Investigation of Arctic mixed-phase clouds during VERDI and RACEPAC:

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1. Introduction

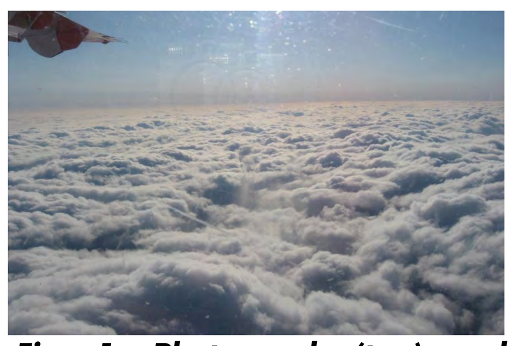
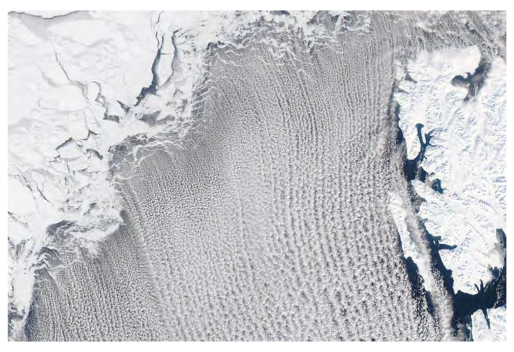


Fig. 1: Photograph (top) and satellite image (bottom, MODIS) of Arctic mixed-phase clouds.



Relevance of Arctic boundary-layer clouds

- Arctic climate most sensitive to climate change
- Arctic clouds play a significant role in the Arctic energy budget
- Variety of formation processes
  - Convection above open water, mixing, radiative cooling
- Variety of microphysical and optical properties
  - Liquid, ice, mixed-phase, ice crystal shape

Why Arctic ?

- Arctic is an ideal test bed for cloud research
- Often no cirrus
- Different situations with open water, sea ice
- No restriction due to commercial air traffic
- Easy coordination of flight pattern

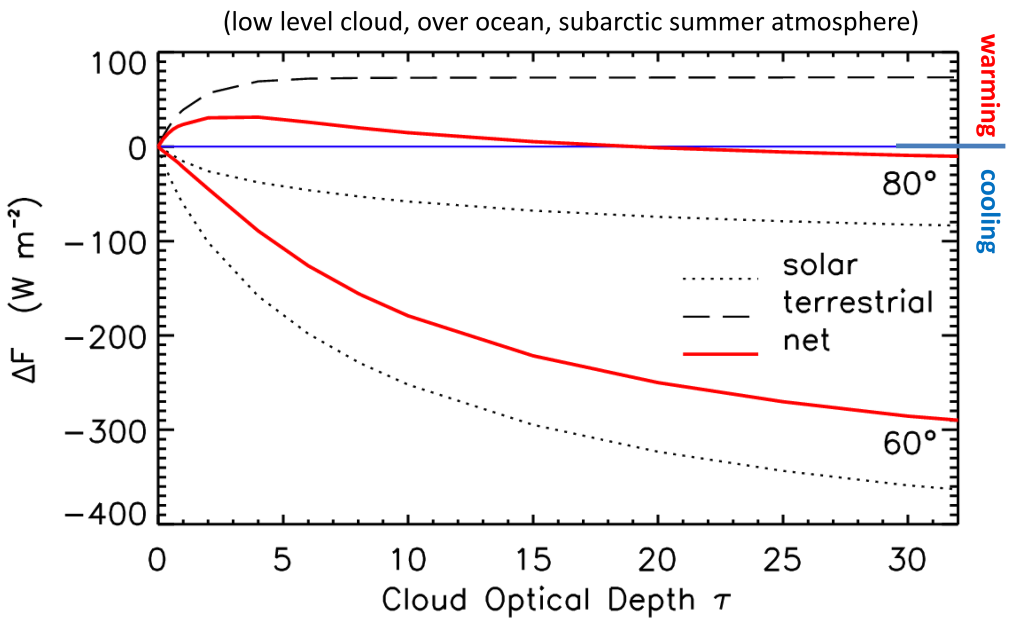


Fig. 2: Cloud radiative forcing at the surface of different optical depth τ and two solar zenith angles. Simulations are done for cloud above open ocean [2].

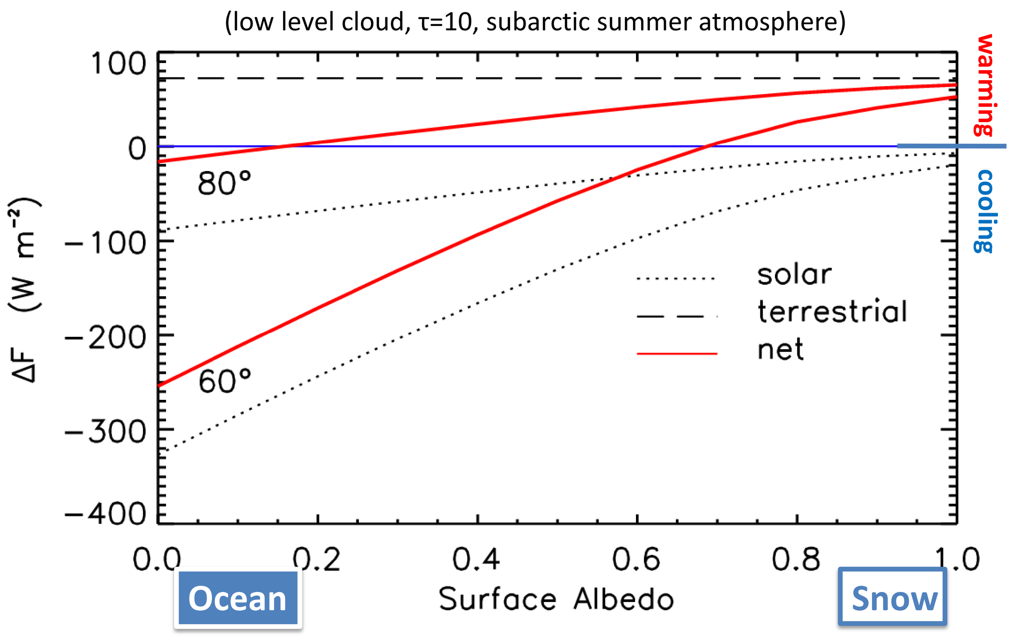


Fig. 3: Cloud radiative forcing at the surface in dependence of surface albedo. Simulations are for a cloud with optical depth of τ=10 and for two different solar zenith angles [2].

2. Airborne Field Campaigns (Inuvik/NWT/Canada)

Study of the Vertical Distribution of Ice in Arctic Clouds (2012)

- 25 April – 17 May, 13 Flights, 49 Flight Hours, 1 Aircraft
- Stable atmospheric conditions, colder temperatures, more sea ice

Radiation–Aerosol–Cloud Experiment in the Arctic Circle (2014)

- 28 April – 23 May, 16 Flights, 88 Flight Hours, 2 Aircraft
- Frequent frontal activity, warmer temperatures, less sea ice

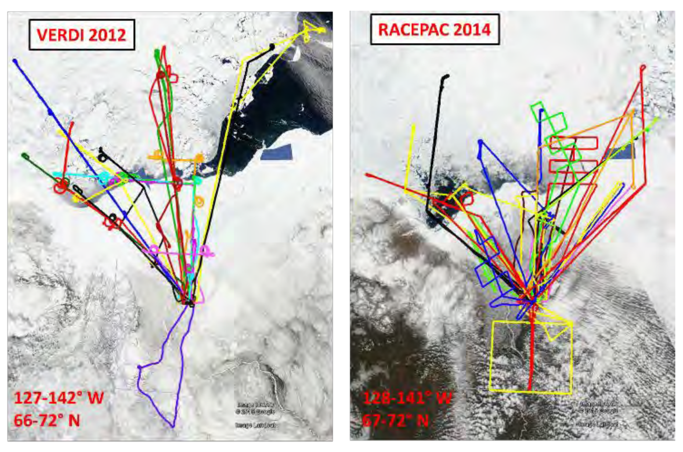


Fig. 4: Flight tracks of VERDI and RACEPAC.

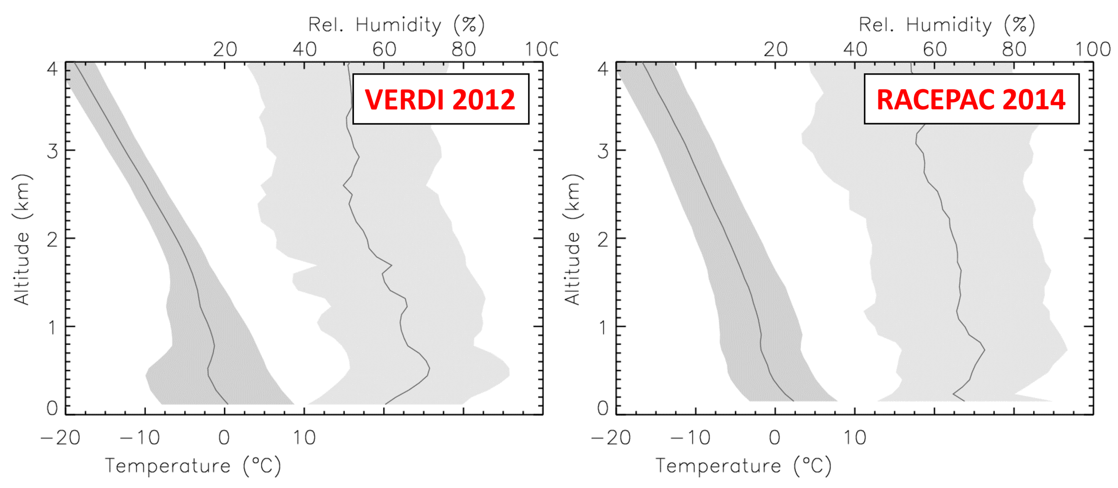


Fig. 5: Mean radio soundings for the period 25 April—24 May during VERDI (left) and RACEPAC (right).

Instrumentation

- Polar 5 and 6 (Basler BT 67) operated and funded by Alfred-Wegener Institute for Polar and Marine Research

Polar 6 = In Situ

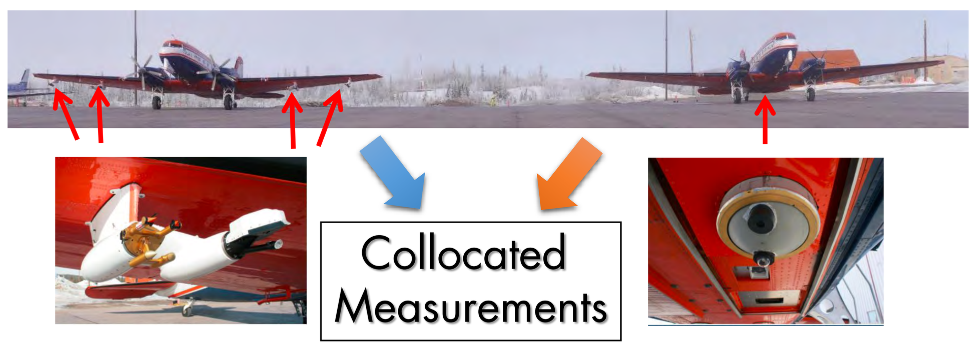
- Cloud particle sampling
- Aerosol particles
- Trace gas CO/CO2

Polar 5 = Remote Sensing

- Cloud radiative properties
- Horizontal variablity
- Vertical variability

Tab. 1: Instrumentation of Polar 5 and 6 during VERDI and RACEPAC.

	VERDI	RACEPAC	
	P5	P5	P6
Standard Meteorology (wind vector, p, T, rH)	x	x	x
Drop Sondes (wind vector, p, T, rH)	x	x	
Cloud Microphysics I (NIXE-CAPS, SID-3, CCP, CAS-DPOL, **PIP)**	x		x
Cloud Microphysics II (Polar Nephelometer, HALO-HOLO, PHIPS)			x
Aerosol Mass Spectrometer (ALABAMA, CToF-AMS)	x		x
Aerosol Sensors (OPC, CPC, UHSAS, SP2)			x
Trace Gas CO/CO_2			x
SMART Albedometer (spectral albedo and reflectivity)	x		x
AISA-Eagle (spectral imaging)	x		x
Digital Camera (180° Fisheye)	x		x
Airborne Mobile Lidar (AMALi)	x		x
Sun Photometer	x		x



Flight strategy

- Cloud and atmosphere sampling combined by remote sensing (500 ft to 10.000 ft)
- **RACEPAC:** collocated measurements with <200 m horizontal displacement (<5min in time, for safety reasons)
- Coordination of A-Train overpasses

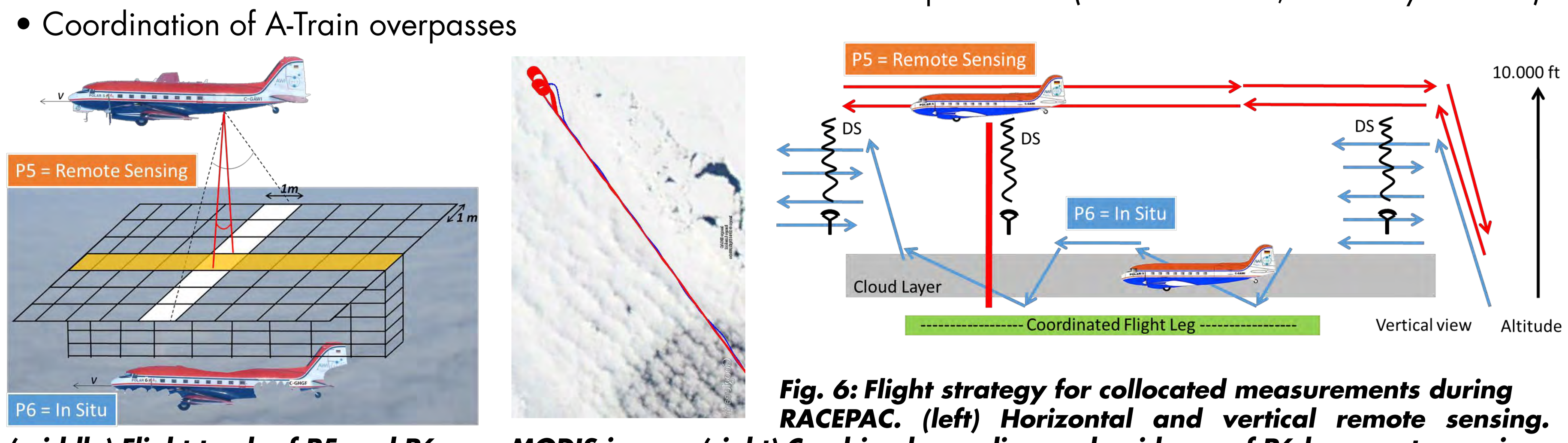


Fig. 6: Flight strategy for collocated measurements during RACEPAC. (left) Horizontal and vertical remote sensing. (middle) Flight track of P5 and P6 on a MODIS image. (right) Combined sampling and guidance of P6 by remote sensing.

A-Train satellite overpass

- 20 May 2014, 21:00 UTC (only Polar 5)
- 45 min / 80 NM along track, 4 cross track legs à 25 NM

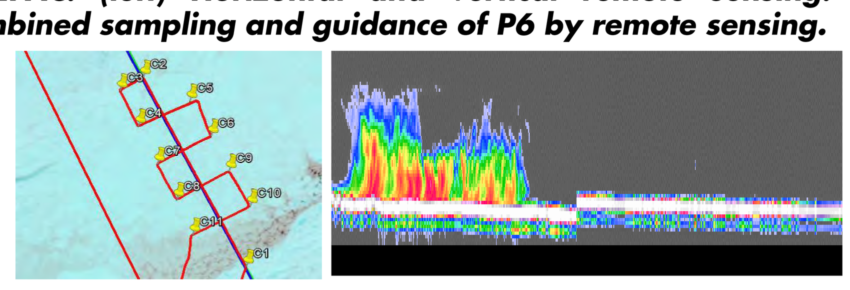
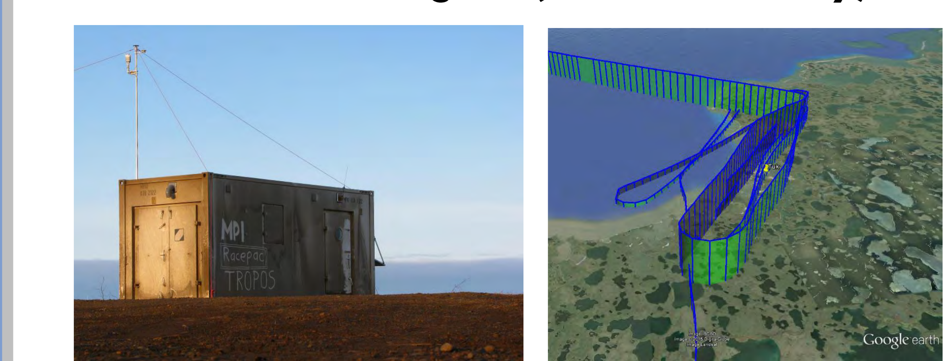


Fig. 7: Flight track and CloudSat profile on 20. May 2014.

Overflights of ground station at Tuktoyaktuk

- Aerosol sampling, 29 April – 17 May
- Cloud condensation nuclei, DMT CCNc, CPCs,
- Black carbon, MAAP, SP2
- Automatic weather station
- **4 low level overflights (3/6/11/13 May)**



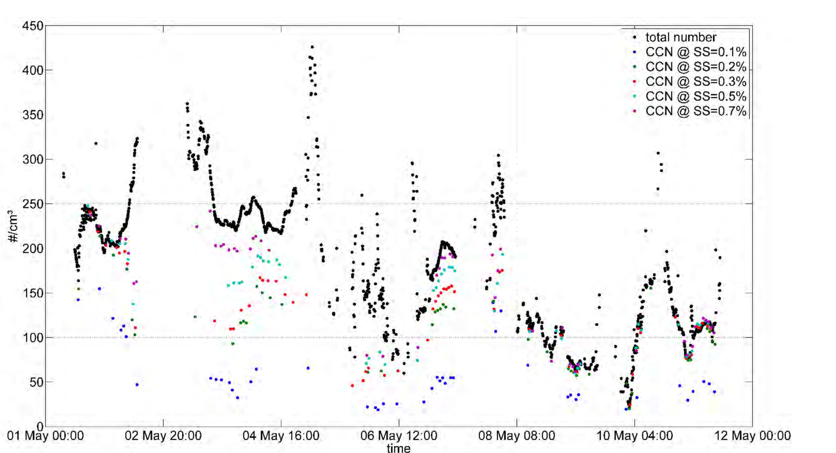


Fig. 8: Left: Image and flight track over Ground station in Tuktoyaktuk. Top: total aerosol particle number concentration and CCN concentration measured at different supersaturation.

3. Some Highlights

In situ cloud particle probing

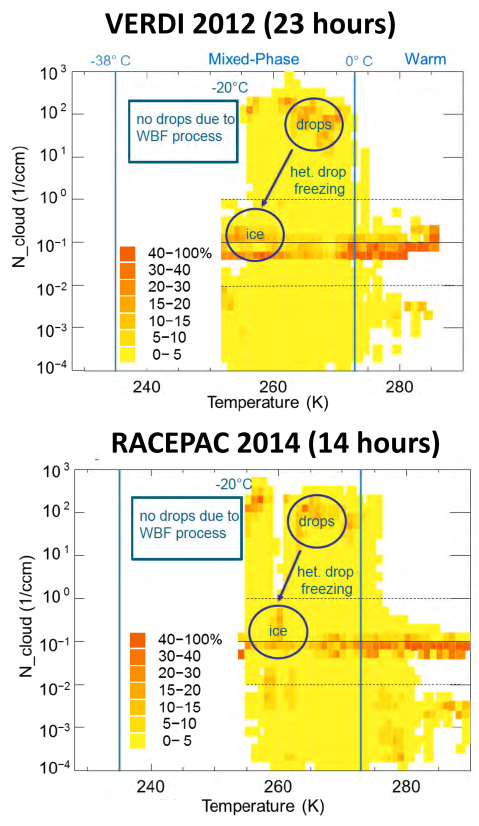


Fig. 9: Nixe-CAPS total particle concentration (3-937 µm).

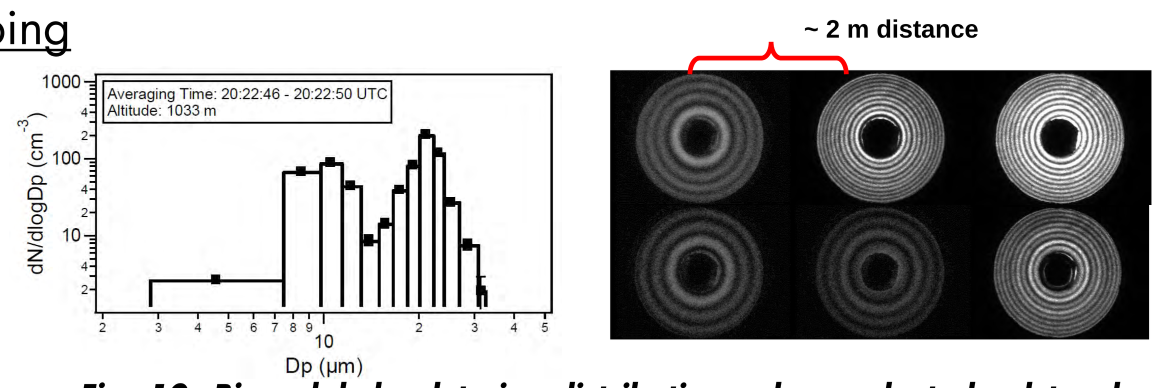


Fig. 10: Bi-modal droplet size distributions observed at cloud top by CDP (left) and SID-3 (right), see [1].

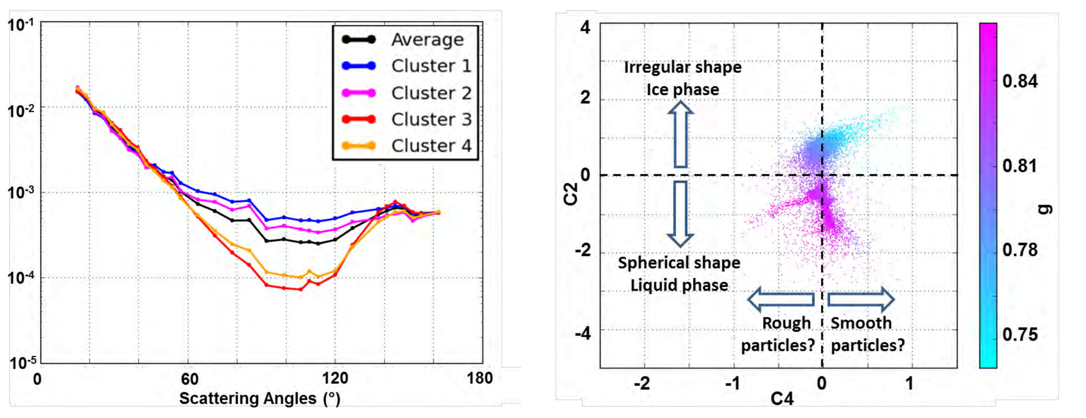


Fig. 11: Clustering of scattering phase functions (left) observed by the Polar Nephelometer. Asymmetry parameter as function of PCA parameters (right).

- Set of 5 (VERDI) and 6 (RACEPAC) particle probes
- Cover sizes from 0.6 µm up to 6.4 mm
- Directional scattering (SID-3,PN, PHIPS)
- Imaging and holography

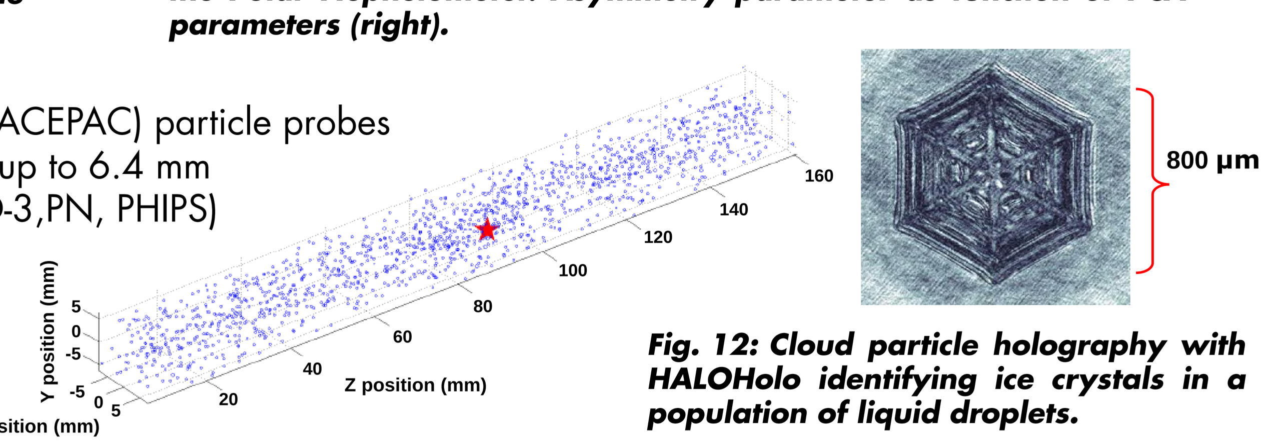


Fig. 12: Cloud particle holography with HALOHolo identifying ice crystals in a population of liquid droplets.

Aerosol Characterization

Trace Gas Sampling

- Sensors for particle concentrations, sizes and chemical composition and trace gas CO/CO_2
- High concentrations in upper altitudes suggest long range transport

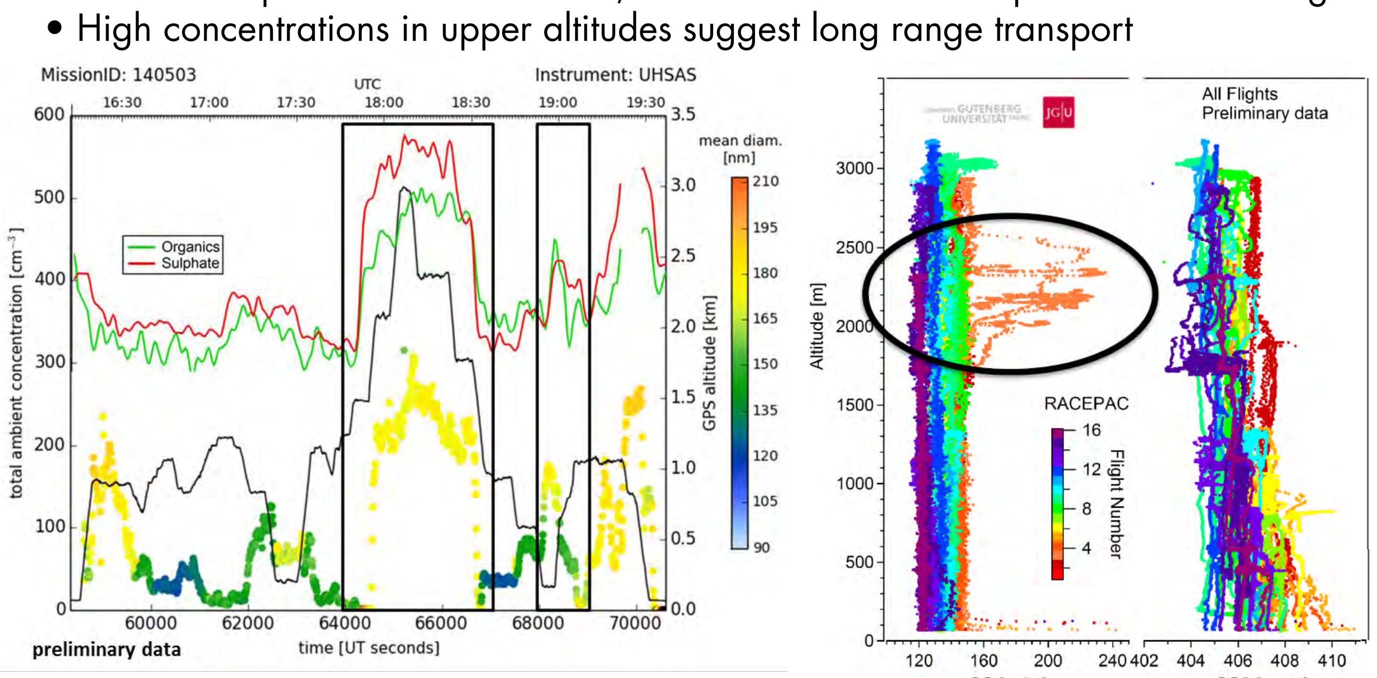
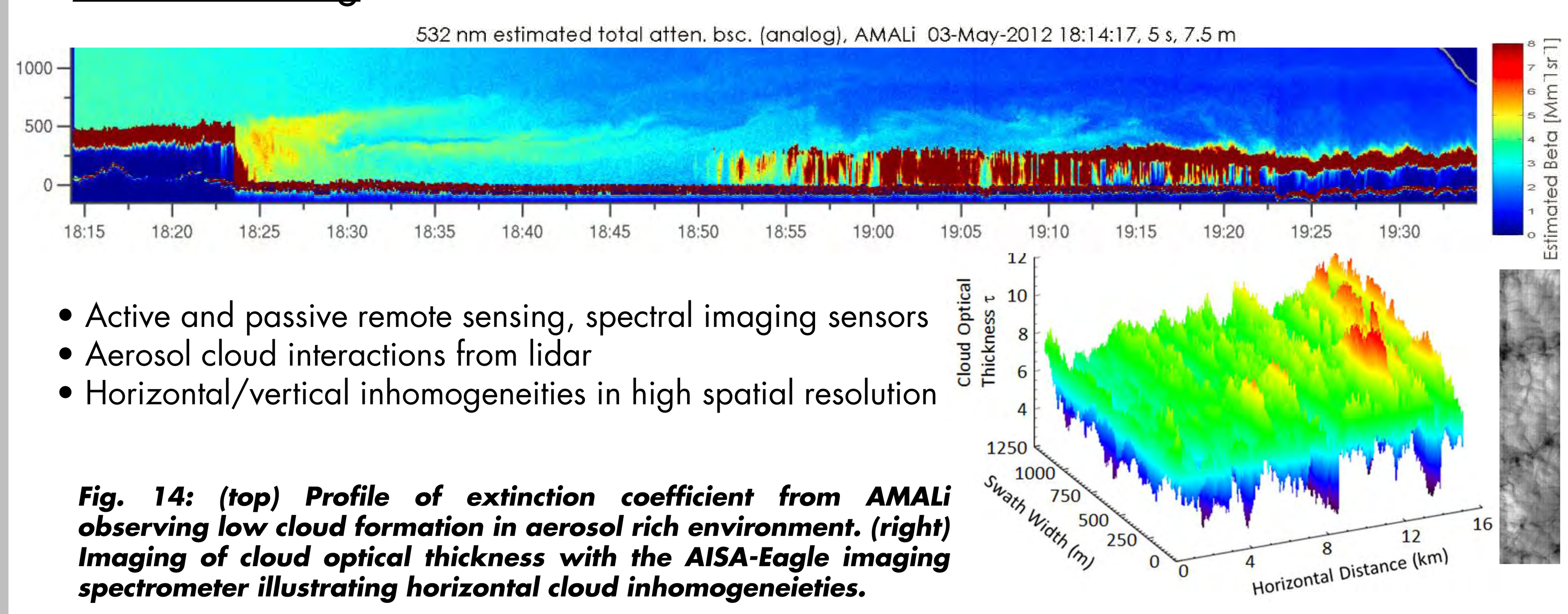


Fig. 13: (left) Aerosol characterization in terms of concentration, size and chemical composition by CToF-AMS, UHSAS, SP2.

(Right) Profiles of CO, CO_2 concentration of all flights during RACEPAC.

Remote Sensing



- Active and passive remote sensing, spectral imaging sensors
- Aerosol cloud interactions from lidar
- Horizontal/vertical inhomogeneities in high spatial resolution

Fig. 14: (top) Profile of extinction coefficient from AMALi observing low cloud formation in aerosol rich environment. (right) Imaging of cloud optical thickness with the AISA-Eagle imaging spectrometer illustrating horizontal cloud inhomogeneities.

4. Modeling Activities

- DSN, direct numerical simulation (MPI Hamburg, lower Figure)
- COSMO- ART used as an LES model (KIT, right Figure)

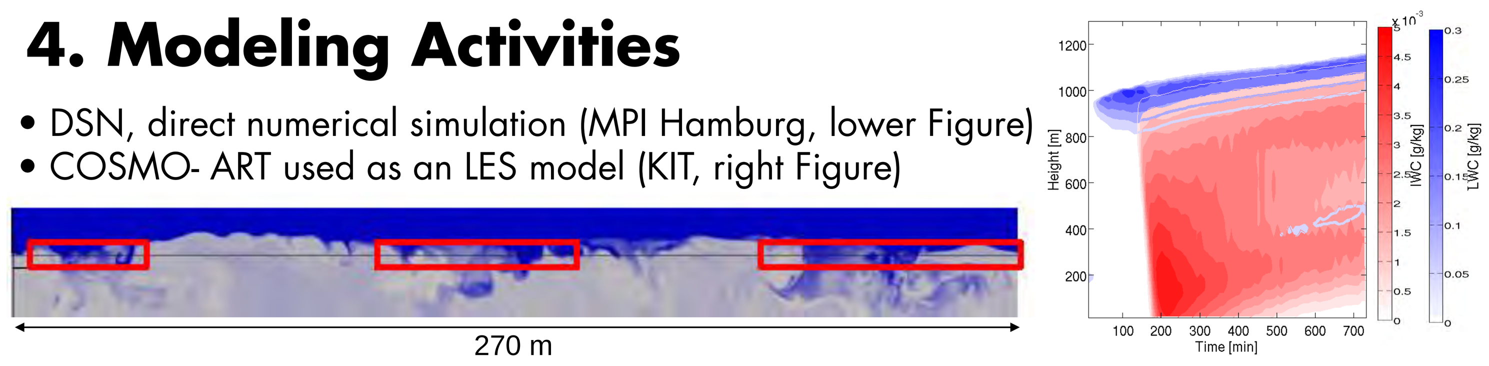


Fig. 15: Cloud liquid and ice water from DNS (left) and LES (right) simulations.

[1] Klingebiel, M., de Lozar, A., Molleker, S., Weigel, R., Roth, A., Schmidt, L., Meyer, J., Ehrlich, A., Neuber, R., Wendisch, M., and Borrmann, S.: Arctic low-level boundary layer clouds: in situ measurements and simulations of mono- and bimodal supercooled droplet size distributions at the top layer of liquid phase clouds, Atmos. Chem. Phys., 15, 617-631, 2015.
[2] Wendisch, M., Yang, P., and Ehrlich, A., eds.: Amplified climate changes in the Arctic: Role of clouds and atmospheric radiation, vol. 132 (3), 1-34, Sitzungsberichte der Sächsischen Akademie der Wissenschaften zu Leipzig. Mathematisch-Naturwissenschaftliche Klasse, S. Hirzel Verlag, Stuttgart/Leipzig, 2013

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