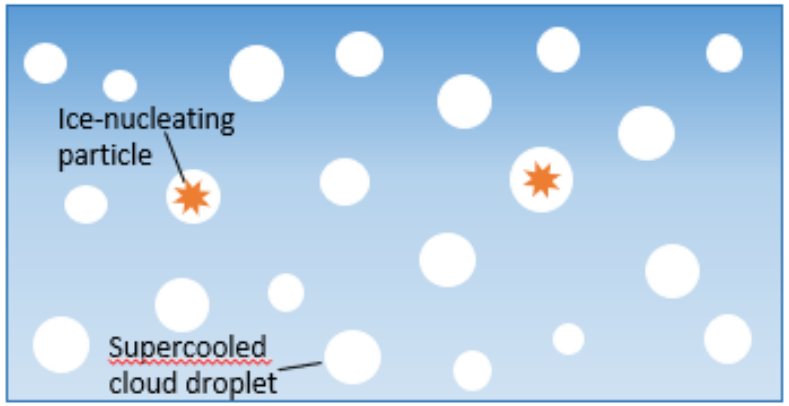
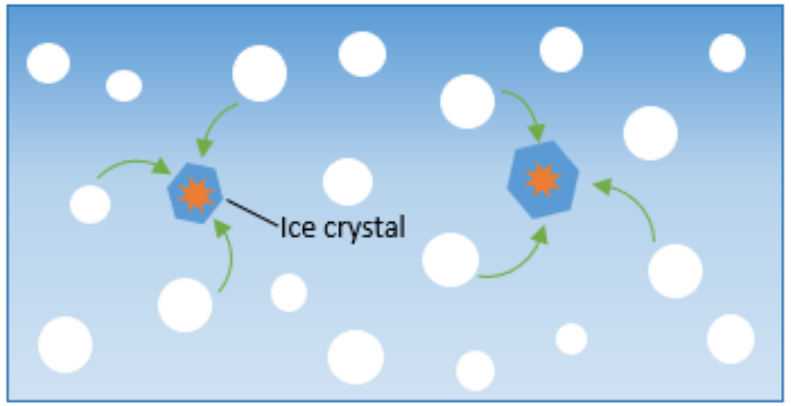
Ice production in cold-air outbreak clouds during ACAO and M-Phase

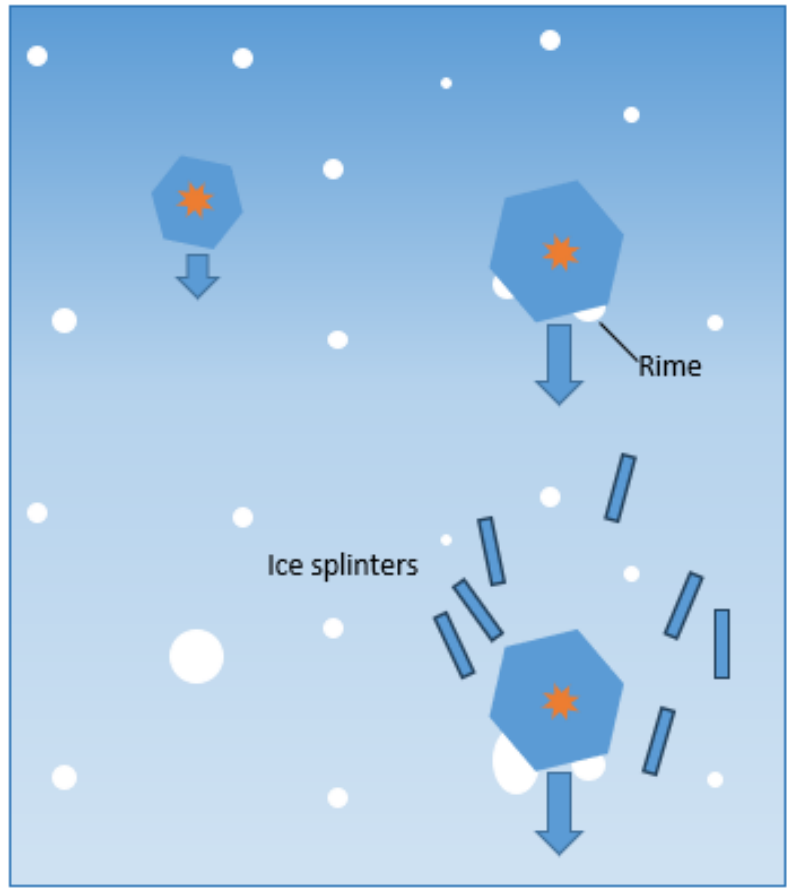
Ben Murray

Michael Biggart, Erin Raif, Gary Lloyd, Mark D. Tarn, Joseph Robinson, Polly B. Foster, Sam Clarke, Sarah L. Barr, Daniel K. E. Smith, Martin W. Gallagher, Ian Crawford, Floor van den Heuvel, James B. McQuaid, Thomas Lachlan-Cope, Paul Barrett, Keith N. Bower, Ken S. Carslaw, Ian A. Renfrew, Paul R. Field, Thomas W. Choularton, Paul A. Barrett and Steven J. Abel

What controls the ice particle concentration in a cloud?







Two schools of thought on what controls the ice particle number concentration in clouds:

- Secondary ice production (rime-splintering, collisions etc) swamps the effect of ice-nucleating particles

- Primary production on ice nucleating particles (INPs)

Measurements from ACAO and M-Phase

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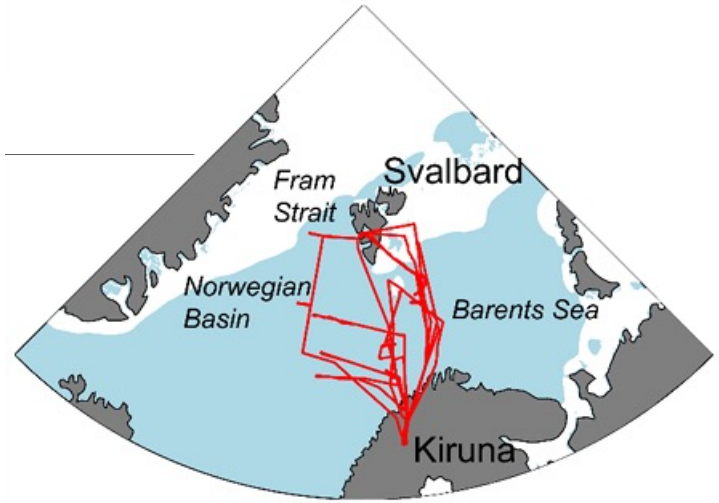
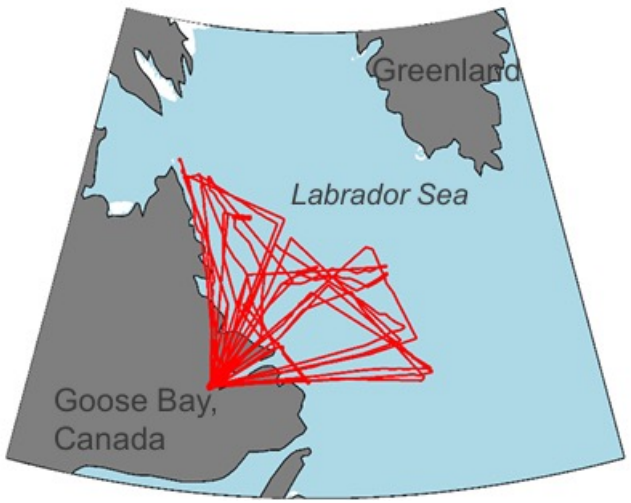
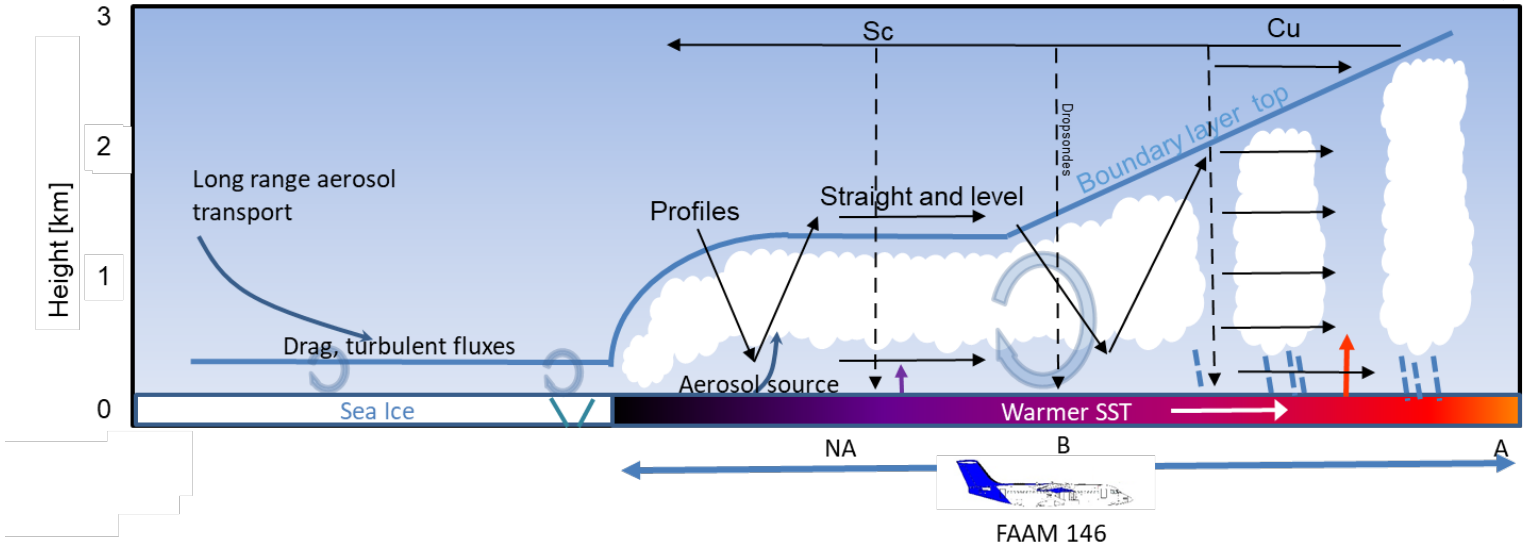
ACAO



M-Phase





Meased aerosol properties (INP) in air relevant for the CAO clouds that we also probed.

Ice particle concentrations, at cloud top temperature, vs INP concentrations

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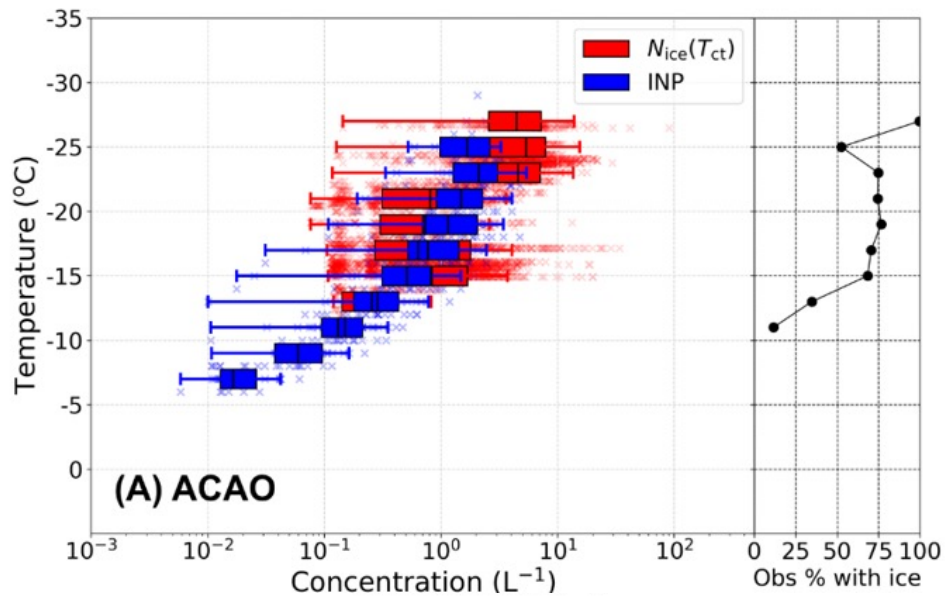
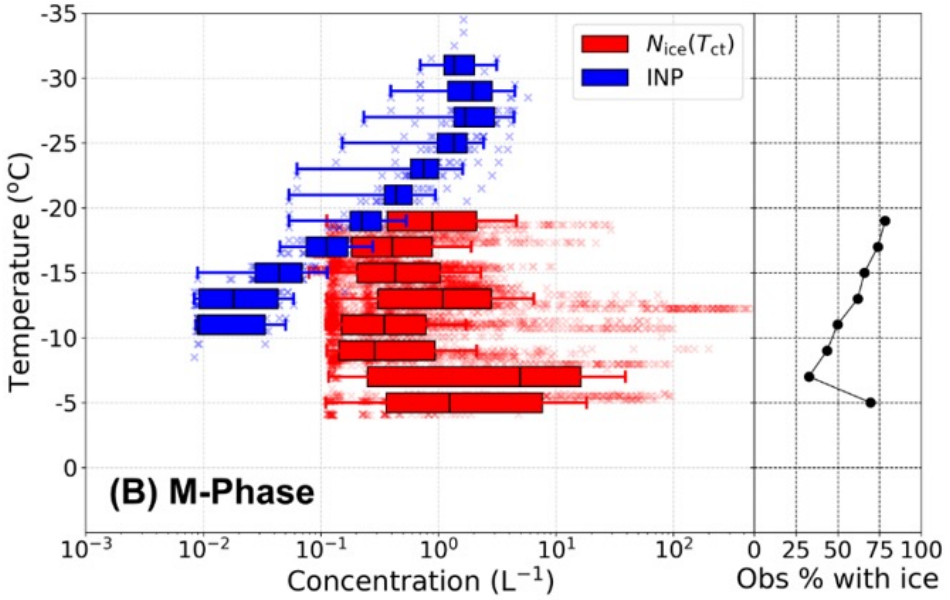
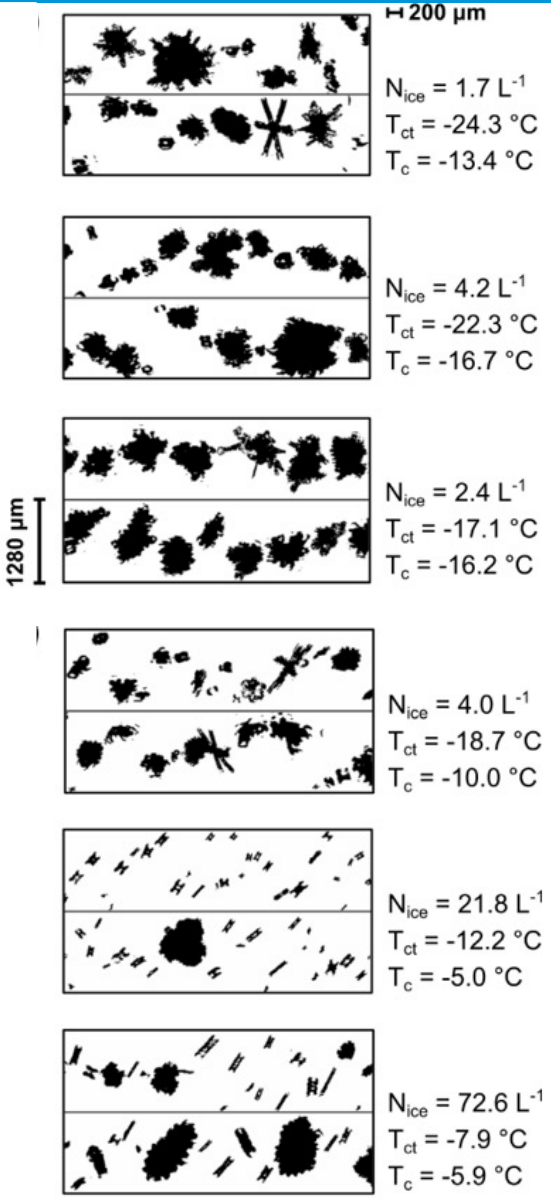


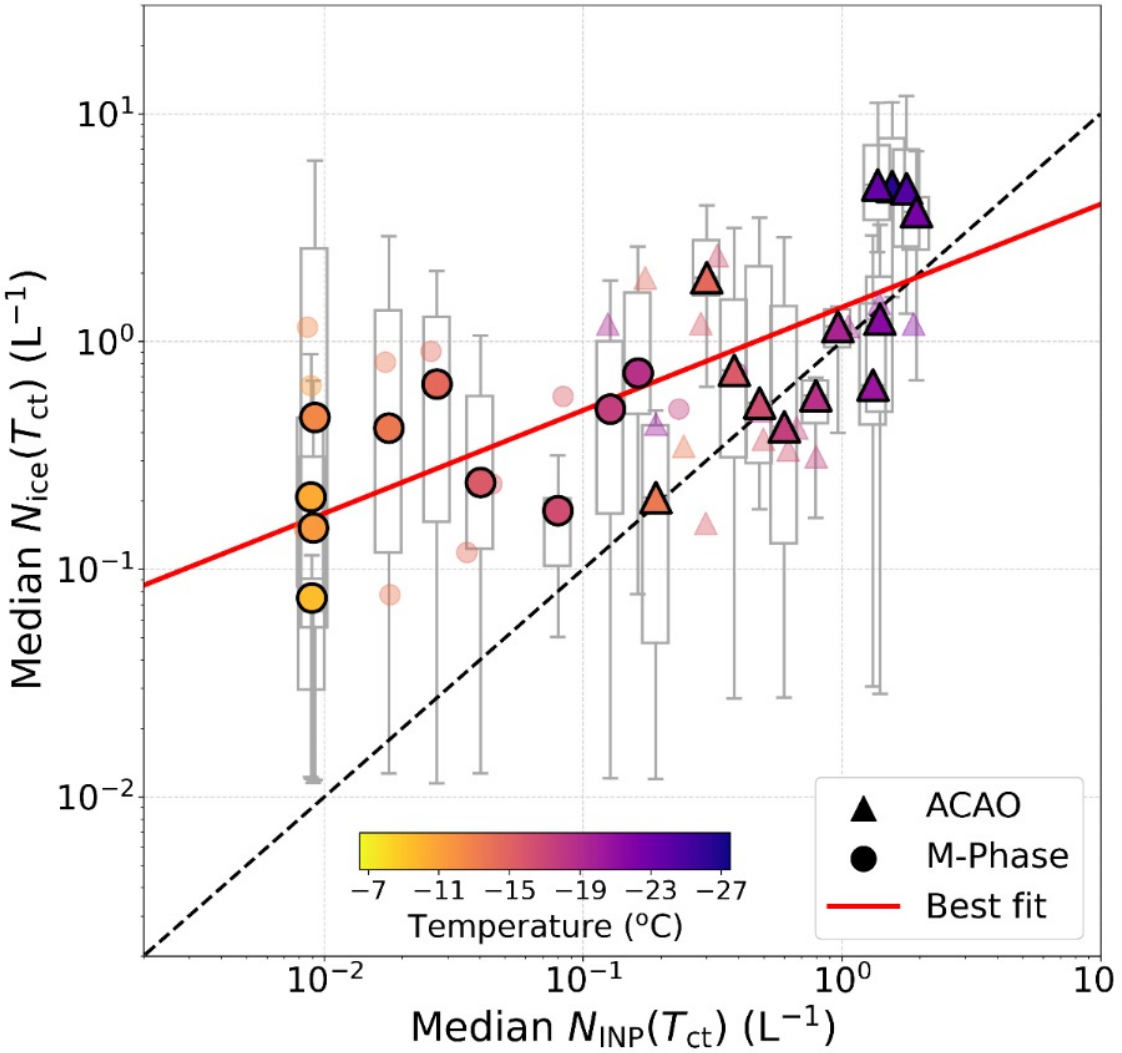


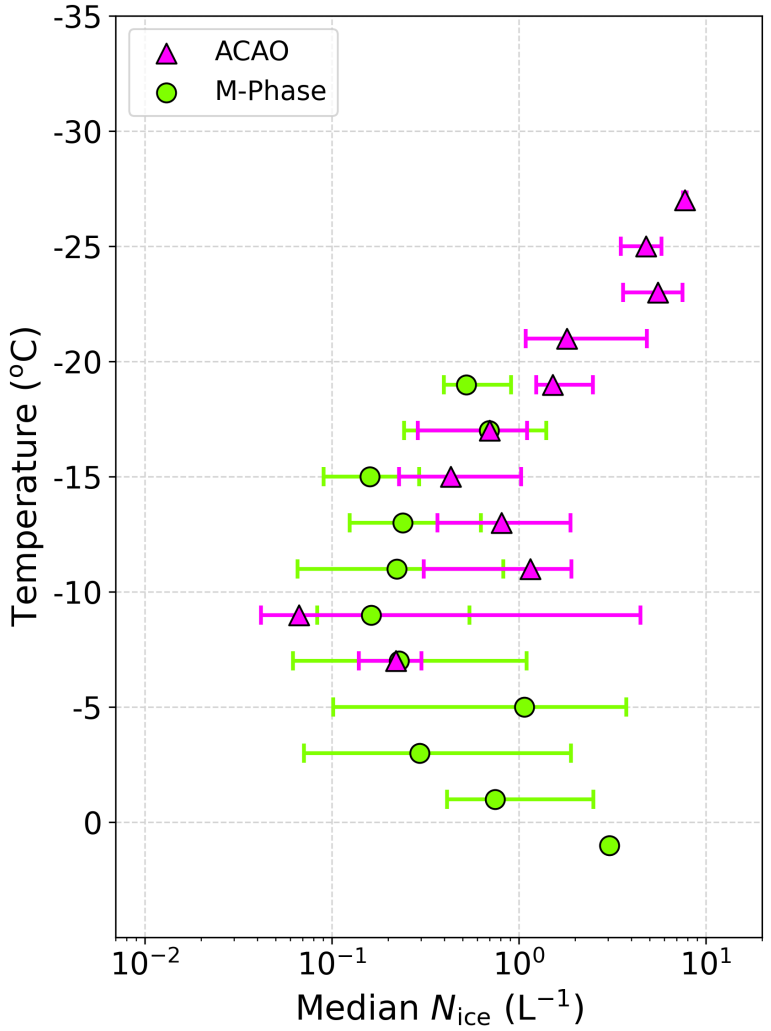


- ACAO: Ice concentrations driven by primary production on INP at cloud top.
- M-Phase: Ice concentrations driven by secondary production above -8ºC

See Michael Biggart's Poster on SIP

Median INP concentrations correlate with median ice concentrations





- Even with SIP processes active, INP drive ice production

Max ice concentrations are not driven by INPs

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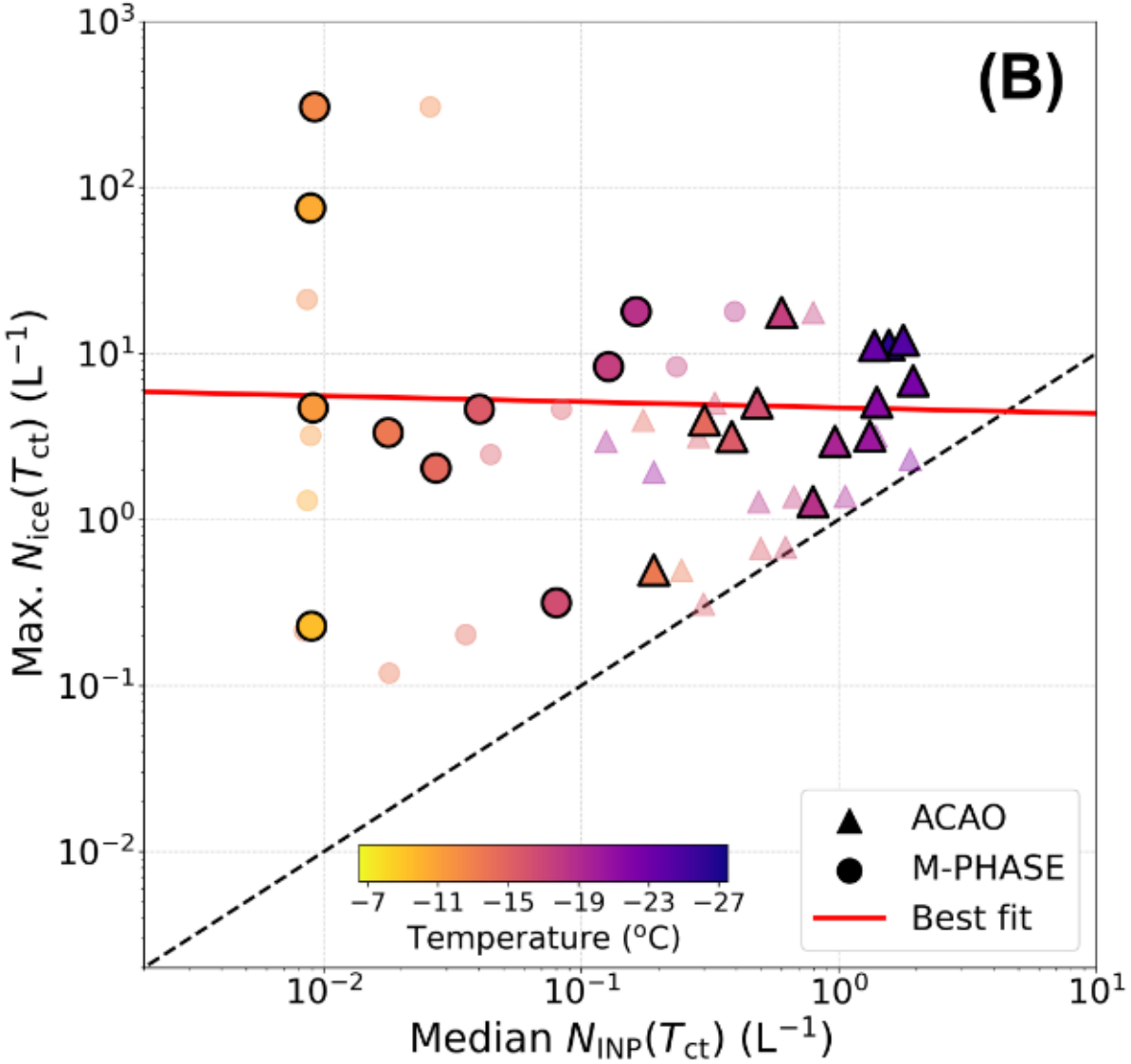


Comparison with the Southern Hemisphere

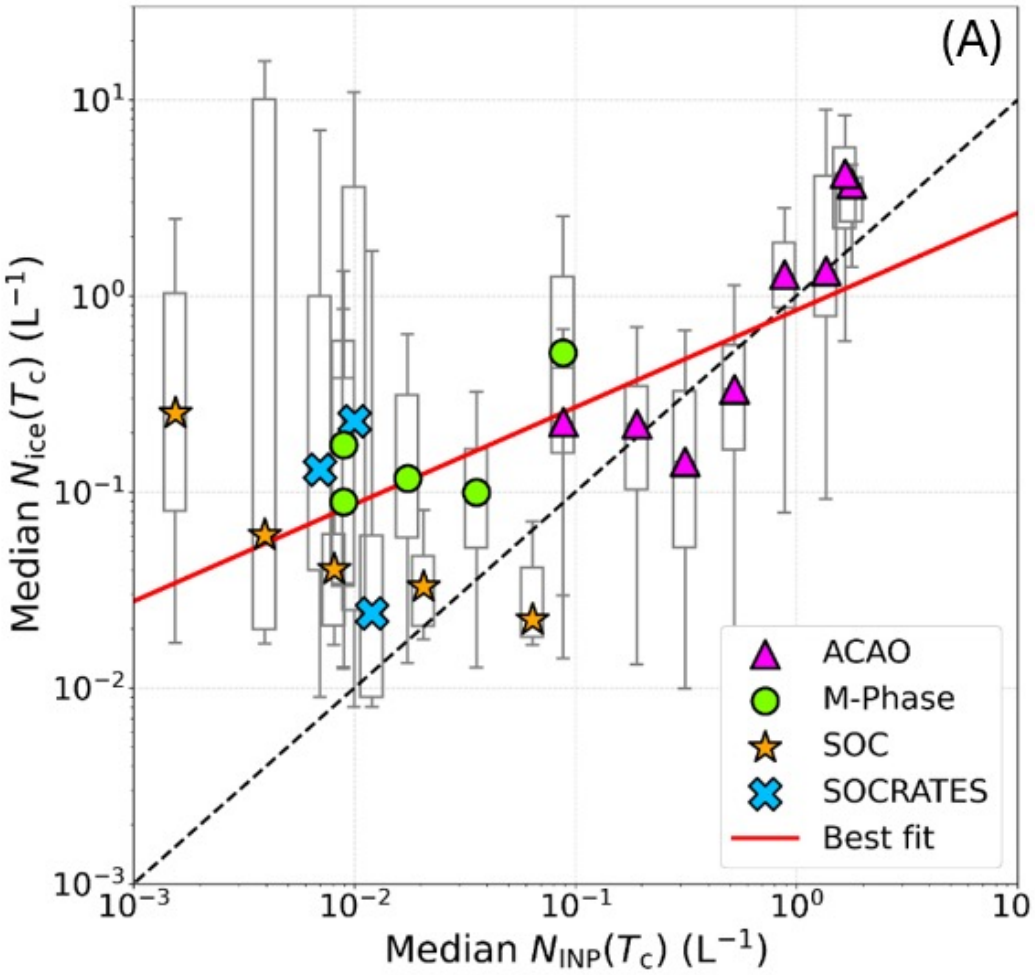
M-Phase ACAO

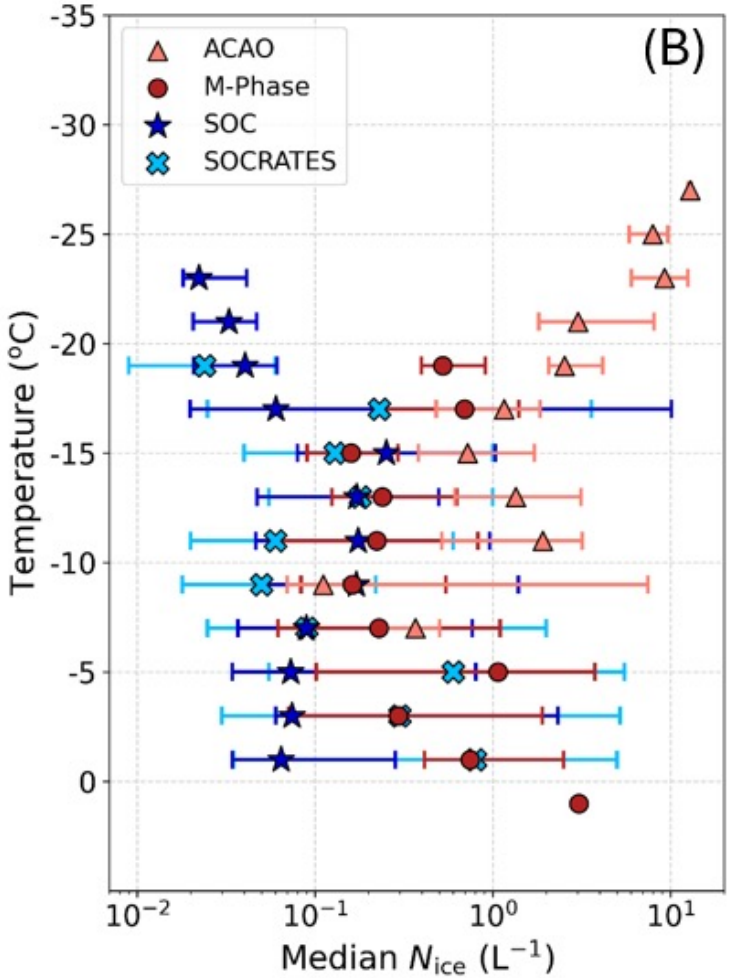
SOC

SOCRATES

Jarvinen et al. JGR, 2022

Comparison with the Southern Hemisphere





- Fewer ice crystals in SH, correlating with fewer INPs
- Even when SIP is active, ice concentrations are driven by primary ice production on INP.
- Need to represent INP variability around the globe.

Why was the INP concentration so high in ACAO?

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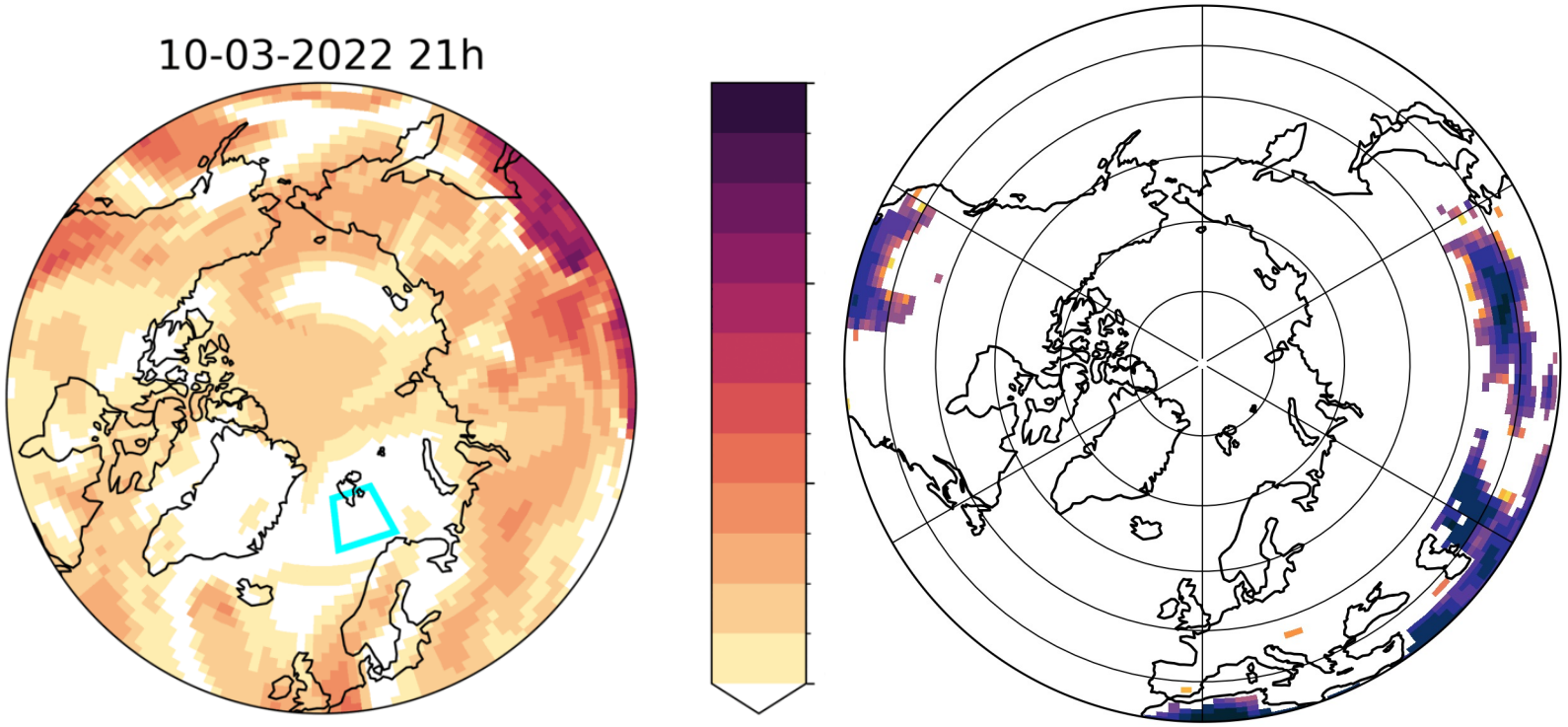
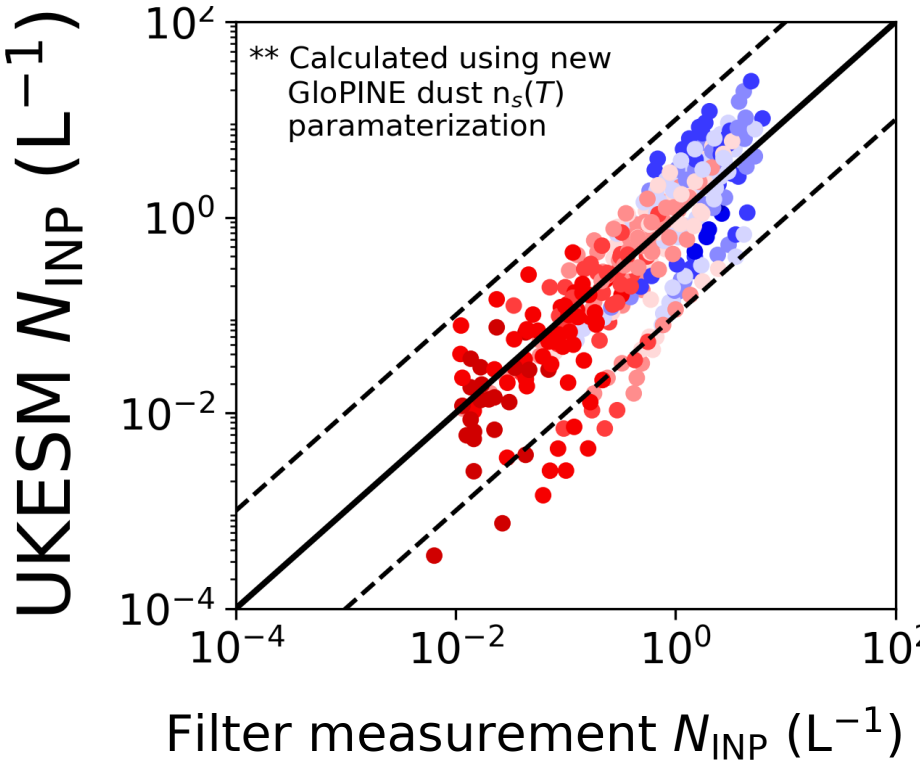
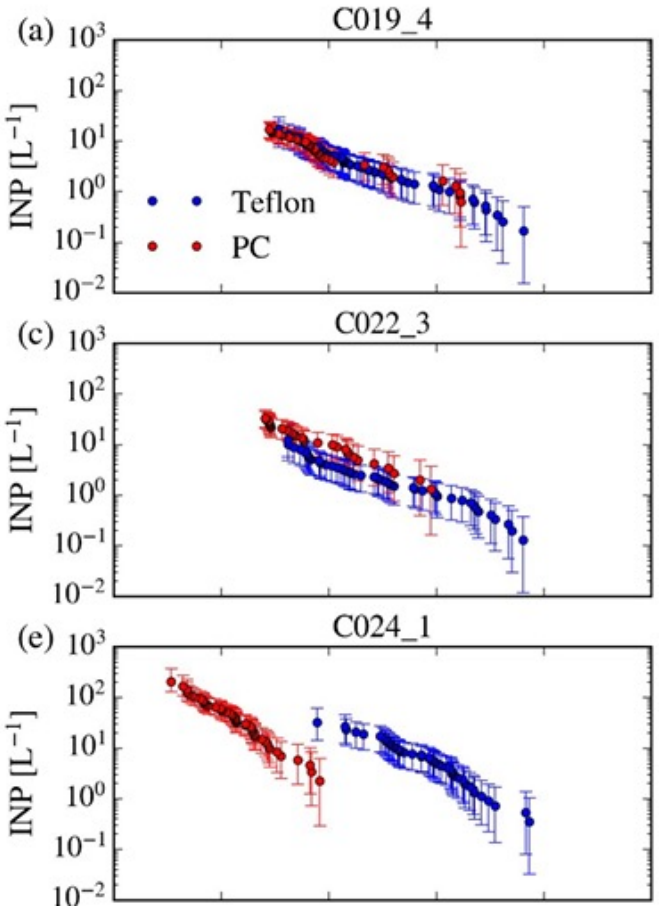




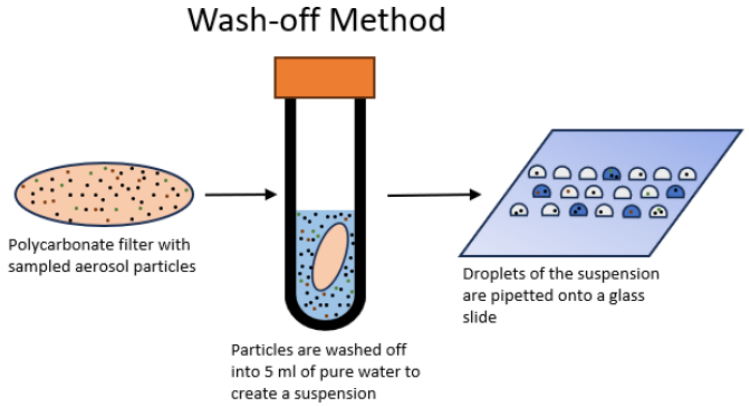
- Dust input from Asia (under polar dome?)
- New model based on PINE measurement network is a good predictor of ACAO INP concentration

The INP filter issue ☹

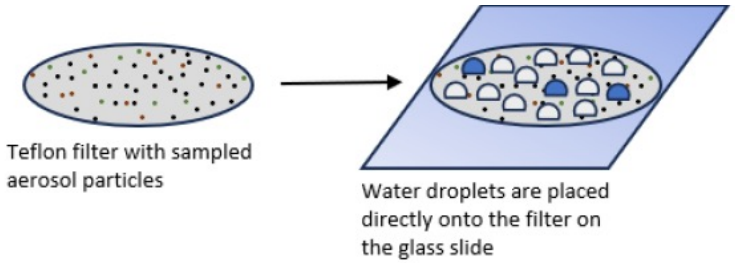


Sanchez-Marroquin 2021: FAAM SE UK

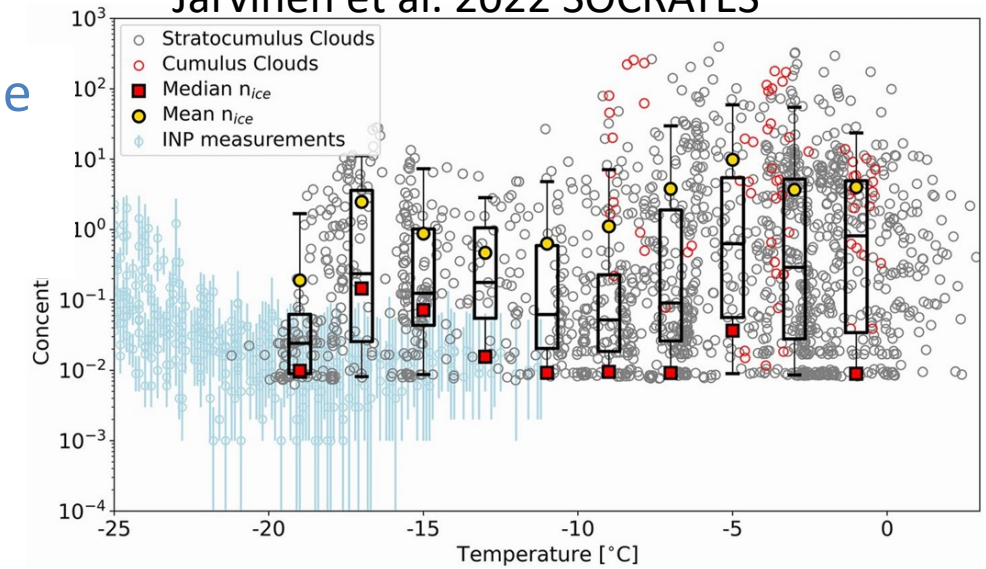
- Polycarbonate wash-off technique



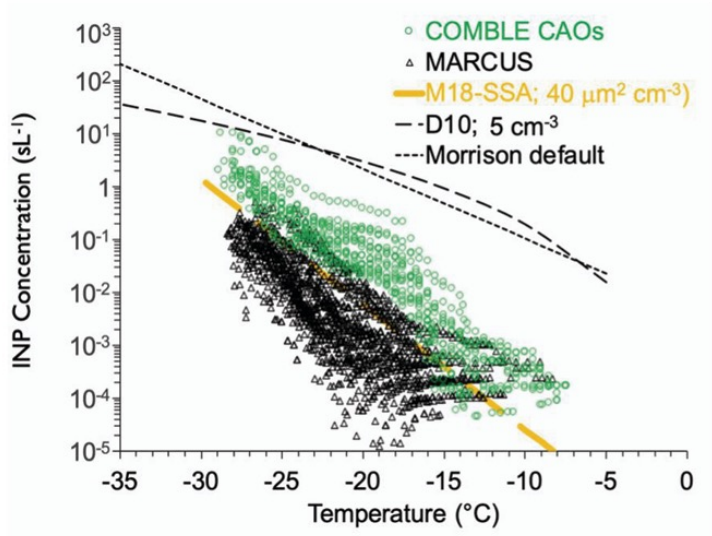
- We used the droplet-on-filter Teflon technique



Jarvinen et al. 2022 SOCRATES



Geerts et al. 2022 COMBLE



Discrepancies between wash-off and drop-on techniques: In lab tests vs SO

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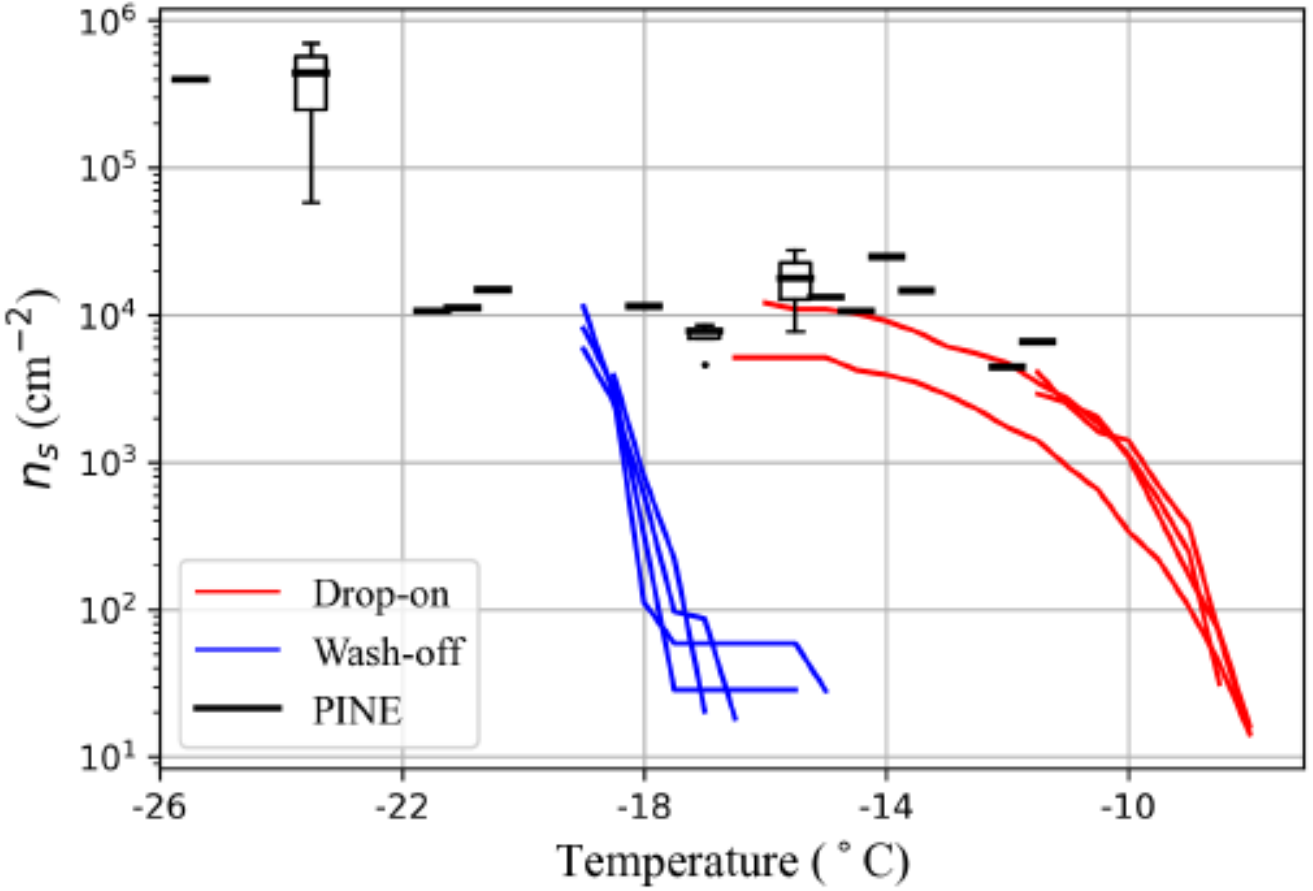
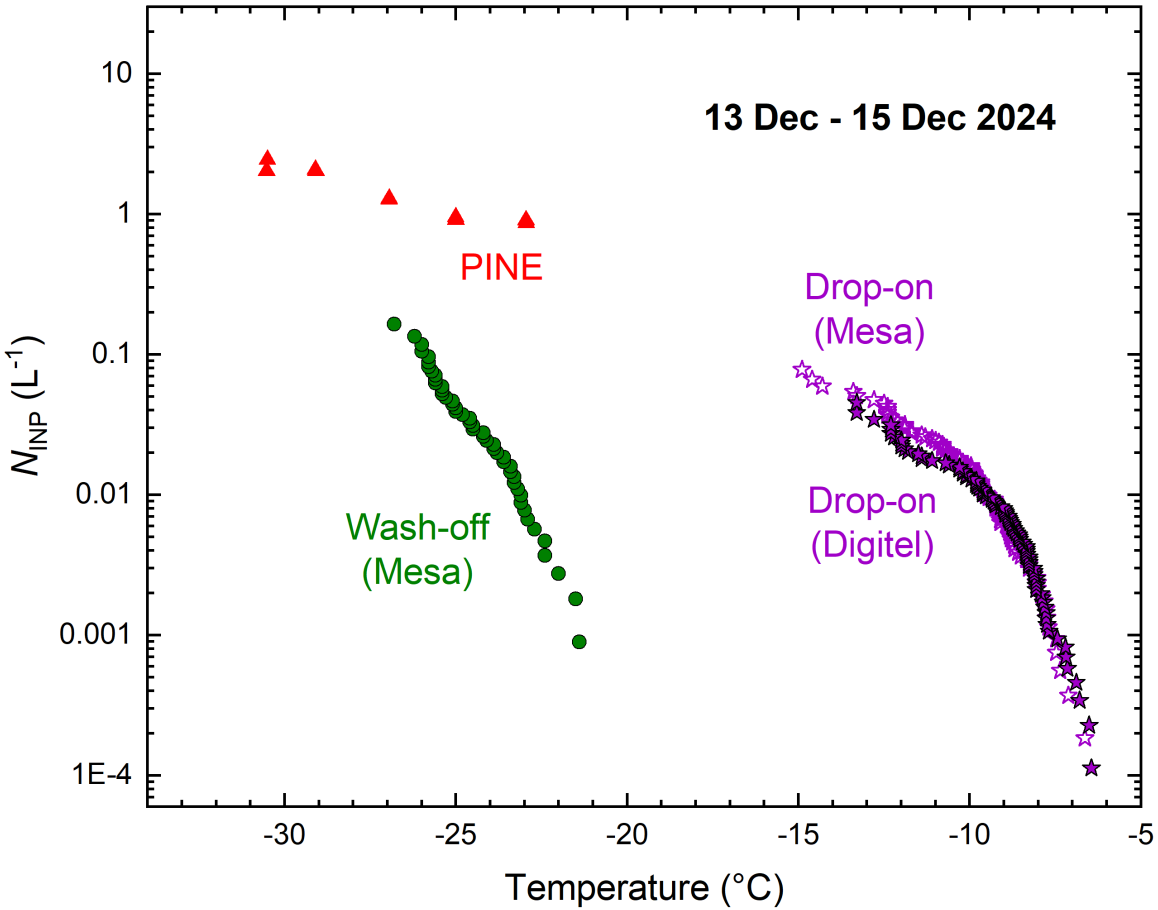
Laboratory tests with bacterial proteins



Robinson et al., 2026, *Aerosol Res. Discuss.*

Extreme Southern Ocean case



Discrepancies between wash-off and drop-on techniques: Southern Ocean

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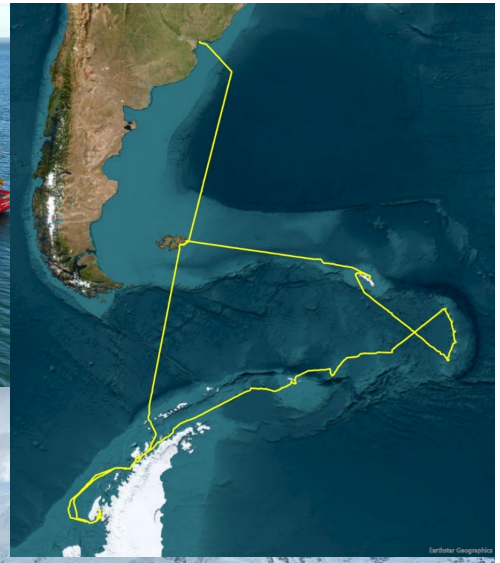

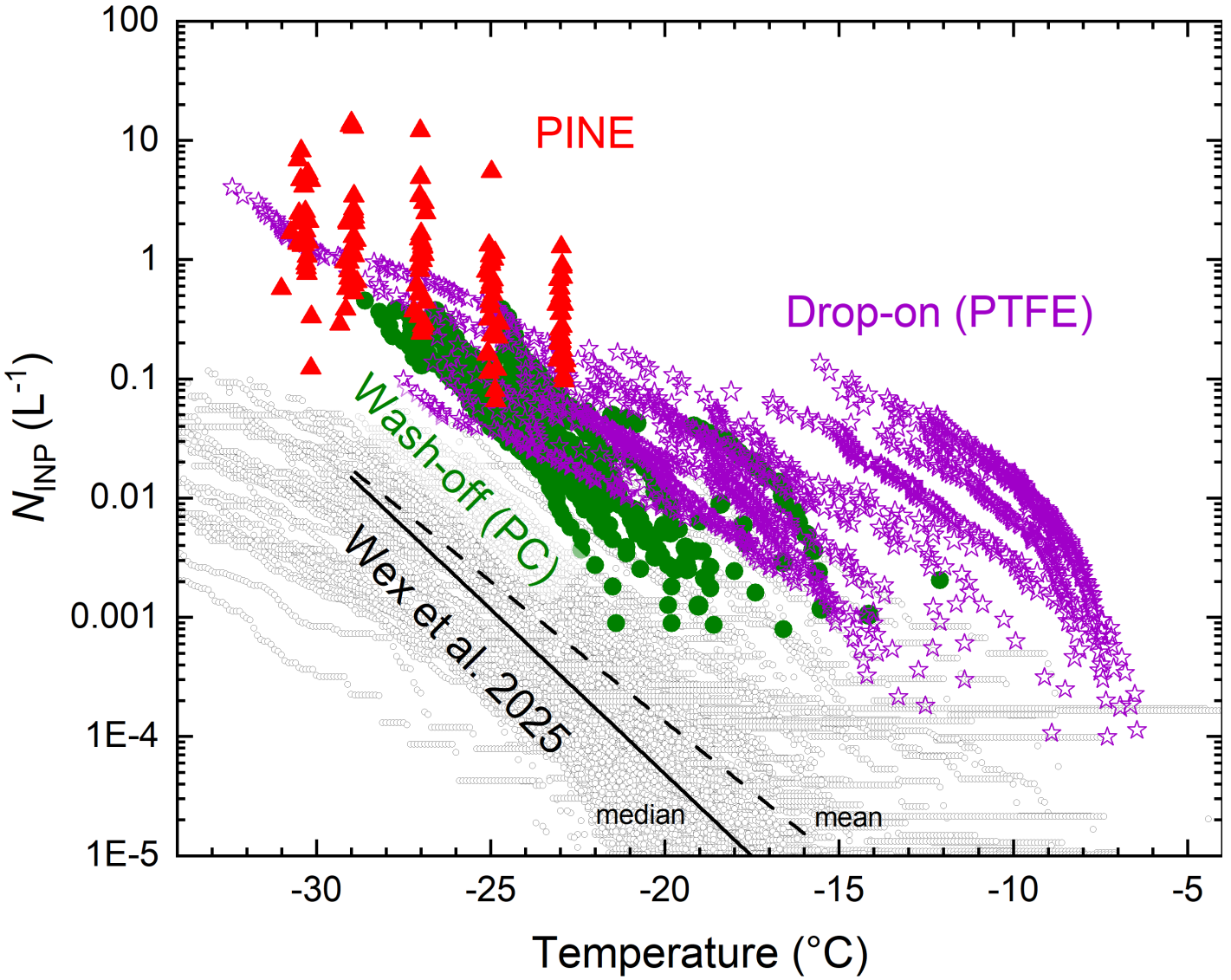

Maybe the INP concentrations were higher during SOCRTATES than reported?

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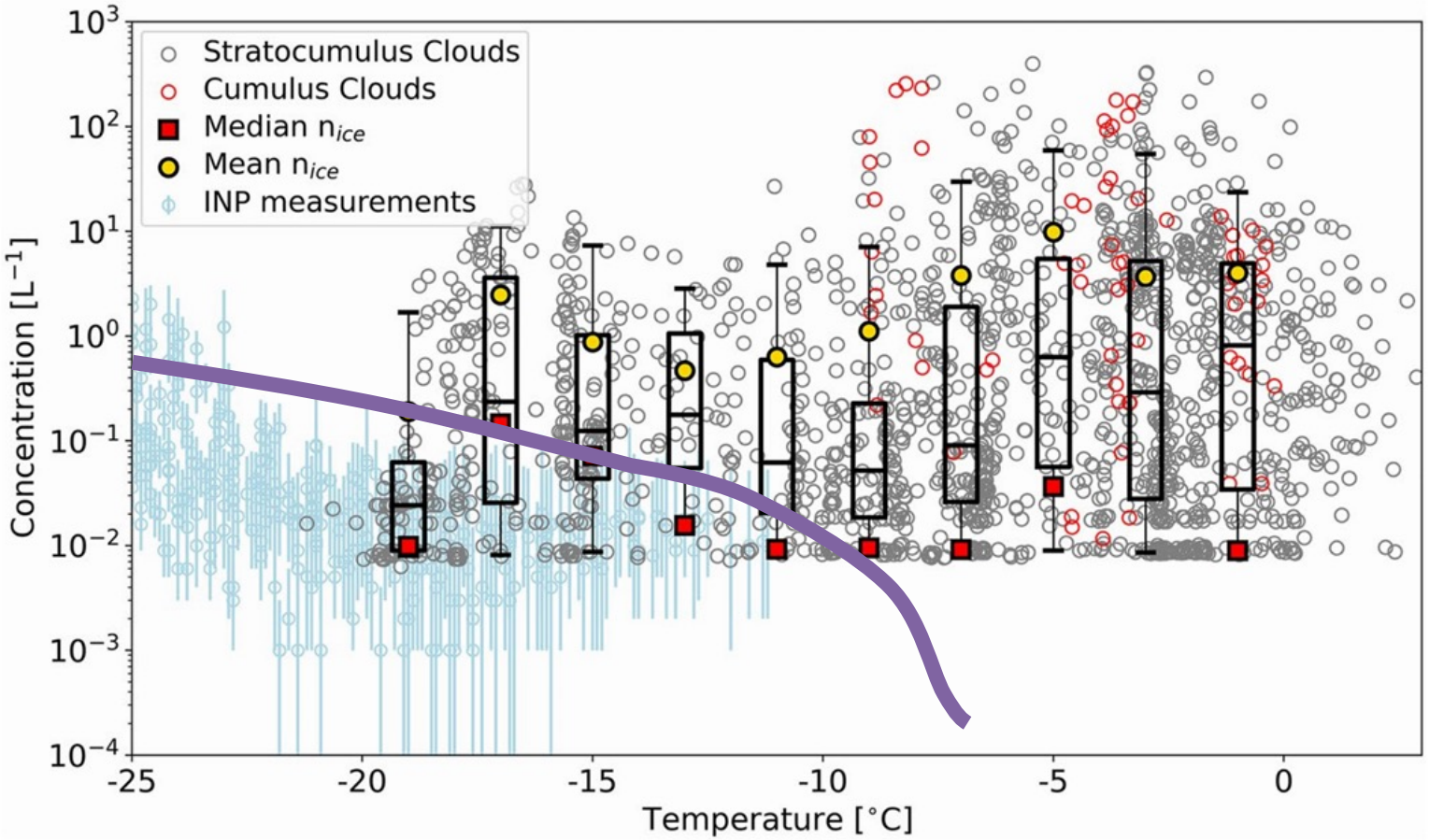

- Our high INP curves from the SO are a plausible match to the median ice concentrations below ~-10°C from SOCRATES
- H-M was active in SOCRATES.
- A problem in Arctic measurements?

Conclusions

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- INPs are the primary driver of median ice particle concentrations in shallow marine mixed-phase clouds
- SIP serves to amplify the ice particle concentrations in pockets of some warmer clouds
- The INP concentration is highly variable around the globe and ice production in clouds needs to be linked to INP concentration to represent the cloud-phase feedback.

UKRI Natural Environment Research Council

Immediate synergy

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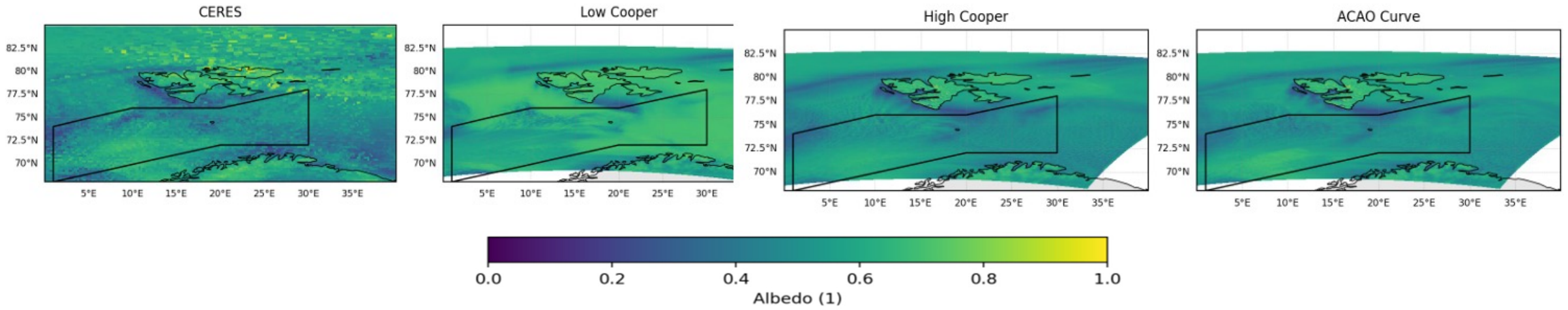
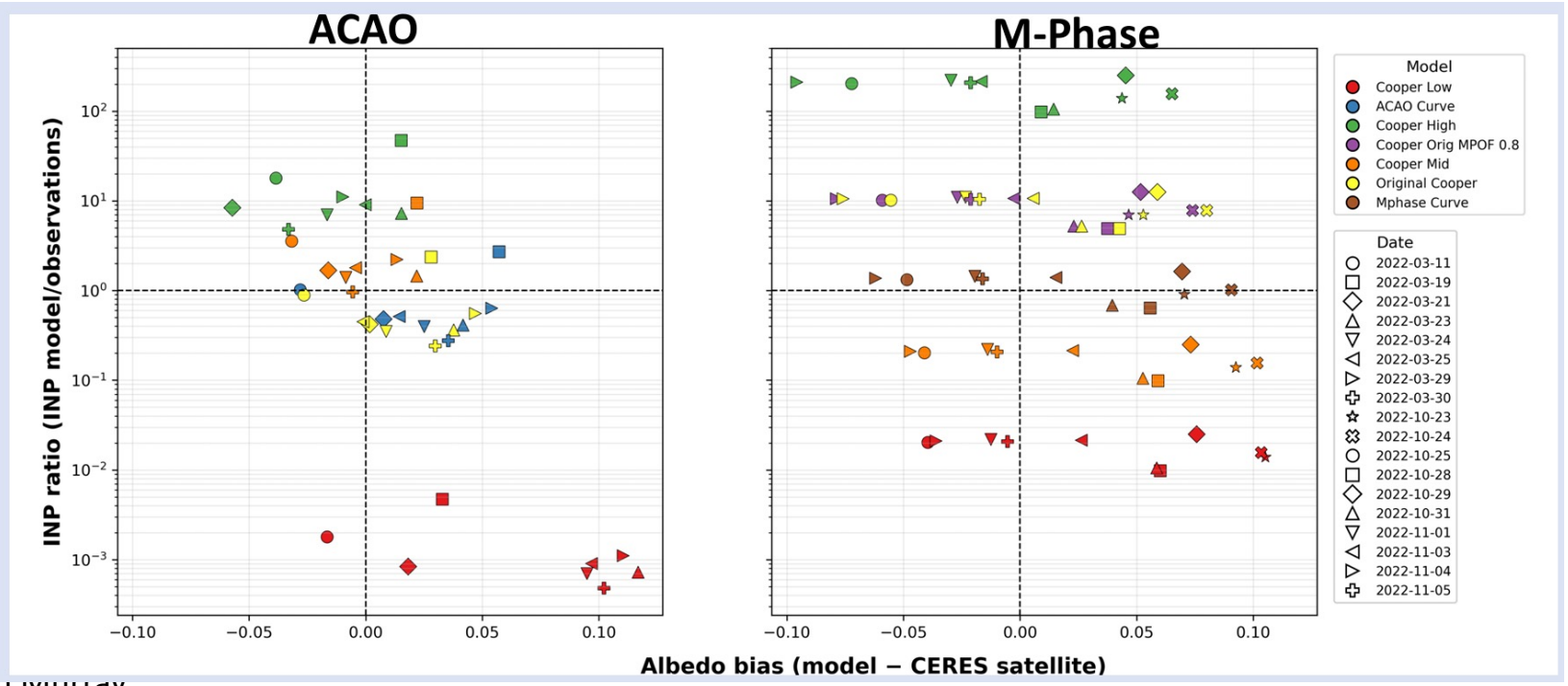
- Evidence of dust from other flights in ACAO
- Regional UM modelling might benefit from measurements from other aircraft. E.g. LWP
- Need for intercomparison of techniques

Modelling ACAO and M-Phase case studies





Get smallest biases in albedo when we use INP spectra representative of those measured on the day

INP analysis: polycarbonate vs PTFE filters

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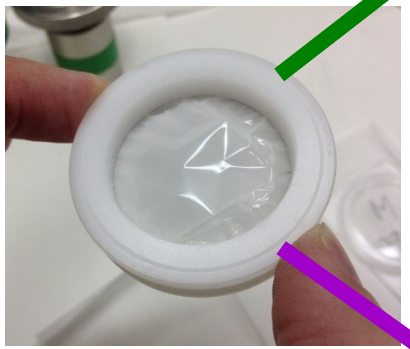
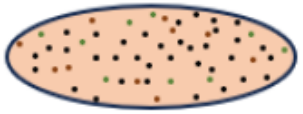
Robinson et al., 2026, *Aerosol Res. Discuss.*

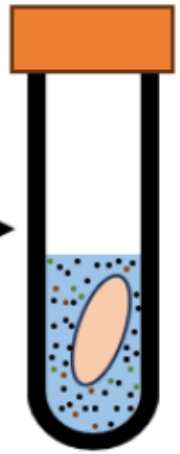
Wash-off Method

Polycarbonate (PC) filters

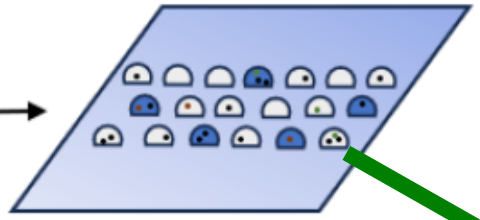




Polycarbonate filter with sampled aerosol particles



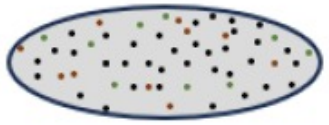
Particles are washed off into 5 ml of pure water to create a suspension



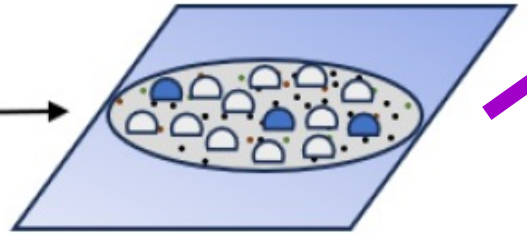
Droplets of the suspension are pipetted onto a glass slide

Drop-on Method

Teflon (PTFE) filters



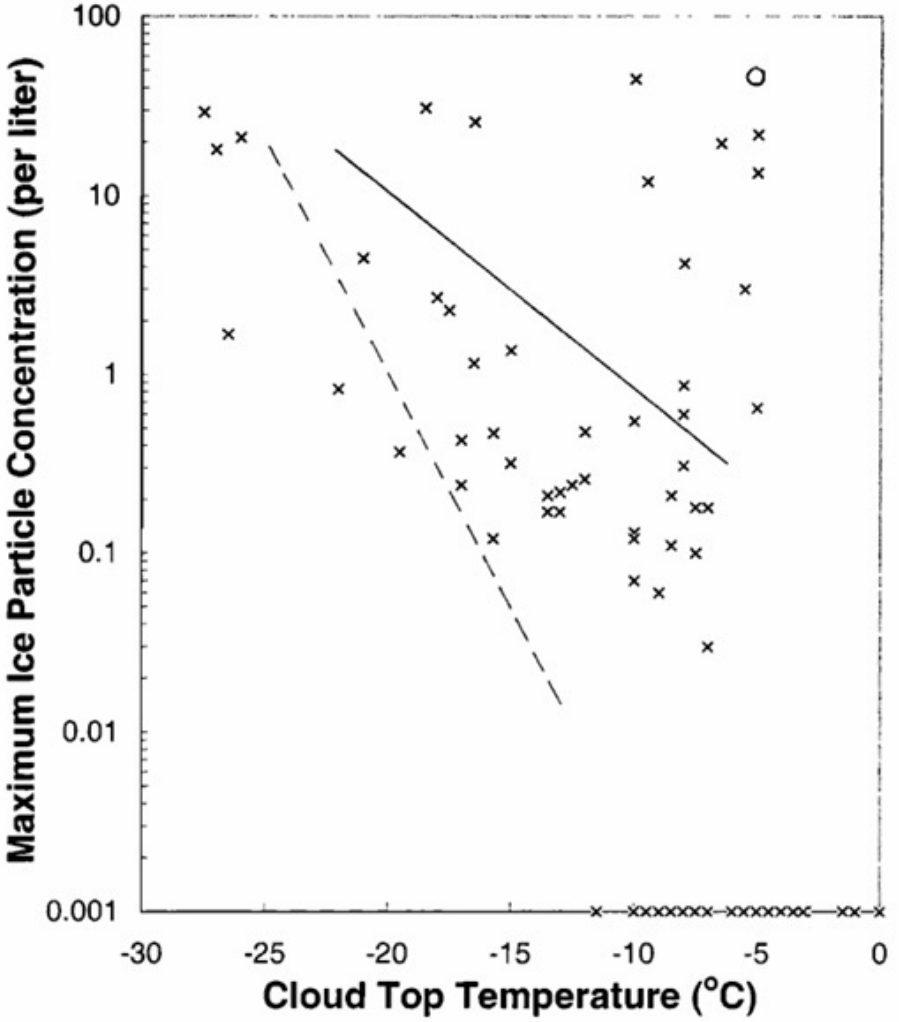
Teflon filter with sampled aerosol particles



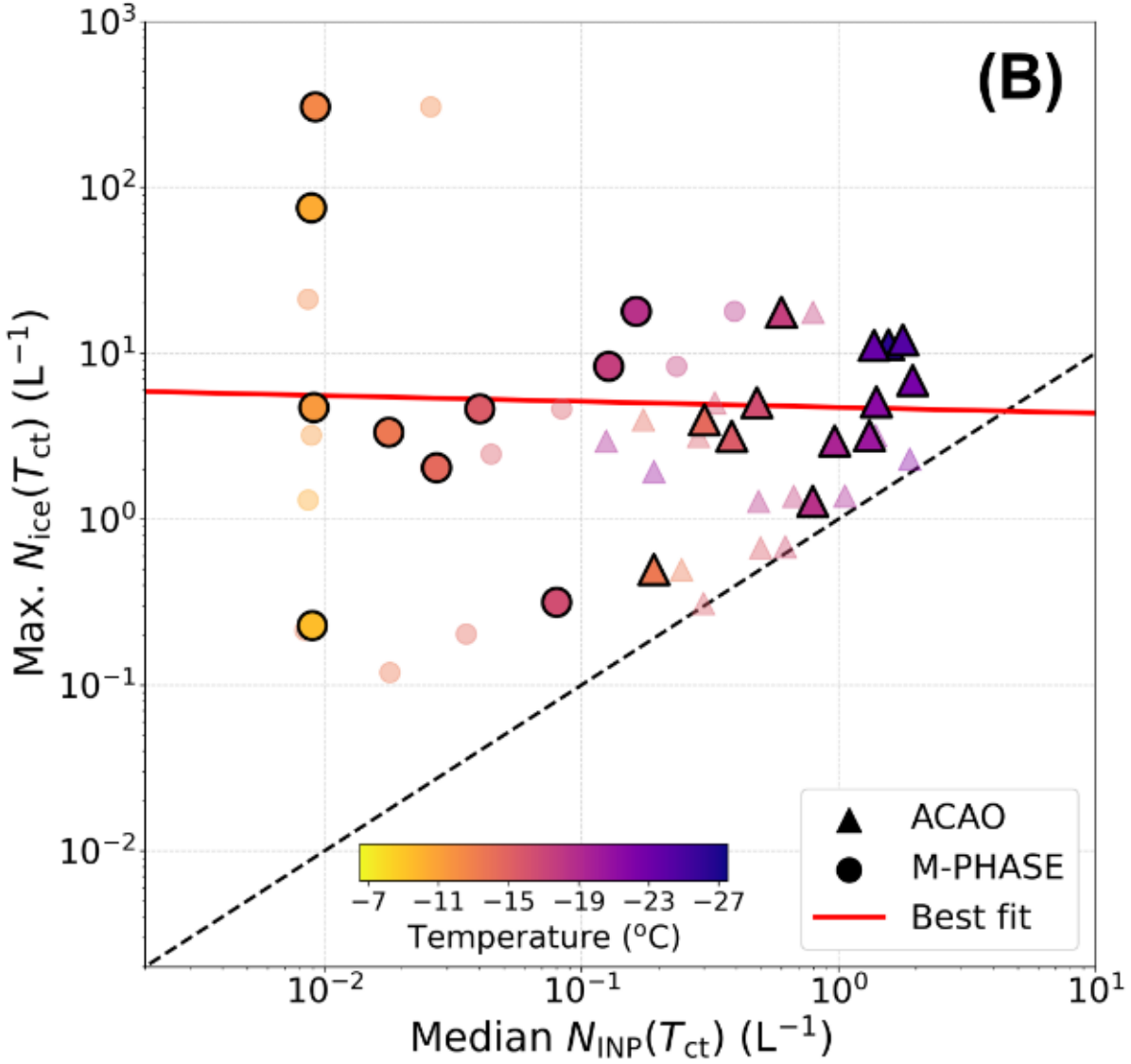
Water droplets are placed directly onto the filter on the glass slide

Prof. Ben Murray

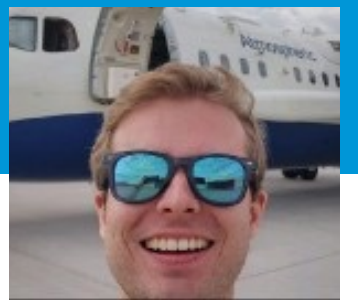
Max ice concentrations are not driven by INPs



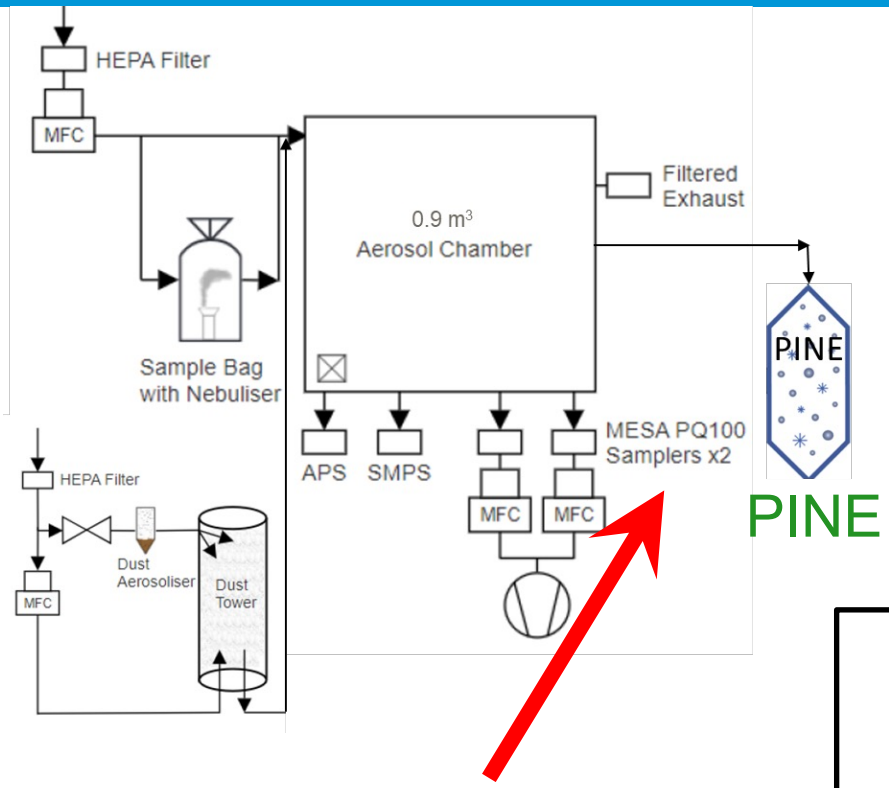
Rangno and Hobbs 2001: Ice in Arctic clouds



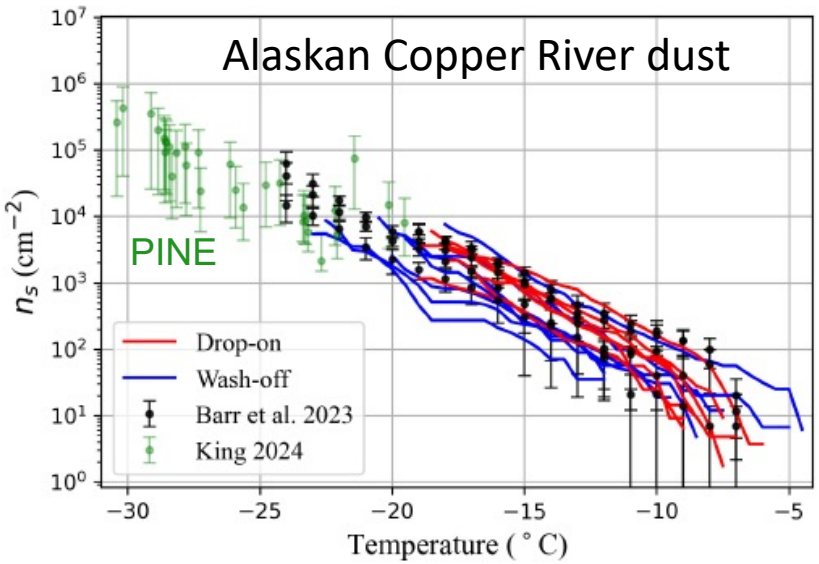
Lab measurements of PC vs. PTFE filters



Joe Robinson



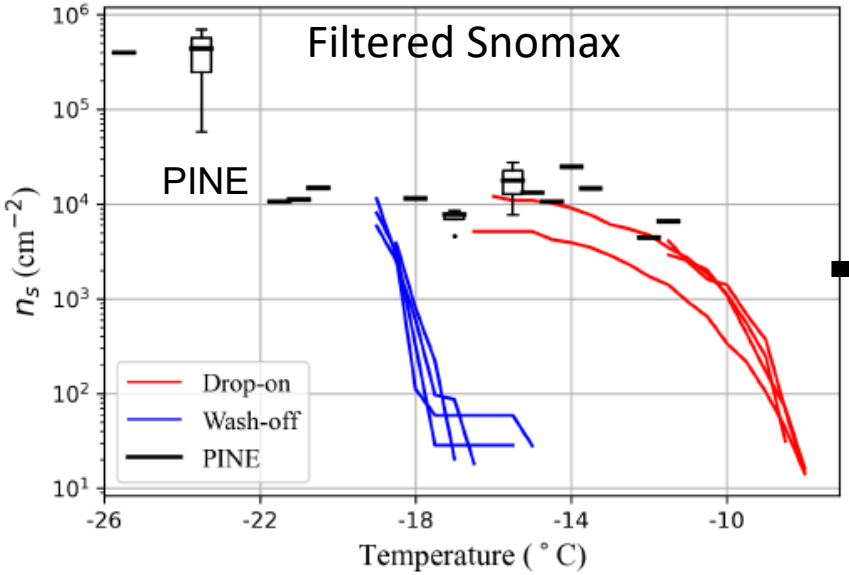
PINE

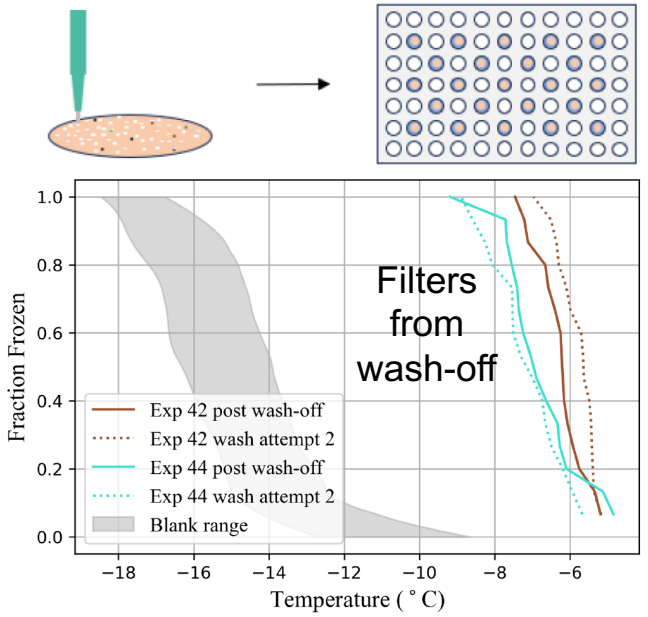


→ Little difference for minerals

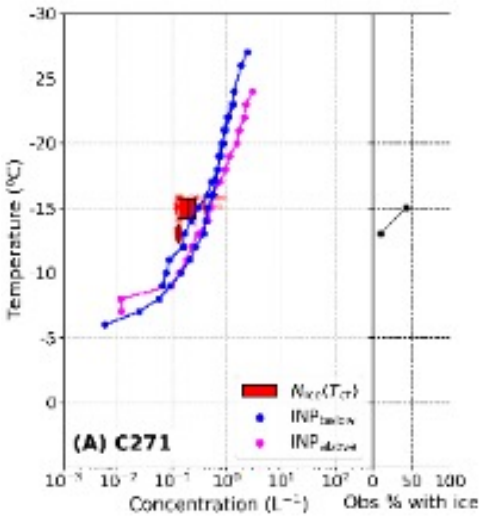
→ Proteinaceous INPs stick to PC filters

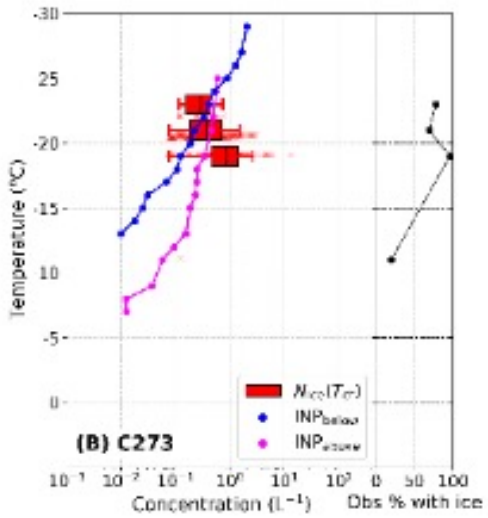
Two parallel filters:
PC vs PTFE
(wash-off vs. drop-on)

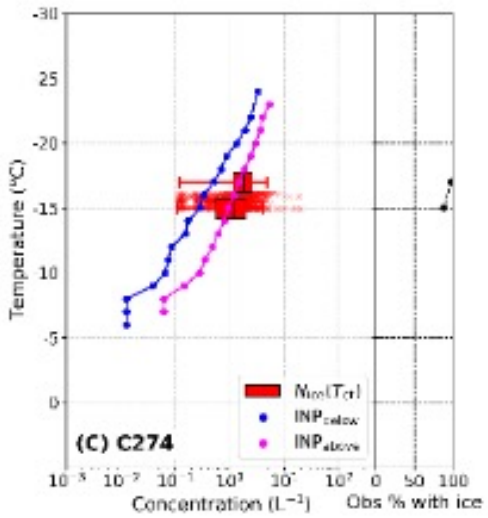


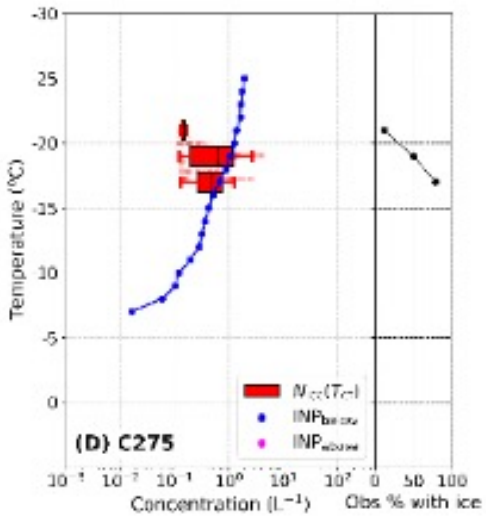


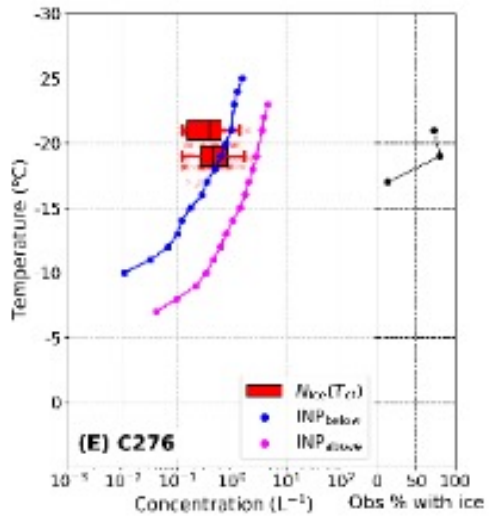
Robinson et al., 2026,
Aerosol Res. Discuss.
Prof. Ben Murray

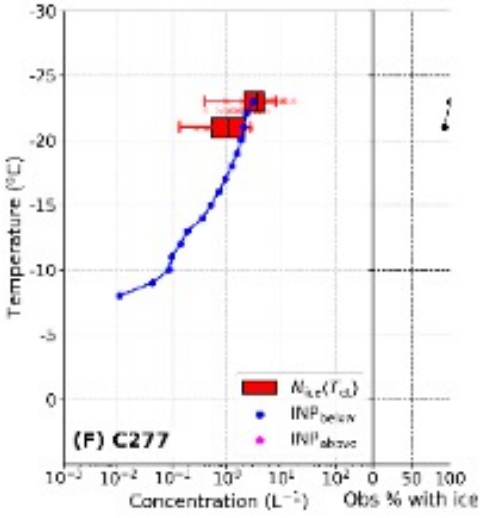

(A) C271
Temperature (°C)
Concentration (L⁻¹)
Obs % with ice

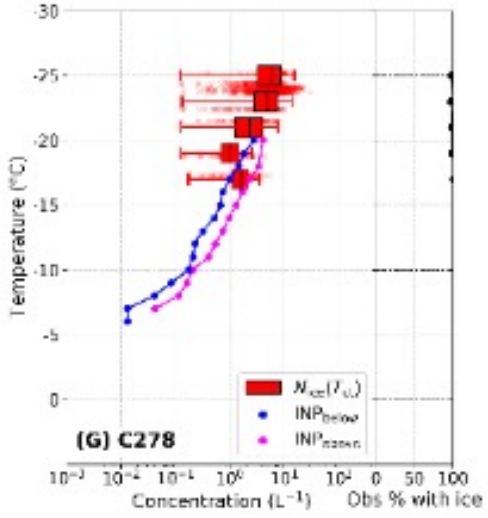

(B) C273
Temperature (°C)
Concentration (L⁻¹)
Obs % with ice

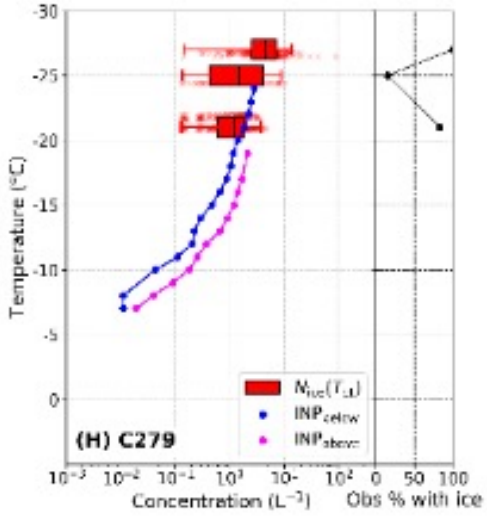

(C) C274
Temperature (°C)
Concentration (L⁻¹)
Obs % with ice

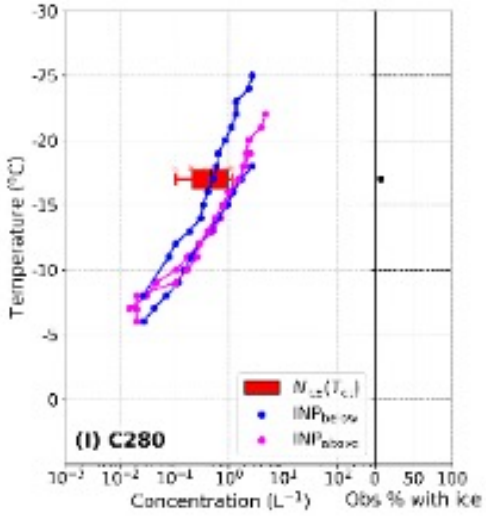

(D) C275
Temperature (°C)
Concentration (L⁻¹)
Obs % with ice

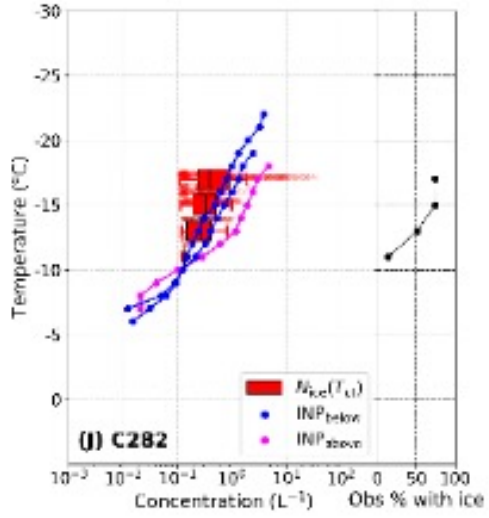

(E) C276
Temperature (°C)
Concentration (L⁻¹)
Obs % with ice

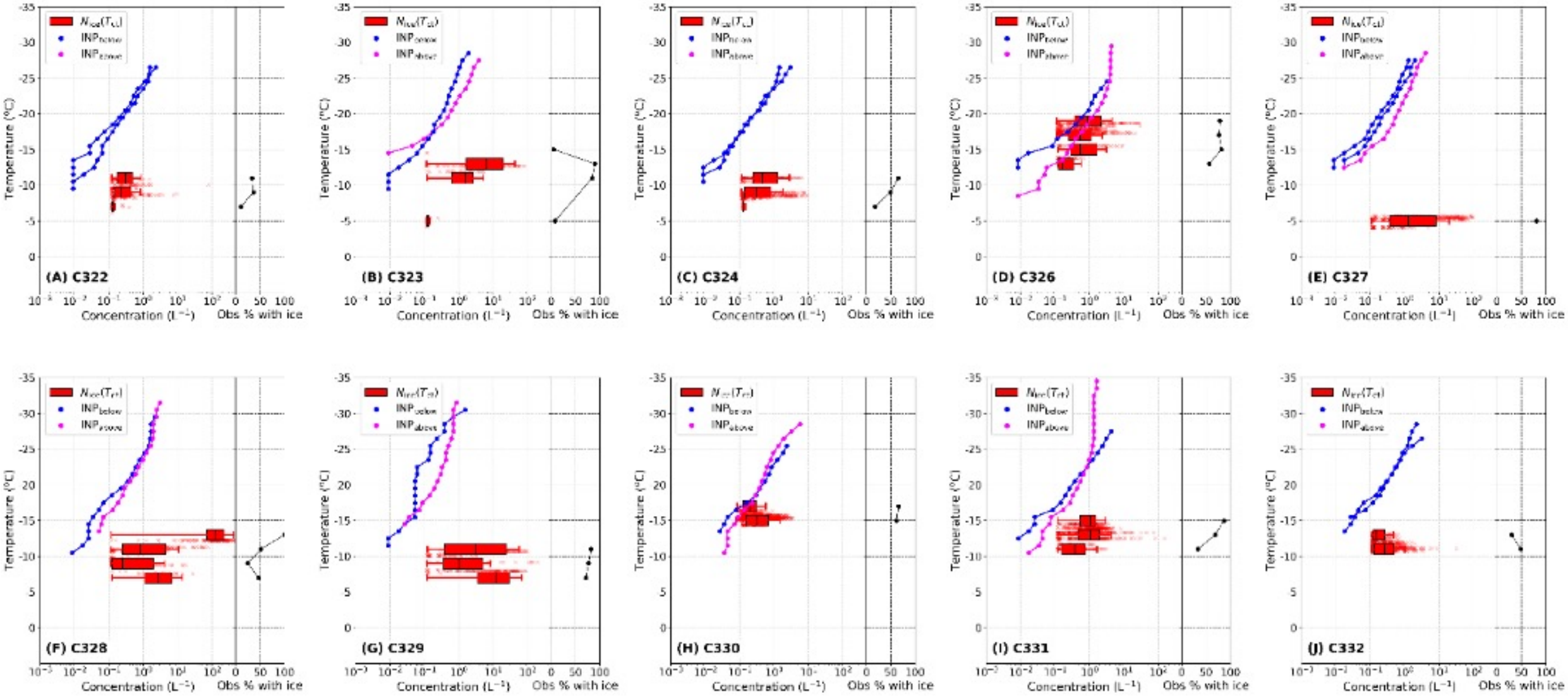

(F) C277
Temperature (°C)
Concentration (L⁻¹)
Obs % with ice


(G) C278
Temperature (°C)
Concentration (L⁻¹)
Obs % with ice


(H) C279
Temperature (°C)
Concentration (L⁻¹)
Obs % with ice

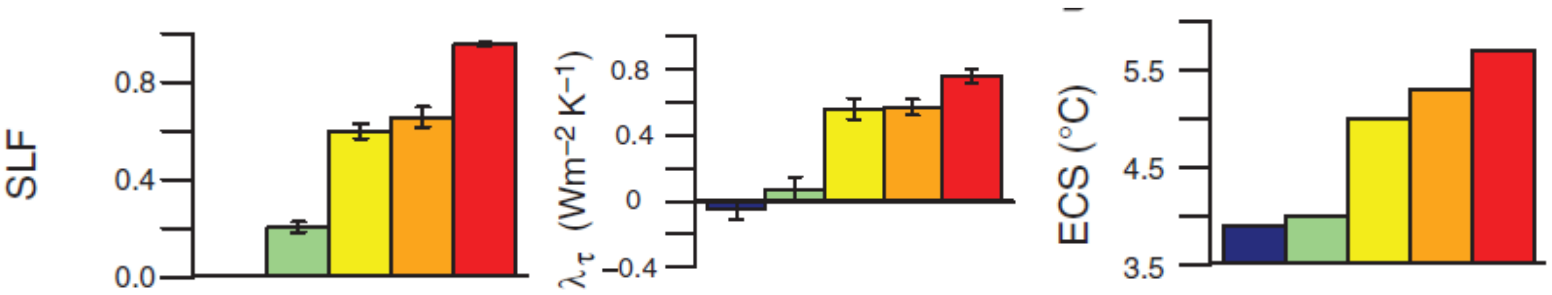

(I) C280
Temperature (°C)
Concentration (L⁻¹)
Obs % with ice


(J) C282
Temperature (°C)
Concentration (L⁻¹)
Obs % with ice


(A) C322
(B) C323
(C) C324
(D) C326
(E) C327
(F) C328
(G) C329
(H) C330
(I) C331
(J) C332
Temperature (°C)
Concentration (L⁻¹)
Obs % with ice

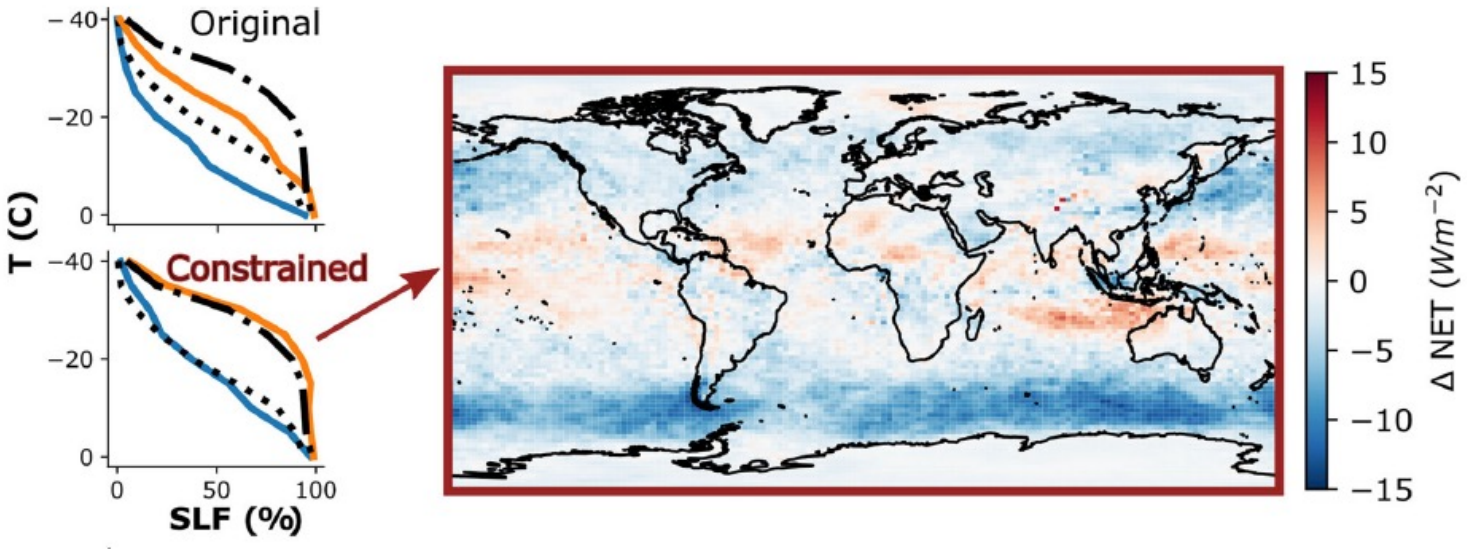
Feedbacks linked to ice production

Tan et al. Science, 2016



- ECS ~1 ºC larger with more realistic supercooled fraction

Hofer et al. 2024



- Tuning liquid vs ice at cloud top leads to +1 K warming by 2100

Maybe the INP concentrations were higher during SOCRTATES than reported?

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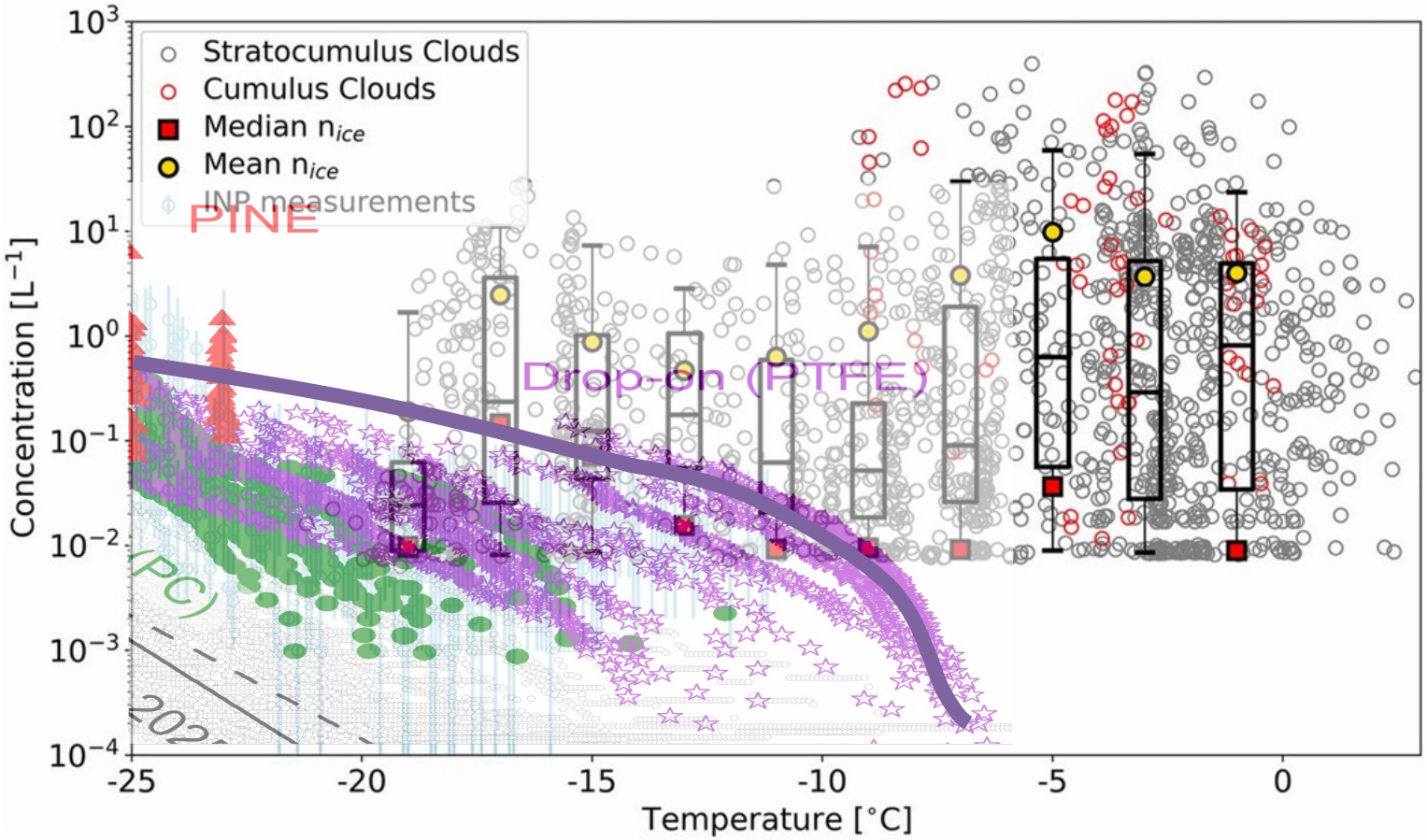
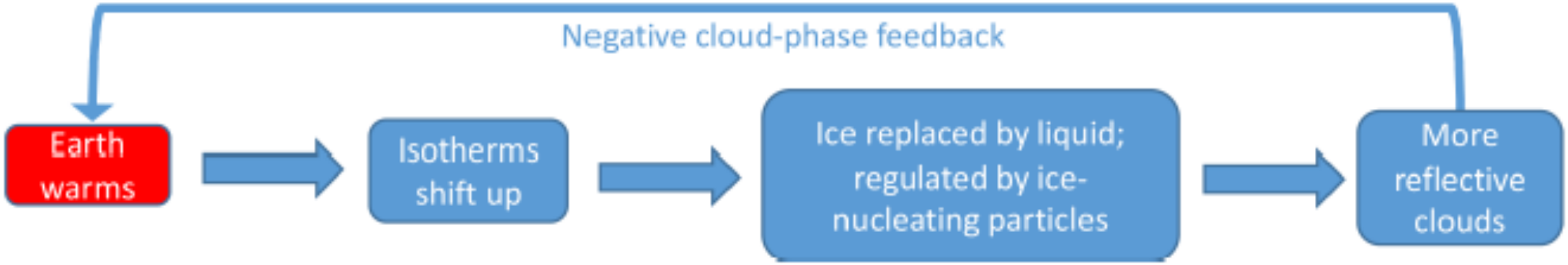
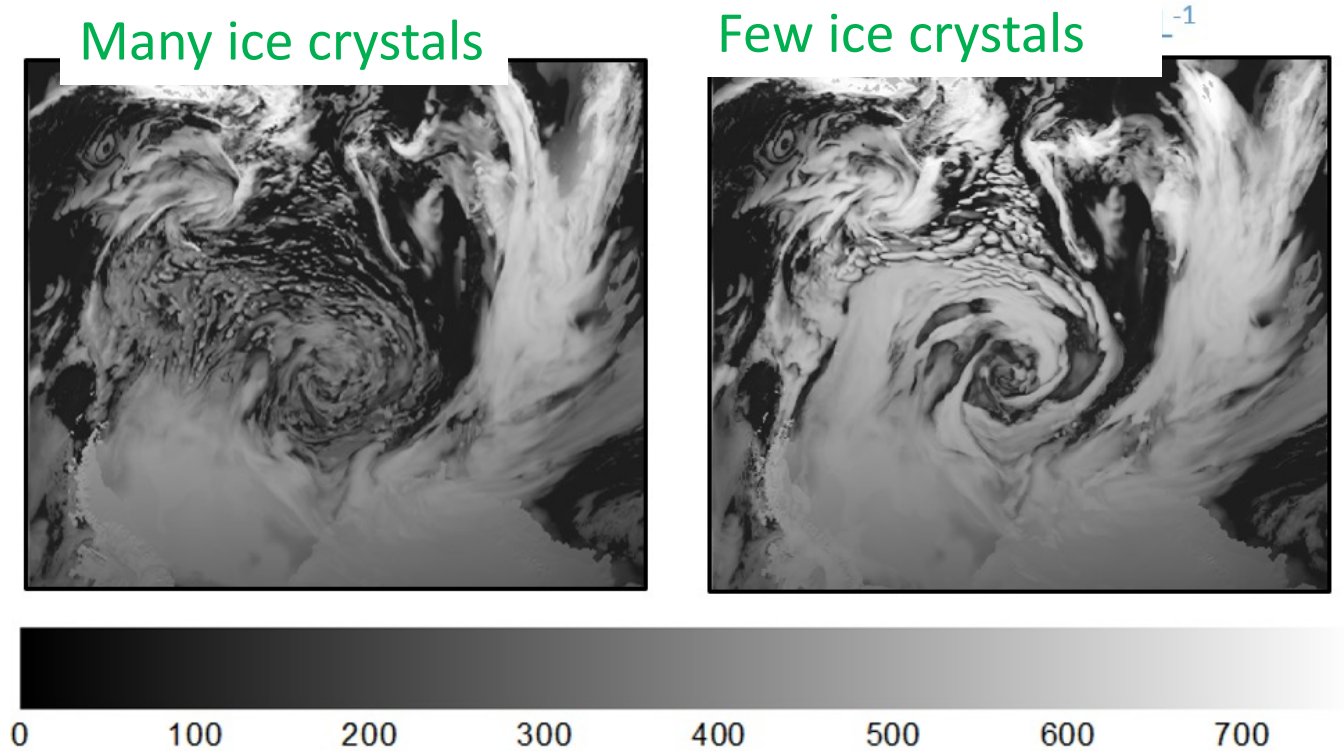


- Our high INP curves from the SO are a plausible match to the median ice concentrations below ~-10°C from SOCRATES
- H-M was active in SOCRATES.

The cloud-phase feedback



Murray et al. ACP (2021); Storelvmo 2015



Murray et al. ACP (2021); Vergara-Temprado 2018

Two contrasting cold-air outbreak aircraft campaigns

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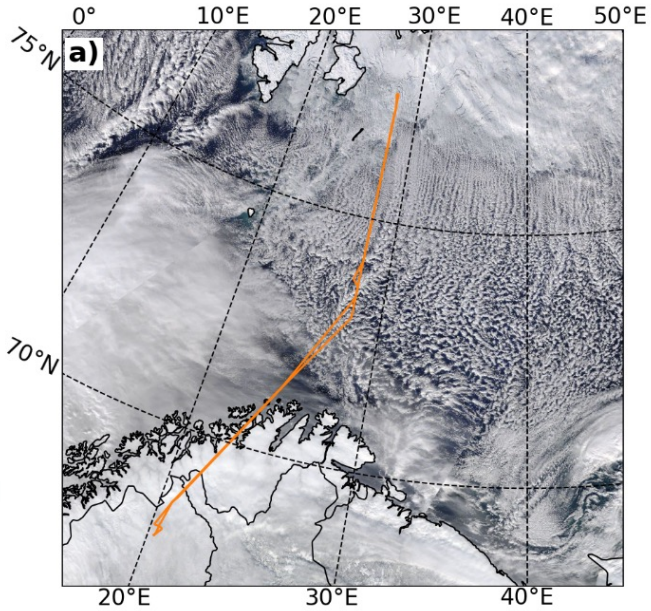
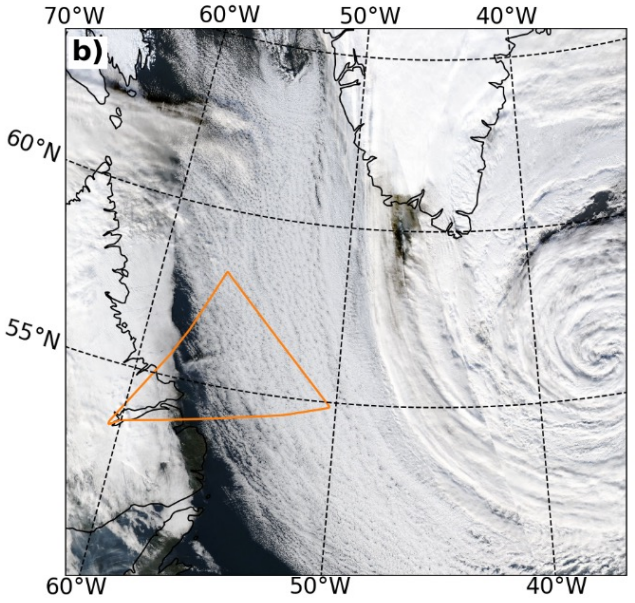
ACAO

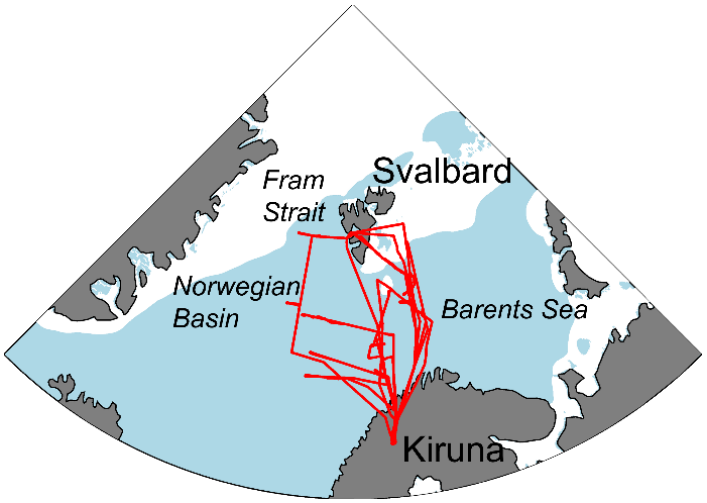
- Barents/Norwegian Sea
- 11 flights
- 7th March to 1st April 2022
- North of Scandinavia
- 8 CAO cases
- 855 km of in-cloud

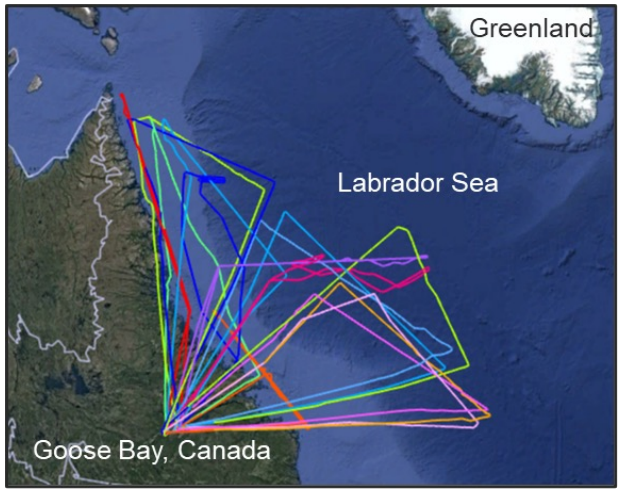




M-Phase

- Labrador Sea
- 15 flights
- 12 CAO flights
- 2 aerosol flights
- 18th Oct to 5th Nov 2022
- 1680 km of in-cloud data





Using CAOs as natural laboratories

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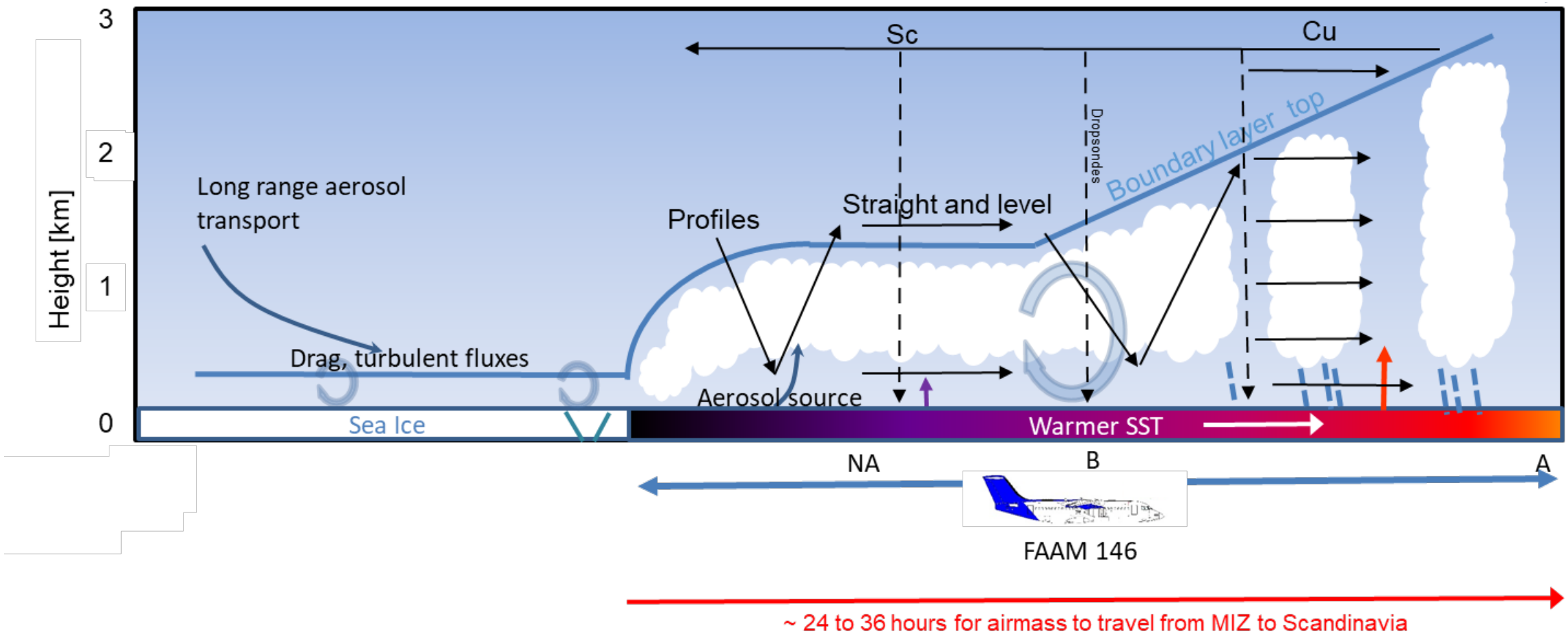
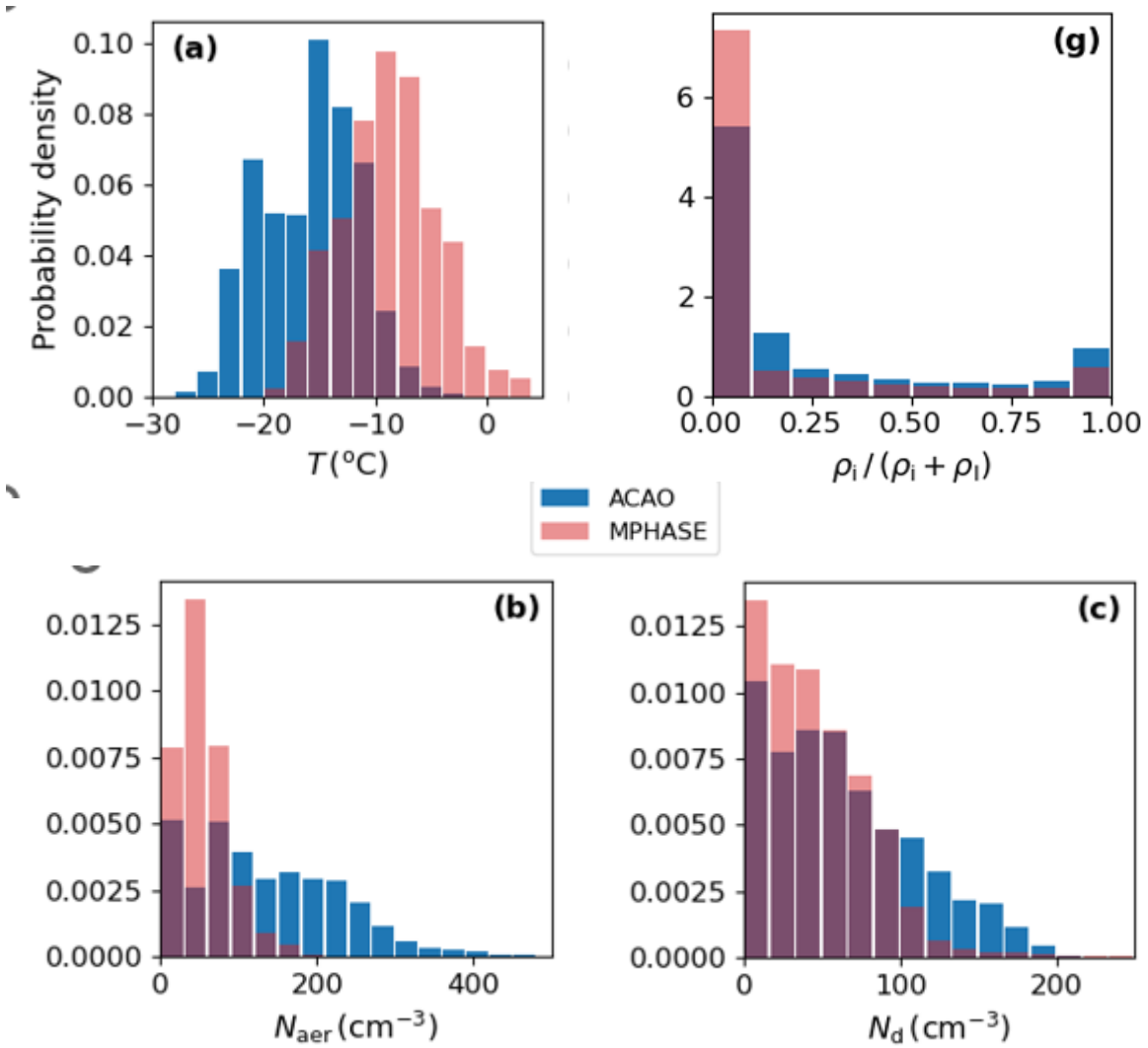
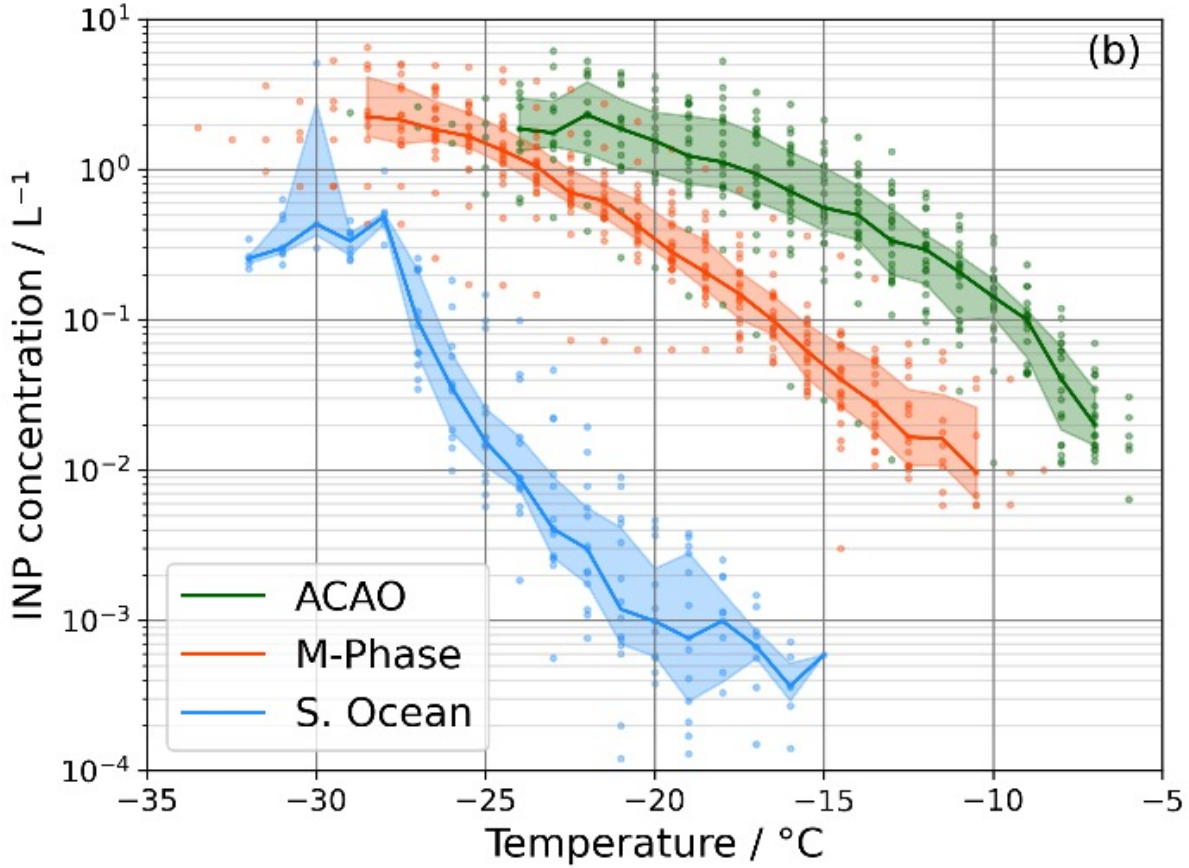
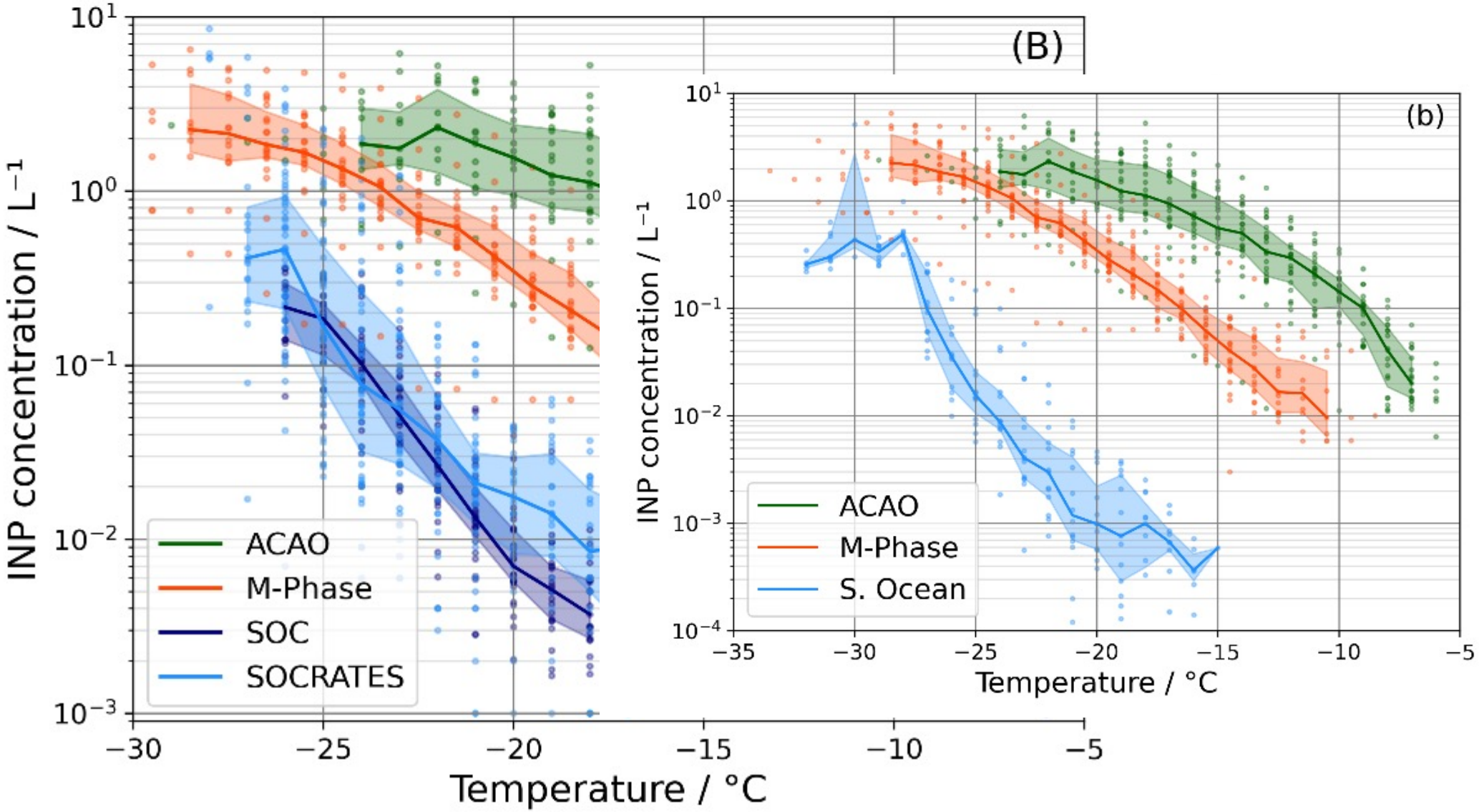
Measurements of the cloud, aerosol and boundary layer development along the CAO trajectory



Characteristics of aerosol and clouds in the two campaigns






(B)
(b)
INP concentration / L⁻¹
Temperature / °C
ACAO
M-Phase
SOC
SOCRATES
S. Ocean