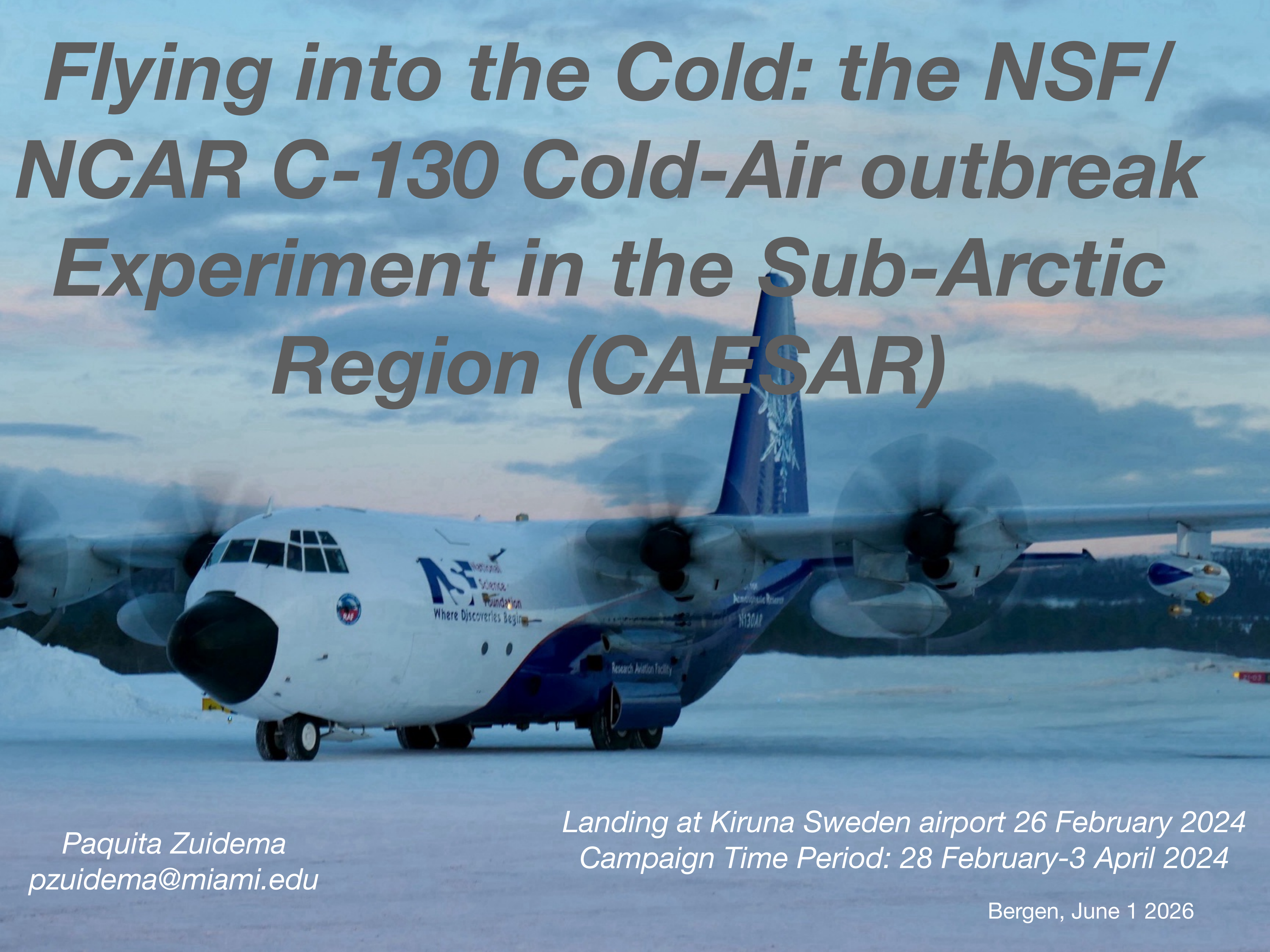

Flying into the Cold: the NSF/NCAR C-130 Cold-Air outbreak Experiment in the Sub-Arctic Region (CAESAR)

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Landing at Kiruna Sweden airport 26 February 2024
Campaign Time Period: 28 February-3 April 2024

Bergen, June 1 2026

University investigators

Paul DeMott/Russell Perkins — *Aerosol Influences on Ice Formation in Arctic Cold Air Outbreak Clouds During CAESAR : aerosol concentrator+CFDC+filters*

Bart Geerts/Jeff French
Tim Juliano/Lulin Xue — *Mesoscale Dynamics and Mixed-phase Microphysics in Arctic cold-air outbreaks: WCR, KPR, WCL, Nevzorov*

Jeff Snider/Markus Petters — *Aerosol Dynamics andAutoconversion during CAESAR: SMPS, UHSAS, SP2, CCN*

Greg McFarquhar
Emma Jarvinen-PHIPS — *Cloud-aerosol-dynamic interactions in Cold Air Outbreaks over the Arctic Ocean: NCAR CDP (2x), 2DS, 2DC, HVPS, King KIT-PHIPS*

Adriana Bailey
Harald Sodemann-cold trap — *Microphysical and dynamical controls on the precipitation efficiency of Arctic clouds: H20 isotope analyzer, cold trap, CVI*

Zhien Wang/John Cassano — *Characterizing and Understanding Atmospheric Boundary Layer Fluxes, Structure and Cloud Property Evolution in Arctic CAOs: Raman Lidar (down) Doppler lidar*

Paquita Zuidema
Florian Tornow/Ann Fridlind — *Arctic cold-air outbreak mixed-phase cloud characteristics, processes, and Impacts in observations and models: GVR (up):*

Yonggang Wang — *Characterization of Boundary Layer Convective Precipitation in CAOs: student outreach*

Jim Doyle (collaborator) — *Polar low & their model representation*

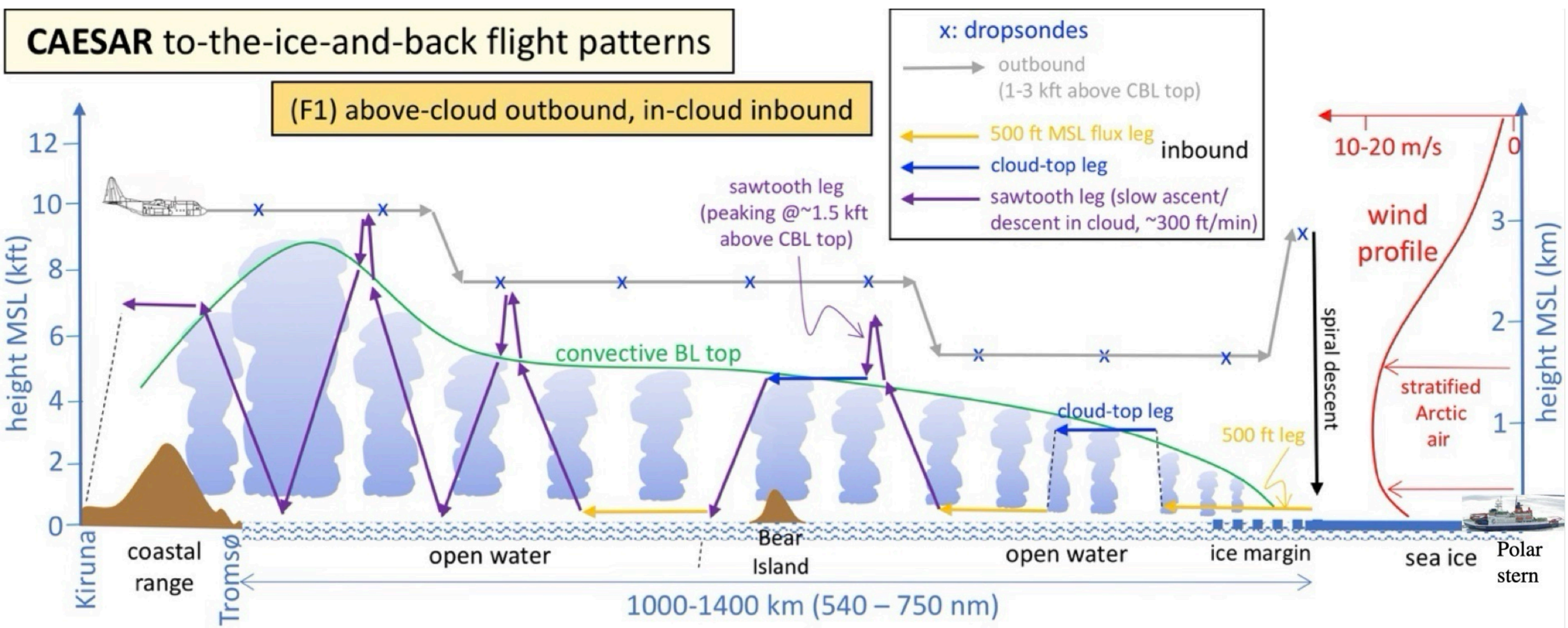
Gunnar Noer/Michael Tjenstrom/Gunilla Svensson — *International collaborations, forecasting support*

WHY ONE MORE SUB-ARCTIC CAMPAIGN??

TABLE 1. Recent significant campaigns with a focus on convective marine mixed-phase clouds.

Campaign	Base	Location	Time Span	CAO-relevant references
Northern Latitudes:				
ARCSIX	aircraft	N of Greenland	summer 2024	–
AC^3	aircraft	Greenland Sea	spring 2022	Wendisch et al. (2025), Schirmacher et al. (2024)
ACAO	aircraft	near Svalbard	spring 2022	Raif et al. (2024)
M-PHASE	aircraft	Labrador Sea	October 2022	Huang et al. (2025)
ACTIVATE	aircraft	NW Atlantic	2020-2022	Seethala et al. (2024), Tornow et al. (2025)
ACLOUD+PASCAL	aircraft+ship	near Svalbard	May-June 2017	Knudsen et al. (2018)
ACCACIA	aircraft	near Svalbard	spring, summer 2013	Abel et al. (2017)
M-PACE	aircraft	Beaufort Sea	autumn 2005	Solomon et al. (2009), Fu et al. (2019)
ARKTIS	aircraft	Greenland Sea	1991, 1993	Brümmer (1999)
NSA	surface	northern Alaska	2004-present	de Boer et al. (2011), Wang et al. (2016)
COMBLE	surface	north Norway	spring 2020	Geerts et al. (2022), Lackner et al. (2023a,b), Mages et al. (2023), Juliano et al. (2024), Xia and McFarquhar (2024), Williams et al. (2024), Wu et al. (2025)
ISLAS	surface	north Norway	spring 2020,2021,2022	Seidl et al. (2024), Dekhtyareva et al. (2026)
MOSAiC	ship	central Arctic	2019-2020	Kirbus et al. (2023), DeMott et al. (2025)
Southern Latitudes:				
SOCRATES	aircraft	Southern Oceans	Jan-Feb 2018	McFarquhar et al. (2021)
MICRE	surface	MacQuarie Island	2016-2018	Tansey et al. (2023)
CAPE-k	surface	Tasmania	April 2024-Sept 2025	-
CAPRICORN I,II	ship	Southern Oceans	March-April 2016, Jan-Feb 2018	Mace et al. (2021)
MARCUS	ship	Southern Oceans	Oct 2017-March 2018	Alexander et al. (2021), Hu et al. (2023)

- Long range of the C-130 plane (~1400 km, from Kiruna to the Greenland MIZ)
- Rich suite of in situ + remote sensing instrumentation



comprehensive in-situ instrument:
Evolved HOLODEC data processing; PHIPS particle habit ID; Nevzorov ice+total water + instruments common to most campaigns

Aerosols&gases: CCN, CN, UHSAS, INP (CSU CFDC+filters), H2O isotopes,SP2 (black carbon),O3,CO2

Diagram credit: Sarah Woods

Remote sensing suite:
newish information from: water vapor & temperature lidar; microwave radiometer; diverse radars (W & K), lidar

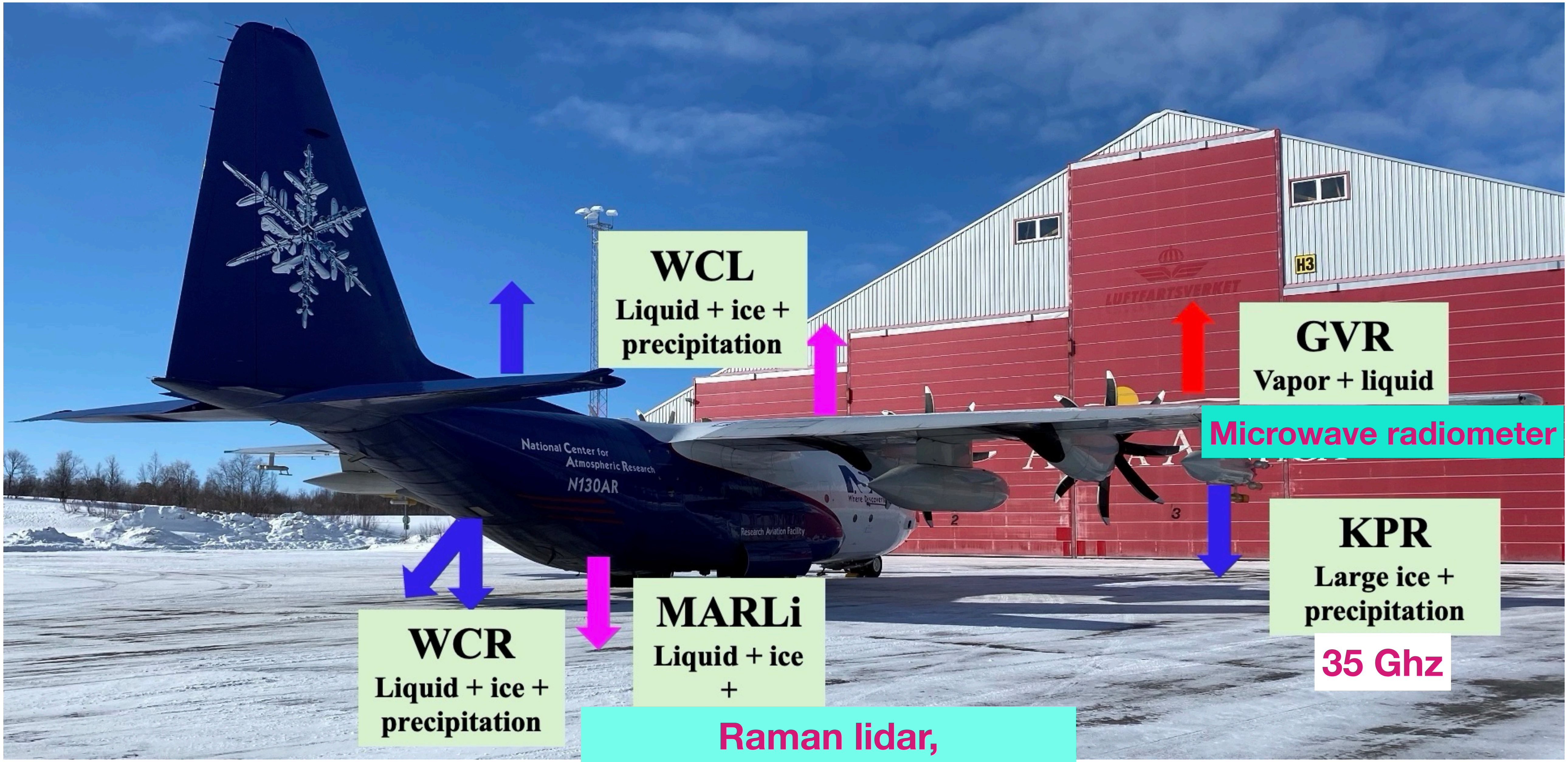


Diagram credit: Zhien Wang

CAESAR hypotheses organized around 5 themes

H1 air-sea exchange and boundary layer. The low-level stratification over the Arctic ice discernably influences subsequent cloudy boundary layer development.

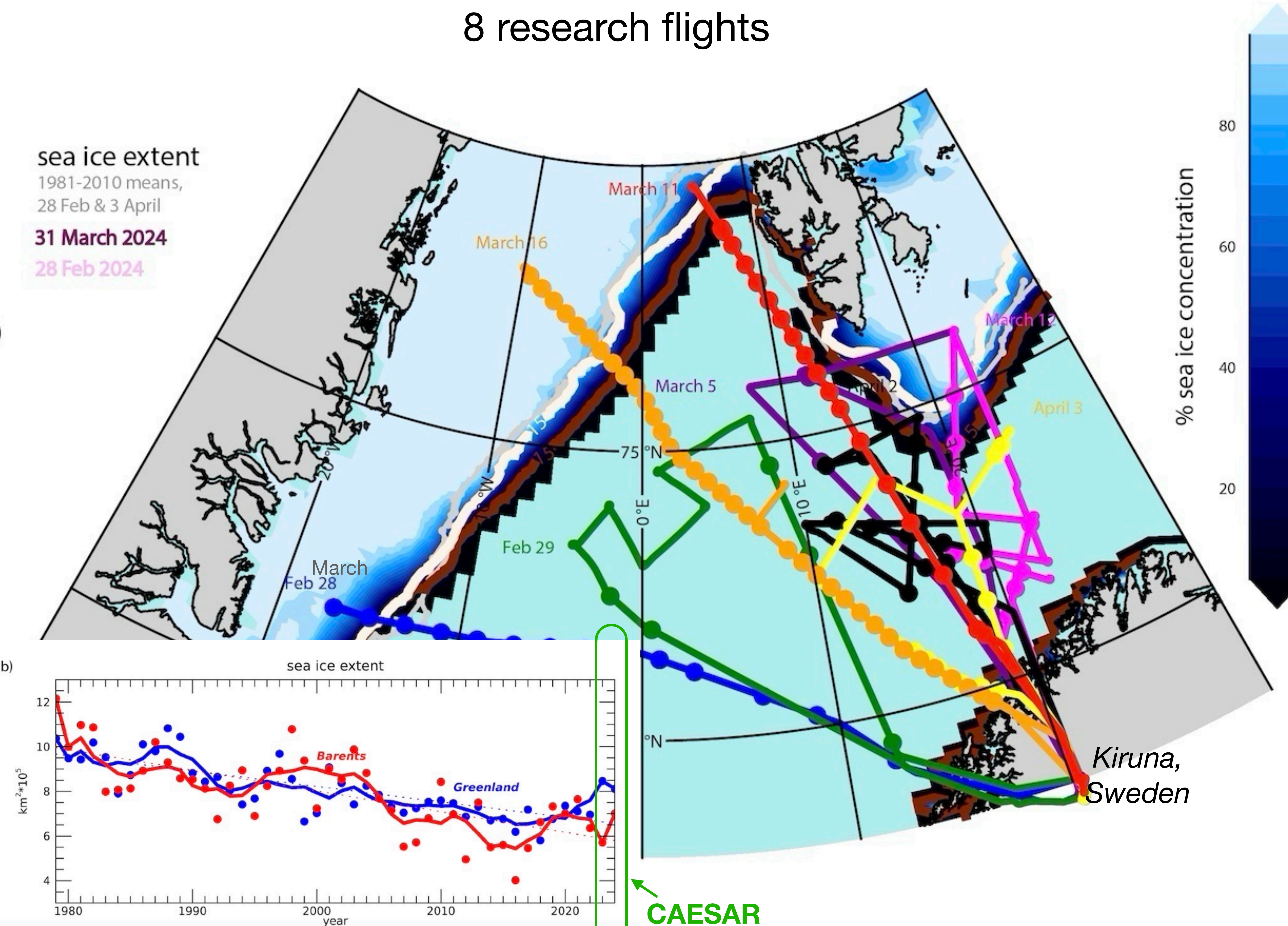
H2 mesoscale organization. Cloud morphological transitions are more correlated to precipitation than to wind shear, air-sea temperature differences, or lower-tropospheric instability.

H3 clouds and precipitation. Secondary ice production (SIP) increases with fetch while remaining insufficient to fully consume the liquid mass. Glaciation sets in when clouds achieve sufficient depth to produce cloud droplet diameters ≥ 20 μm. SIP is symptomatic of cloud morphological transitions to open cells but not necessary for the transition.

H4 aerosols. The major ice-nucleating particle (INP) source is the free troposphere rather than the boundary layer, with immersion freezing of super-cooled liquid dominating the ice nucleation, while oceanic emissions are the primary cloud condensation nuclei (CCN) source.

H5 polar lows. Polar lows are primarily convective systems, initiated in the presence of destabilizing CAO-induced heat fluxes within a convergent frontogenetic shear zone, with intensification arising through interaction with an upper-level potential vorticity anomaly.

8 research flights



83% (30/36) of campaigns possessed CAO conditions reachable by the C-130

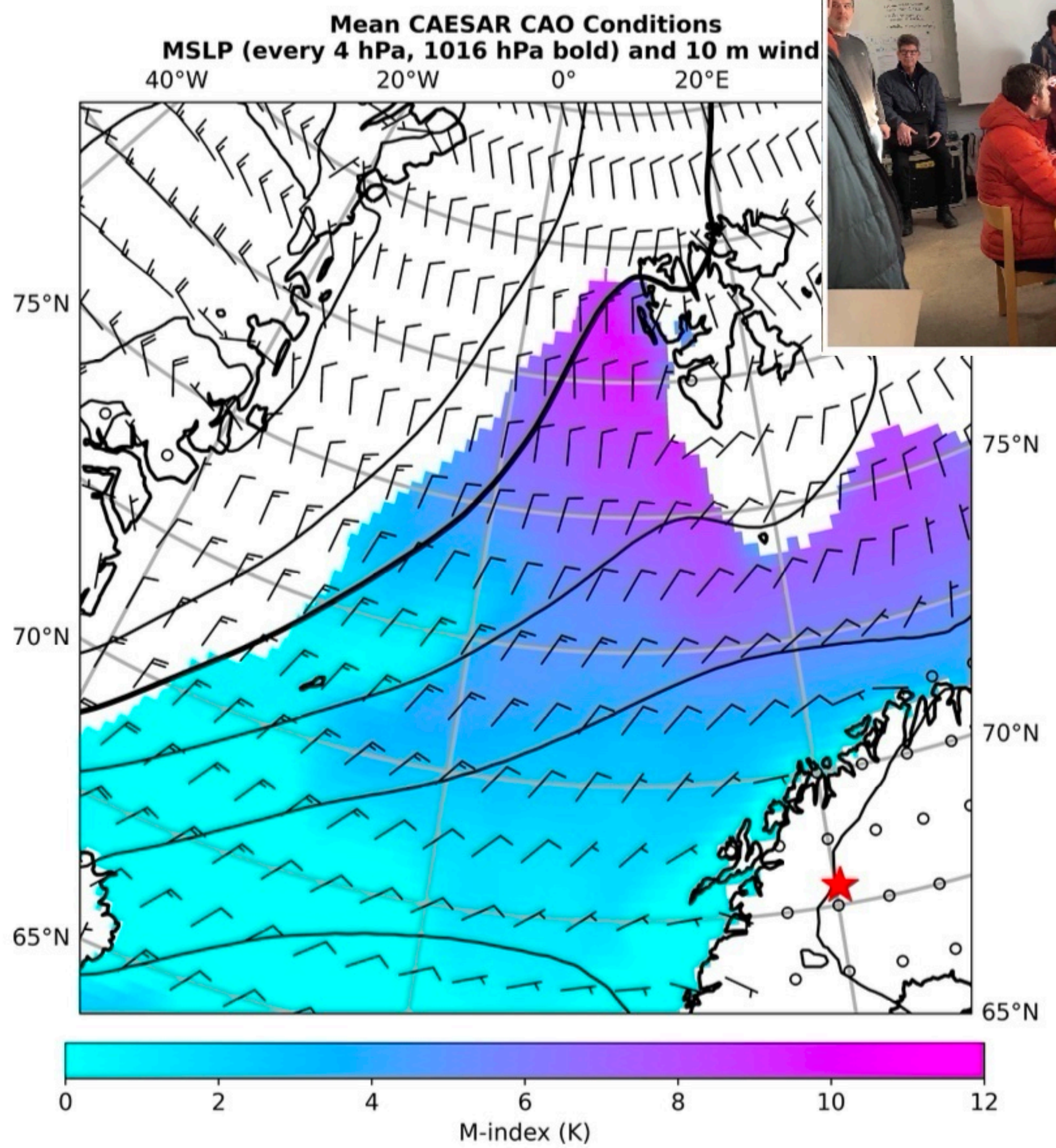
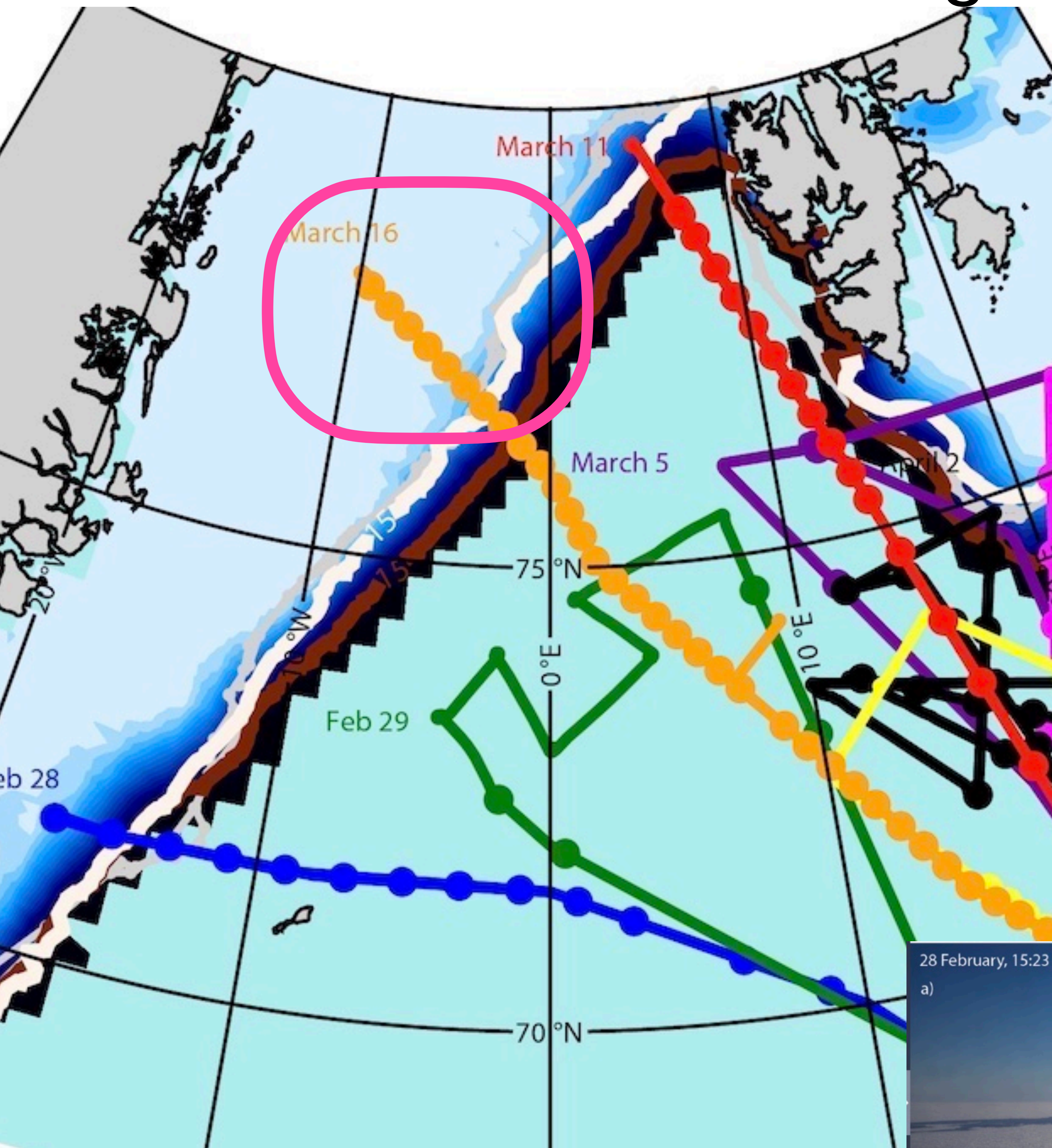
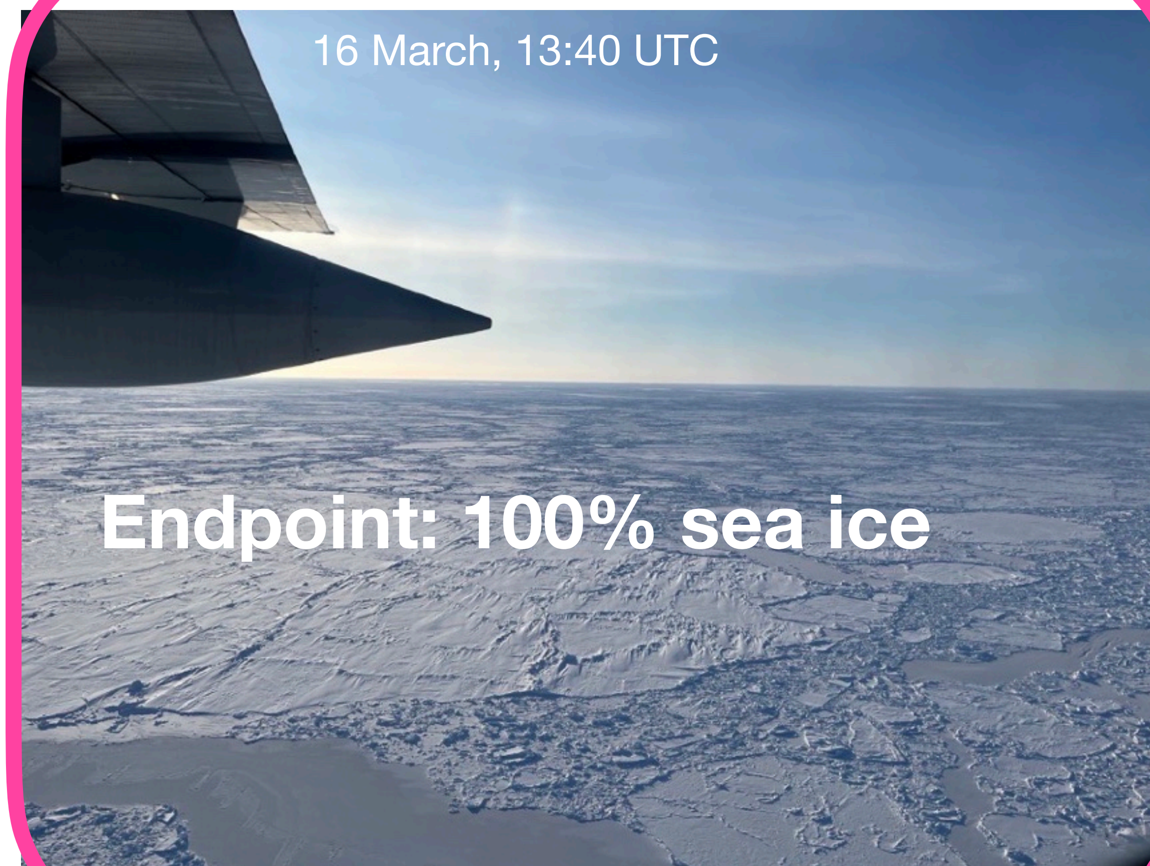


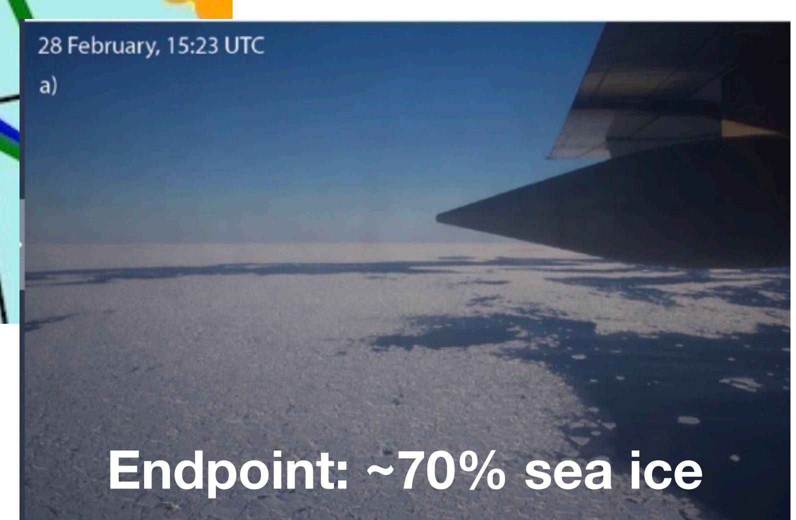
FIG. 2. 83% of the campaign days (30 out of 36 days) contain cloudy cold-air outbreaks reachable by the aircraft, as defined in-field by the forecasting team. ERA5 mean sea level pressure (black contours every 4 hPa, with 1016 hPa contour in bold), mean 950 hPa winds and M-index ($\theta_{surface}$-θ_{850hPA}, in colors, where θ is potential temperature) shown for these 30 days. ERA5-determined 15% sea ice concentrations or greater indicated by the lack of an M-index. The red star denotes Kiruna, Sweden.

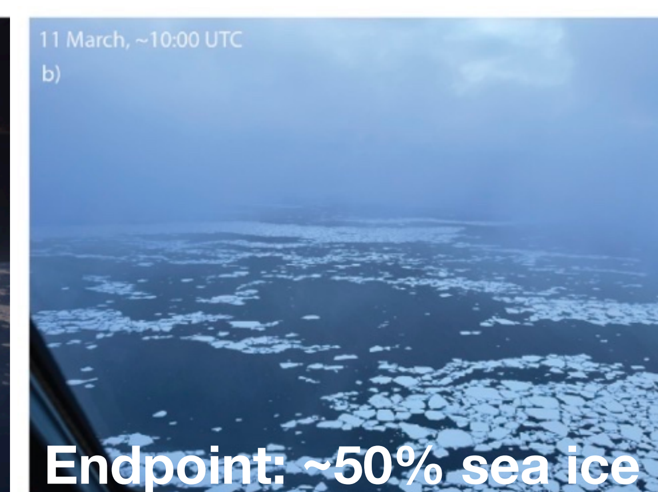
shout-out to Andrew Dzambo for organizing a 'bottom-up' forecasting team

3 flights reached Greenland sea ice - 1 beyond the MIZ: 16 March ‘golden case’

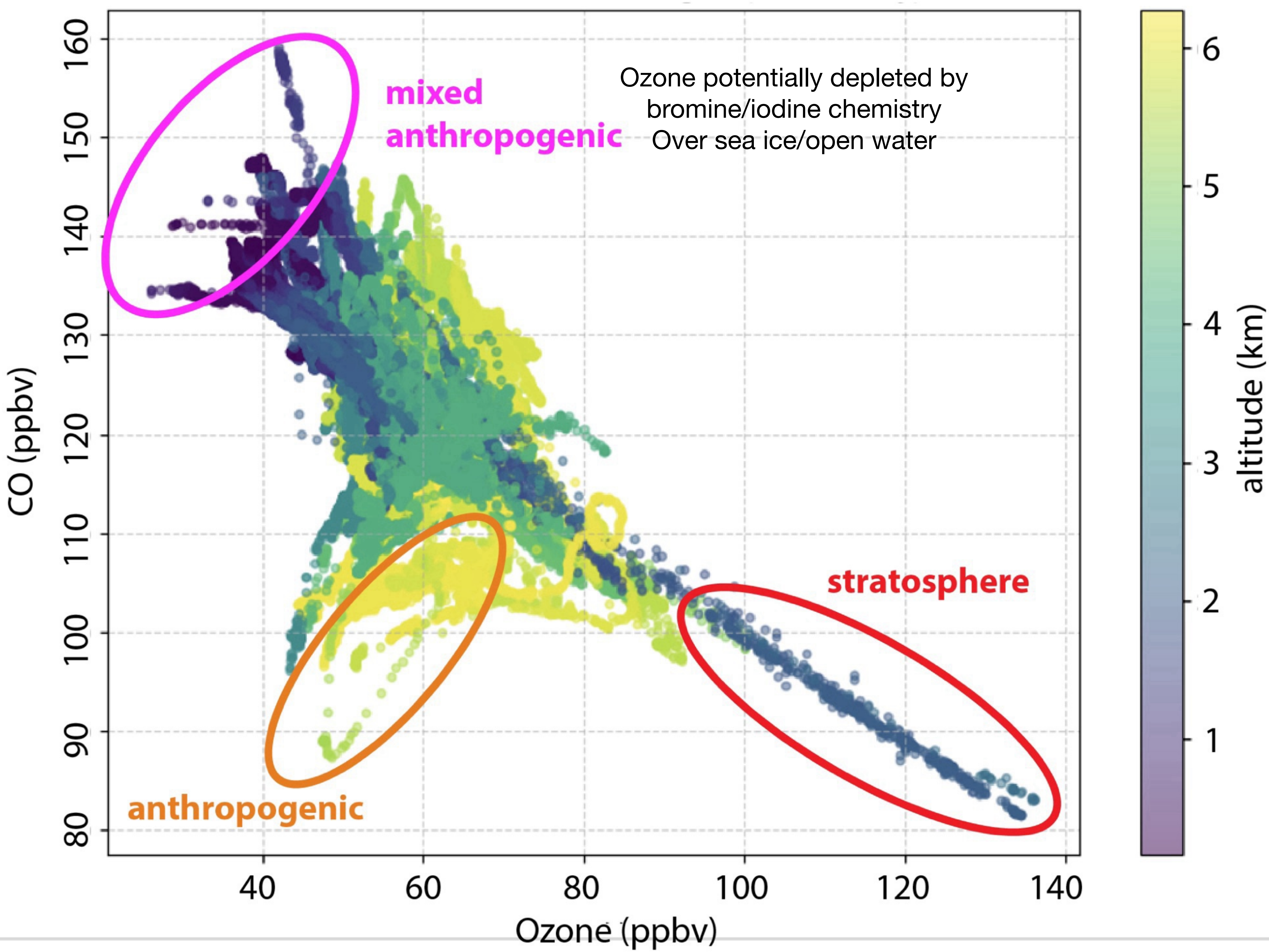








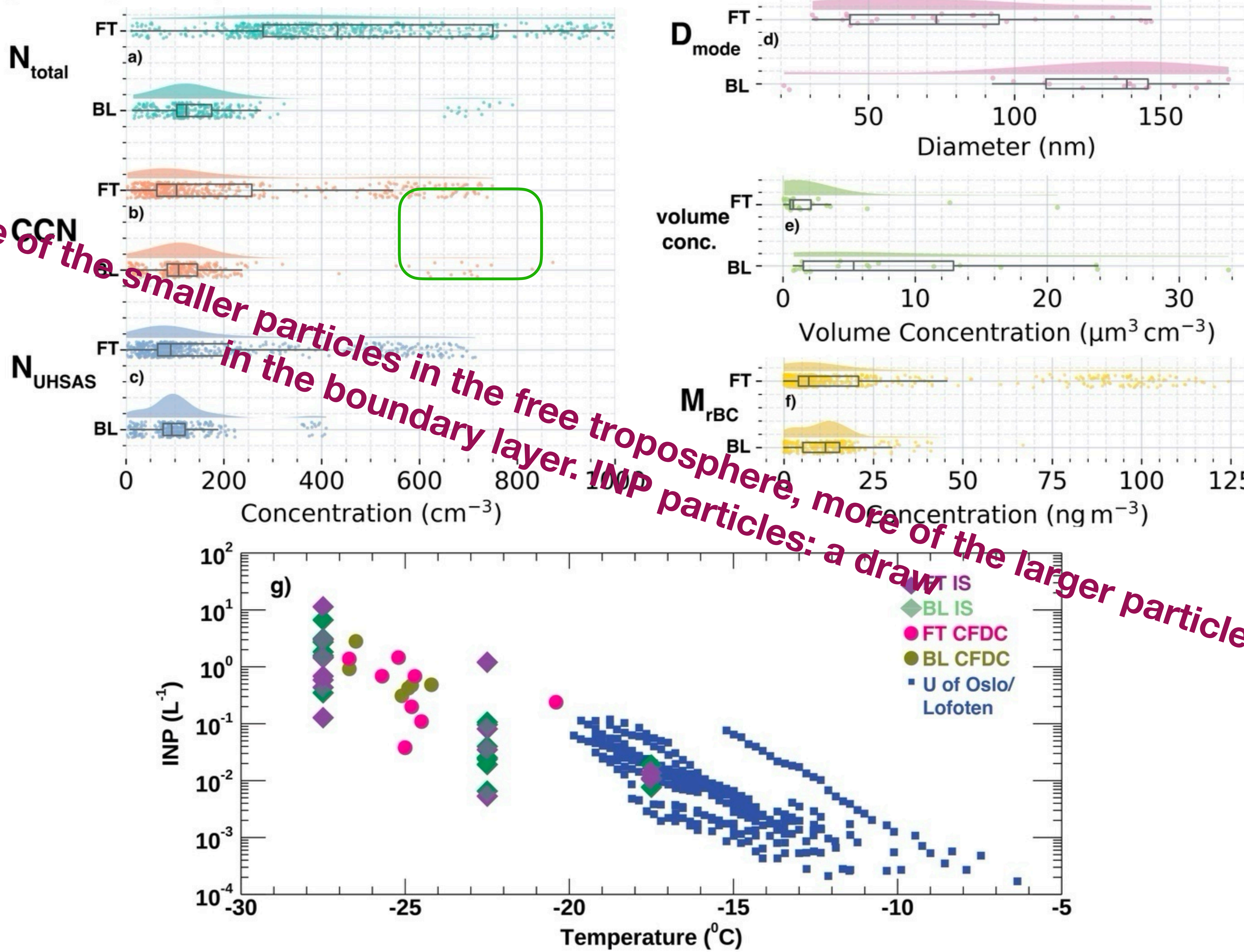
Research Flight (RF)	hours	**Flight Synopsis**
date	dropsondes	(spirals, S; ramps, R; below-cloud leg, BC; above-cloud leg, AC; porpoises, P)
RF01	5.85	**Greenland** marginal ice zone, 71N, 17W endpoint, F1 flight pattern
28 February	12	S-1; R-0; BC-2; AC-1; P-3
RF02	7.13	along+across CAO sampling, **closed-to-open** cell transition
29 February	5	S-5; R-0; BC-3 along wind; AC-4 across wind; P-0
RF04	6.62	warm air intrusion with dust forecast
5 March	5	S-2; R-0; BC-1 across wind; AC-2, 1 along wind; P-0
RF05	5.75	**Greenland** marginal ice zone, 79.6N, 5E endpoint, F1 flight pattern
11 March	18	S-0; R-3; BC-2; AC-2; P-6
RF06	6.37	**quasi-Lagrangian resampling**, south of Svalbard
12 March	9	S-0; R-0; BC-1; AC-2; P-9
RF07	6.6	**Greenland** sea ice, 78N, 10W endpoint, F1 flight pattern
16 March	39	S-1; R-0; BC-4 (1 across wind); AC-5 (1 across wind); P-6
RF09	8.0	coastal **polar low**, modified rosette flight pattern with 5 transects
2 April	17	S-1; R-1; BC-2; AC-3; P-12
RF10	7.55	**local CAO** sampling, 1 young and 1 mature
3 April	9	S-1; R-0; BC-2; AC-5; P-23
Total Flights	53.87 hours	**3 full-fetch, 1 polar low, 1 Q-Lagrangian, 2 local CAO, 1 warm air intrusion**
8	114 sondes	S-11; R-4; BC-17; AC-24; P-62



mixed
anthropogenic
Ozone potentially depleted by
bromine/iodine chemistry
Over sea ice/open water
stratosphere
anthropogenic
CO (ppbv)
160
150
140
130
120
110
100
90
80
40
60
80
100
120
140
Ozone (ppbv)
altitude (km)
6
5
4
3
2
1

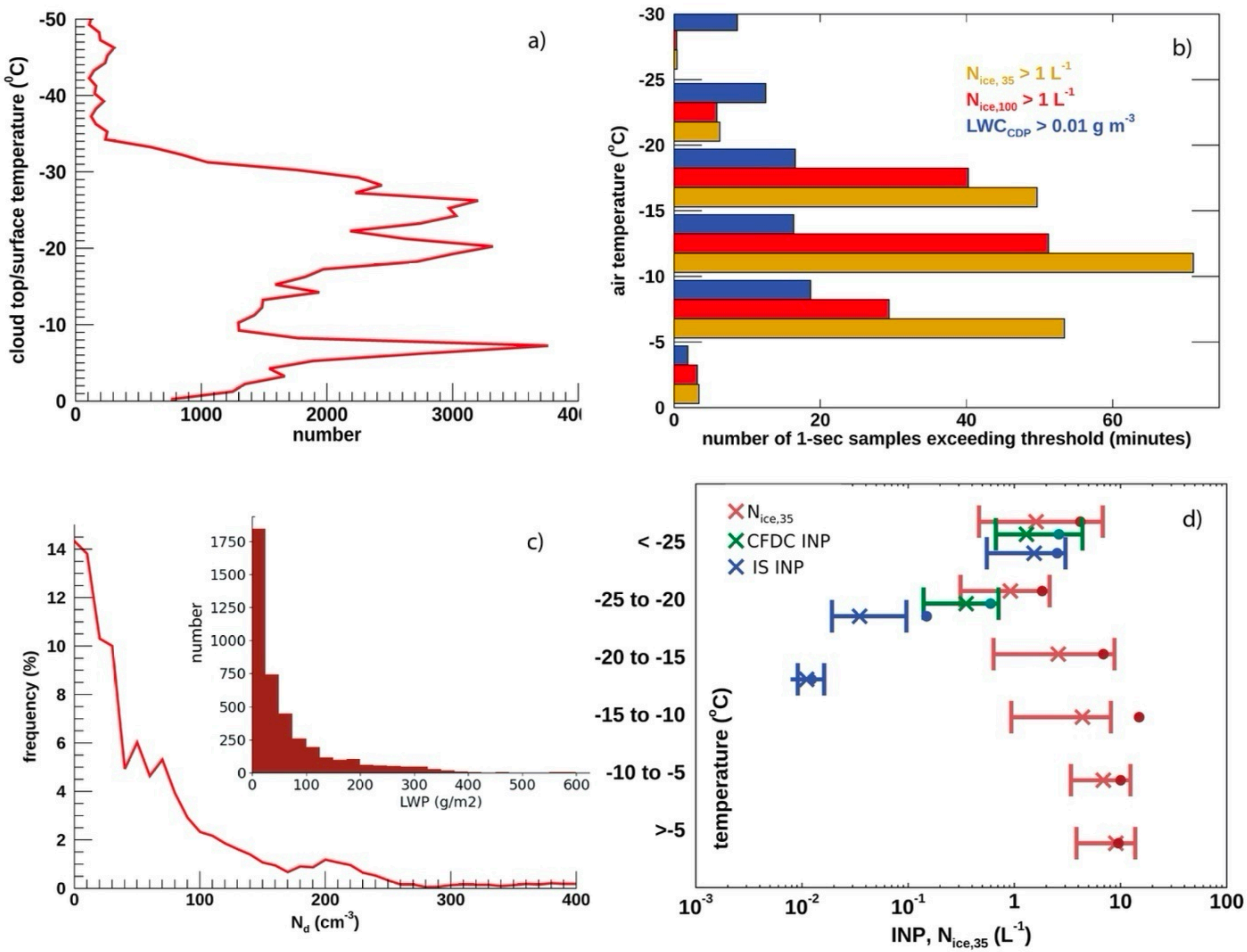
Cai, L., S. Mahant, E. Weissburg, A. Robertson, J. R. Snider, and M. D. Petters, 2026: Observed aerosol properties and aerosol forecast evaluation in the Arctic region during cold air oubreaks. *Atm. Res.*, https://doi.org/10.1016/j.atmosres.2026.108781.

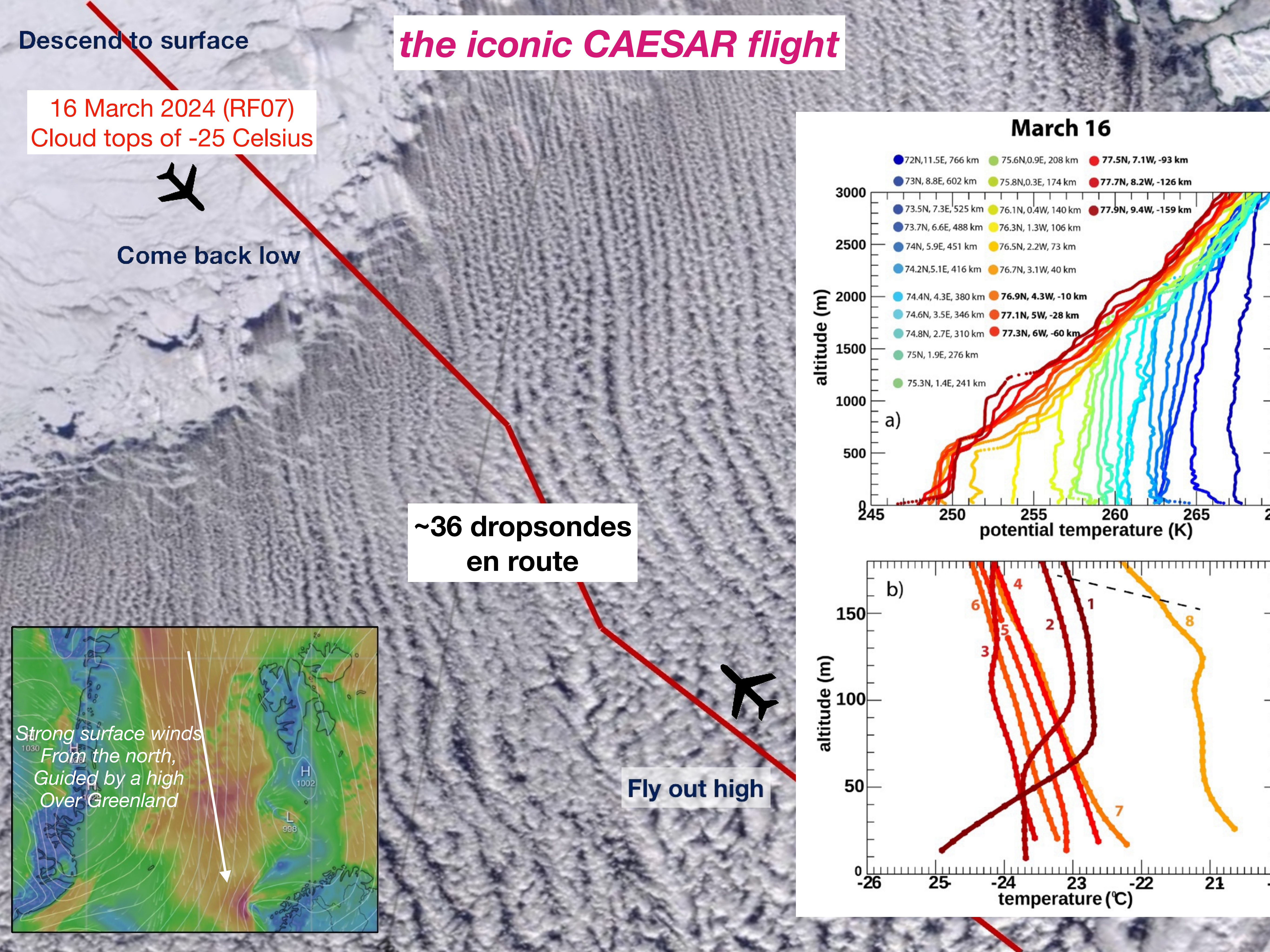
Merged CN,_SMPS+UHSAS+SP2_PCASP



More of the smaller particles in the free troposphere, more of the larger particles in the boundary layer. INP particles: a draw

Clouds tops mostly at -15C to -30C. ice production mostly < 10/L.





the iconic CAESAR flight
Descend to surface
16 March 2024 (RF07)
Cloud tops of -25 Celsius
Come back low
~36 dropsondes
en route
Fly out high
Strong surface winds
From the north,
Guided by a high
Over Greenland
March 16
72N,11.5E, 766 km
73N, 8.8E, 602 km
73.5N, 7.3E, 525 km
73.7N, 6.6E, 488 km
74N, 5.9E, 451 km
74.2N,5.1E, 416 km
74.4N, 4.3E, 380 km
74.6N, 3.5E, 346 km
74.8N, 2.7E, 310 km
75N, 1.9E, 276 km
75.3N, 1.4E, 241 km
75.6N,0.9E, 208 km
75.8N,0.3E, 174 km
76.1N, 0.4W, 140 km
76.3N, 1.3W, 106 km
76.5N, 2.2W, 73 km
76.7N, 3.1W, 40 km
76.9N, 4.3W, -10 km
77.1N, 5W, -28 km
77.3N, 6W, -60 km
77.5N, 7.1W, -93 km
77.7N, 8.2W, -126 km
77.9N, 9.4W, -159 km
a)
altitude (m)
potential temperature (K)
b)
altitude (m)
temperature (°C)