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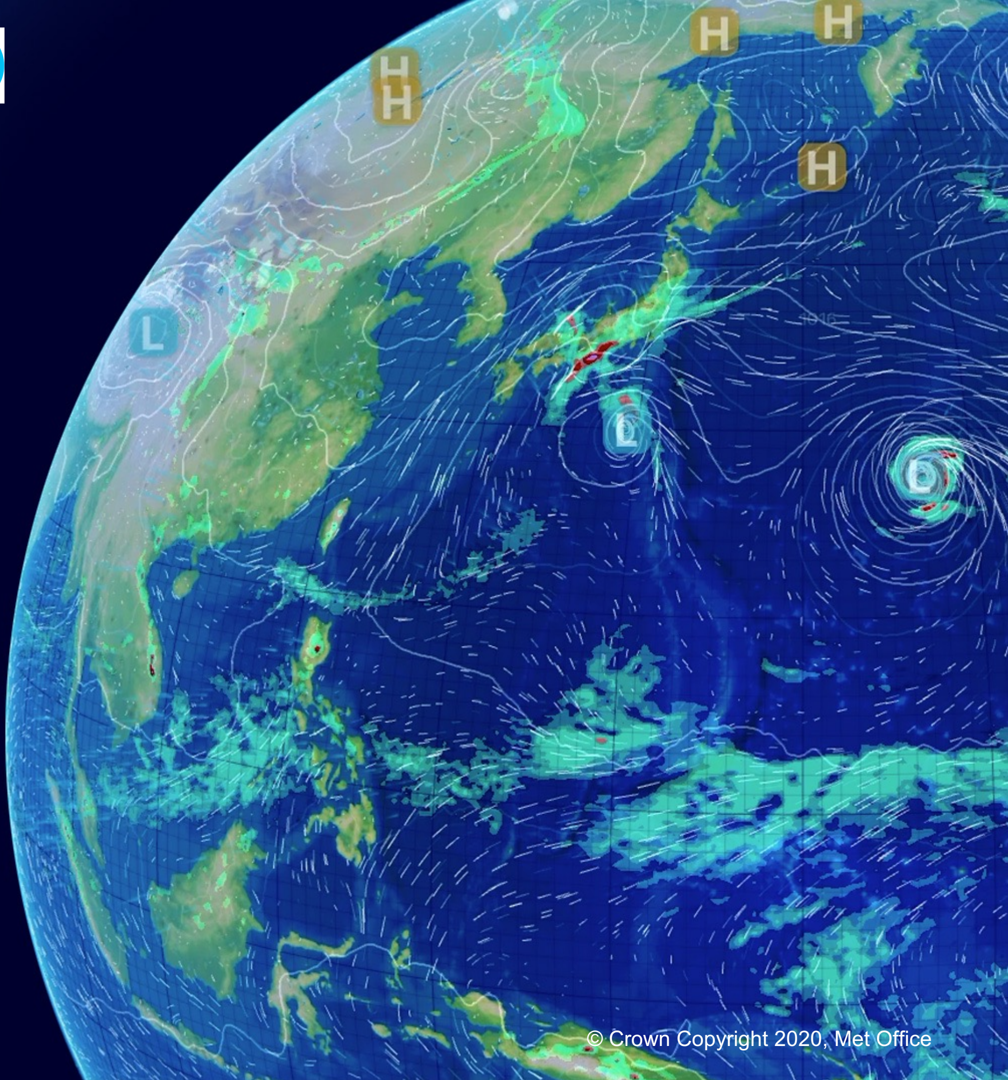
Characterizing mixed phase clouds in diverse cold air outbreak environments: Observations from ACAO and M-Phase

Steven Abel

Benjamin Murray, Matt Evans, Xinyi Huang, Erin Raif, Michael Biggart, Paul Field, Gary Lloyd, Mark Tarn, Dan Smith, Jim McQuaid, Paul Barrett, Joseph Robinson, Ross Herbert, Sam Clarke, Sarah Barr, Richard Cotton, Keith Bower, Joss Kent, Andy Wilson, Dave Tiddeman, James Bowles, Rob King, Kirsty Wivell, Ken Carslaw, Ian Renfrew, Hugh Coe, Thomas Choulარton, and everyone from the ACAO, M-Phase and FAAM teams

Arctic Airborne Workshop, Bergen, June 2026



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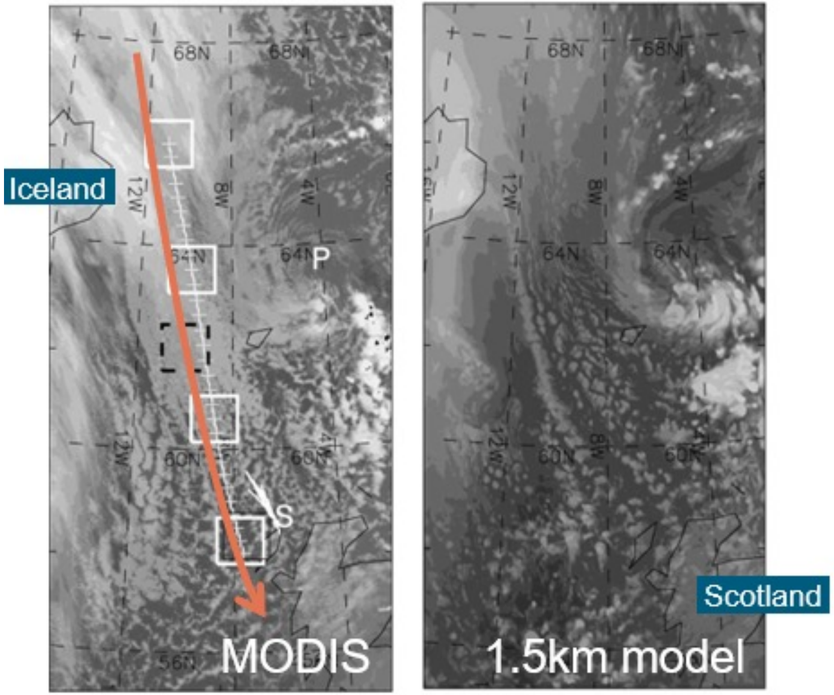
Talk overview

- Mixed-phase cloud biases in cold-air outbreaks (CAOs)
  - → *motivation for ACAO and M-Phase*
- Overview of field campaigns
  - → *ACAO & M-Phase: design and measurements*
  - → *contrasting CAO environments*
  - → *insights into ice production*
- Model response and observational constraints
  - → *sensitivity to ice production*
  - → *constraining cloud structure (ice-liquid overlap)*

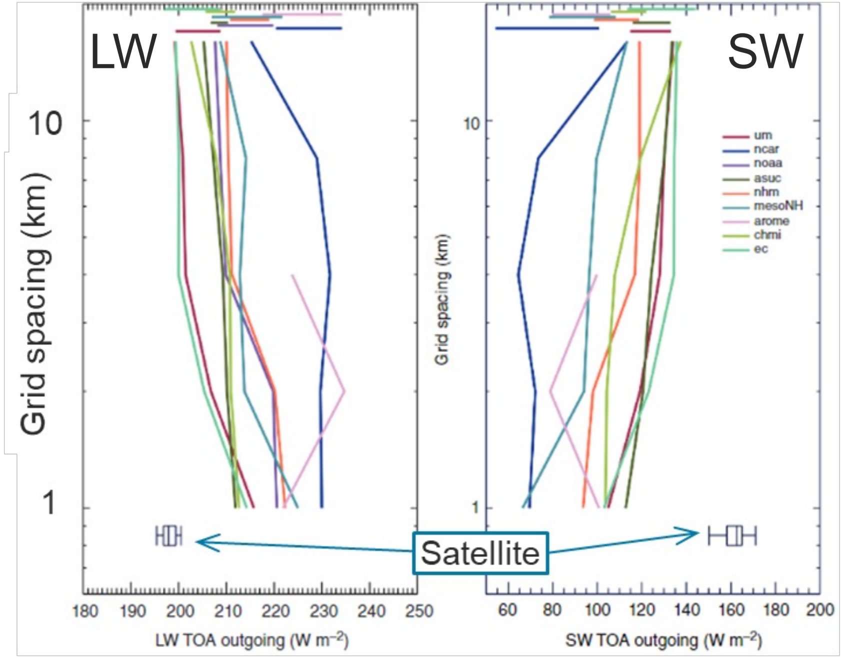
Model cloud and radiation biases

High res. NWP of a CAO



Field et al. (2013)

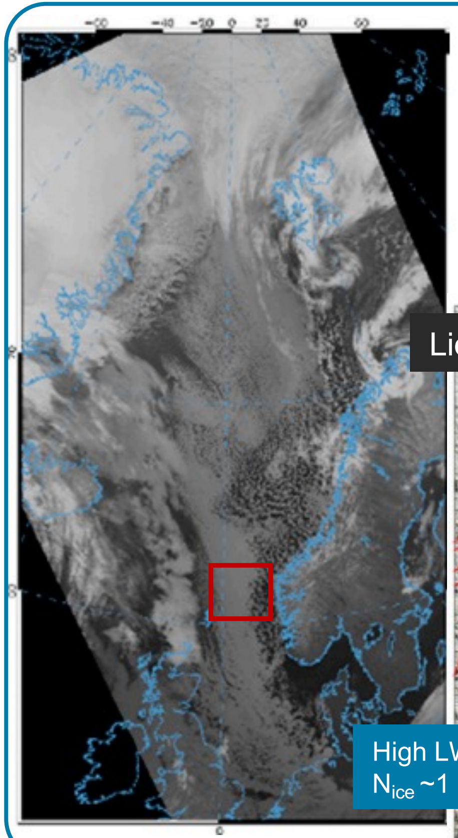
SW and LW TOA flux from 9 different models



Field et al. (2017)

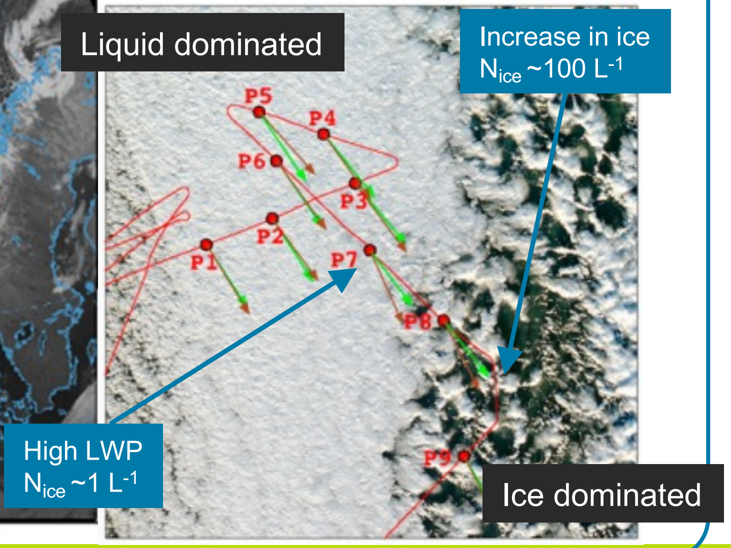
Models tend to break up mixed-phase clouds too quicky leading to radiation biases

Ice-processes can drive cloud transitions, but are often overactive in NWP



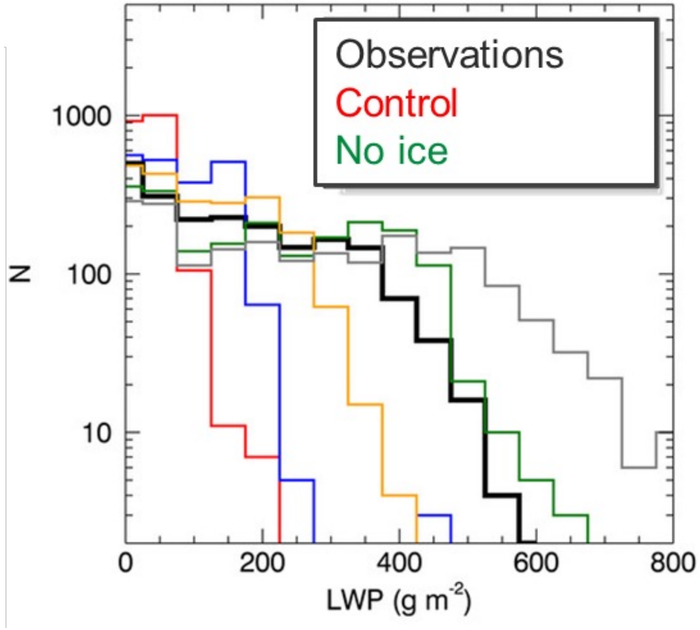
1. Ice processes and precipitation can drive cloud transitions

seen in observations and modelling



2. Model removes liquid too efficiently via ice processes

No ice → best match to observations



Abel et al. (2017)

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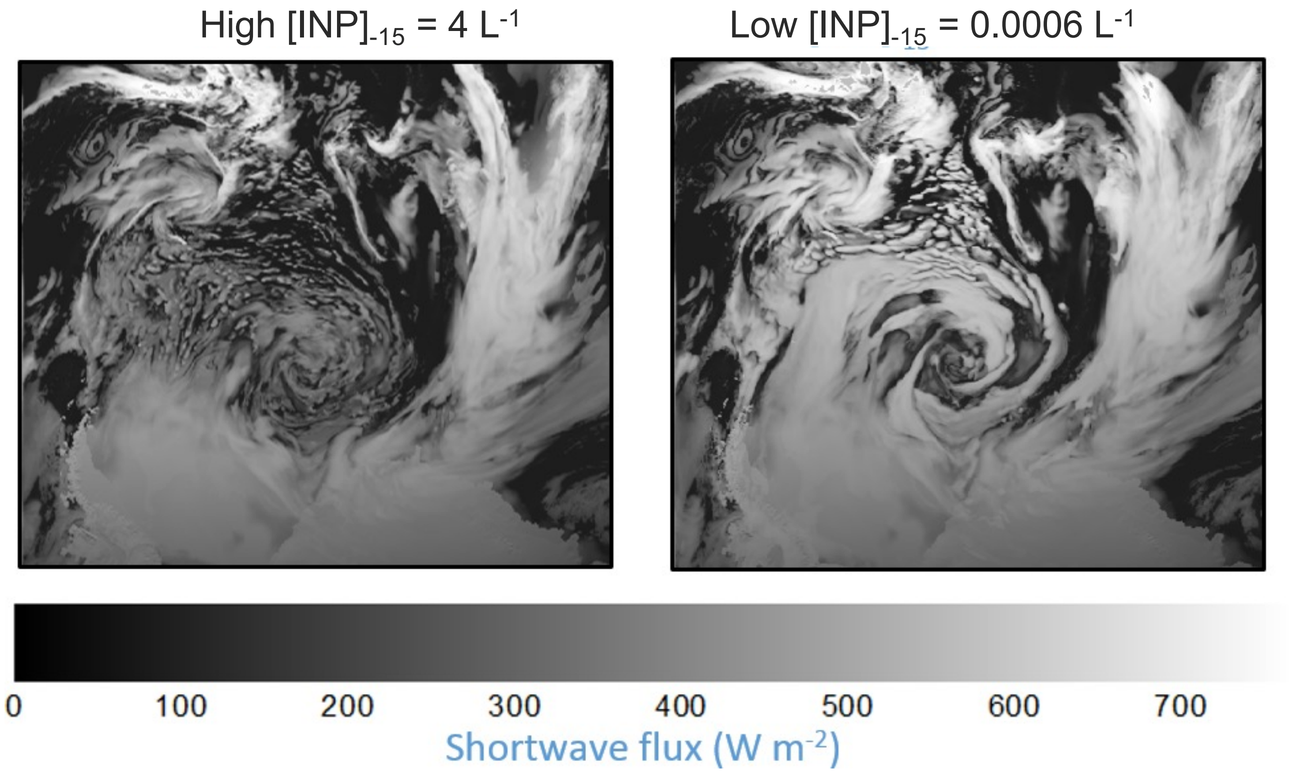
Clouds are highly sensitive to INP, but variability missing in models



CASIM microphysics

New 2M scheme (Field et al., 2023)

Now operational in regional NWP configuration of the Met Office Unified Model

Spatial and time-varying INP are not currently used in Met Office NWP or climate models.

Missing INP variability likely contributes to cloud and radiation biases

Murray et al. (2021)

*INP=Ice Nucleating Particle

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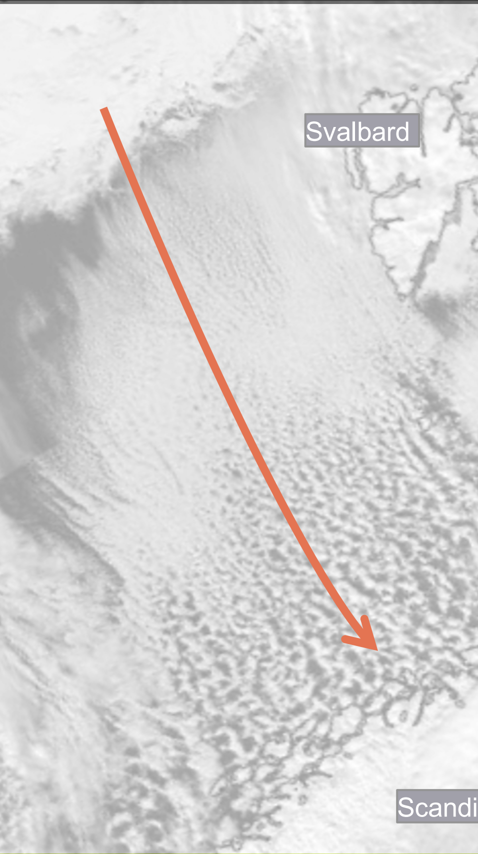
Targeted observations to constrain CAO cloud processes



1. Arctic Cold Air Outbreaks (ACAO)

2. M-Phase

- Aircraft measurements of the cloud, aerosol and boundary layer development within cold-air outbreaks (CAOs)
- Challenge and develop model simulations of mixed-phase clouds

NASA Worldview, 21st March 2021

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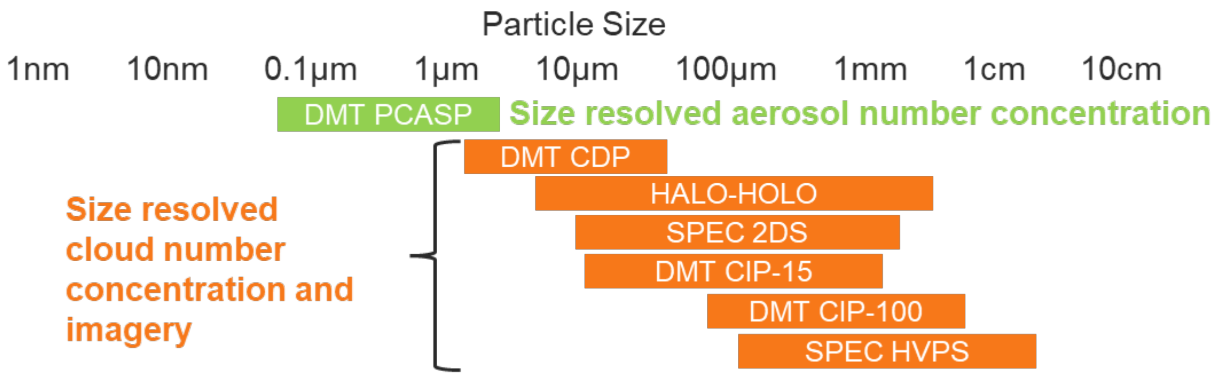
Common instrumentation used in ACAO and M-Phase



Aerosol measurements
CPC: total aerosol
Soot photometer (DMT SP-2)
LAAP-ToF single particle laser mass spectrometer
Nepherlometer
Filters for collecting aerosol for offline INP and composition

Remote sensing
BBR (SW & LW), LWP, SST, downward pointing lidar (cloud top height)

Thermodynamics
3D winds, temperature, pressure
Water vapour (chilled mirrors, WVSS-II, total water probe).
Dropsondes

Cloud physics measurements
Nevzorov: Bulk liquid and ice water contents
Ice particle shape (SPEC 2vCPI, HALO-HOLO, OAPs)

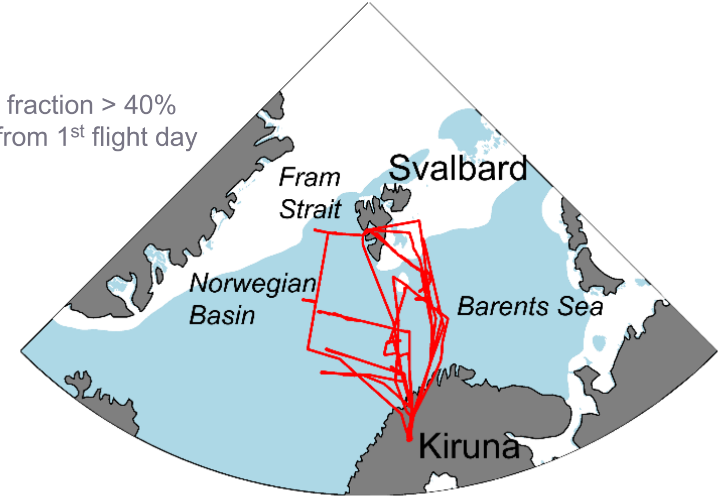
→ Enables direct comparison with a common measurement strategy

Clarke et al. (2026, in review): ACAO and M-Phase data paper

Met Office Aircraft campaigns in contrasting seasons and locations

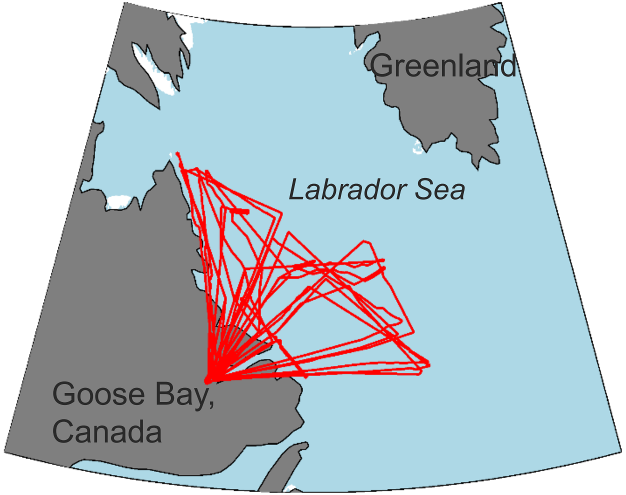
ACAO flight tracks

Sea ice fraction > 40% shown from 1st flight day



- North of Scandinavia (Barents/Norwegian Seas)
- 11 flights
- 7th March to 1st April 2022
- 8 cold-air outbreak (CAO) cases
  - 855 km of in-cloud data
- 1 warm air intrusion

M-Phase flight tracks



- Labrador Sea
- 15 flights
- 18th October to 5th November 2022
- 12 cold-air outbreak (CAO) cases
  - 1680 km of in-cloud data
- 2 aerosol flights

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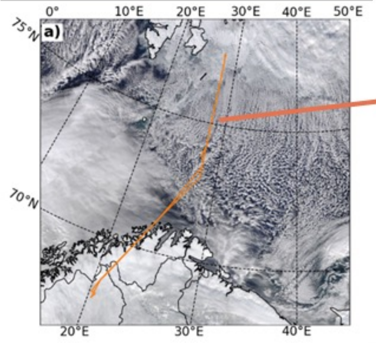
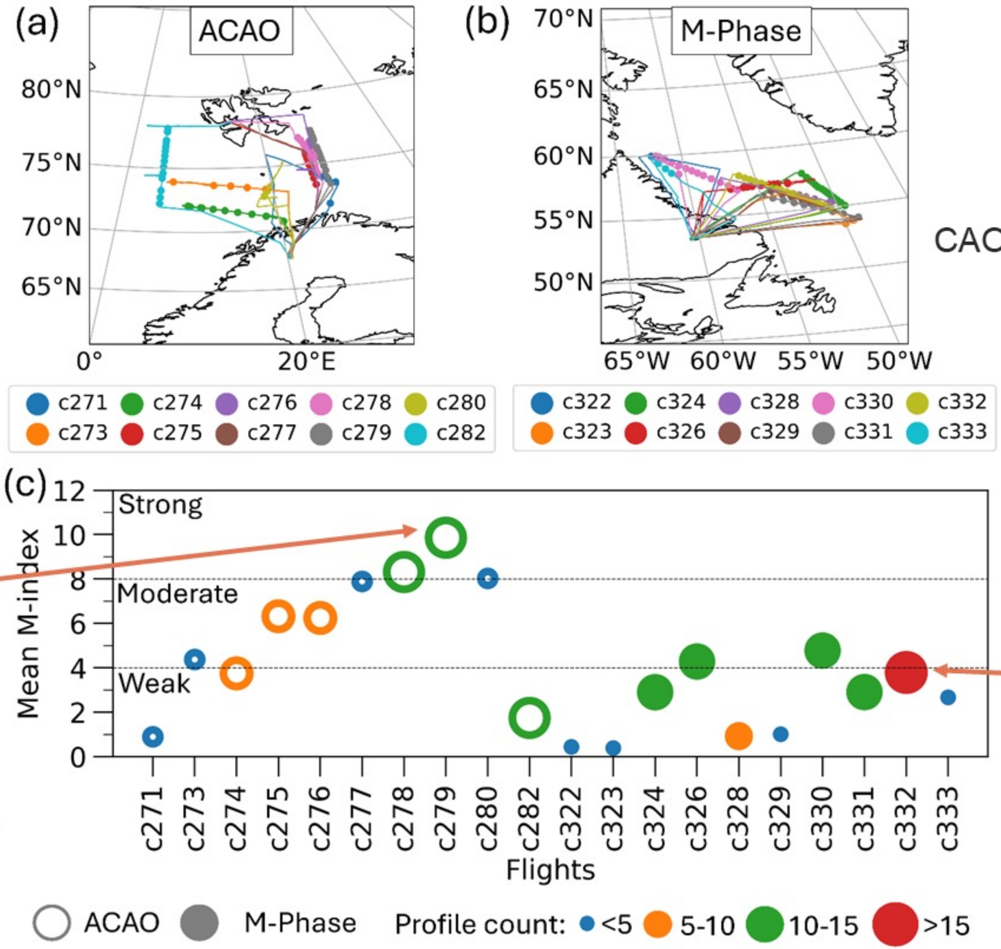
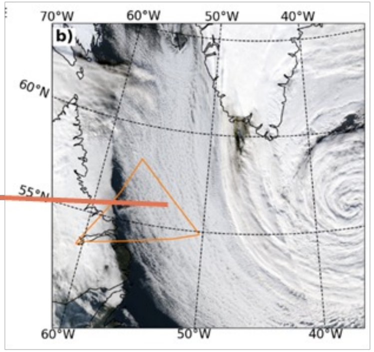


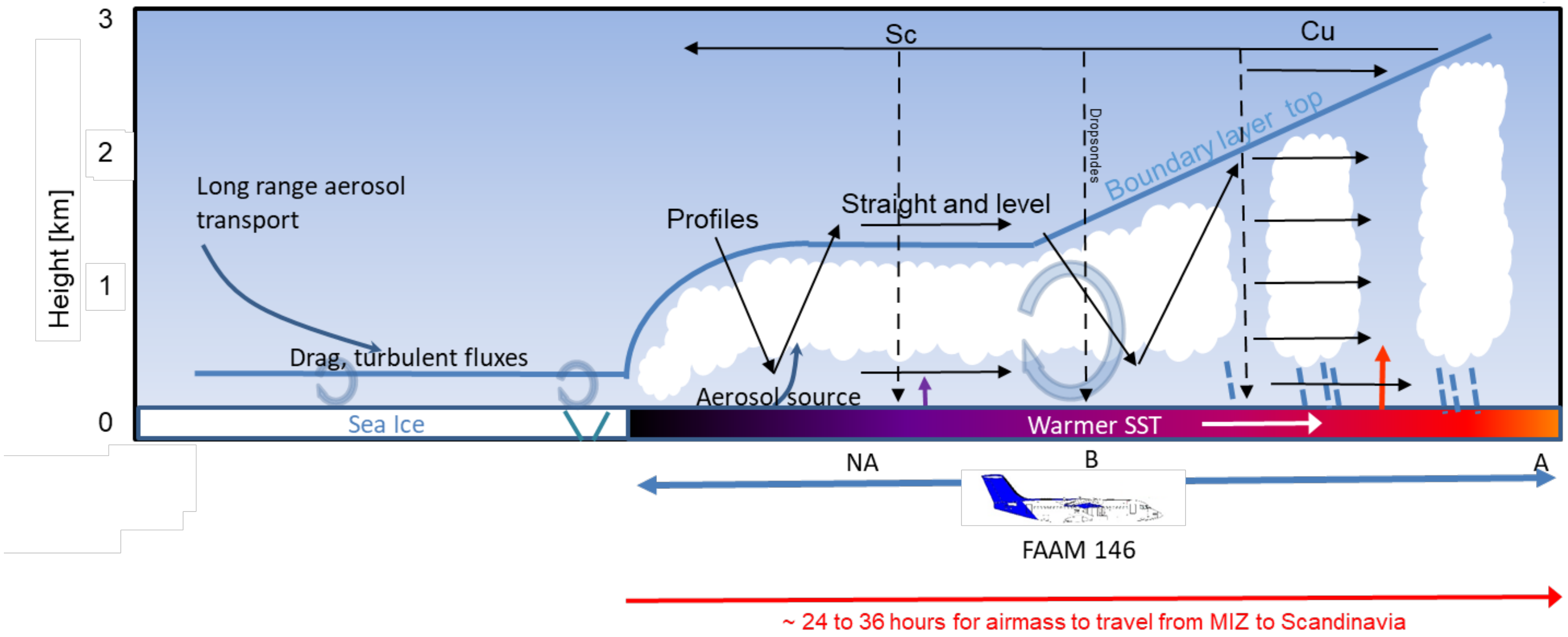




CAO index $M = \theta_{SKT} - \theta_{800}$

Aragon et al. (2025): https://doi.org/10.1029/2024JD043033

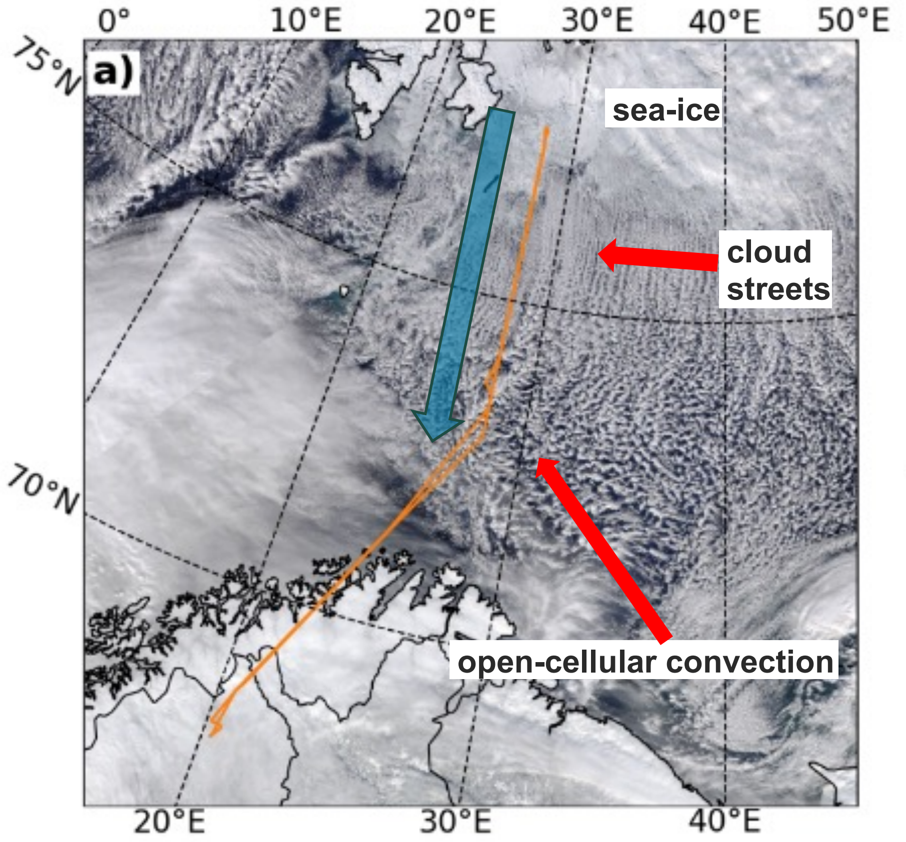
Measurement strategy



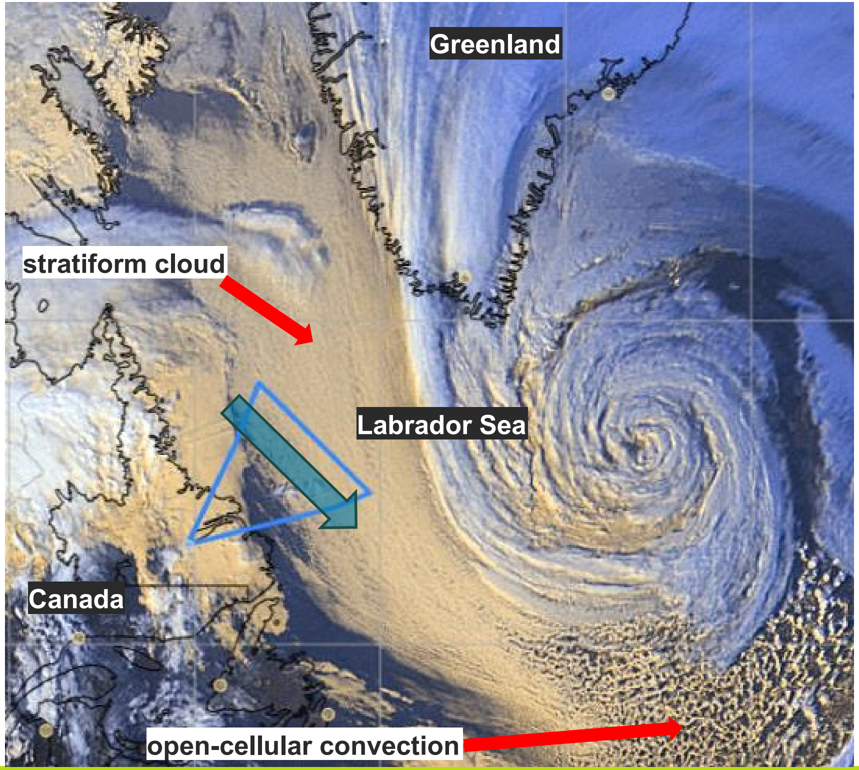
Measurements of the cloud, aerosol and boundary layer development along the CAO trajectory

Example flight-tracks

ACAO



M-Phase



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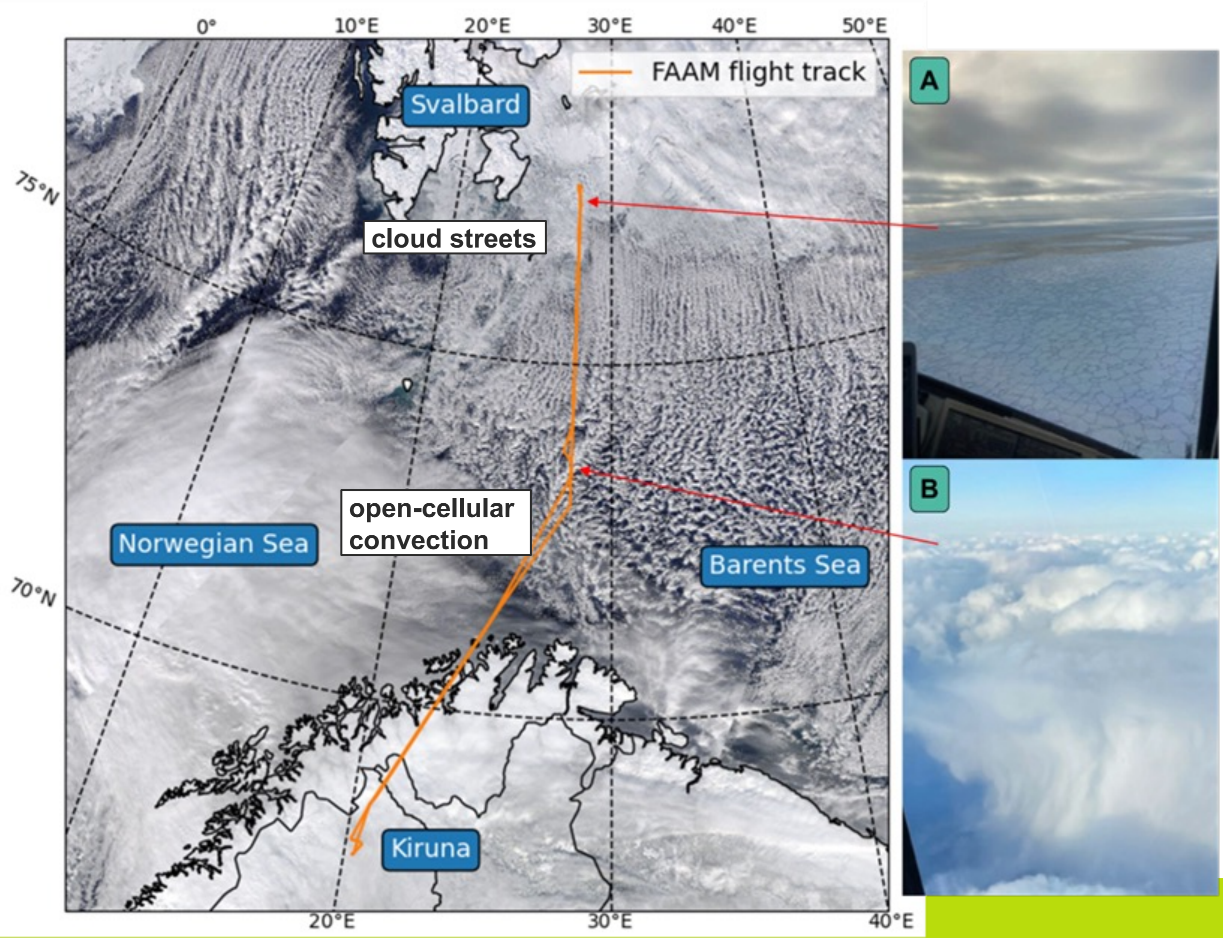
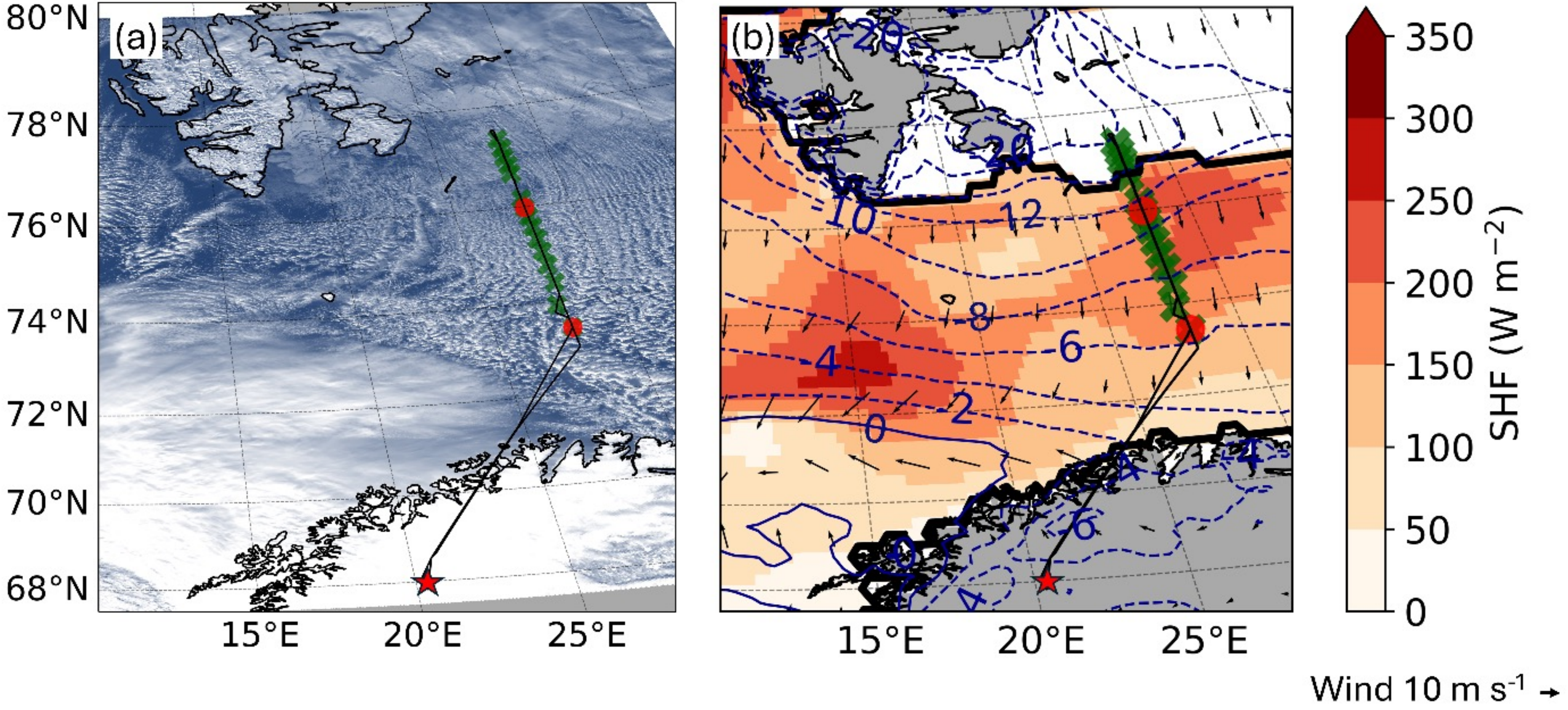
Measurements made over sea-ice, open ocean, and in different cloud regimes

An example flight from ACAO



CAO clouds form near the ice edge

Heavily precipitation in cumulus



Aragon et al. (2025)

SHF = sensible heat flux

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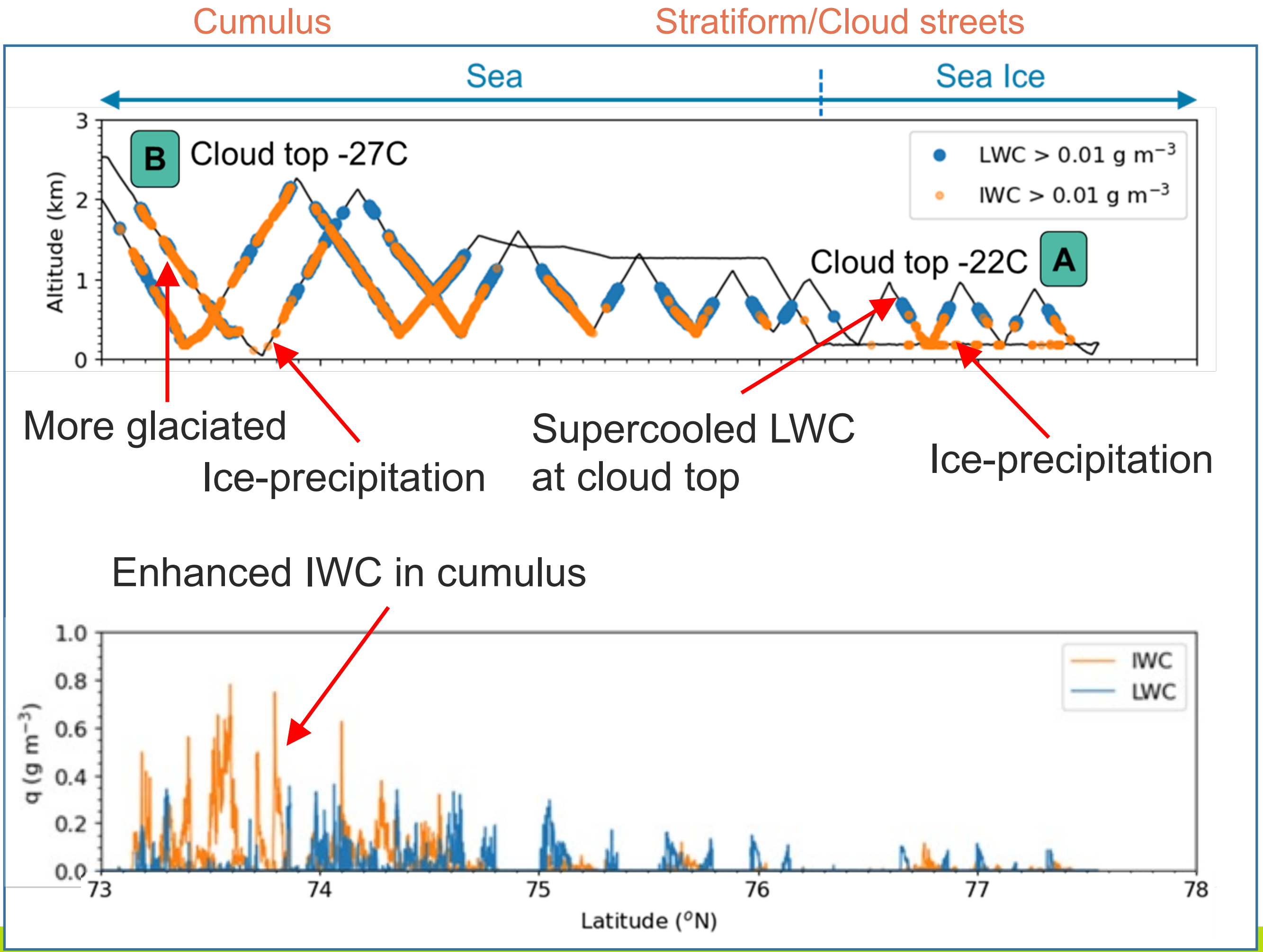
Saw-tooth profiles to measure aerosol, cloud and boundary layer development along CAO flow

Sub-cloud and above-cloud legs to measure aerosol (20 min for INP)



LWC = liquid water content, IWC = ice water content

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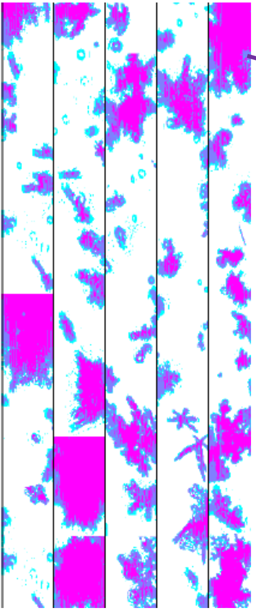
Cumulus

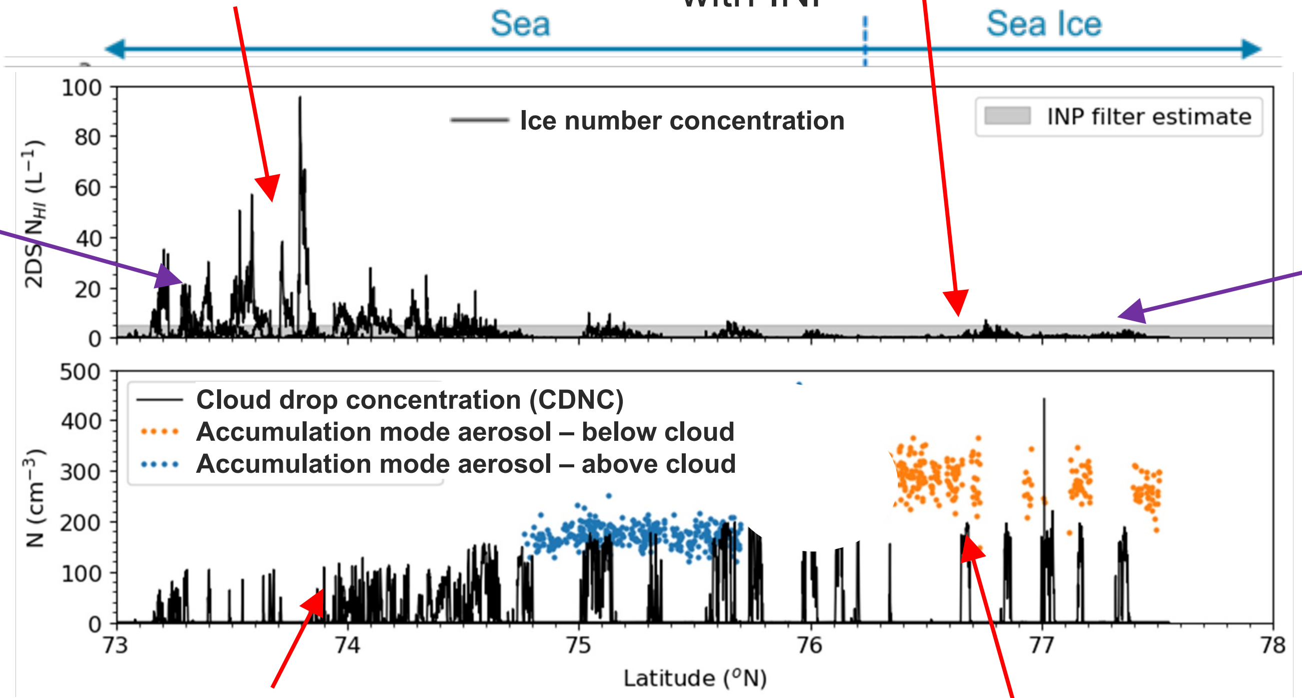
Stratiform/Cloud streets

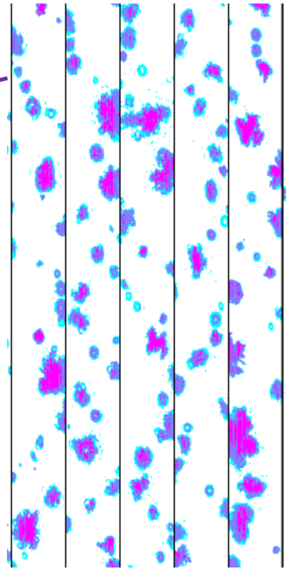
SIP in Cumulus

Ice concentration consistent with INP

960µm







Lower CDNC from precipitation scavenging?

High CDNC for ACAO Arctic haze?

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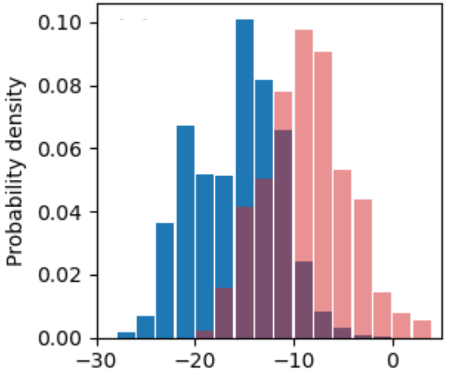
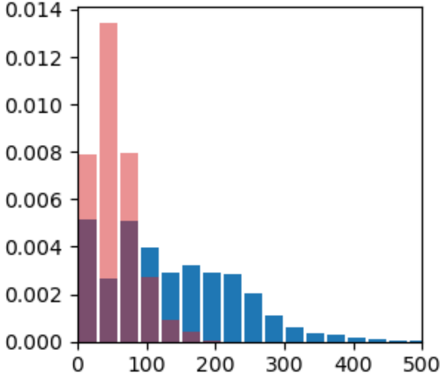
Cloud properties (ACAO vs MPHASE)

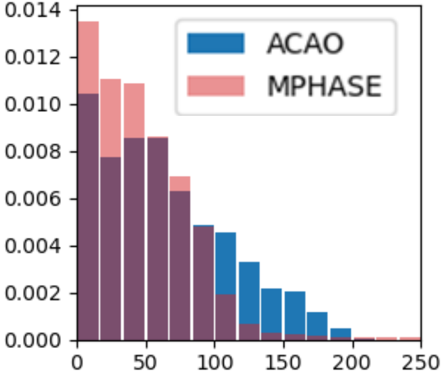
Temperature (°C)



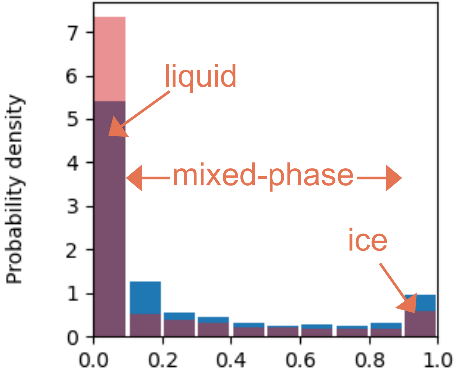
Aerosol conc. (cm^{-3})



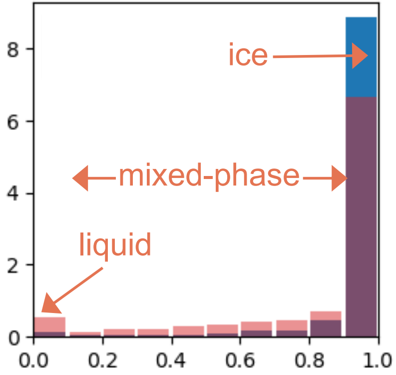
CDNC (cm^{-3})



Cloud phase



Precipitation phase



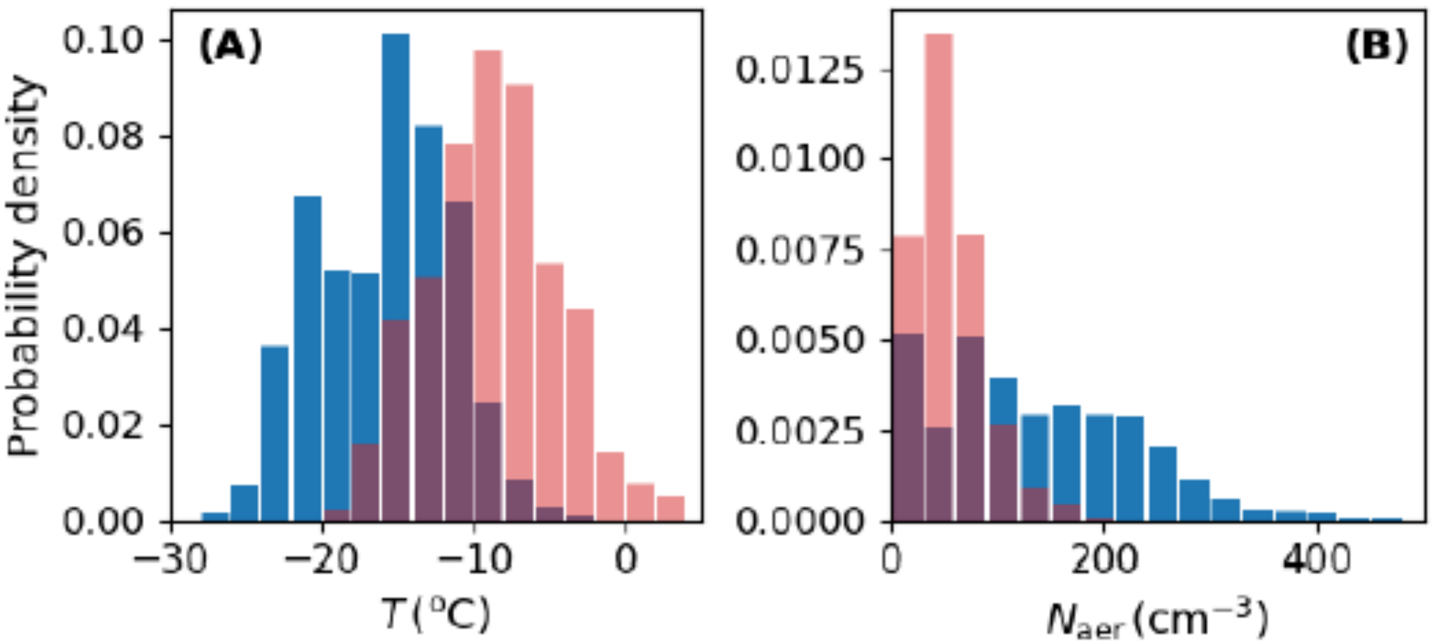
- Good range of cloud temperatures to explore ice production in mixed-phase clouds. Colder clouds measured in ACAO
- Clean clouds but some variability in aerosol and cloud drop number concentration.
- Clouds tend to be dominated by supercooled liquid water, but often mixed-phase
- Sub-cloud precipitation dominated by ice-phase

CDNC = Cloud Drop Number Concentration

Cloud phase from measured IWC/(LWC+IWC)

Cloud temperature

Aerosol concentration ~ CCN



ACAO

M-Phase

- ACAO clouds were **colder** than M-Phase.
- ACAO mostly below –8°C; M-Phase includes –3 to –8°C where SIP (Hallett-Mossop) is active.

- ACAO had more accumulation-mode aerosol → linked to **Arctic haze**.

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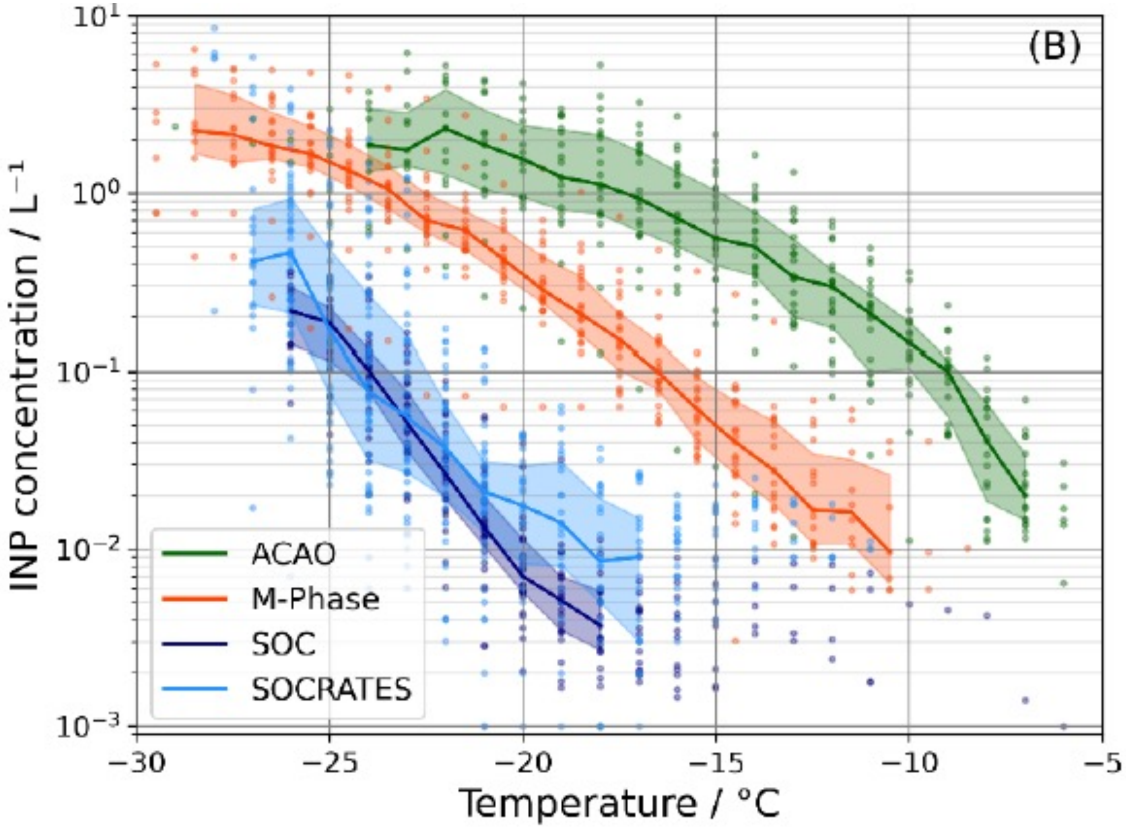
INP measurements (northern CAOs vs Southern Ocean)

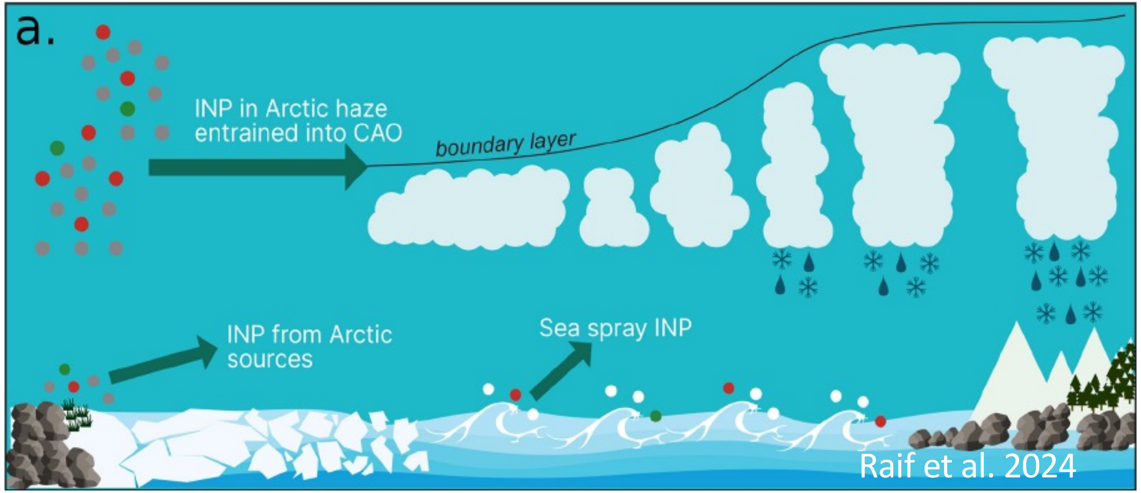


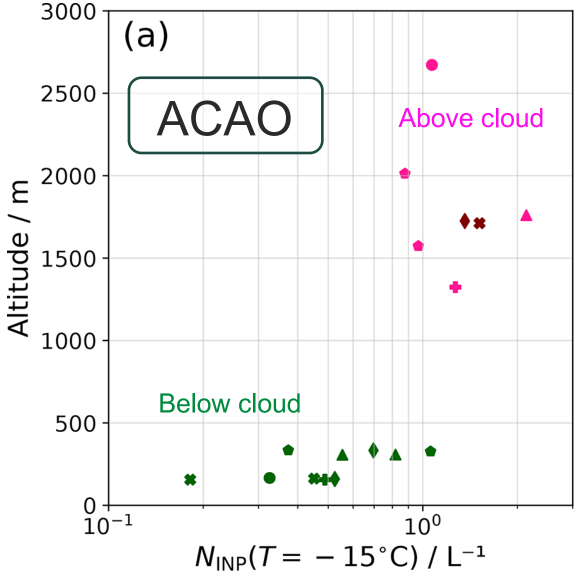
INP environments differ drastically between campaigns and hemispheres, setting up strong contrasts in primary ice production.

- ACAO was a **colder, higher-aerosol** environment
- M-Phase was **warmer and potentially more favourable for SIP via H-M**

Murray et al. (2026, in review)

Where do these INP come from?





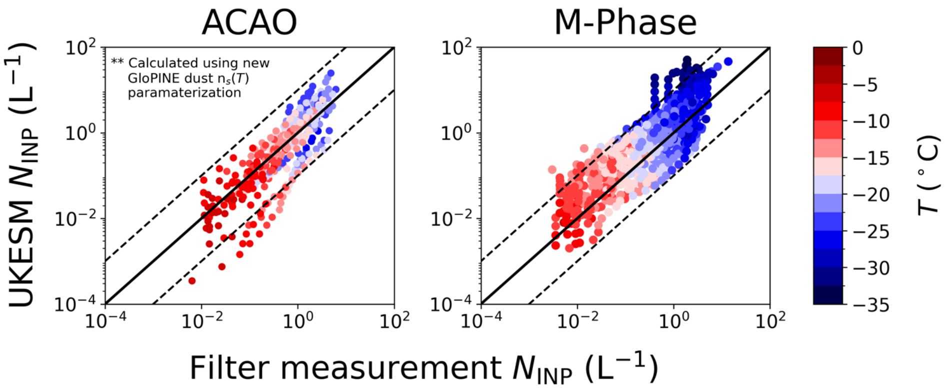
- Composition analysis suggests that dust/organics contribute more to INP population than sea-spray

- **Hypothesis**: Linked to a reservoir of aerosol in the high-Arctic being drawn southwards in CAOs.

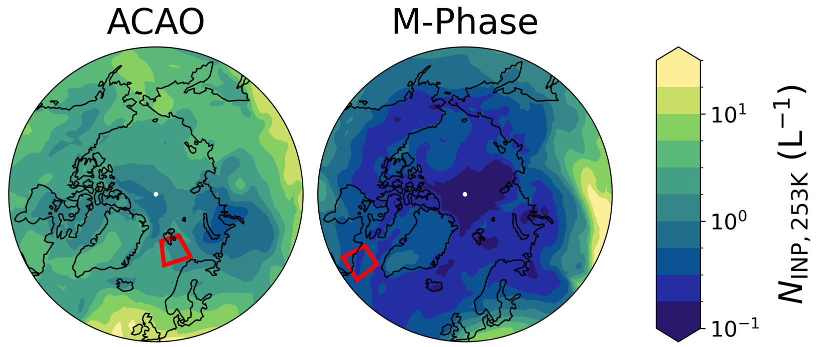
Raif et al. (2024): https://doi.org/10.5194/acp-24-14045-2024

New INP modelling reproduces ACAO/M-Phase contrast

1. Model captures observed INP variability



2. Higher INP environment in ACAO reproduced

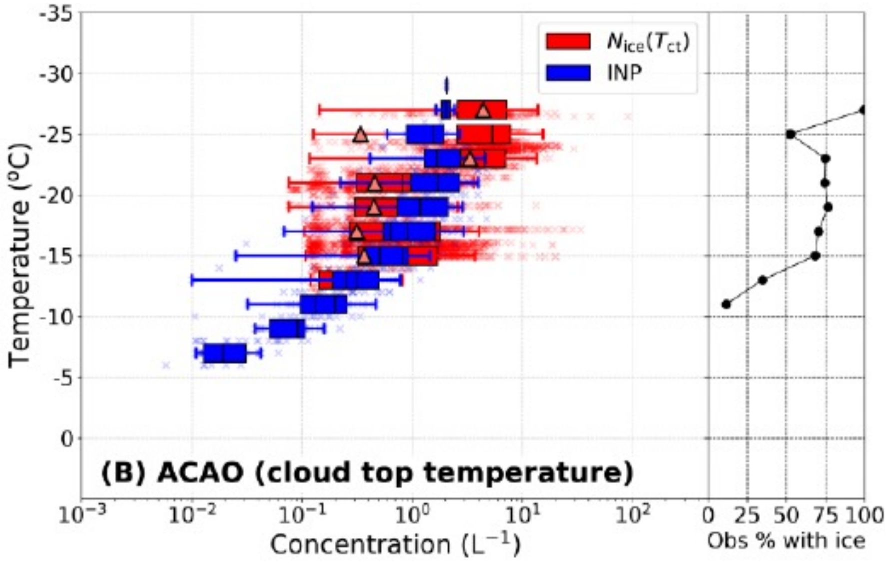


→ Model can be used to interpret regime differences

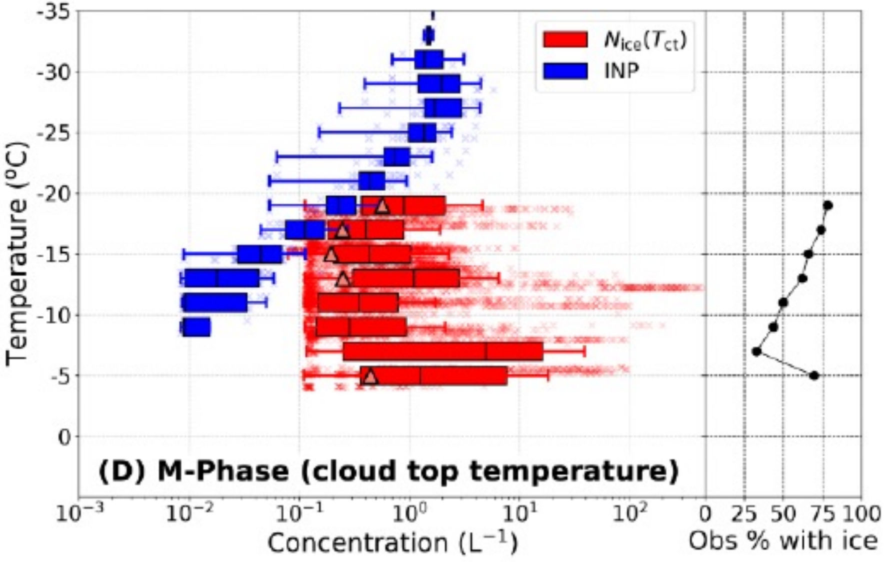
→ Much of the INP in ACAO is old aerosol emitted from the low-mid latitudes weeks to months earlier (*Herbert et al. 2025*)

INP and ice concentration (N_{ice}) vs T

ACAO



M-Phase

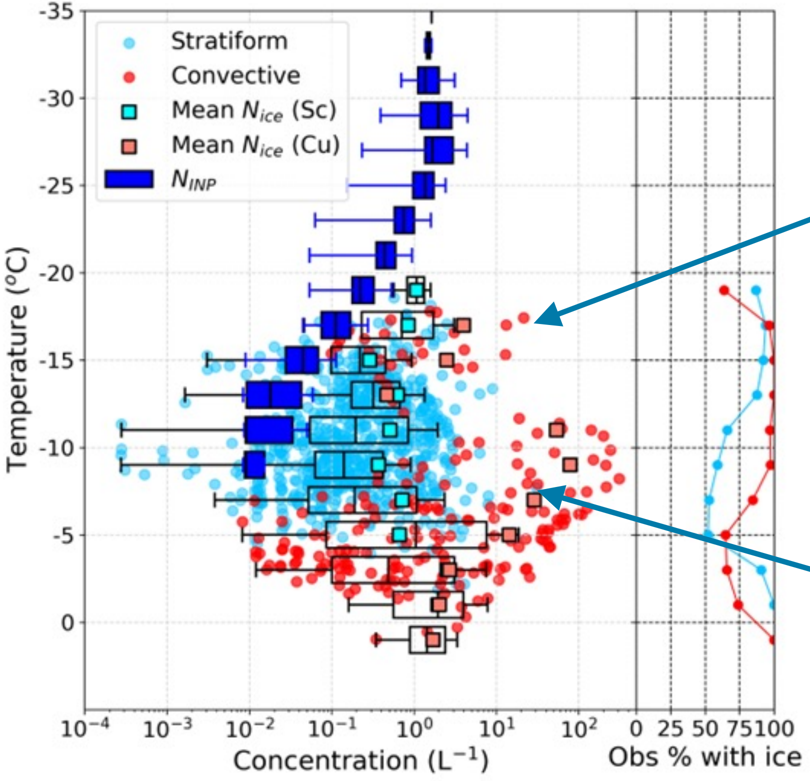


- Median N_{ice} is close to *INP* → **primary ice explains most ice**.
- Small SIP enhancements appear (esp. around –15°C), but not dominant.

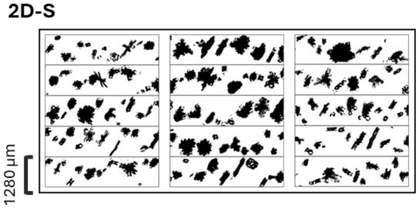
- Median N_{ice} far exceeds *INP* → **secondary ice production often dominates** in these warmer clouds.

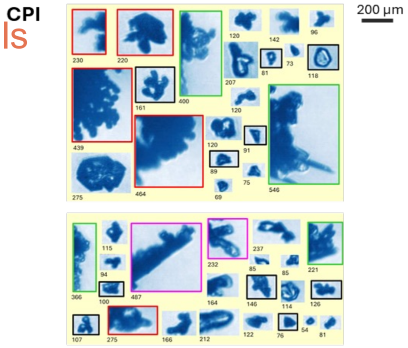
Murray et al. (2026, in review): Ben Murray will delve into this more in his talk tomorrow

M-Phase: Highest N_{ice} associated with SIP more frequently observed in convective regime

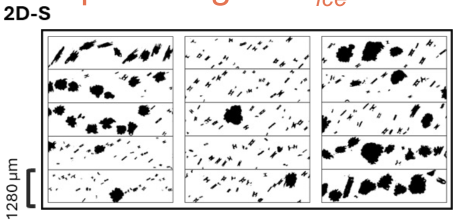


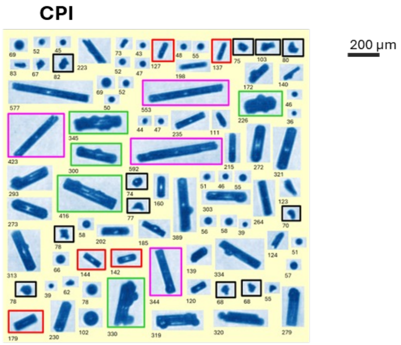
Fragile dendritic ice crystals → possible ice-collisional break-up → N_{ice} ⬆





H-M regime: graupel and splinters → rime-splintering → N_{ice} ⬆





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Biggart et al. (2026): chat to Michael Biggart at his poster about conditions favourable for SIP

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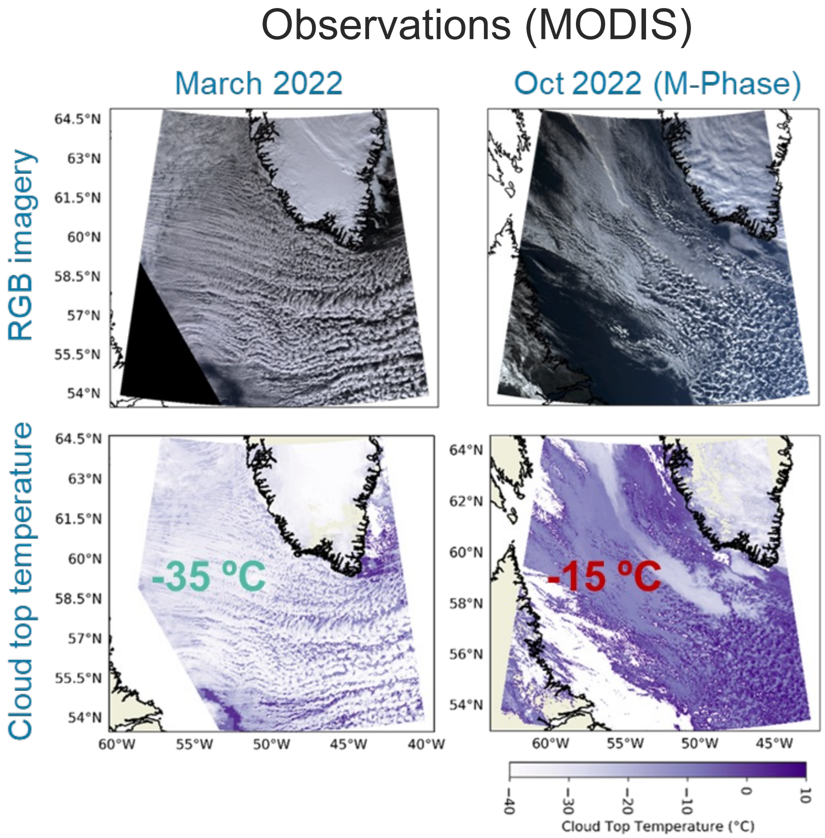
Implications for modelling CAO clouds

- Wide range of mixed-phase cloud conditions observed
- Aerosol and INP are highly variable
- Ice concentrations linked to INP and secondary ice production (SIP)
- Ice production varies across cloud regimes and thermodynamic environments

→ How do these processes influence modelled cloud behaviour?

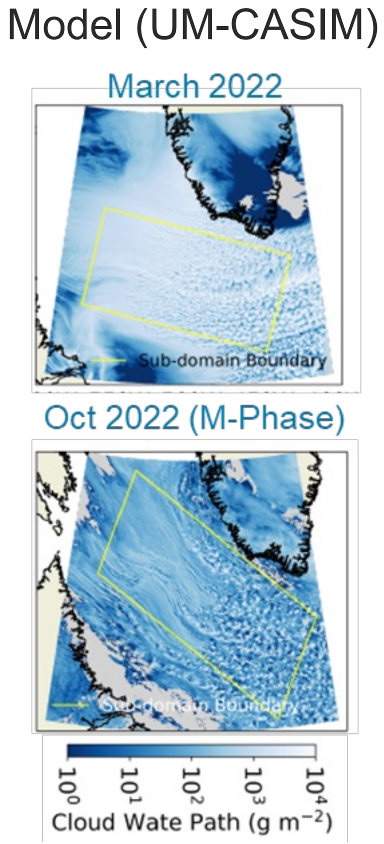
Modelling: Contrasting CAO cases in the Labrador Sea



March springtime case
cold case: T = -35 ºC

October autumnal case
warmer case: T = -15 ºC

These contrasting environments provide a testbed for modelling cloud responses to ice production processes



Huang et al. (2025): https://doi.org/10.5194/acp-25-11363-2025

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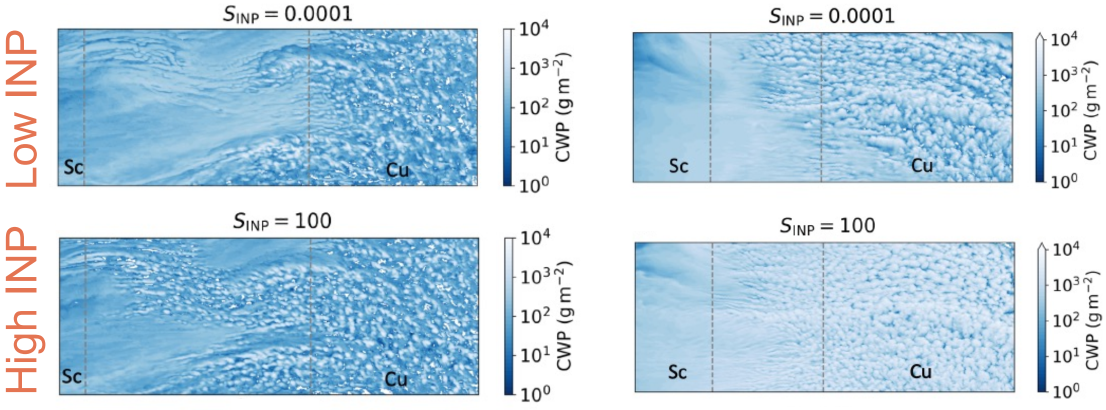
Opposing cloud responses in contrasting CAO regimes

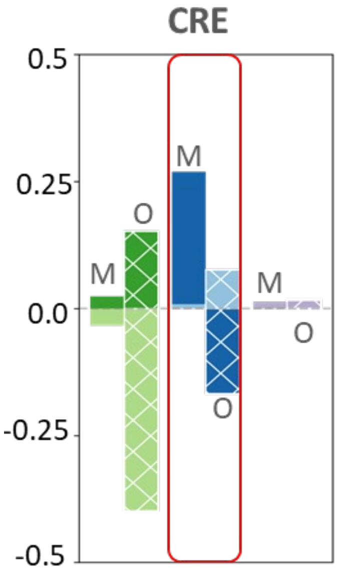
October warm case:
liquid dominated

March cold case:
ice dominated



Enhanced ice-production leads to faster precipitation induced break-up of the stratiform cloud

Enhanced ice-production leads to larger and brighter convective clouds



Warm (Oct) enhanced ice → CRE decrease

Cold (March) enhanced ice → CRE increase

Ice production can drive opposite cloud and radiative responses in contrasting CAO regimes

Huang et al. (2025) also explore cloud response to changing CDNC and SIP

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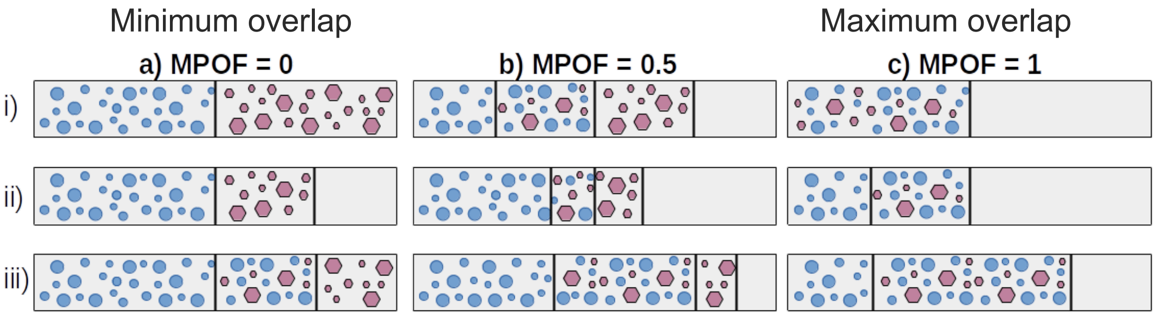
Representing ice-liquid overlap in model grid-boxes

A hole in a stratus cloud deck due to cloud seeding with aircraft, using dry ice
This is where super cooled cloud droplets are converted into ice crystals
, which then precipitate out of the cloud deck.

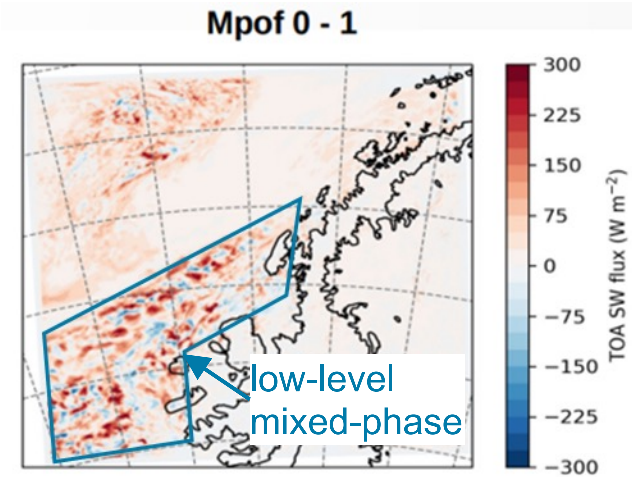
Sewell et al. (1973)

Model uses the mixed-phase overlap factor (*mpof*) = **0.5**



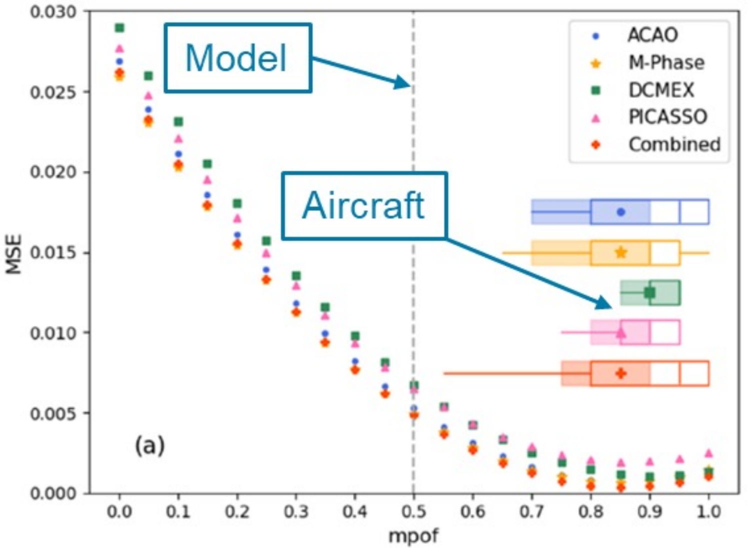
- More overlap → more efficient ice-liquid interaction
- MPOF is poorly constrained by observations

Clouds are highly sensitive to ice-liquid overlap
Aircraft observations favour higher MPOF (greater overlap)



lower overlap (mpof=0) → more liquid water maintained → more extensive and brighter clouds

Smith et al. (2025): https://doi.org/10.1029/2025JD044452



A measure of the difference between observations and the mpof parameterisations

chat to me at poster about the methodology to derive mpof from aircraft obs

Evans et al. (2025): https://doi.org/10.1002/qj.5041

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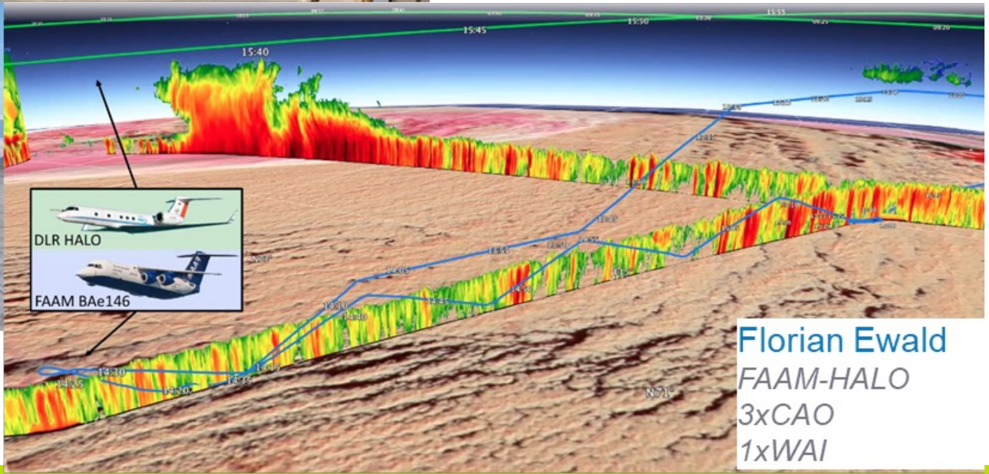
Clarke et al. (2026, in review): ACAO and M-Phase data paper

7 | DATASET AVAILABILITY

Aircraft data are available for the ACAO flights C271–C282 through a permanent CEDA archive at https://catalogue.ceda.ac.uk/uuid/ee96bac7c6e747c3b74ff952634ff2d7/ (FAAM Airborne Laboratory and National Centre for Atmospheric Science 2025a) and for the M-Phase flights C319–C333 through a permanent CEDA archive at https://catalogue.ceda.ac.uk/uuid/2040b17716fd49f2ac8b0b35c773d609/ (FAAM Airborne Laboratory and National Centre for Atmospheric Science 2025b). The INP filter data along with uncertainty estimates for the ACAO flights are available at https://doi.org/10.5281/zenodo.11221599 (Raif et al. 2024a) and for the M-Phase flights are available at https://zenodo.org/records/14781199 (Tarn et al. 2025). For a detailed analysis of the ACAO INP filter measurement the reader is directed to Raif et al. (2024b). LAAPToF, CVI, CPC-b and GRIMM skyOPC data are available for the M-Phase campaign at https://doi.org/10.5281/zenodo.17334975 (Wu and Coe 2025). The cloud phase fractions are available at https://zenodo.org/records/14526275 (Evans et al. 2025). Most of the data are given in netcdf format and can be easily plotted using open-source Python packages.

Opportunities for new science from combining campaigns

- ACAO and M-Phase provide unique datasets to examine CAO clouds across contrasting environments
- Opportunities to synthesize datasets with other campaigns



Questions?