. Green plus is the retrieval from Shupe (2007). Blue cross represents the retrieval products from Wang et al., (2004). Dark blue circle is from Dong & Mace (2003), and orange triangle is from Deng & Mace (2006).

(4) Examine mixed-phase cloud microphysics-aerosol-dynamics-radiation interactions in CESM-CAM5

Using CAM5 we investigated distinct contributions of mixed-phase ice nucleation, shallow cumulus detrainment, and large-scale environments (circulation, temperature, and water vapor) to the cloud phase partitioning. We found that the CNT ice nucleation scheme increases the SLF especially at temperatures colder than -20°C, and improves the model agreements with A-Train satellite observations in the Arctic in the boreal summer. The decrease of transition temperature above which all detrained cloud water is liquid from 268 to 253 K enhances the SLF at warmer temperatures and improves the SLF mostly over the Southern Ocean. Low SLF biases in wind-driven aerosol (e.g., sea salt) source regions are reduced through nudging large-scale winds. Low SLF biases are further reduced with nudging water vapor through a significant decrease of ice water content. Our results point out the necessity of improving representations of cloud microphysics as well as large-scale dynamics in the model. These results have been published in Wang et al. (2018).

We quantified, for the first time to our knowledge, dust radiative effects on climate by glaciating mixed-phase clouds, using two models (CAM5 and E3SMv1) with three ice nucleation parameterizations (CNT; Niemand et al. 2012; and DeMott et al. 2015). Modeled vertical profiles of dust extinction and dust INPs concentrations were evaluated by observations. Through model experiments, we found that dust INPs induce a global mean net cloud radiative effect of 0.05 to 0.26 W m^{-2} by glaciating mixed-phase clouds, with a predominant warming in the Northern Hemisphere midlatitudes. However, a cooling effect is found in the Arctic due to reduced longwave cloud forcing. This work was published in Shi and Liu (2019).

We contributed to a study which examined the correlation of ice particle effective radius near convective cloud top with aerosol loadings of different aerosol types, based on analysis of satellites observations. Our role is to provide modeling expertise to corroborate the satellite derived ice effective radius and aerosol relationships under different convective strengths, and to illustrate the underlying mechanisms of aerosol effects on ice clouds. We found the potent role of aerosols from anthropogenic pollutions on anvil cloud properties by affecting ice nucleation in deep convective clouds. This work was published in Nature Geoscience (Zhao et al., 2019).

The PI of this project, Liu was invited to write an overview paper (Fan et al., 2016: Review of aerosol-cloud interactions: Mechanisms, significance and challenges). He contributed to the section on aerosol effects on mixed-phase and ice clouds. The paper is featured as a "Highly Cited Paper" by Clarivate Analytics' Web of Knowledge and as "the most read paper from the past 12 months on the Journal of the Atmospheric Sciences website". It has been cited by 119 times according to Web of Science (as of February 22, 2020).

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

1. **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.

2. **Zhang, M.**, S. Xie, **X. Liu**, W. Lin, K. Zhang, H.-Y. Ma, X. Zheng, and Y. Zhang (2019), Toward understanding the phase partitioning of Arctic mixed-phase clouds simulated in E3SM with ARM M-PACE observations, *Earth and Space Science*, in revision.

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6. 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.

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