Project: **1430**
Project title: **Ice optical sensitivities of cloud-radiative heating in ICON**
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Report period: **2024-07-01 to 2026-06-31**

Nhrs requested	*Nhrs used*	*Work storage*	*Archive*
Y1: 13545 (granted) Y2: 8250 (granted)	Y1: 11342 Y2: 0	Y1: 3 Gb Y2: 4 Gb	Y1: 44 Tb Y2: 0 Tb

Project Overview

Ice clouds tend to absorb and reemit longwave (LW) radiation and scatter shortwave (SW) radiation, leading to top-of-atmosphere (TOA) LW warming and SW cooling. However, these radiative properties of ice clouds also impact heating and cooling within the atmosphere, and this atmospheric *cloud-radiative heating* has been understudied relative to TOA radiative impacts. While the TOA impacts of ice clouds determine equilibrium climate sensitivity, the atmospheric cloud-radiative heating (CRH) is more directly useful in predicting cloud impacts on circulation features—from the strength of the Northern Hemisphere jet streams to the Hadley cell extent to variability in the El Niño Southern Oscillation. Ice microphysical processes can strongly determine CRH by producing more or less in-cloud ice. CRH also depends on the optical properties of this cloud ice after formation, including absorptivity and angular distribution of scattering. This project has investigated this last factor.

Technical aspects

1. ICON-NWP simulations

This project completed six deep convection-resolving simulations with ICON version 2.6.4 over the Asian monsoon region (5°S-40°N, 55°E-115°E) in Year 1. These runs employed 2.5-km equivalent resolution (R2B10 icosahedral grid), a 24-second time step, and 75 vertical levels on a hybrid sigma height grid. They were initialized and nudged every 3 hours using ECMWF analysis data of the Integrated Forecast System. They also coupled the ecRad radiative transfer schemes to either one- or two-moment microphysical schemes and either Fu, Yi13, or Baran16 ice optical schemes. The Fu scheme is the default choice in ICON and assumes all ice crystals are hexagonal plates. Yi13 and Baran16 schemes leverage in-situ measurements to represent an ensemble of ice crystal habits, including hollowness and surface roughness. In our runs, 2D fields were output half-hourly and 3D fields on an hourly basis between 5 August 2017 12:00 UTC and 9 August 2017 12:00 UTC, corresponding to StratoClim field campaign flights over the domain of interest.

2. Synthetic flight tracks

An additional six shorter-duration ICON version 2.6.4 runs were completed for 8 August 2017 from 03:00-09:00 UTC during StratoClim Flight 7, based on restart files from our initial six runs. These produced both 2D and 3D output every 10 minutes during the flight time for a ±0.25°x0.25° domain around the StratoClim flight track bounds. 20 values were randomly sampled with replacement within this domain for the time and pressure level closest to the aircraft. We sampled in this way until the end of the flight time to generate 20 “synthetic flight tracks” from the ICON model output. We then calculated vertical profiles of model bias using the difference between values along these synthetic flight tracks and the actual in-situ ones.

3. Antarctic climatology

With shifting research priorities, we have unfortunately not completed runs to generate a multi-year surface-flux climatology over Antarctica with various ice optical schemes, as proposed in the last cycle. For this reason, we do not renew our compute time request for 2026-2027.

Scientific Results

The full ICON-NWP simulations reveal several key results. First, all microphysics-optics couplings in ICON version 2.6.4 underestimate outgoing longwave radiation (OLR) over the Asian monsoon region-

--by between 2.8 and 5.9%. Differences in domain-mean OLR across the microphysics-optics couplings are smaller, no more than 2%, but with lowest OLR consistently from the Fu optical scheme. Second, optical sensitivity in the domain-mean CRH is smaller than its microphysical sensitivity. While Sullivan & Voigt 2021 found a four-fold change in maximum CRH across ice microphysics schemes, our simulations indicate only a two-fold change across ice optics schemes. Importantly, these figures are for daily-mean net CRH, and when we stratify CRH into SW versus LW and daytime versus nighttime components, the CRH differences with optics become more pronounced. A third finding is then that the daytime SW heating is reduced by 0.5-1 K d^{-1} in the multi-habit ice optical schemes (Yi13 and Baran16) relative to the single-habit one (Fu). This bias indicates that use of the Fu ice optical scheme by default reduces the SW heating that generates mesoscale circulations within anvil clouds, prolonging their lifetime and extending their horizontal coverage. This idea aligns with the lowest OLR from the Fu optical scheme, mentioned above. This study also examines how ice cloud mass mixing ratio, mean precipitation, and extreme precipitation change across the microphysics-optics coupling and is in preparation for the *Journal of Geophysical Research* (Sepúlveda Araya et al. 2026).

Analysis of the synthetic flight tracks supported an evaluation of upper tropospheric-lower stratospheric (UTLS) properties over the Asian monsoon region in ICON version 2.6.4 (Sullivan et al. 2026-1). This study found that the upper troposphere was too cold and the lower stratosphere was too warm and dry relative to the aircraft observations of the StratoClim flight campaign. As a result of these thermodynamic biases, ICON overestimates the amount of upper-tropospheric cloud ice and underestimates the lower-stratospheric ice. These cloud biases are also exacerbated by a large overestimate (by 80%) of mean convective updraft strength, relative to superpressure balloon measurements. To our knowledge, this study represented one of the first evaluations of UTLS structure in a storm-resolving framework.

Finally, we highlight two other efforts that have leveraged the simulation output generated in this DKRZ allocation. First, Sullivan et al. 2026-2 visualized the CRH from a mesoscale convective system (MCS) in this project's ICON NWP output, using ParaView volume rendering. They also stacked 2D fields of column-integrated cloud ice mass (ice water path) to create spatiotemporal renders in which one can examine spatial cloud structures, as well as their duration in time. The study emphasized the utility of more sophisticated visualization techniques—including rendering but also topological data analysis—to understand cloud evolution, build intuition about cloud structures, and more rigorously evaluate simulations. Recent acceptance of this work in the *Bulletin of the American Meteorological Society* should provide exposure for a broad readership to the ICON modeling framework. Second, Makgoale et al. 2026 have applied the Python FLEXible object TRacKeR (PyFLEXTRKR) convective tracking algorithm to the ICON NWP output to extract MCSs across our six runs. A study in preparation will examine CRH, system structure (including extent and depth), and precipitation characteristics over MCS lifecycle in the ICON model relative to geostationary satellite data. Despite not completing the simulations proposed in the last cycle, this project has then yielded a substantial body of scientific work from the simulations done in Year 1.

Publications

E. I. Sepúlveda Araya, S. C. Sullivan, and A. Voigt. Ice crystal complexity leads to weaker ice cloud radiative heating in idealized single-column simulations (2025). *Atmos. Chem. Phys.* **25** pp. 8943-8958.

S. C. Sullivan-1, A. Voigt, E. I. Sepúlveda Araya, S. Bucci, A. Miltenberger, M. K. Kupinski, C. Rolf, and M. Krämer. Evaluation of upper-tropospheric lower-stratospheric properties over the Asian monsoon region in a storm-resolving model (2026). *Atmos. Chem. Phys.* **26** pp. 1685-1698.

S. C. Sullivan-2, D. Bayly, N. Cherukuru, J. A. Levine, E. I. Sepúlveda Araya, T. E. Makgoale, A. Arellano, and K. M. Wood. Advanced visualization techniques for insight in clouds and climate research (2026). [Accepted at *Bull. Amer. Meteorol. Soc.*]

Sepúlveda Araya, E. I.; Sullivan, S. C.; Makgoale, T.; Järvinen, E.; and Kupinski, M. K. Ice-cloud radiative heating and macrostructure show sensitivity to ice-cloud optics in storm-resolving simulations (2026). In prep for J. Geophys. Res.

Makgoale, T. E.; Sullivan, S. C.; Sepúlveda Araya, E. I.; and Järvinen, E. Simulated cloud-radiative heating and precipitation over mesoscale convective system lifecycles (2026). In prep for J. Atm. Sci.