

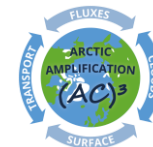
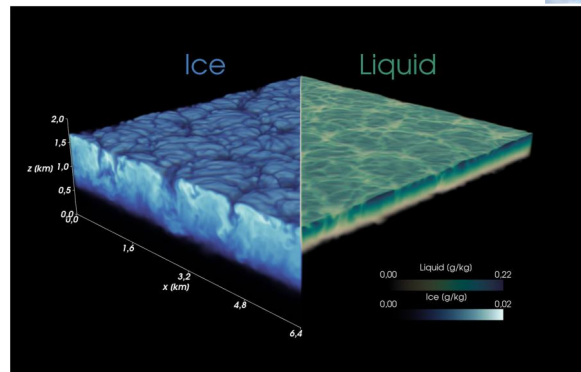
Modeling-guided planning of MCAO flights during HALO-(AC)³

Roel Neggers, Fiona Paulus, Niklas Schnierstein, Manfred Wendisch, and many others in (AC)³ and beyond

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UNIVERSITY OF COLOGNE



DFG

Contents

Lagrangian Large-Eddy Simulation (LES) of MCAOs based on airborne field campaign data

- Motivation, Objectives, Method
- Opportunities and Challenges

HALO Research Flights 10 & 11 during HALO-(AC)³

- Pre-flight planning
- Datasets collected
- Post-flight LES

Main outcomes: What worked, and what not?

Summary and Outlook

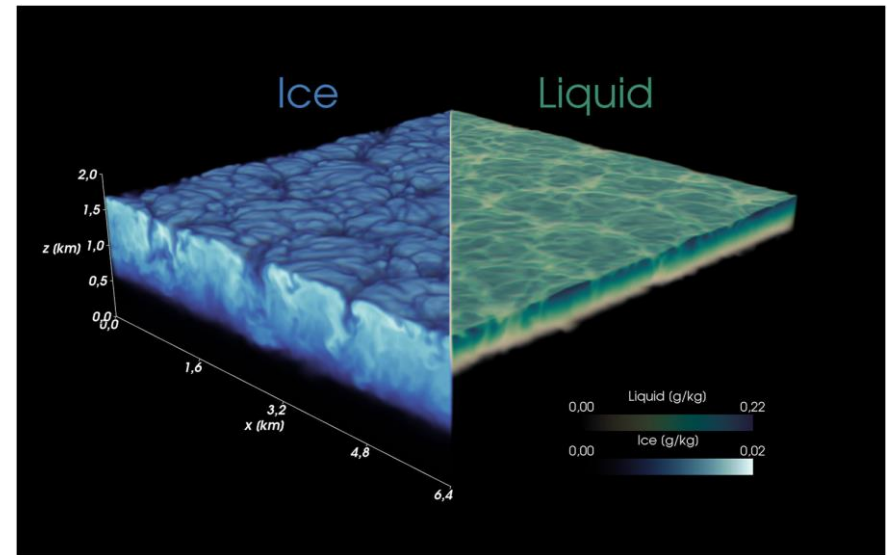
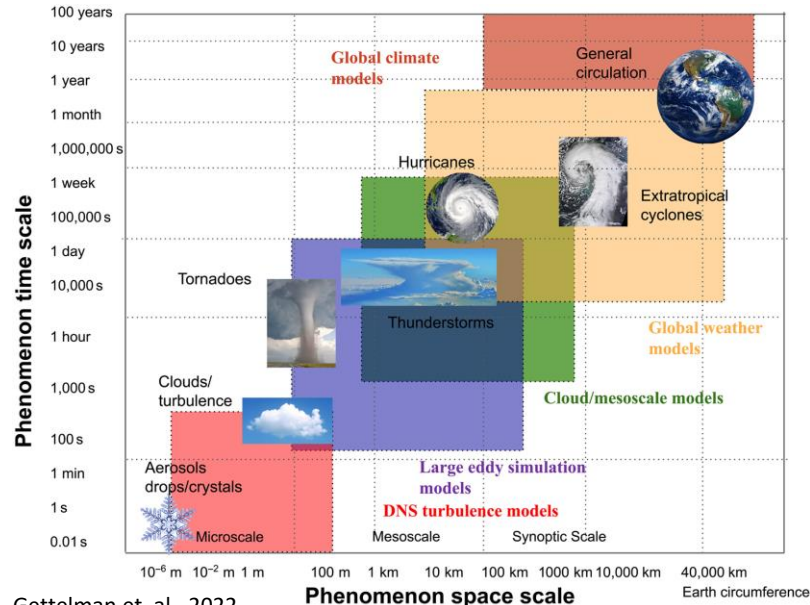
Large-Eddy Simulation (LES)

Time-integration of discretized GFD equations within a limited (often periodic) domain

Part of the inertial subrange of turbulence is resolved on the grid

Initial state, boundary conditions and larger-scale forcings have to be prescribed

A virtual laboratory for gaining scientific insight at process level



LES of MCAOs based on airborne field campaign data

Main objectives:

- To derive the initial state, boundary conditions and larger-scale forcings from available measurements *as much as possible*
- Evaluate against *independent* data on clouds, turbulence, radiation

Typical problems to overcome in the Arctic:

- Data gaps: Measurements do not cover everything needed to drive an LES
- Spatial gaps: The full MCAO fetch is not completely sampled
- Numerical challenge: Simulating the full fetch at turbulence-resolving resolutions in large domains
- Evaluation challenge: How to compare models and (cloud) measurements

→ Motivates the *integrated Lagrangian* sampling and simulation of MCAOs for multiple days

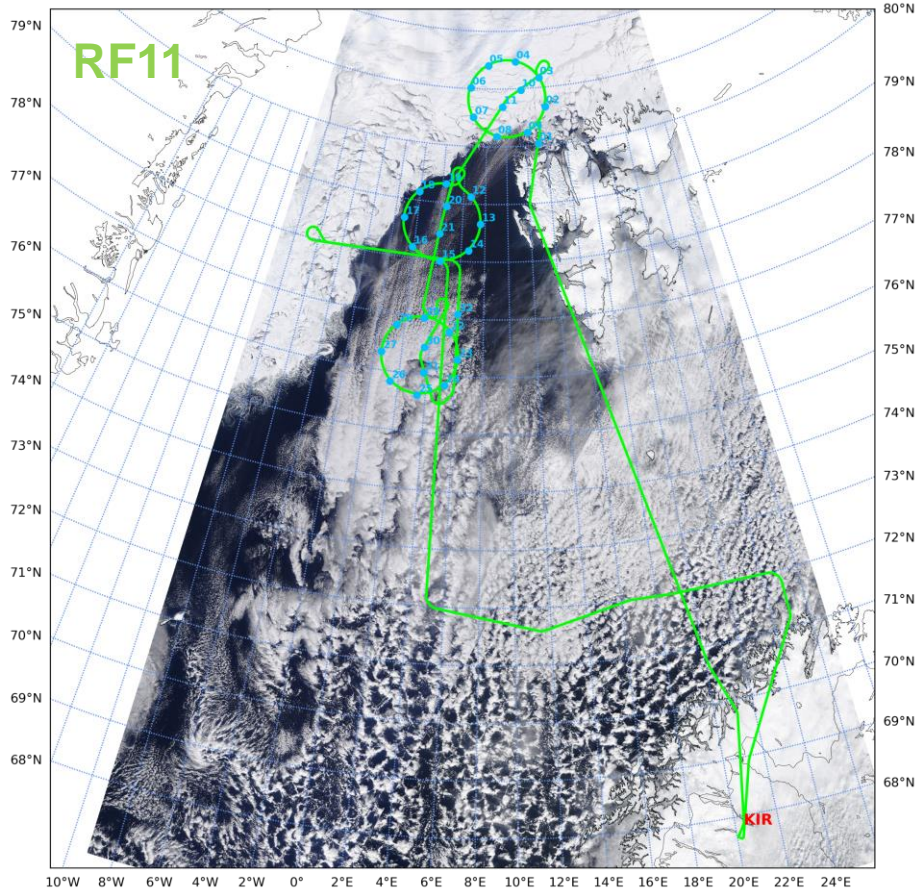
Our main objectives during HALO-(AC)³

- Can the “circle method” for measuring divergence using mesoscale dropsonde patterns provide reliable estimates of the larger-scale forcings needed for LES in the Arctic?
→ **Yes:** *Paulus et al. (2024)* <https://doi.org/10.1175/JAS-D-24-0034.1>
- Can we drive high-resolution Lagrangian LES of observed MCAOs **exclusively** with airborne measurements along its trajectory?
→ **Yes:** *Paulus et al. (2026)* <https://doi.org/10.5194/egusphere-2026-554>
See also Fiona’s poster
- Can we as modellers help optimize the HALO flight planning for achieving these goals?



HALO RF10 & 11 29-30 March 2022

MODIS VIS, NASA WorldView



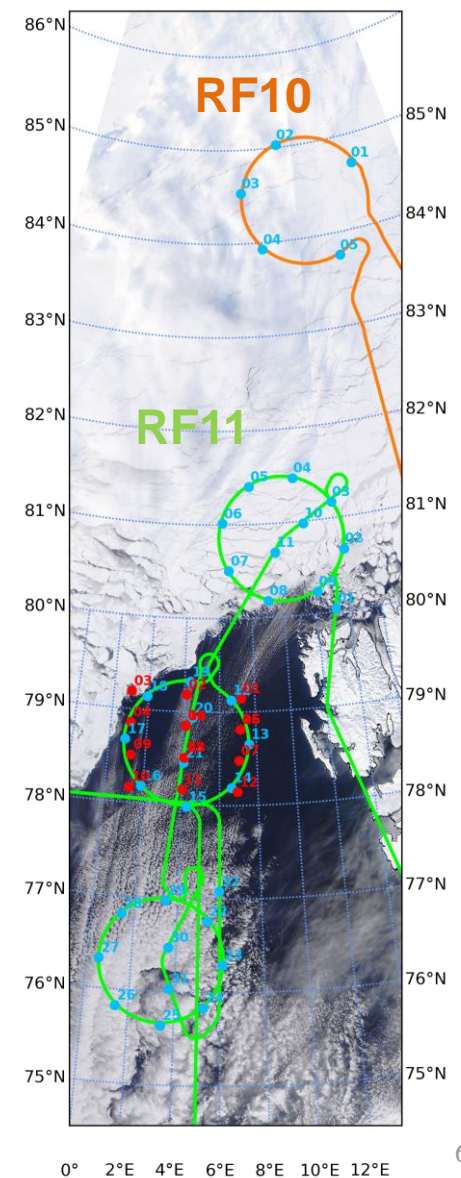
Southbound air mass was sampled for two days

Four mesoscale circles positioned along the forecasted air mass trajectory

Collocated flights:

- HALO sondes
- P5 sondes (+1 hr)

→ *How did we arrive at this flight plan?*



Pre-flight planning (involving modelers)

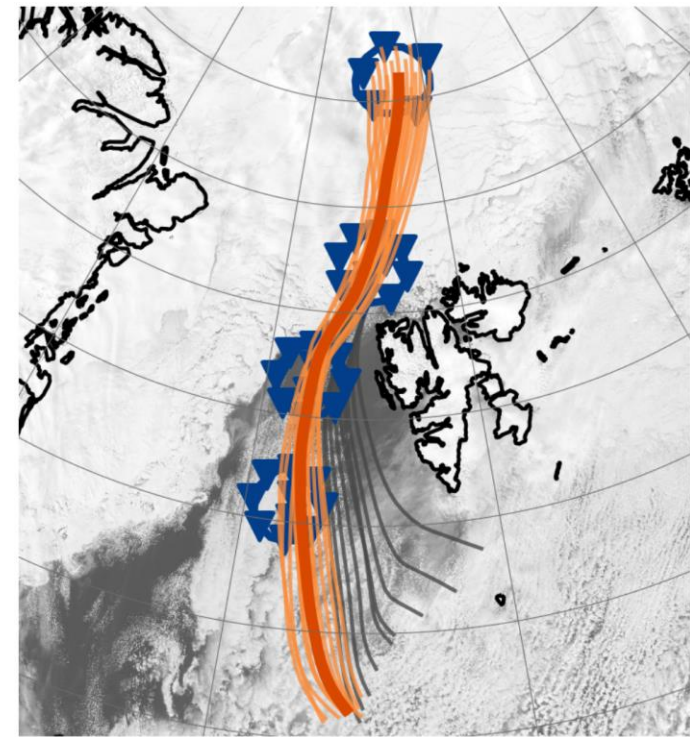
During dry runs for HALO-AC³, the circle method was thoroughly tested in the target area using both reanalysis and ICON-NWP data

The 29-30 March MCAO event was first identified about a week before it happened. Fortunately, the low-level flow forecast was persistent and accurate

LAGRANTO trajectories were calculated on a daily basis, for setting the waypoints

Based on these trajectories, the decision was made to

1. adopt a two-day flight plan (following CSET)
2. include four mesoscale circles
3. operate the full HALO instrumentation payload, and bring MANY dropsondes!



Forward Lagranto trajectories initiating at the northernmost Initial Circle (IC) at 870 hPa. Red: Mean trajectory. Orange: touching all circles. Grey: discarded. Thanks to Benjamin Kirbus.

Datasets

Table 1. Variables used in the LES for initialisation (I), evaluation (E), boundary condition (BC) and larger scale forcing (F).

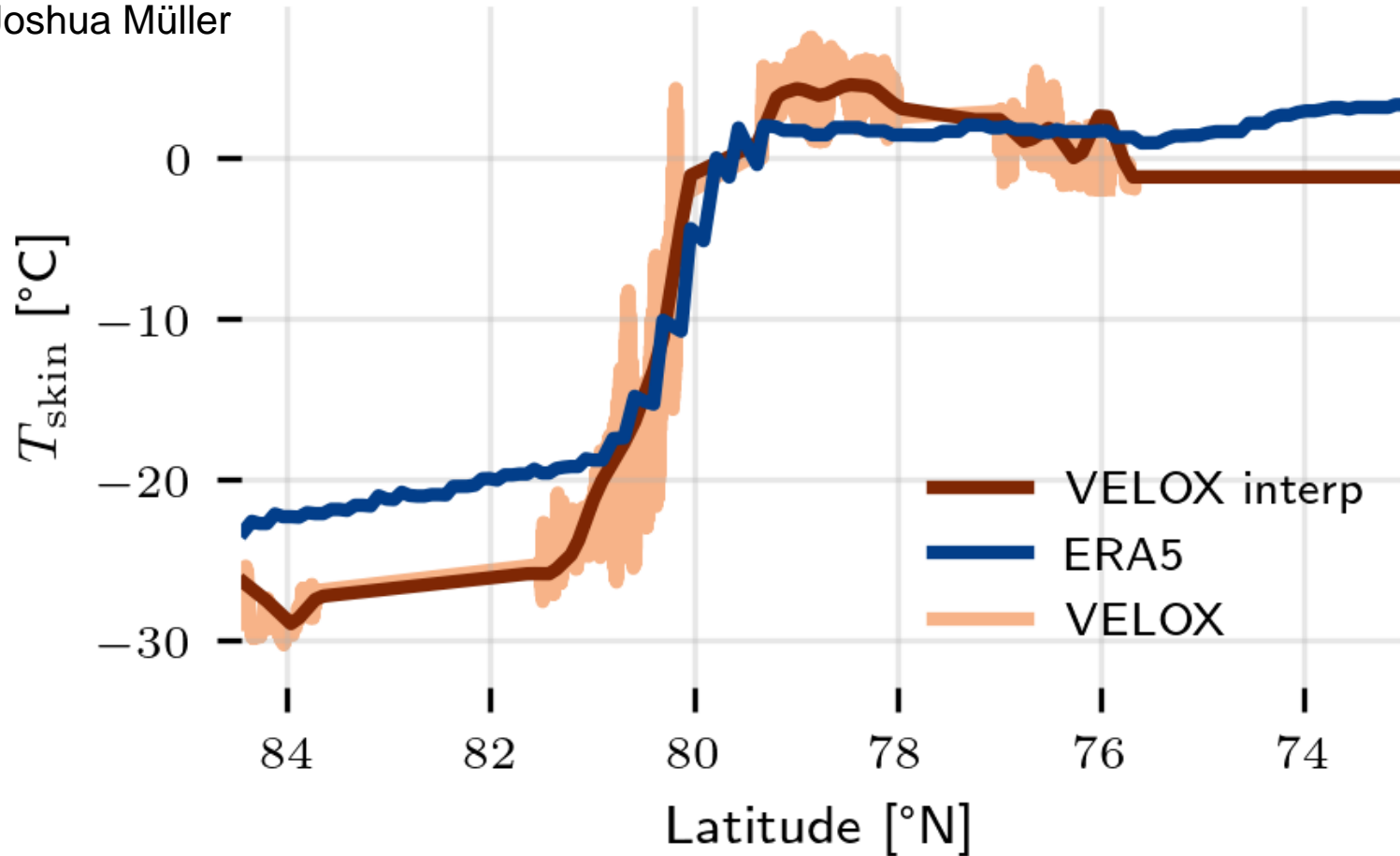
| Variable | Unit | Description | Instrument | Platform | Reference | Usage |
|--|-----------------------------------|------------------------------------|-------------------------------|------------|------------------------------------|-------|
| T | K | Air temperature | Dropsonde, CMET | HALO, CMET | Vaisala (2023); Voss et al. (2010) | I,E |
| q | kg kg^{-1} | Specific humidity | | | | I,E |
| p | hPa | Pressure | Dropsonde | HALO | Vaisala (2023) | I,E |
| u, v | m s^{-1} | Horizontal wind components | | | | I |
| $-\mathbf{v}_h \cdot \nabla T$ | K s^{-1} | Advection of air temperature | Regression from Dropsondes | HALO | Paulus et al. (2024) | F |
| $-\mathbf{v}_h \cdot \nabla q$ | $\text{kg kg}^{-1} \text{s}^{-1}$ | Advection of specific humidity | | | | F |
| $-\mathbf{v}_h \cdot \nabla u, -\mathbf{v}_h \cdot \nabla v$ | m s^{-2} | Advection of meridional/zonal wind | | | | F |
| u_g, v_g | m s^{-1} | Geostrophic wind | | | | F |
| w | m s^{-1} | Subsidence | | | | F |
| T_{skin} | K | Surface skin temperature | | | | VELOX |
| sic | % | Sea ice fraction | BC | | | |
| α | | Surface albedo | | | | BC |
| z_0 | m | Roughness length for momentum | | ERA5 | Hersbach et al. (2020) | BC |
| $z_{0,h}$ | m | Roughness length for heat | | | | BC |
| z_c^t | m | Cloud top height | AMALi | HALO | Stachlewska et al. (2009) | E |
| IWV | kg m^{-2} | Integrated water vapour | HAMP | HALO | Mech et al. (2014) | E |
| LWP | g m^{-2} | Liquid water path | HAMP, MiRAC | HALO, P5 | Mech et al. (2014, 2019) | E |
| IWP | g m^{-2} | Ice water path | MiRAC | P5 | Mech et al. (2019) | E |

All dropsondes launches were successful! (Big thanks to Fiona and Geet George)

Having the VELOX IR camera data later proved crucial for improving the LES

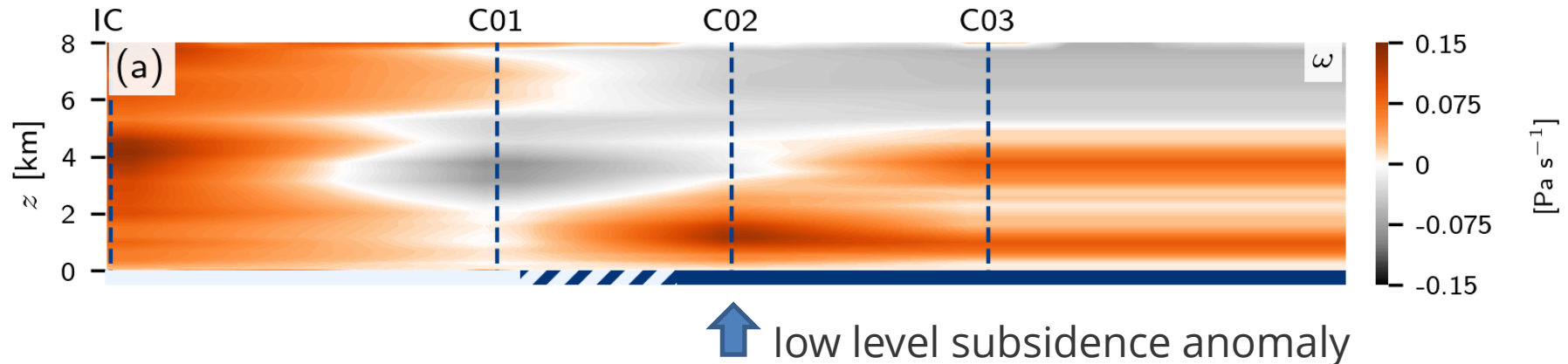
T_{skin} from ERA5 and VELOX

Thanks to Joshua Müller



OBSERVATIONAL MESOSCALE FORCING

- Interpolation of observed subsidence profiles along the trajectory
- IC: Initial Circle (RF10) C01: first circle during RF11 etc
- Linear regression for horizontal advection of Temperature, Water vapor, Zonal and Meridional wind
- Similar for geostrophic wind (pressure gradient force)

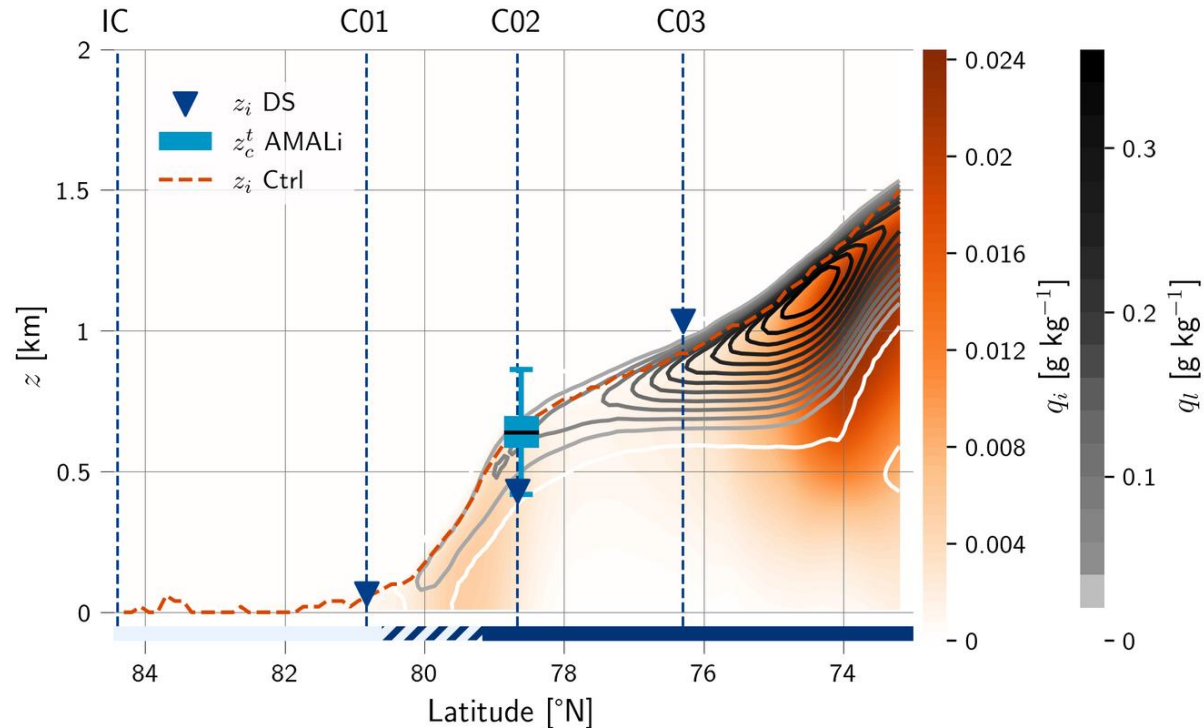


Post-flight LES

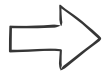
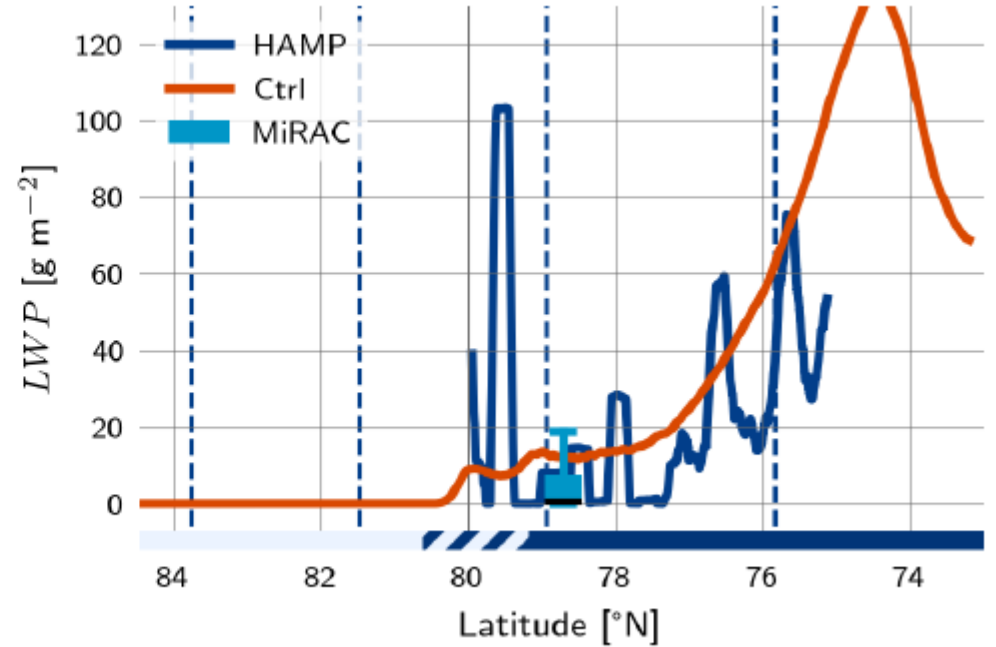
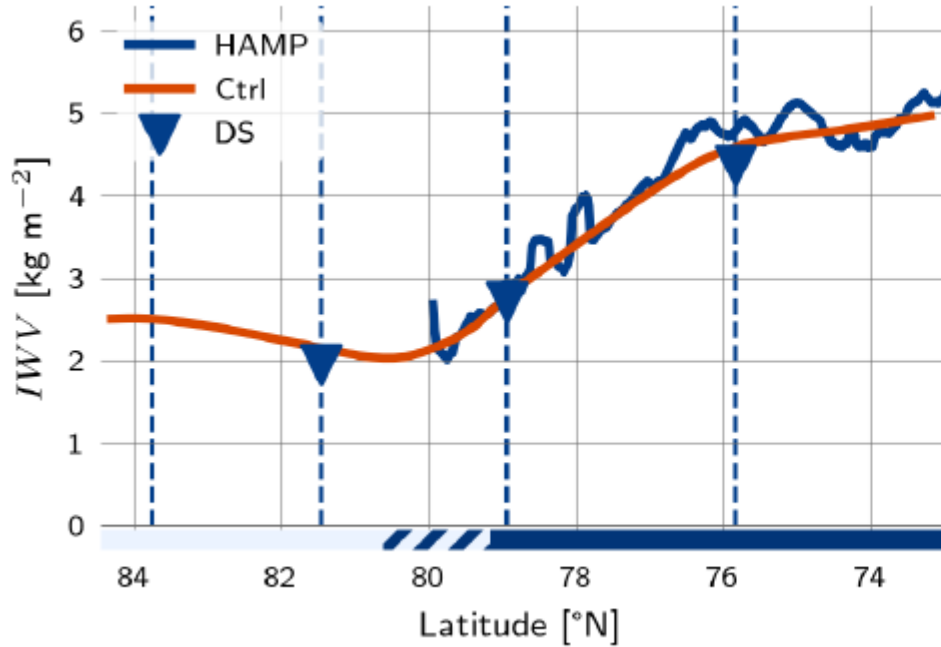
DALES code (Heus et al. 2010) featuring double moment microphysics (Chylik et al 2023)

Evaluation of the control run (Ctrl)

- Inversion height z_i , cloud liquid water q_l and ice q_i
- The observed evolution of ABL depth is generally reproduced
- Some disagreement between the measurements at C02
- After C02 the ABL deepening slows for a while



MODEL EVALUATION

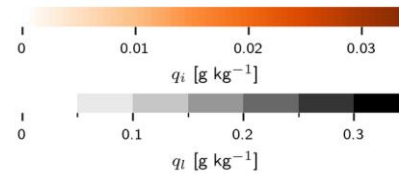


LES reproduces key features of ABL evolution of the observed MCAO

SUBSIDENCE SENSITIVITY

Variation of subsidence forcing to test the impact on cloud evolution

- **NoSub** No Subsidence
- **Sub10** 10% of observed subsidence
- **Sub50** 50% of observed subsidence
- **Ctrl** Observed Subsidence
- **Sub200** 200% of observed subsidence



Stronger subsidence delays:

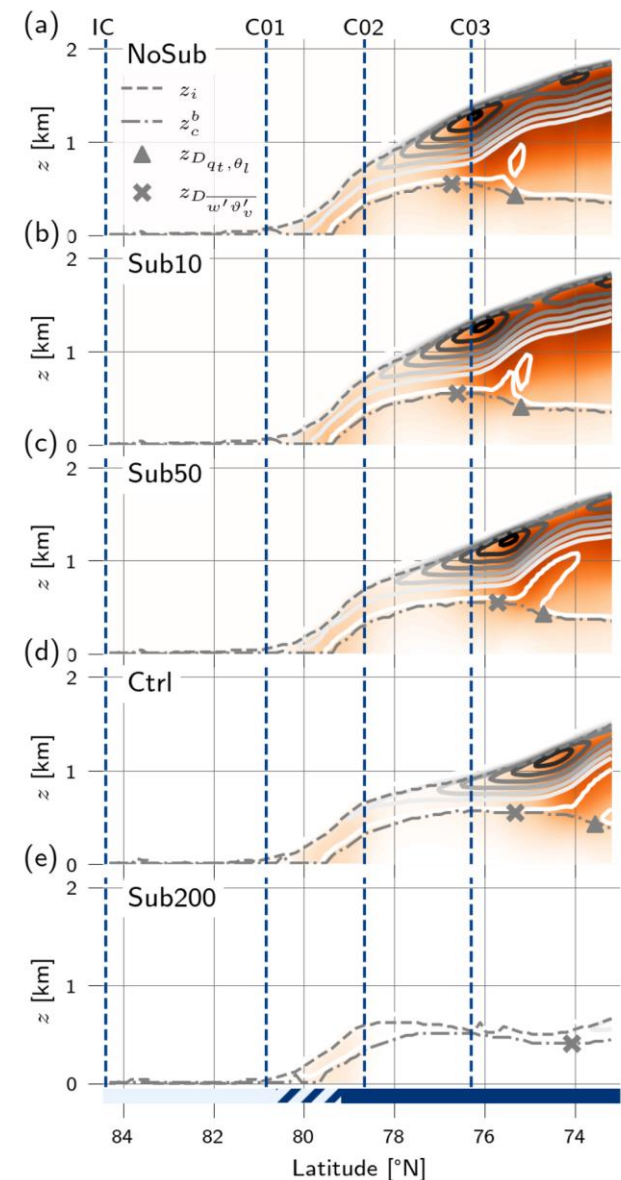
- boundary layer deepening
- maxima in LWP, graupel path and surface precipitation
- timepoint of **decoupling**

Two decoupling definitions:

(X) **Buoyancy flux decoupling**: Bretherton and Wyant (1997)

(▲) **Thermodynamic decoupling**: Wood & Bretherton (2004), Abel et al (2017)

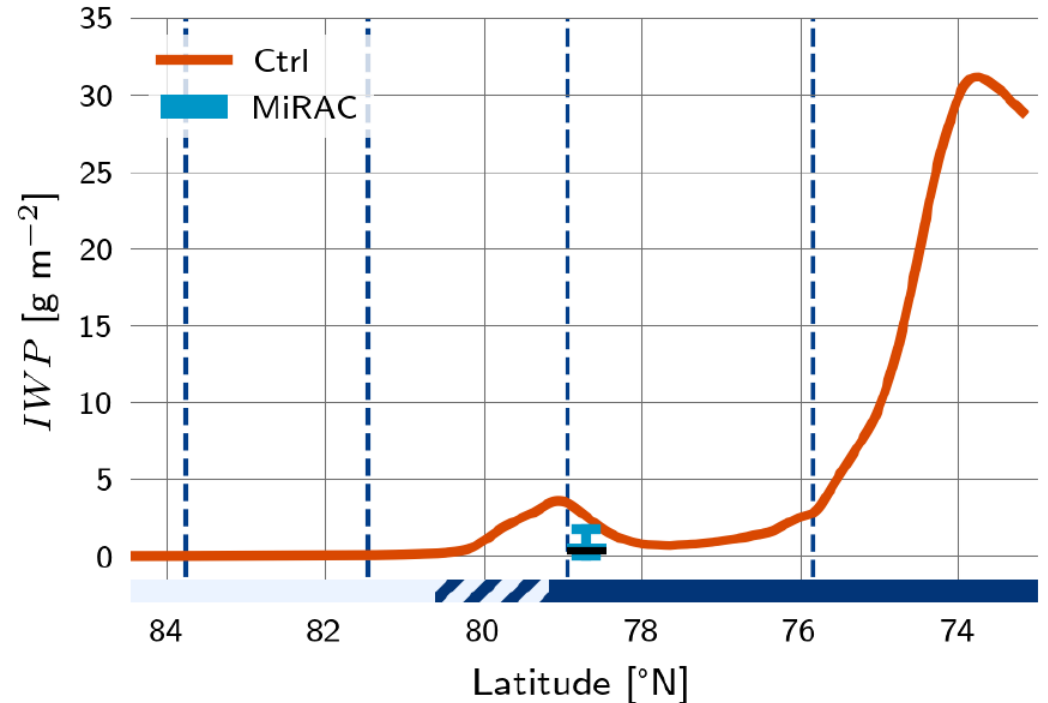
→ buoyancy flux decoupling *always precedes* thermodynamic decoupling



Looking back: What worked, and what not?

Properties we did not (yet) manage to obtain from HALO data:

- Surface roughness length and albedo (lower boundary conditions)
- Ice Water Path (IWP)
 - Luckily, P5 had MiRAC:
 - Microphysical data (SpecMAX)
 - Turbulence properties (P5/P6)
 - Aerosol (WALES, P6)



Summary and conclusions

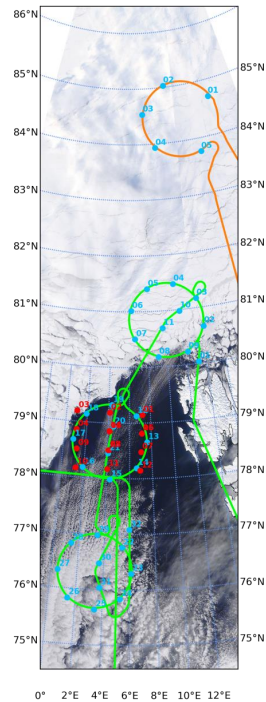
It is possible to (almost) fully constrain LES experiments with airborne field campaign data in the Arctic

This requires close collaboration and coordination between modeling and measurement experts, both before and after the campaign

Using HALO data instead of reanalysis fields significantly improved the LES realization. More observational data could still be introduced

The LES results elucidate the role of mesoscale subsidence in MCAO air mass transformations:

1. Subsidence can significantly delay decoupling, glaciation and the formation of open cells
2. A cloud-circulation coupling mechanism at high latitudes?



Outlook

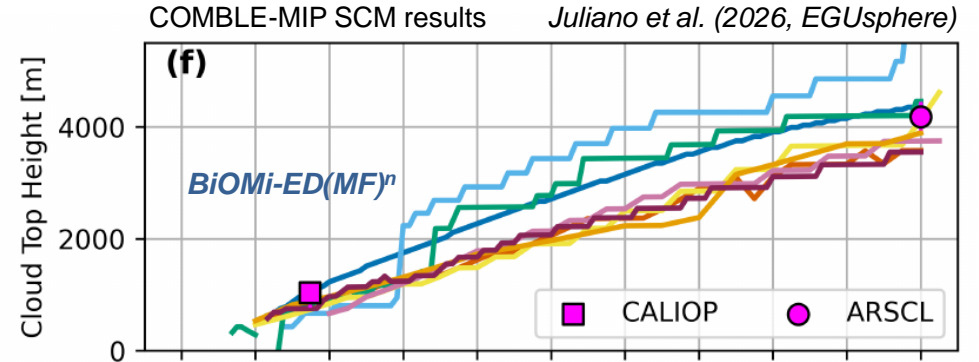
Building a suite of recent MCAO cases for improving circulation models:

- COMBLE, HALO-(AC)³, CAESAR
- BiOMi-ED(MF)ⁿ: A spectral eddy-diffusivity multiple mass flux scheme coupled to a thermal population model

Neggers (JAMES, 2015); Neggers and Griewank (JAMES, 2021, 2022)

Next-gen version of the Dual Mass flux scheme

Implemented in DALES, python SCM version on github soon



CONIDA campaign: Contrasting Polar Night and DAY

- Night : Nov / Dec 2028
- Day : Spring / Summer 2029
- Our plan: Lagrangian flights and LES, this time for air masses moving *into* the Arctic