Final Technical Report

Freezing Processes in Southern Ocean Mixed Phase Clouds

Department of Energy, Office of Science, Biological and Environmental Research, Earth and Environmental Systems Science Division, Atmospheric System Research

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[1] The PI role was switched from A. Gettelman to C. McCluskey in October 2022.

Abstract

Southern Ocean (SO) low-level clouds remain a challenge for Earth system models to represent accurately. This project utilized DOE ARM observations and the Community Atmosphere Model (CAM) to improve process-level understanding of aerosol-cloud interactions and cloud microphysics for SO mixed-phase clouds. Specifically, our efforts include two main topics: 1) investigate the SO aerosol, cloud condensation nuclei (CCN), and ice nucleating particle (INP) population based on observations and determine predictive skill of simulating SO INPs, and 2) assess the ice formation pathways, including ice nucleation and secondary ice production, in SO mixed phase clouds utilizing a combination of observations and modeling tools. Studies focused on SO aerosol and INP resulted four manuscripts. Ice formation pathways in SO mixed phase clouds were investigated, revealing observed evidence of SIP active across all mixed phase temperatures. However, a key finding of this project is that despite significant progress in predicting SO INPs, the role of INP variability in SO cloud phase, precipitation, and radiative properties remain unknown due to challenges in microphysics parameterizations.

Section 1: Project Activities

Section 1.1: Project Goals

Low-level mixed phase clouds over the SO region are associated with a cooling effect on the planet and therefore serves as an important buffer to warming. The cooling effect is associated with a transition of ice containing clouds in present day to an expected liquid-dominated cloud field in a warmer climate. As such, uncertainties in the representation of SO cloud amount, phase, and lifetime directly influence simulated past, present and future climate. The SO region challenges numerical models because there have historically been few field observations to constrain aerosol-cloud interaction processes. This project targeted the DOE ASR Southern Ocean Cloud and Aerosol Processes focus area by utilizing the recent DOE Measurements of Aerosols, Radiation, and Clouds over the Southern Ocean (MARCUS) and the NSF Southern Ocean Cloud Radiation and Aerosol Transport Experimental Study (SOCRATES) observations to revisit aerosol and cloud parameterizations used in Earth system models.

Section 1.2: Southern Ocean Aerosol and Ice Nucleation:

Observations from the MARCUS and SOCRATES were used to investigate aerosol populations that contribute to the available cloud condensation nuclei (CCN) and ice nucleating particle (INP). Specifically, we aimed to investigate the role of marine aerosol on INP populations using an existing parametrizations for marine INPs and mineral dust INPs. Observations of aerosol surface area and INPs were used to perform a closure study for SO INPs, which is the first of it's kind. We identified marine aerosol as the dominate INP source in the marine boundary layer, and evidence of mineral dust contributing to INPs aloft (McCluskey et al., 2023; Moore et al., 2024). Variability in modeled INPs was primary driven by variability in simulated dust amount, highlighting a need for quantitative dust measurements to assess simulated INP populations.

We also identified seasonality in CCN number concentrations, highlighting a summertime source of CCN at the highest latitudes measured during MARCUS (Niu et al., submitted). These observations were also used to assess simulated CCN in CAM, revealing a missing source and an overall low bias in SO CCN in CAM. This low bias in CCN was consistent with a low bias in sulfate accumulation mode aerosol support by SOCRATES observations.

Results regarding SO aerosol, INPs, and CCN are summarized in Figures 1 and 2 and in publications (*McCluskey et al.,* 2023; *Moore et al.,* 2024; *Niu et al.,* submitted to ACP). Additionally, PhD Candidate Qing Niu continues to investigate the low CCN bias in CAM as part of her dissertation during a visit at NCAR.

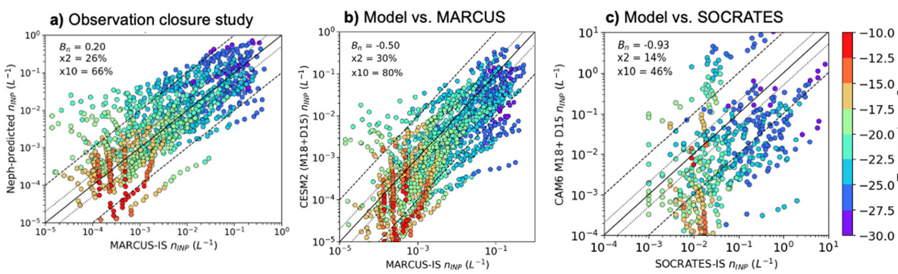

Figure 1. An assessment of INP predictive skill relative to observations from MARCUS (a-b) and SOCRATES (c). In a), observed aerosol surface area is used as input to the M18 parameterization only for an observation closure study; in b) and c), model aerosol values are used as input to M18 and D15. Comparisons demonstrate predictive skill within an order of magnitude in the marine boundary layer (MARCUS), however predictive skill declines when assessed against airborne INP measurements (SOCRATES).

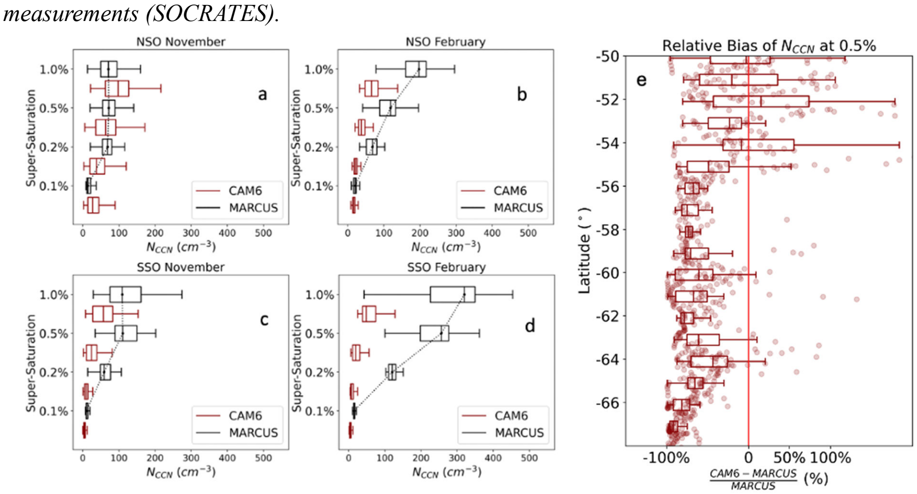

Figure 2. Model (red) and observed (black) CCN number concentrations over the Northern Southern Ocean (NSO, 50-60S, a-b) and southern Southern Ocean (SSO, 62-68S, c-d) for austral winter (a and c) and summer (b and d) at measured supersaturation with respect to water. (e) Low bias in simulated Southern Ocean marine boundary layer CCN number concentrations compared to MARCUS observations associated with missing summertime source. Figure from Niu et al. (submitted to ACP).

Section 1.3: Southern ocean cloud freezing processes:

The second major theme of this project was to assess the freezing processes responsible for ice formation in Southern Ocean mixed phase clouds. We reported on evidence for secondary ice production across all mixed phase temperatures, a surprising result that highlights the need to update SIP mechanism in CAM (*Jarvinen et al.,* 2022). Modeling experiments performed with CAM indicated that SO clouds were agnostic to ice nucleation, where no change in top of atmosphere metrics were found due to changes in ice nucleation (Figure 3). These results were unexpected and required us to more deeply interrogate the model microphysics with a holistic approach that considered the processes prior and subsequent to ice nucleation.

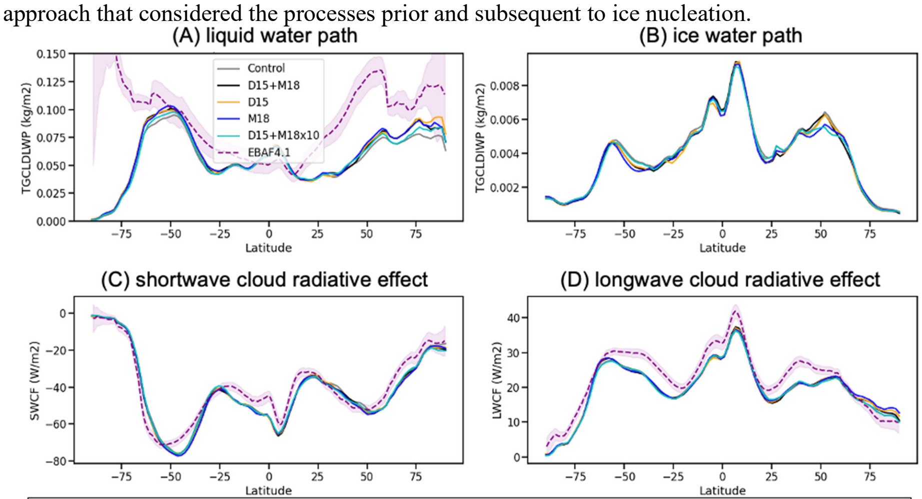

Figure 3. Simulated zonal mean (a) liquid water path, (b) ice water path, (c) shortwave cloud radiative effect, and (d) longwave cloud radiative effect from CAM6 simulations with 5 different representations of ice nucleation: 'control' (default physics, grey), 'D15+M18' (updated INP scheme from McCluskey et al., 2023, black), 'D15' (dust only, orange), 'M18' (marine only, blue), 'D15+M18x10' (same as 'D15+M18' but with the marine INPs amplified by a factor of 10, teal). Also shown are observations from CERES (purple).

Our analysis revealed *immersion freezing of rain* (*ImmFrzRain*) as the dominate primary ice formation process for temperatures ranging from -5 to -25 C, whereas *immersion freezing of cloud droplets* (*ImmFrzCld*) contributed only at temperatures less than -25 C. The *ImmFrzRain* process produces ice at a rate that far exceeds *ImmFrzCld*, dampening any influence of changing INP number concentrations. We hypothesize that a low cloud droplet number bias drives an over-active cloud-to-rain autoconversion process, which generates erroneously high rain number concentrations at supercooled temperatures subject to the *ImmFrzRain* process. A major conclusion of this study was that **despite progress in predicting Southern Ocean ice nucleating particles (Section 1.2), the impacts of INPs on Southern Ocean cloud phase, precipitation, and radiative properties remain unknown due to deficiencies in microphysics parameterizations.** Our suggested path forward requires additional observations of all components of the mixed phase cloud system and necessary changes to the microphysics scheme to address biases in processes that occur prior and subsequent to ice nucleation. These findings are in preparation for publication to *Geophysical Research Letters.*

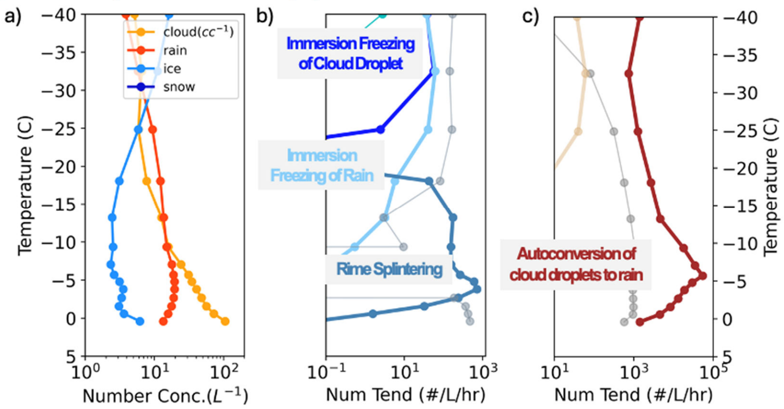

Figure 4. Simulated a) hydrometeor number concentrations and number tendency rates for b) ice and c) rain hydrometeors for mixed phase temperatures over the SO region (-65<Lat<-50 and 80<Lon<165) from CAM6.

Section 2: Products

Section 2.1: Peer-Reviewed Publications

Burrows, S., C. S. McCluskey, G. Cornwell, I. Steike, K. Zhang, B. Zhao, M. Zawadowicz, A. Raman, G. Kulkarni, S. China, A. Zelenyuk, and P. J. DeMott (2022), Ice-nucleating particles that impact clouds and climate: Observational and modeling research needs, *Reviews of Geophysics*, doi: 10.1029/2021RG000745.

McCluskey, C. S., Gettelman, A., Bardeen, C. G., DeMott, P. J., Moore, K. A., Kreidenweis, S. M., et al. (2023). Simulating Southern Ocean Aerosol and Ice Nucleating Particles in the Community Earth System Model Version 2. *Journal of Geophysical Research: Atmospheres*, *128*(8), e2022JD036955. doi: 10.1029/2022JD036955.

Niu, Q., G. M. McFarquhar, R. Marchand, S. Cavallo, C.Flynn, P.J. DeMott, C. S. McCluskey, and R. S. Humphries, 62°S Witnesses the Transition of Boundary Layer Marine Aerosol Pattern Over the Southern Ocean (50°S–68°S, 63°E–150°E) During the Spring and Summer: Results From MARCUS (I), *Journal of Geophysical Research: Atmospheres,* 129(9), e2023JD040396, doi: 10.1029/2023JD040396.

Moore, K. A., Hill, T. C. J., McCluskey, C. S., Twohy, C. H., Rainwater, B., Toohey, D. W., et al. (2024). Characterizing Ice Nucleating Particles Over the Southern Ocean Using Simultaneous Aircraft and Ship Observations. *Journal of Geophysical Research: Atmospheres*, 129(2), e2023JD039543, doi: 10.1029/2023JD039543.

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Niu, Q., C. S. McCluskey, and G. M. McFarquhar, Marine Boundary Layer Cloud Condensation Nuclie Bias over the southern Ocean: Comparisons between the Community Atmosphere Model 6 and Field Observations, *submitted to Journal of Geophysical Research: Atmospheres*

Järvinen, E., C. S. McCluskey, F. Waitz, M. Schnaiter, A. Bansemer, C. G. Bardeen, A. Gettelman, A. Heymsfield, J. Jensen, J. Stith, W. Wu, J. J. D'Alessandro, G. M. McFarquhar, J. A. Finlon, T. C. J. Hill, E. J. T. Levin, K. A. Moore, and P. J. DeMott, Ice Crystal Properties and Evidence for Secondary Ice Production in Southern Ocean Stratocumulus Clouds, *J. Geophys. Res. Atmo,* doi: 10.1029/2021JD036411.

Secondary:

Lasher-Trapp, S., E. L. Scott, E. Järvinen, M. Schnaiter, F. Waitz, P. J. DeMot, C. S. McCluskey, and T. C. J. Hill, Observations and Modeling of Rime Splintering in Southern Ocean Cumuli (2021), *J. Geophys. Res. Atmos.*, doi: 10.1029/2021JD035479.

McFarquhar G. M., C. Bretherton, R. Marchand, A. Protat, P. J. DeMott, S. P. Alexander, G. C. Roberts, C. H. Twohy, D. Toohey, S. Siems, Y. Huang, R. Wood, R. M. Rauber, S. Lasher-Trapp, J. Jensen, J. Stith, J. Mace, J. Um, E. Järvinen, M. Schnaiter, A. Gettelman, K. J. Sanchez, C. S. McCluskey, L. M. Russell, I. L. McCoy, R. Atlas, C. G. Bardeen, K. A. Moore, T. C. J. Hill, R. S. Humphries, M. D. Keywood, Z. Ristovski, L. Cravigan, R. Schofield, C. Fairall, M. D. Mallet5, S. M. Kreidenweis, B. Rainwater, J. D'Alessandro, Y. Wang, W. Wu, G. Saliba, E. J. T. Levin, S. Ding, F. Lang, S. C. H. Truong, C. Wolff, J. Haggerty, M. J. Harvey, A. Klekociuk, and A. McDonald, Observations of clouds, aerosols, precipitation, and surface radiation over the Southern Ocean: An overview of CAPRICORN, MARCUS, MICRE and SOCRATES (2020), *Bull. Am. Meteorol. Soc.* 1–92. Doi:10.1175/BAMS-D-20-0132.1.

Twohy, C. H., P. J. DeMott, L. M. Russell, D. W. Toohey, B. Rainwater, R. Geiss, K. J. Sanchez, S. Lewis, G. Roberts, R. S. Humphries, C. S. McCluskey, K. Moore, P. W. Selleck, M. D. Keywood, J. P Ward, and I. M McRobert, Cloud-Nucleating Particles over the Southern Ocean in a Changing Climate (2021), *Earth's Future,* doi: 10.1029/2020EF001673.

Section 2.2: Conference Presentations

Observation-Enabled Assessment of Simulated Southern Ocean Aerosol and INP Populations in the Community Atmosphere Model Version 6, Oral Presentation at the *American Geophysical Union Fall Meeting*, December 8 2020, virtual.

Observed and Modeled Southern Ocean Aerosols and Clouds, Oral Presentation for the *Karlsruhe Institute of Technology Institute of Meteorology and Climate Research Colloquium*, November 17, 2020, virtual, ***INVITED.***

Examining Southern Ocean Aerosol-Cloud Interactions via Airborne Observations and Numerical Modeling, Oral Presentation for the *NASA Student Airborne Research Program Summer Internship Seminar Series,* July 27, 2020, virtual, ***INVITED***.

The Critical Role of Observations in Developing Numerical Representations of Ice Nucleating Particles for Southern Ocean Mixed Phased Clouds, Oral Presentation at the *12th Annual*

Symposium on Aerosol-Cloud-Climate Interactions at the American Meteorology Society Annual Meeting, January 13, 2020, Boston, MA, USA, ***INVITED***.

McCluskey, C. S. et al., "Observations and Modeling of SO INP amounts and composition", Oral Presntation at the *DOE Virtual Workshop on High-Latitude Marine Boundary Layer Clouds*, September 8, 202, Virtual.

McCluskey, C. S. et al., "Simulated Southern Ocean Aerosol and Ice Nucleating Particles" Poster Presentation at the *DOE Atmospheric System Research Science Meeting*, June 24, 2021, Virtual.

Evaluation of Simulated Southern Ocean Ice Nucleating Particles and implications for climate, Oral Presentation at the *American Meteorological Society's Annual Meeting 13th Symposium on Aerosol - Cloud - Climate Interactions*, January 11 2021, virtual, ***INVITED***

McCluskey et al., "Marine Ice Nucleating Particles: Progress and Needs", Oral Presentation at *2022 American Geophysical Union Fall Meeting,* Dec 15, 2022, Chicago, IL, USA, ***INVITED***.

McCluskey et al., "Simulating Freezing Processes in Southern Ocean Low-Level Mixed Phase Clouds", Poster Presentation at *2022 Joint Atmospheric Radiation Measurement (ARM) User Facility/Atmospheric System Research (ASR) Principal Investigators Meeting*, Oct 25, 2022.

McCluskey, C. S., "Impacts of Ice Nucleating Particles on Southern Ocean Mixed Phase Clouds", Oral Presentation (Virtual) for the British Antarctic Survey Seminar Series, Sept 22, 2022, ***INVITED.***

McCluskey, C. S., "Ice Nucleating Particle Impacts on Southern Ocean Clouds", Keynote Lecture (Virtual) for the University of Illinois at Urbana-Champaign *AAAR Student Symposium*, Sept 8, 2022, ***INVITED.***

McCluskey et al., "What processes control Southern Ocean low-level cloud ice budgets in CESM2?", Oral Presentation at the *Clouds in the Polar Regions Joint Conference* at the *Collective Madison Meeting*, Aug 9, 2022.

McCluskey, C. S., "Levering Observations and Numerical Modeling to Investigate Ice Nucleating Particle Populations and Mixed Phase Aerosol-Cloud Interactions over the Southern High Latitudes", Oral Presentation at the *Virtual Ice Nucleation colloquium*, May 5, 2022, Virtual, ***INVITED***.

McCluskey, C. S., "Simulating Remote Aerosol and Ice Nucleating Particle Populations", Oral Presentation at the *Cryosphere and ATmospheric CHemstriy (CATCH) Open Science Workshop*, May 12, 2022, Virtual, ***INVITED.***

McCluskey et al., "Ice, Ice, Maybe? Southern Ocean Aerosol-Cloud Interactions", Oral Presentation at the *Pacific Northwest National Laboratory Atmospheric, Climate, and Earth Sciences Division Seminar Series*, October 2023, Richland, WA, ***INVITED.***

McCluskey et al., "Process-level model diagnostics from in situ observations of aerosol abundance, composition, and cloud activation", Oral Presentation at the *AeroCOM/AeroSAT conference*, October 2023, Richland, WA.

McCluskey et al., "Aerosol-ice interactions in Southern ocean clouds", Oral Presentation at the *28th International Union of Geodesy and Geophysics General Assembly*, July 12, 2023, Berlin, Germany ***INVITED.***

McCluskey et al., “Ice, Ice, Maybe? CAM6 Ice Formation in Southern Ocean Mixed Phase Clouds”, Seminar at the *San Jose State University Department of Meteorology and Climate Science*, Feb 16, 2023, virtual, ***INVITED.***

McCluskey et al., “Ice, Ice, Maybe? CAM6 Ice Formation in Southern Ocean Mixed Phase Clouds”, Oral Presentation at the *CESM Winter Atmosphere Modeling Working Group Meeting*, January 31, 2023, Boulder, CO, USA.

McCluskey et al., “Ice, Ice, Maybe? Southern Ocean Aerosol-Cloud Interactions”, Oral Presentation at the *9-1*, 15 August, 2024, Telluride, Colorado, ***INVITED.***

McCluskey et al., “Aerosol-Cloud Interactions in Southern Ocean Mixed Phase Clouds”, Seminar at the *National Institute of Polar Research*, 17 July, 2024, Tokyo, Japan, ***INVITED.***

McCluskey et al., “Ice, Ice, Maybe? Southern Ocean Aerosol-Cloud Interactions”, Seminar, Department of Atmospheric Science, University of Wyoming, 23 April, 2024, Laramie, WY, ***INVITED.***

Section 2.3: Graduate Student and workforce development

a) PhD Candidate Qing Niu (University of Oklahoma; Advisor: Greg McFarqhuar)
PI’s Role: Host and mentor for student visit from 05/01/2023 to 05/31/2025.
Outcome: in 2 publications (Niu et al., 2024; Niu et al., submitted) and a collaboration with Dr. Susannah Burrows (PNNL) to add CCN diagnostics to the E3SM diagnostics framework. Ms. Niu is also preparing an additional modeling study leveraging these new diagnostics for publication as part of her dissertation.

b) PhD Candidate Ci Song (University of Wyoming; Advisor: Daniel McCoy)
PI’s Role: Committee Member
outcome: This collaboration will result in one co-authored manuscript lead by student.

c) Dr. Kathryn Moore (Colorado State University; Advisors: Sonia Kreidenweis and Paul DeMott)
PI Role: collaborator using observations to constrain CAM6.
Outcome: co-authored manuscript (Moore et al., 2024)

d) PhD Candidate Yishi Hu (University of Oklahoma; Advisor: Zachary Lebo)
PI’s Role: Co-Host for student visit from 8/5/2024 to 12/20/2024
Outcome: adding secondary ice projection mechanisms to the WRF model, publication in preparation.