Extratropical cloud process studies

Ann Fridlind, NASA GISS: *Brief overview of relevant processes*
Susannah Burrows, DOE PNNL: *Marine sources of CCN/INPs*
Xiaohong Liu, Texas A&M University: *Secondary ice production*
Johannes Muelmenstaedt, DOE PNNL: *Rain processes*

Brief overview of relevant processes

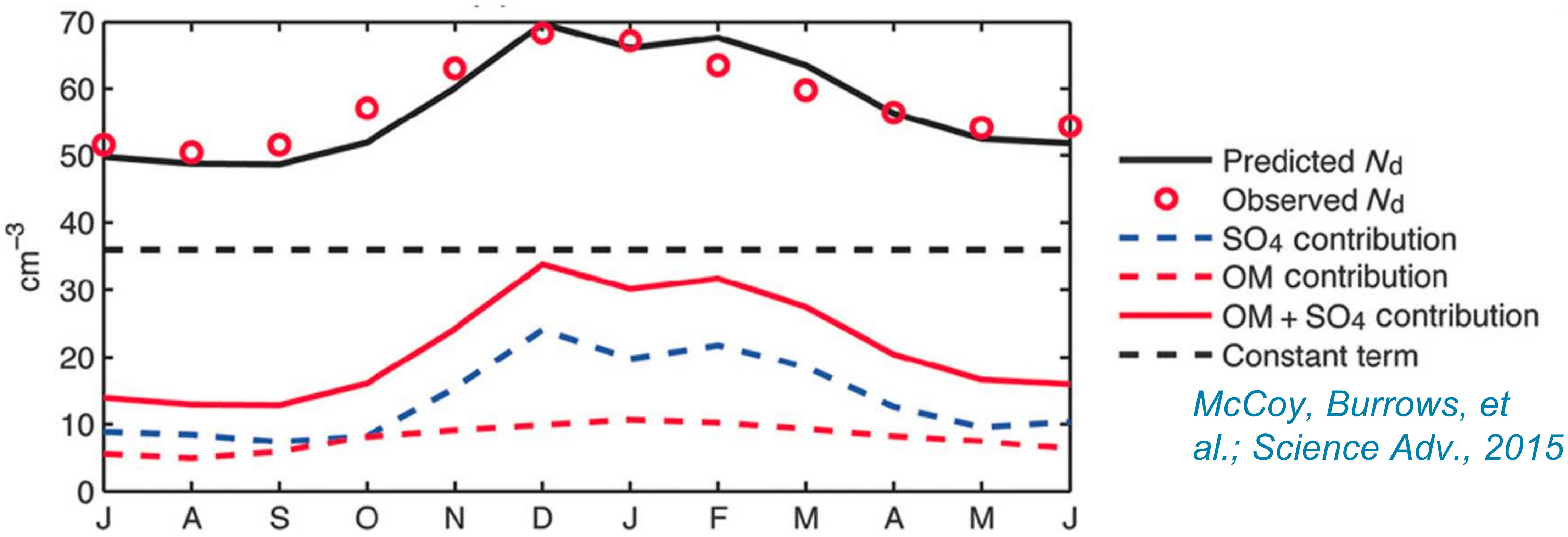
- **aerosol environment (hygroscopic and ice nucleating)**
  - sources (long-range transport, **ocean surface fluxes**, nucleation)
  - sinks and transformation (precipitation scavenging, cloud processing, dry deposition, coagulation, condensation / coatings)
  - vertical exchange (cloud-top entrainment, precipitation, sublimation/evaporation)
- **thermodynamic and dynamic environment**
  - large scale motion (operating on stability and saturation fields)
  - gravity waves
  - turbulence (wind shear and buoyancy sources; surface and cloud top)
  - surface fluxes (momentum, heat, moisture)
  - mesoscale structure (e.g., convective rolls, cellular, MBL convective complexes)
- **cloud environment**
  - liquid sources (droplet activation, condensation)
  - ice sources (**heterogeneous** and homogeneous, **secondary ice production**, vapor growth)
  - sinks and transformation (evaporation/sublimation, **collision-coalescence/rain formation**, aggregation, riming, sedimentation, melting, evolution of ice crystal shape/density/size)
- **coupling**

Seasonal, regional-scale variability in CCN over the Southern Ocean is controlled primarily by sulfate aerosol, secondarily by sea spray

N_d derived from MODIS satellite.

SO_4 from AEROCOM multi-model median; largely DMS-derived.

All data are from 35°S-55°S, averaged over 5°x15° boxes, with monthly resolution.



McCoy, Burrows, et al.; Science Adv., 2015

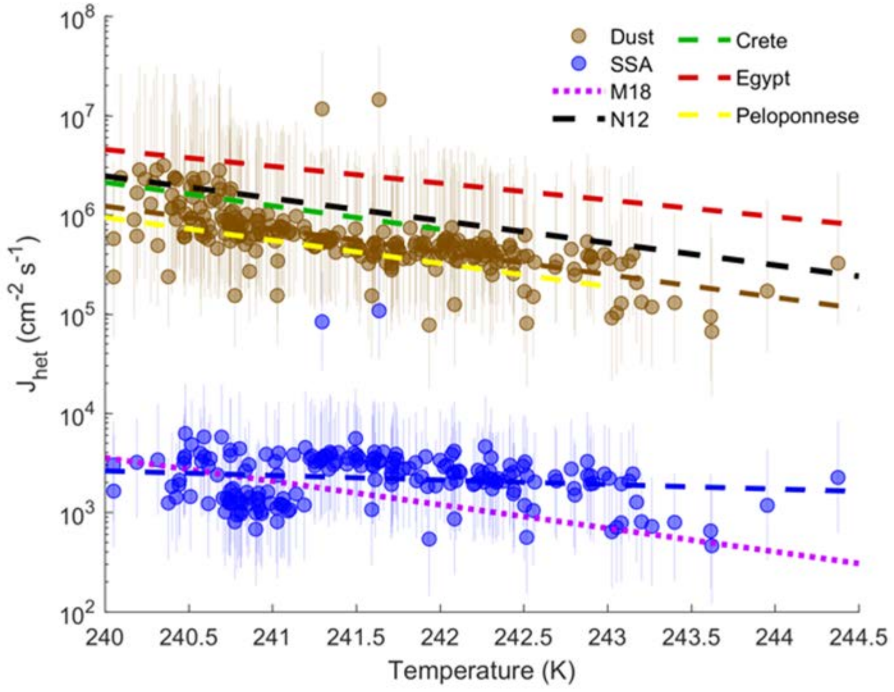
Important notes:

- Sea spray is highly variable on daily-weekly time scales (e.g., Hartery et al, 2020, JGR-A) but did not explain seasonal, regional-scale variability in N_d in this study
- Sea spray (with associated organic matter) may increase in importance as a CCN source below 50 S (McCoy and Burrows, et al., 2015, Sci. Adv.; Quinn et al., 2017, Nature)
- Continental outflow regions and **the entire Northern Hemisphere** are influenced by pollution aerosol, dust, etc.. (Hamilton et al., 2014, PNAS)

Sources and variability of Ice-Nucleating Particles (INPs) in marine air

INP sources

- Sea spray: Abundant, but inefficient
- Dust: Episodically present, but highly efficient
- Biological particles may also matter



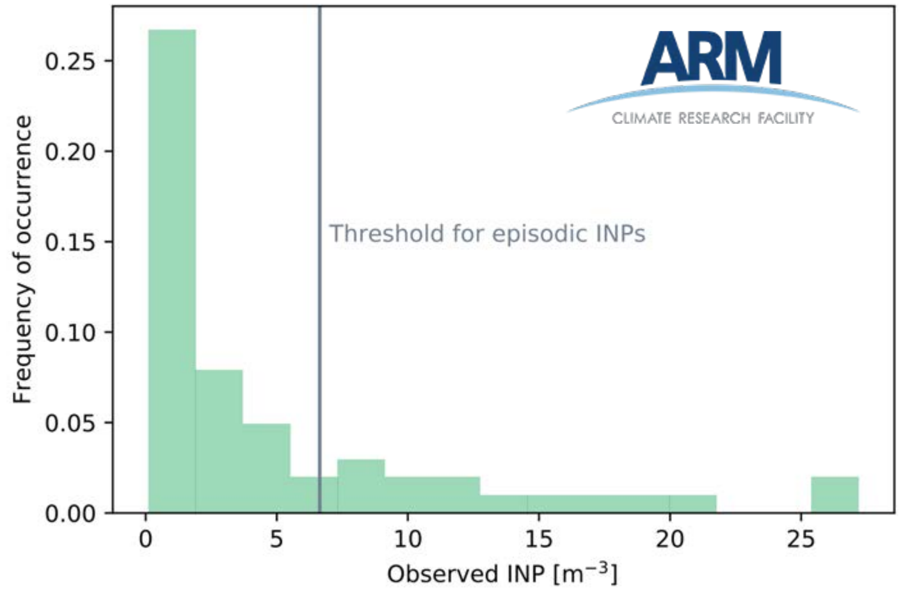
Direct ambient measurements of freezing rate coefficients: dust is ca. 100x - 1000x more efficient at nucleating ice than ambient sea spray.

Cornwell, G., McCluskey, C. S., DeMott, P. J., Prather, K. A., and **Burrows, S. M.** (2021). Determining heterogeneous ice nucleation rate coefficients from ambient measurements, *in prep.*

INP variability

The distribution of INP concentrations in marine boundary layer air has a "long tail". Rare, but strong, peak episodic events could be caused by:

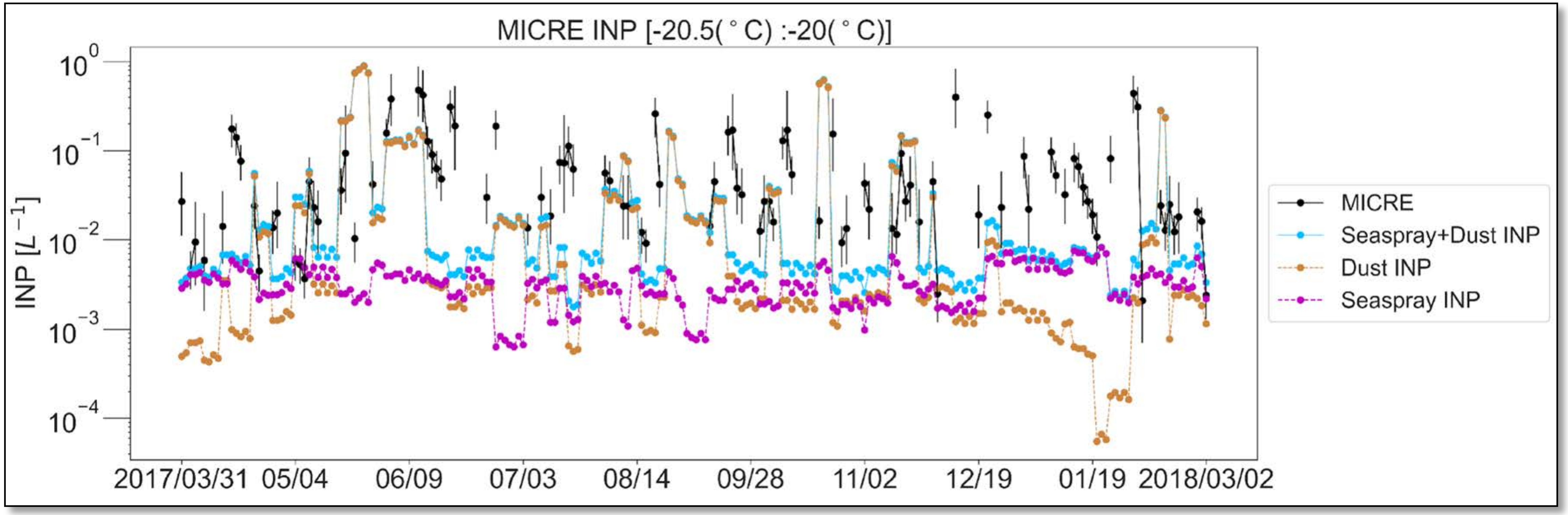
- Dust (regional or long-range transport)
- Biological influences (marine/continental)



Pooled PDF of marine INP number concentration (253 K / -20°C) from Mace Head, MAGIC, MARCUS

Steinke, I., DeMott, P. J., Deane, G., Hill, T. C. J., Maltrud, M., **Raman, A.**, and **Burrows, S. M.** (2021). A numerical framework for simulating episodic emissions of high-temperature marine INPs, *ACPD, in discussion.*

First long-term surface observations of INPs at Macquarie Island (MICRE) reveal challenges for model simulation of Southern Ocean INPs



INP parameterizations:

- Dust: DeMott et al. (2015)
- Sea spray: McCluskey et al. (2018)

Aerosol fields: E3SMv1 (MAM4) with prescribed meteorology

- Modeled INPs capture background concentrations well, but peak INP days are poorly captured.
- These issues are **not revealed well by short-term field campaigns** such as CAPRICORN (McCluskey et al., 2019, GRL), SOCRATES, or MARCUS – highlighting the value of long-term INP observations.
- **Open question: How much does this short-term variability matter to S. Ocean clouds?**

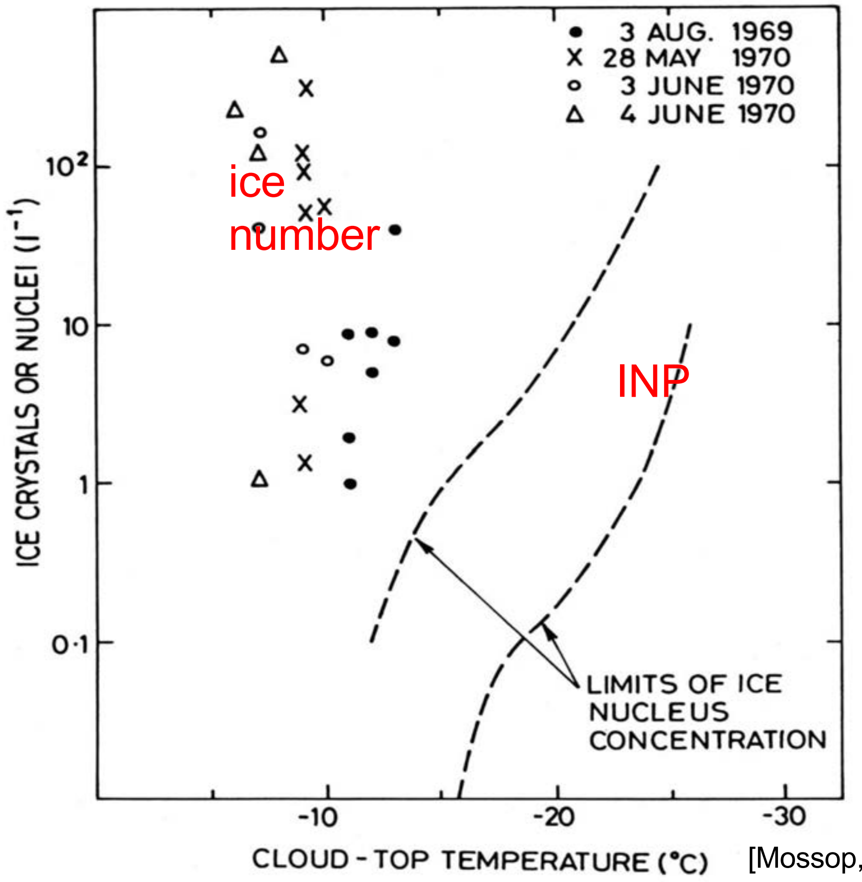
U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

Raman, A., DeMott, P. J., Hill, T. C., Zhang, K., Ma, P. L., Singh, B., and **Burrows, S.M.** (2021). Investigating seasonal variability in marine ice nucleating particles from climate model simulations and observations in the Southern Ocean. *Atmospheric Chemistry and Physics, in prep.*

Secondary ice production

- **Motivation:**

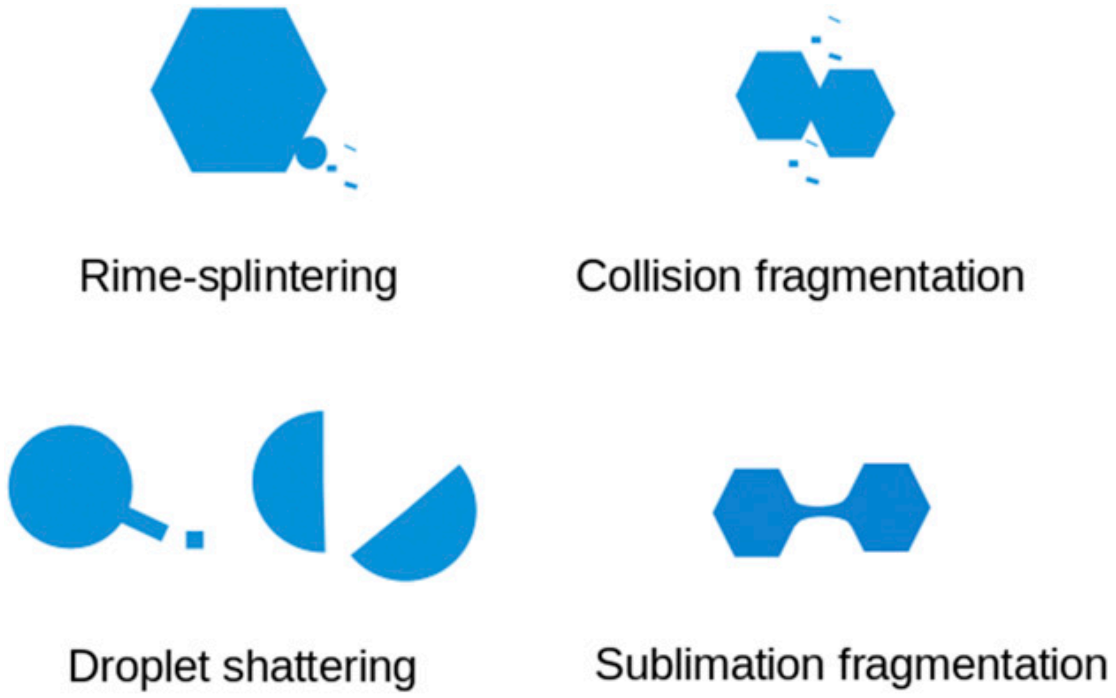


[Mossop, 1985]

Measured **Ni** ≫ **INPs** at T warmer than -15 °C
Indicating the importance of **SIP**

- **Definition: Secondary ice production (SIP)** is processes that produce new ice crystals in the presence of ice crystals from primary ice nucleation.

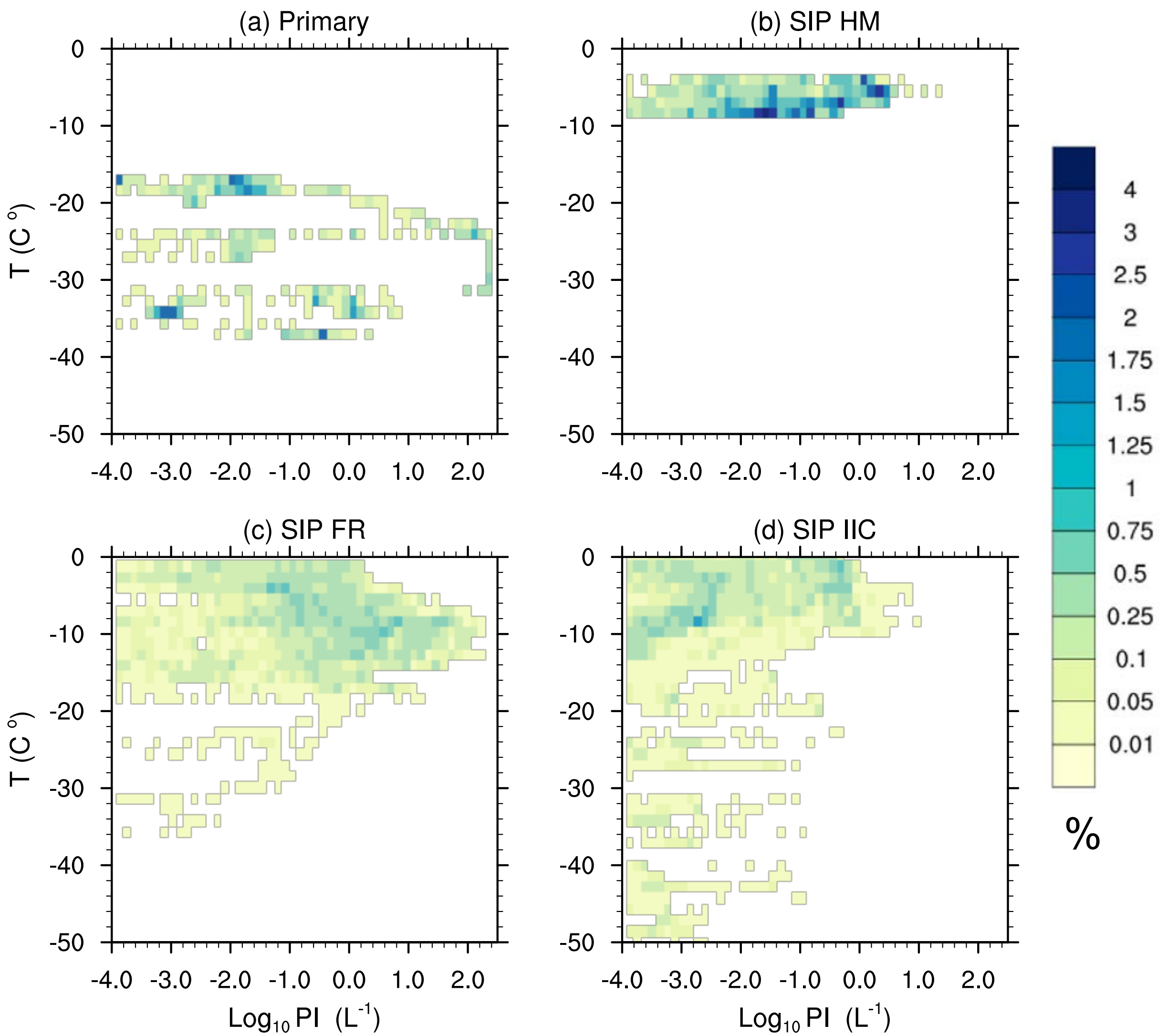
- **Four mechanisms:**



[Field et al., 2017]

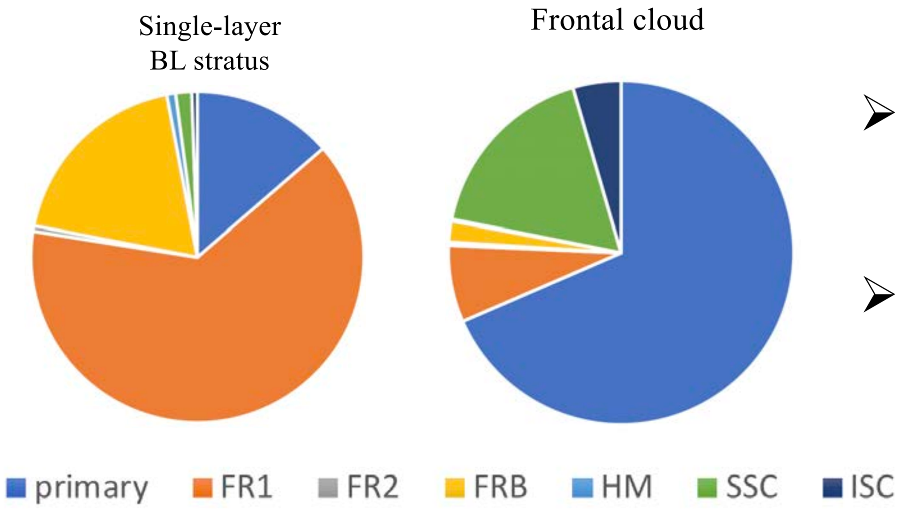
Impacts of SIP on Arctic clouds during M-PACE

Frequency of SIP occurrence (all periods)



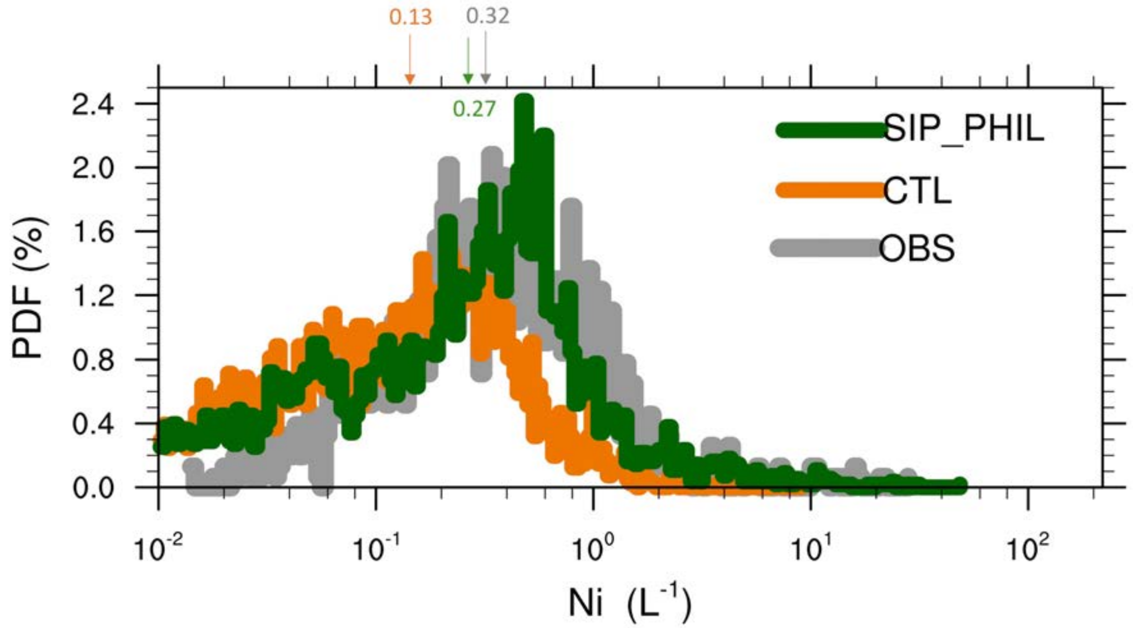
- ➢ Hallett-Mossop (rime splintering) happens in a narrow temperature range
- ➢ Rain fragmentation peaks at around –10 ℃
- ➢ Ice-ice collision fragmentation happens in a wider temperature range

Relative contributions from ice nucleation and SIP



- ➢ Primary ice nucleation is dominant in the cold frontal cloud
- ➢ SIP is more important for moderately cold cloud

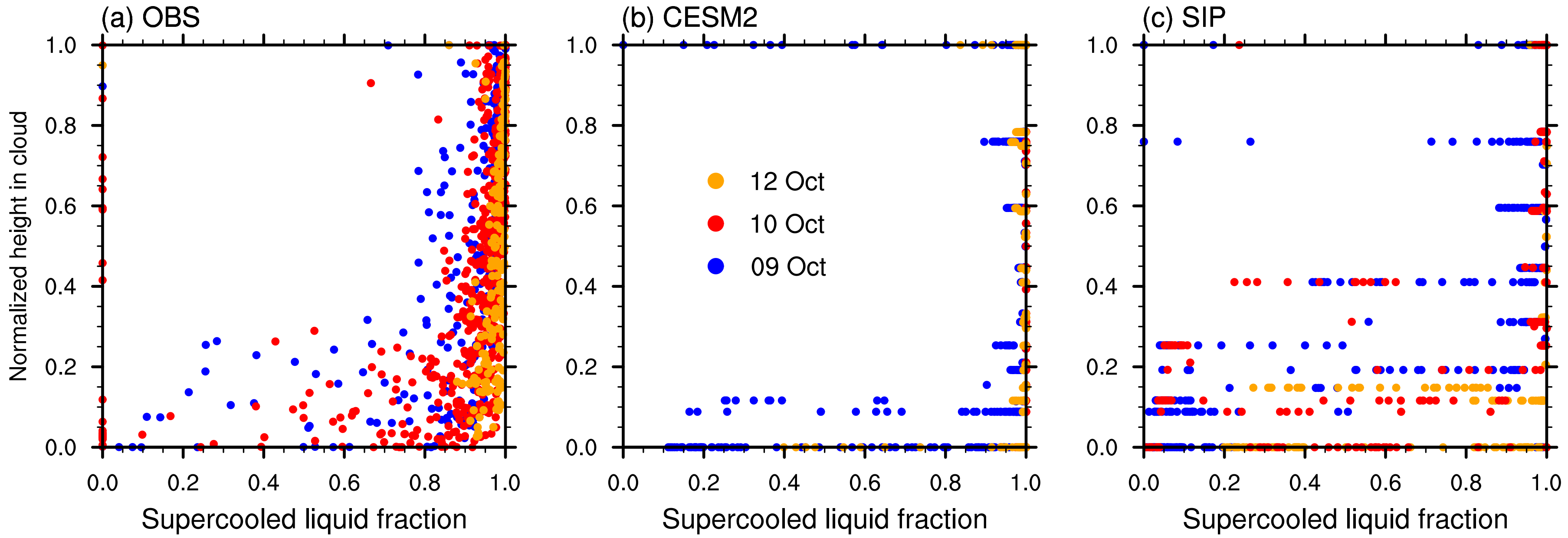
SIP shifts ice number spectrum to right



Zhao, X., Liu, X., Phillips, V. T. J. and Patade, S.: Impacts of secondary ice production on Arctic mixed-phase clouds based on ARM observations and CAM6 single-column model simulations, Atmospheric Chemistry and Physics, 21(7), 5685–5703, https://doi.org/10.5194/acp-21-5685-2021, 2021.

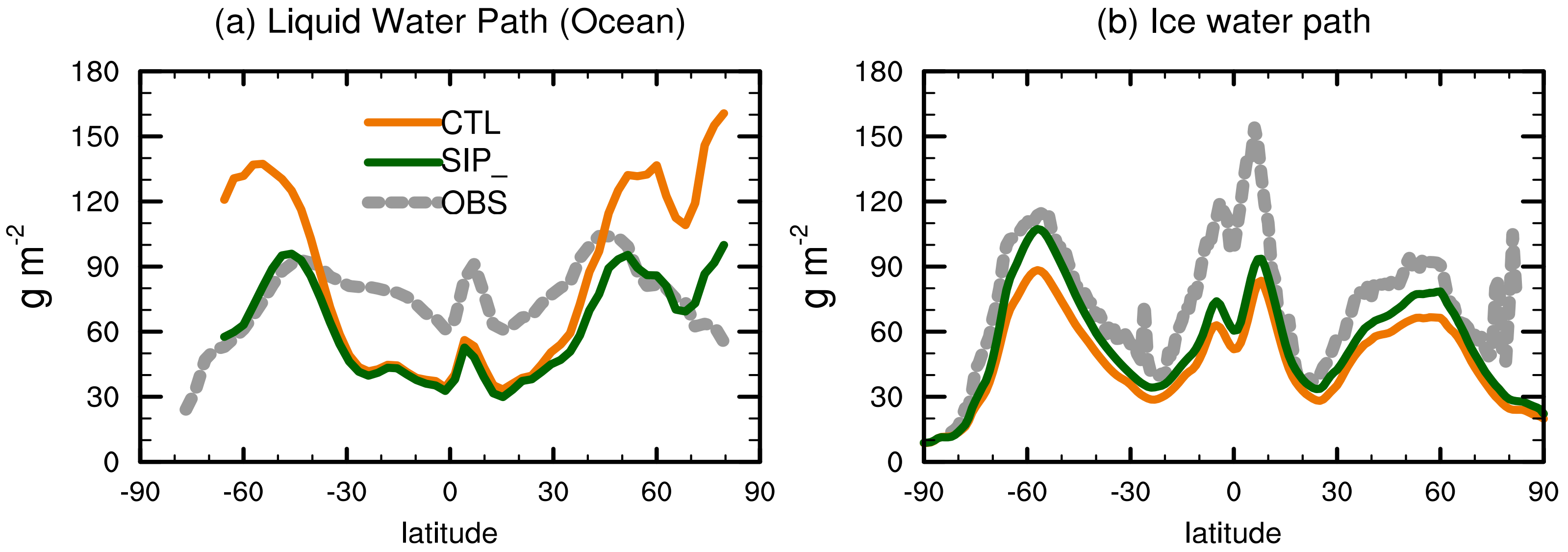
Impacts of SIP on extratropical clouds

SIP changes cloud phase of single-layer clouds



- SIP increase mixed-phase cloud occurrence from 27% to 58%
- SIP generates more ice near cloud base, contributed by rain freezing break-up

SIP global impacts on cloud water and radiative effects



SIP global impacts:

- **Cloud water**:

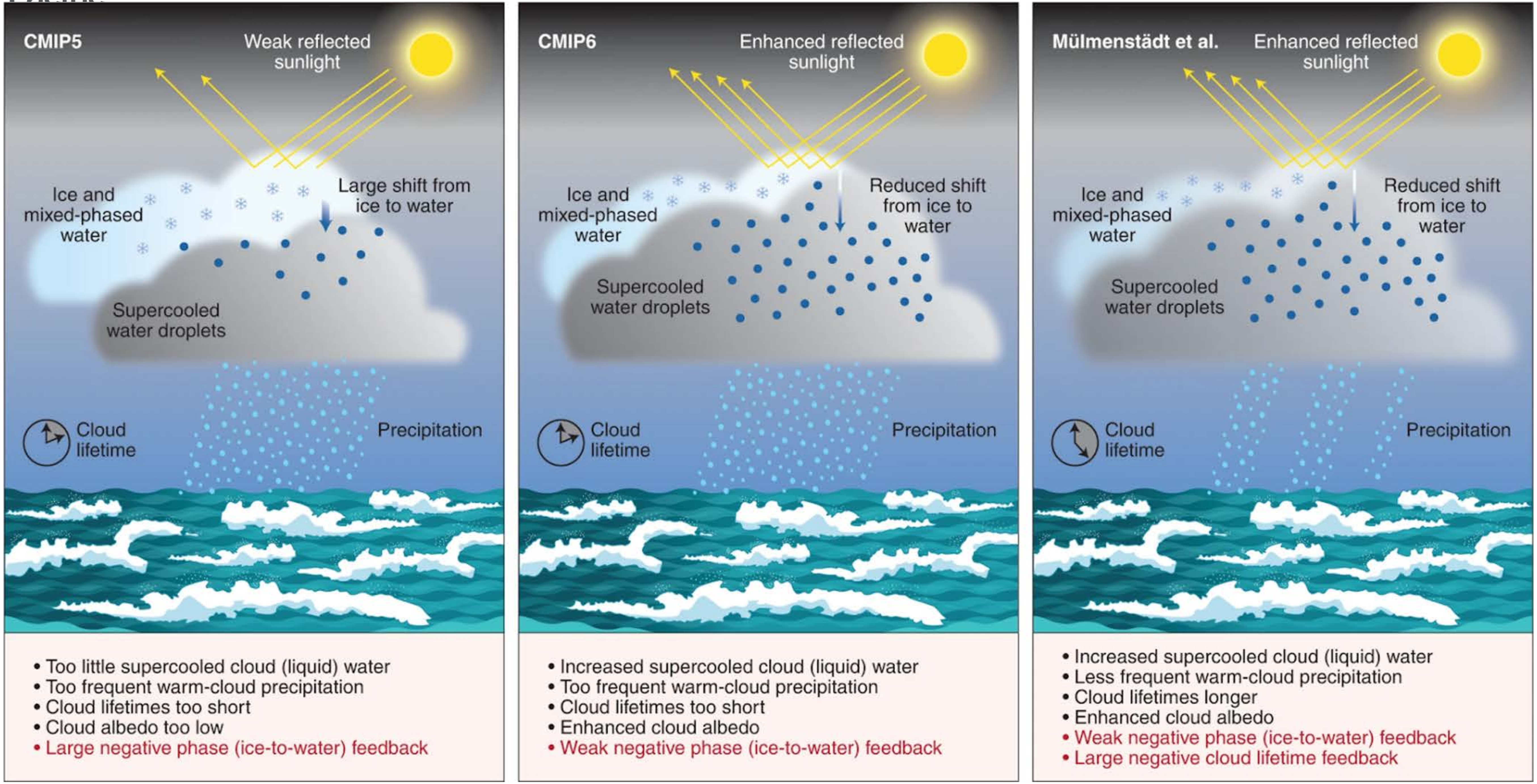
  Less **LWP (–22%)**, more **IWP (23%)**

- **Radiative effects**:

  Weaken by **1 W m^{-2}**

Zhao, X. and Liu, X.: Global Importance of Secondary Ice Production, Geophysical Research Letters, e2021GL092581, https://doi.org/10.1029/2021GL092581, 2021.

Climate is sensitive to rain processes



Stephens (*Nat. Clim. Change* 2021); Tsushima et al. (*Clim. Dynam.* 2006); also, e.g., McCoy et al. (*J. Clim.* 2020)

Climate is sensitive to rain processes… or is it?

- Rain and evaporation are both cloud sinks
- How important is each? They have opposite-sign responses to warming (cloud feedback) and to CCN (aerosol ERF)!
- Do the real atmosphere and parameterized clouds/turbulence paint the same picture?
- Regime dependence: cyclone vs cold sector stratus vs cold sector shallow cu

What does “cloud sink” mean at climate-relevant scales? E.g., if a cloud evaporates, does a different one pop up, or is that moisture gone? Need to understand the cloud field dynamics.

If climate is sensitive to rain processes… what are rain processes sensitive to?

- INP?
- CCN?
- Dynamics?

Obvious to everyone but me?
… please discuss!

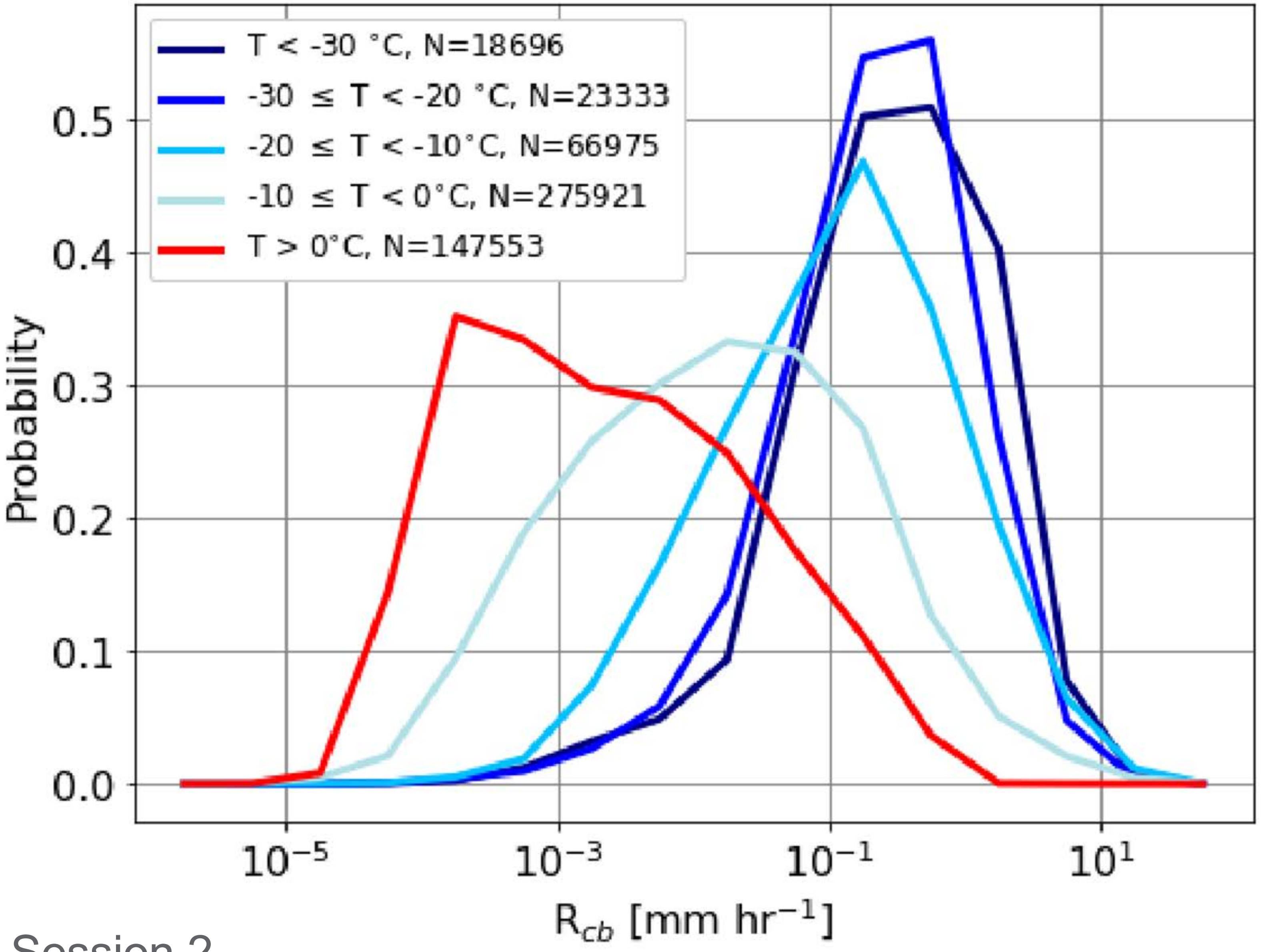


Figure stolen from Stanford et al., Poster Session 2

Timeline and possible strategy

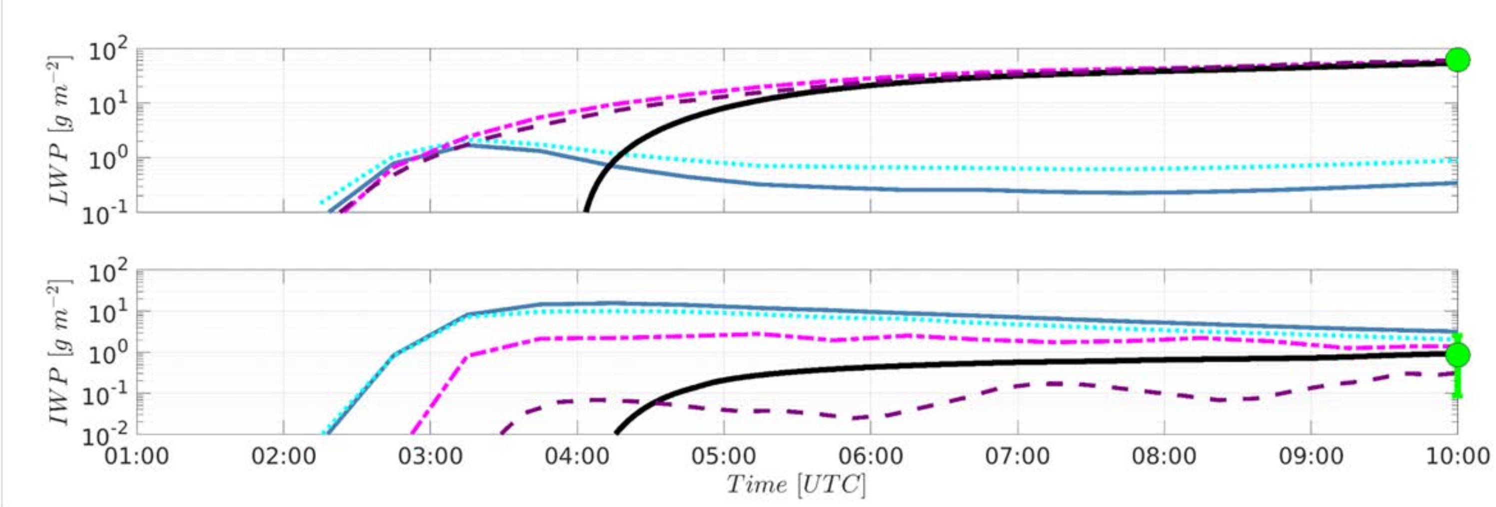
- **Cloud Properties & Measurements Working Group (first report)**
  - stimulating joint community exercises could increase ARM's reach and impact, as demonstrated historically—e.g., Klein et al. (2009) M-PACE CAO case
  - driven from the modeling side with an emphasis on observational constraint

- **2020 ARM/ASR PI Meeting Breakout (key findings)**
  - support for group activity spanning LES to ESM, with a focus on observational constraint of processes to which ESMs are established to be sensitive (as in GASS Diurnal Cycle of Precipitation project led by Shaocheng Xie)
  - support for new and revisited LES/SCM case studies and pairing to ESM analysis
  - support for readily accessible and low-overhead easy-to-use LES/SCM library with standardized format (e.g., DEPHY), and some efforts already made
  - strong support for low-overhead participation options!
  - two-pronged approach suggested: intercomparison activities + one-stop shop

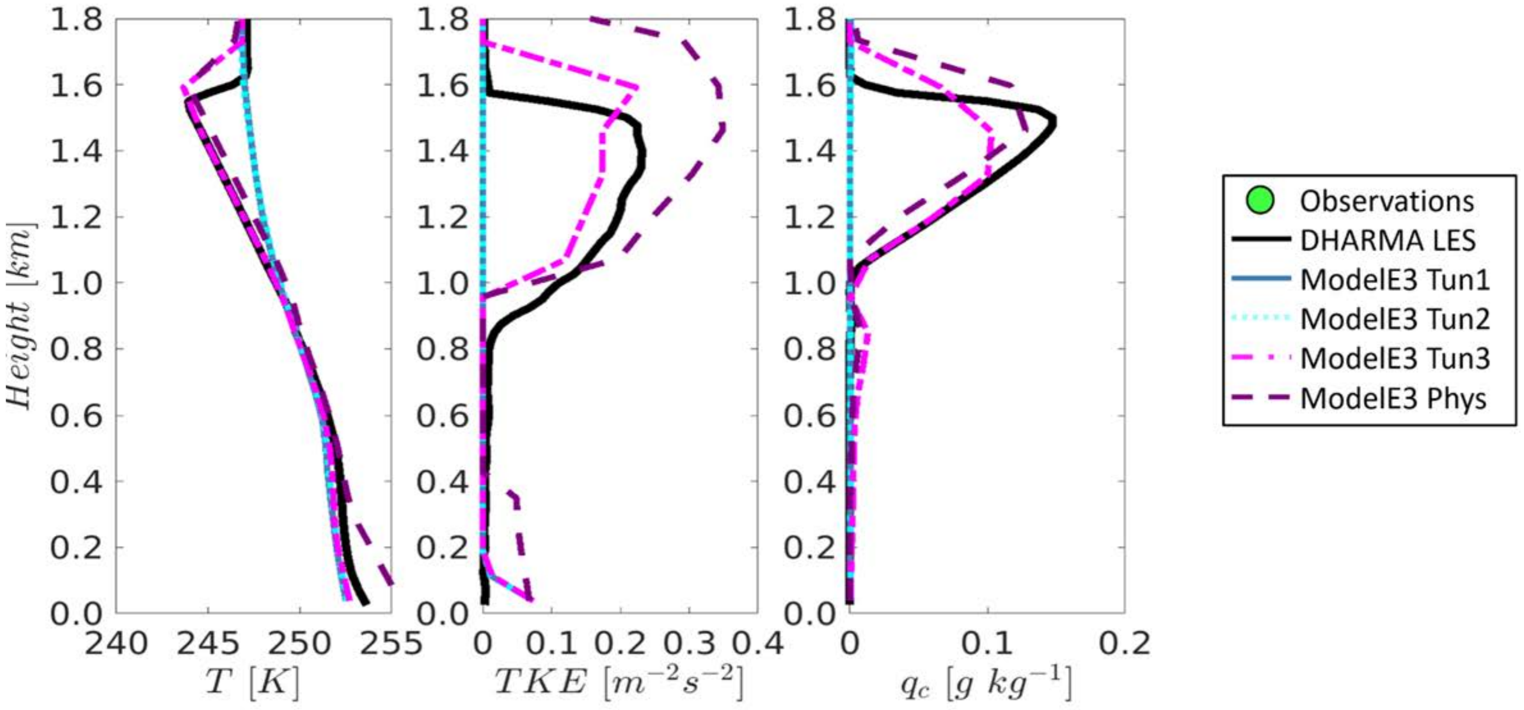
- **What next?**
  - focus on aerosol+cloud processes associated with extratropical cloud feedbacks?
  - propose a set of modular community exercises at GASS summer 2022 meeting?

Timeline and possible strategy

- **How might new LES/SCM case studies be improved?**
  - Lagrangian approach widely advocated (e.g., Ali and Pithan 2020) introduces a test of whole cloud lifecycle (e.g., Neggers et al. 2015)
  - realistic interactive aerosol introduces a test of key processes that feed back on cloud evolution (e.g., Yamaguchi et al. 2017), can include surface fluxes
  - now that we converged by tightening constraints (Klein et al. 2009 —> Morrison et al. 2011 —> Ovchinnikov et al. 2014), we may learn from sequentially relaxing and even reducing (e.g., interactive surface fluxes in LES vs SCM)

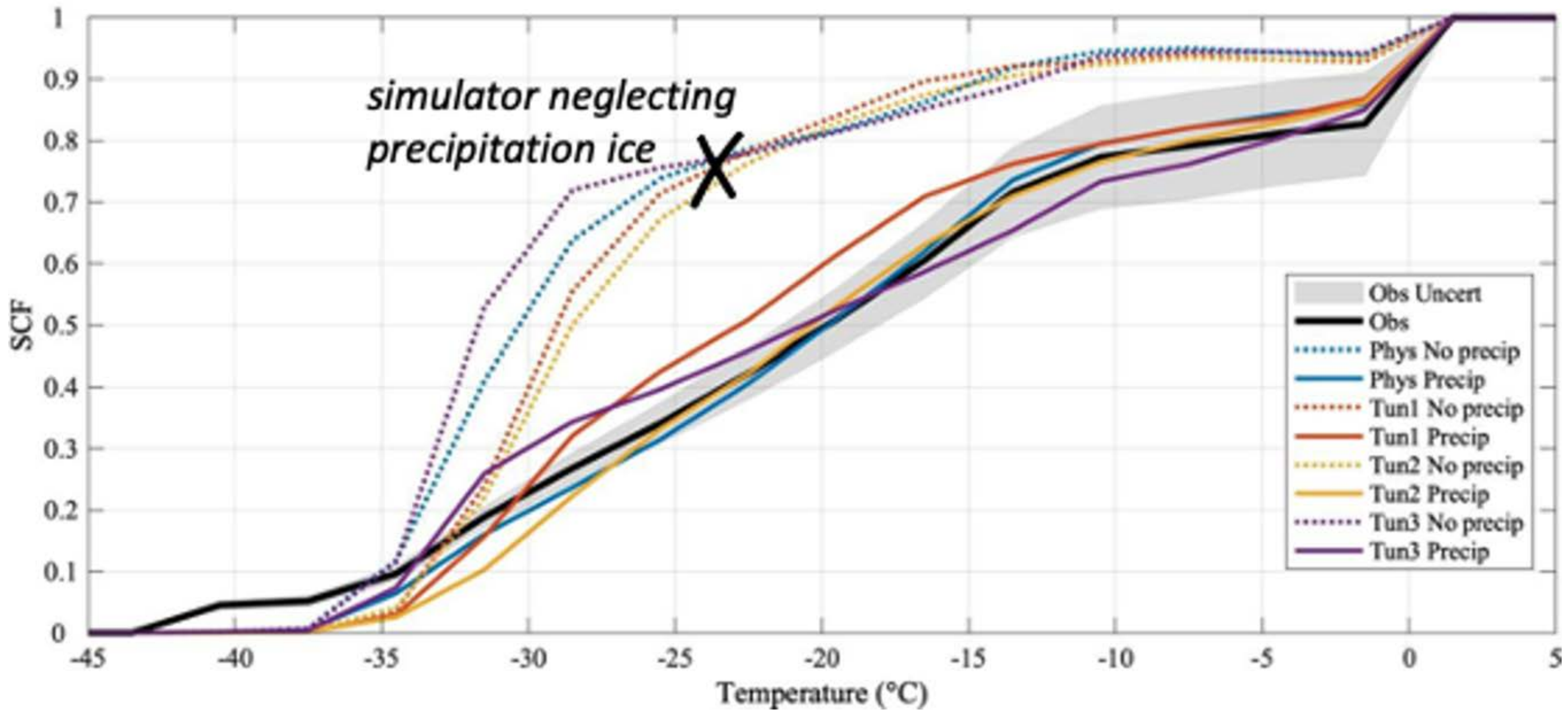


Lagrangian LES/SCM case study of highly supercooled elevated decoupled Antarctic stratus observed to be drizzling and snowing during the AWARE campaign (Silber et al. 2020 and submitted)

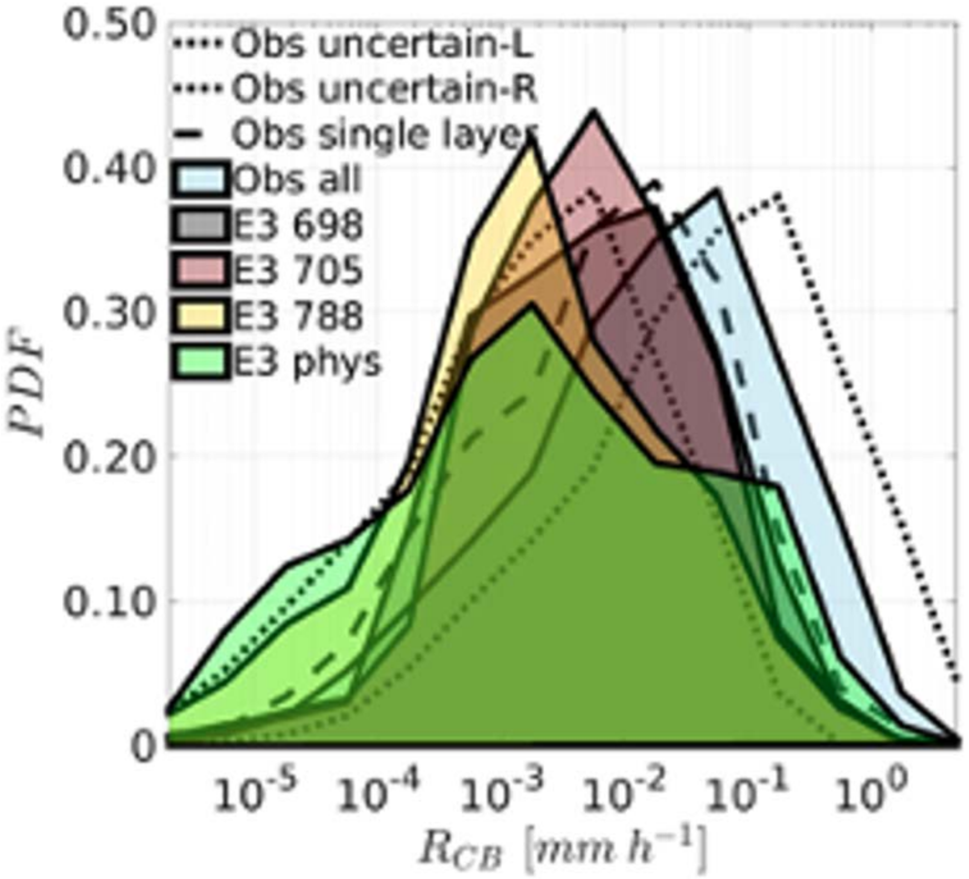


Timeline and possible strategy

- **How might ESM observational constraints be linked?**
  - if Lagrangian SCM performance is a “fingerprint” of ESM behavior along similar trajectories (Neggers 2015 using SCT case), shouldn’t it be relatable to relevant observational metrics?
  - extratropical cloud feedback process targets might include satellite-constrained SCF statistics or ground-based statistics analyzed in a process-oriented manner
  - and more ideas welcomed ...



ModelE3 physics tunings: (1) reproduce CALIPSO supercooled cloud fraction fairly well (at least globally) when the COSP simulator approach accounts for precipitation (Cesana et al. submitted)



(2) reproduce weak precipitation rates compared with supercooled cloud base rates over NSA 2011–2019 (Silber et al. 2021, submitted and in prep.)

What are high-priority processes for improved understanding of extratropical cloud feedbacks?

Target process or knowledge gap	**Strategy and/or target observations**
Marine sources of CCN / INPs	● improved and *parallel* measurements of marine aerosol, CCN, and INP
Primary ice formation	● AEROICESTUDY aerosol–ice formation closure pilot study
Secondary ice production	● *parallel* measurements of ice crystal and INP numbers
Bridging from small-scale field campaigns to climate-relevant processes	● LES-SCM comparisons ● Responses of climate models to observed quantities (e.g., INP(T) as in Tan et al.)
Breaking multi-fidelity / equifinality in models	● Identify observable variables that are sensitive to only a small number of model parameters (e.g., warm rain rate as in Mulmenstadt et al., 2020)
...	...