Retrieval of snow layer and melt pond properties from airborne imaging spectrometer observations

HS6.6
PICO4.9

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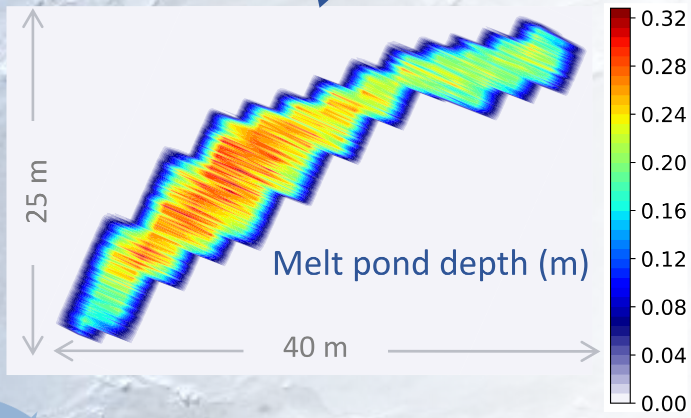
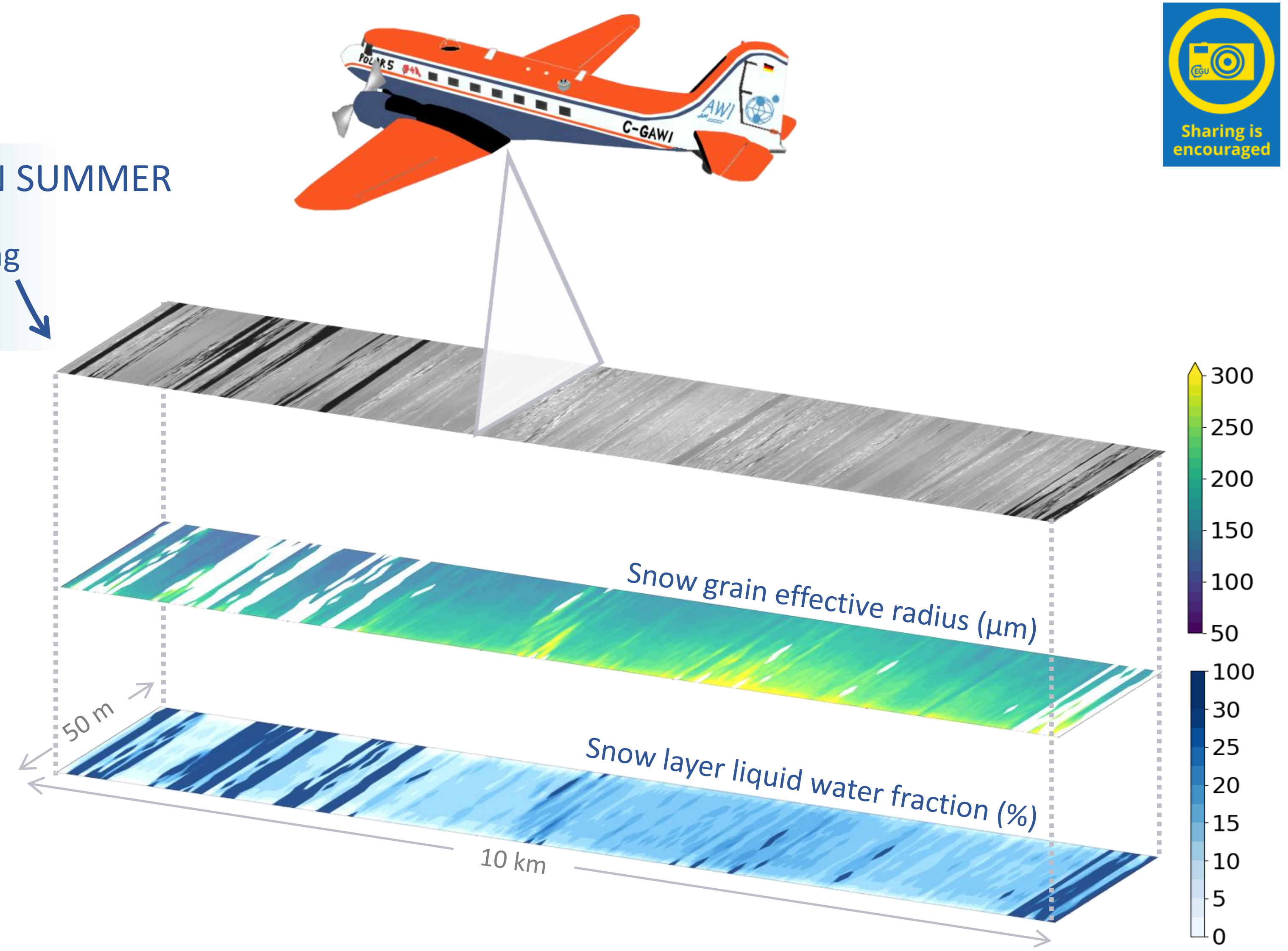
ARCTIC SEA ICE SURFACE IN SUMMER

Snow metamorphism & melting

Melt pond formation





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Retrieval of snow layer and melt pond properties from airborne imaging spectrometer observations

OVERVIEW

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Abstract

NAVIGATION

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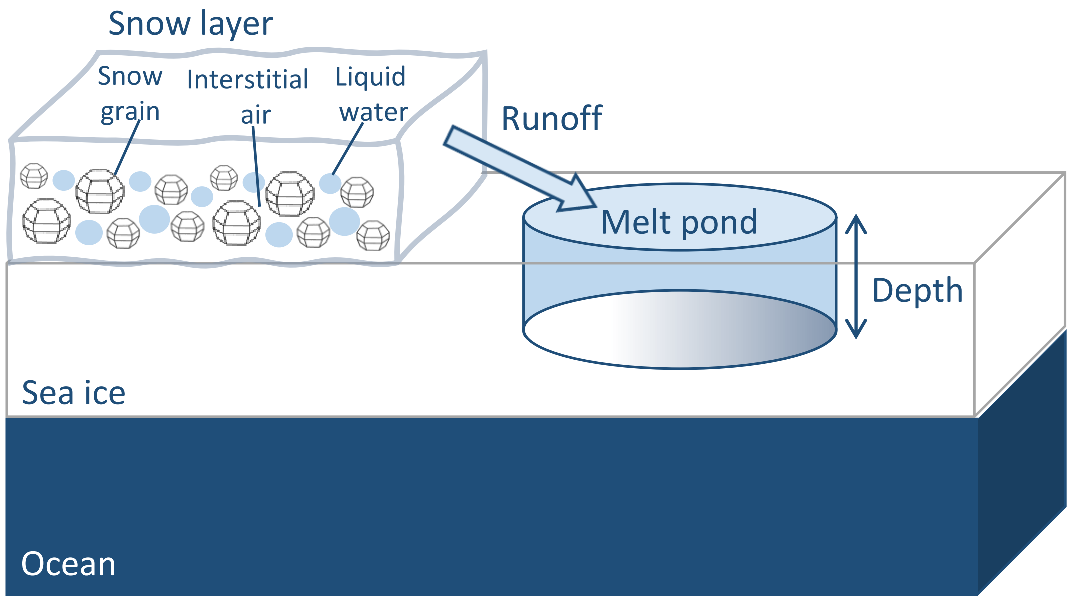
first slide

Motivation and basics

Arctic surface albedo decrease
with melting progress

I. SNOW MELTING II. PONDING



MEASUREMENT

Reflectance

$$\mathcal{R}_\lambda = \frac{\pi \cdot I_\lambda^{\uparrow}}{F_\lambda^{\downarrow}}\ \mathrm{sr}$$

upward radiance $I_\lambda^{\uparrow}$ (W m^{-2} nm^{-1} sr^{-1})
downward irradiance $F_\lambda^{\downarrow}$ (W m^{-2} nm^{-1})

RETRIEVAL

Snow layer liquid water fraction

$$f_{\mathrm{LW}} = \frac{\mathrm{LWC}}{\mathrm{TWC}}$$

liquid water content LWC (g m^{-3})
total water content TWC (g m^{-3})

Effective snow grain radius

$$r_{\mathrm{eff}} = \frac{3}{4}\frac{\int_{L_{\min}}^{L_{\max}} V(L)\cdot n(L)\,\mathrm{d}L}{\int_{L_{\min}}^{L_{\max}} A(L)\cdot n(L)\,\mathrm{d}L}$$

gamma size distribution n
max. dimension L (m)
effective area A (m^2)
and volume V (m^3)

Melt pond depth

z (m)

Measurements

Arctic CLoud Observations Using airborne measurements during polar Day (ACLOUD)[1,2]

23 May – 26 June 2017

Research aircraft *Polar 5* (AWI)[3]

- Upward radiance

  Spectral imaging spectrometers

  AisaEagle λ = 400 – 990 nm

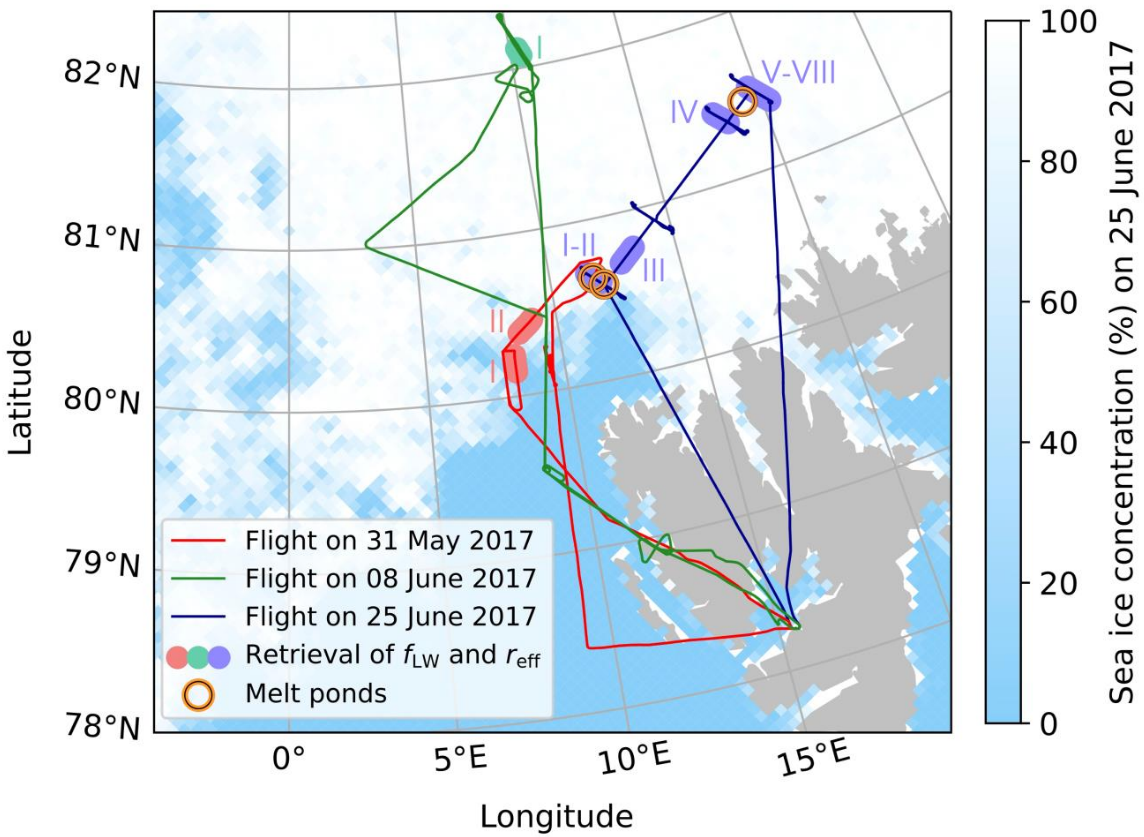
  AisaHawk λ = 940 – 2500 nm

- Downward irradiance

  SMART albedometer λ = 400 – 2150 nm

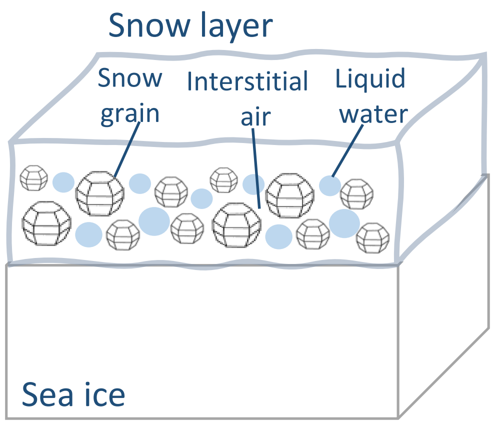
→ Only cloud-free atmospheric conditions regarded to simplify radiative transfer simulations and retrievals

Highlighted retrieval areas along 3 flight tracks



[1]Wendisch et al. (2019), [2]Ehrlich et al. (2019), [3]Wesche et al. (2016)

SIMULATIONS



Ice crystal

droxtal shape

Liquid water spheres

YANG-TABLES[1]

MIE-TOOL[2]

Gamma size distribution → Scattering properties

- Phase function
- Single scattering albedo
- Extinction coefficient

Simulation of snow layer reflectance spectra with *libRadtran*[2,3]

with

r_{eff} **= 50 – 800 µm (step: 50 µm)**

f_{LW} **= 0 – 30 % (step: 2.5 %)**

for selected flight sections

- Aircraft altitude & heading
- Solar azimuth & zenith angle
- Radiosonde profiles

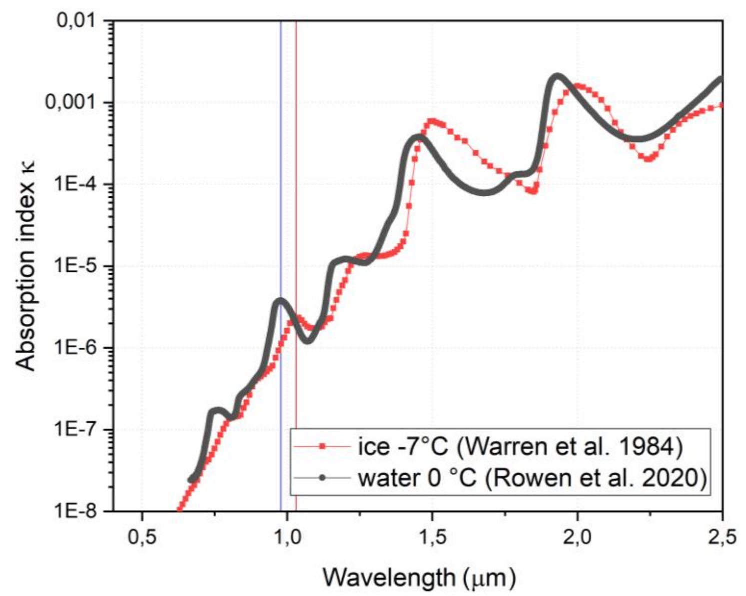
(Aircraft altitude & heading and solar azimuth & zenith angle: temporally averaged)

[1]Yang et al. (2000) , [2]Mayer et al. (2019), [3]Emde et al. (2016)

Retrieval of snow layer properties

THEORY

Spectrally shifted absorption maxima of liquid water and ice



Snow layer reflectance spectrum sensitive to

- Liquid water fraction f_{LW}
- Effective radius r_{eff}

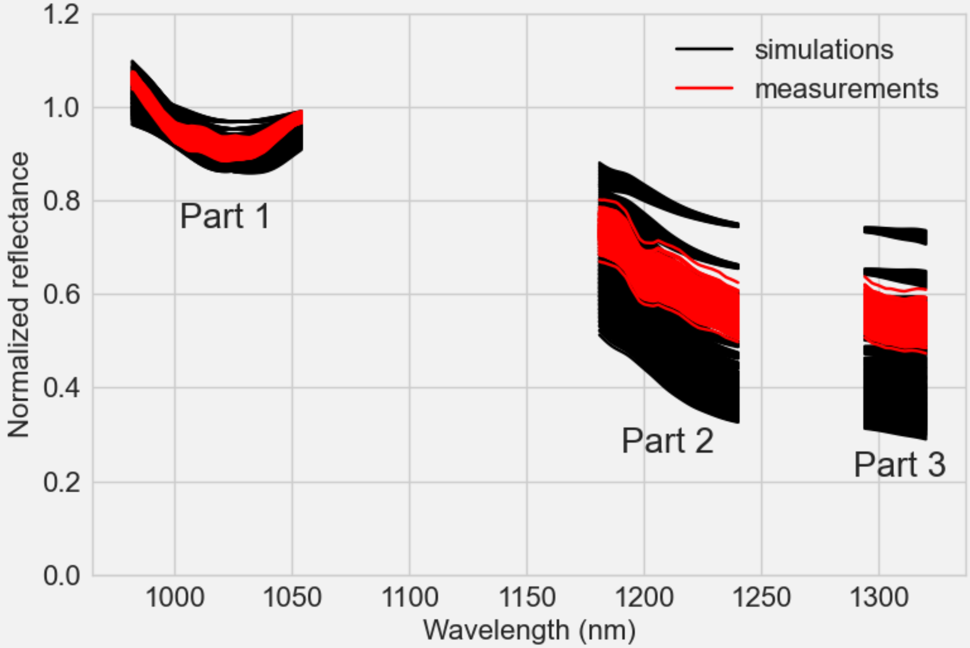
APPROACH

Simulations (*libRadtran*)
Snow layer reflectance spectra for varying f_{LW} and r_{eff}

Airborne measurements

COMPARISON

(Least square fit)

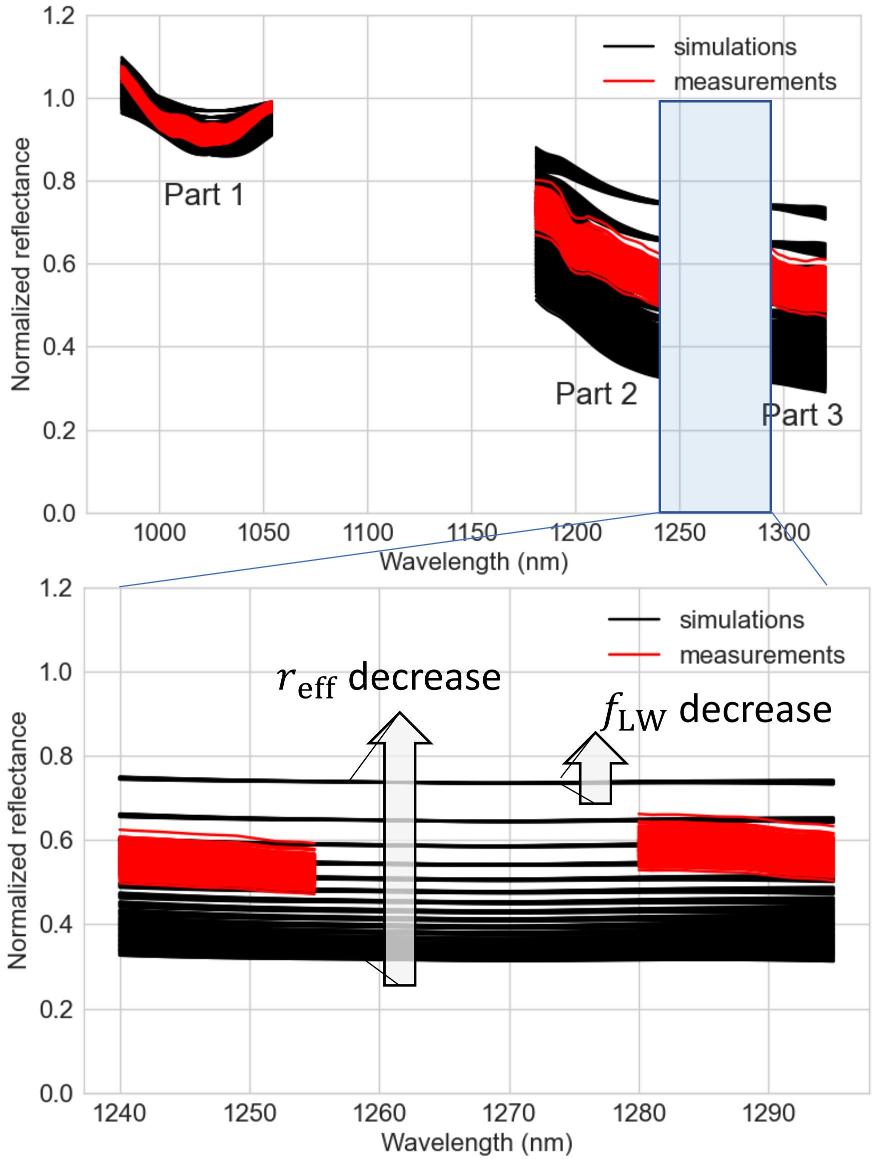


Retrieval of f_{LW} (Part 1) and r_{eff} (Part 1-3)

Adapted approach of Green et al. (2002), Donahue et al. (2022)

Retrieval of snow layer properties

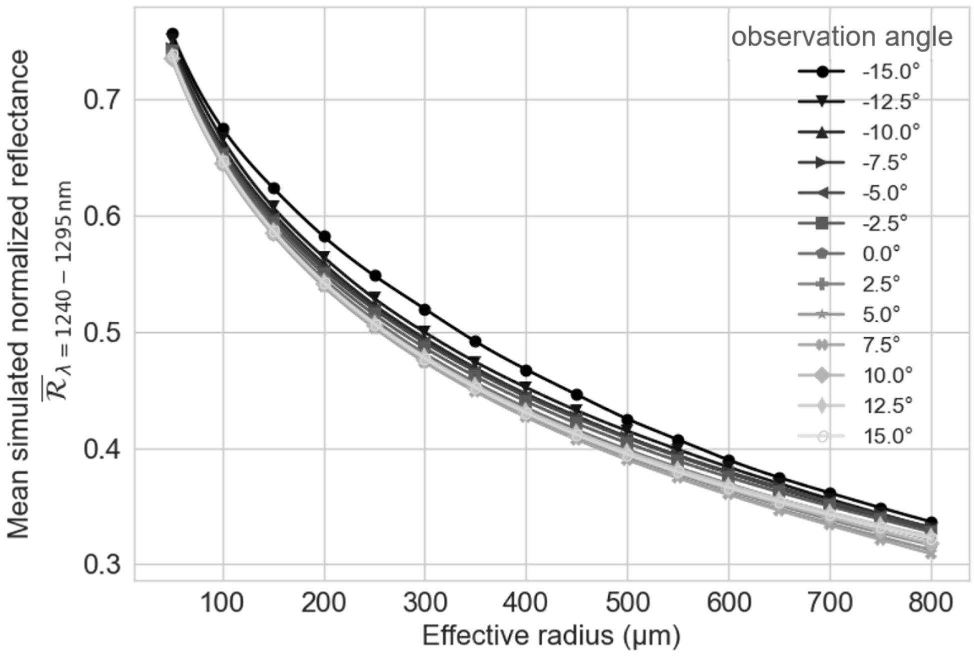
APPROACH → spectral independence of f_{LW}



λ = 1240 – 1295 nm isolated dependence on r_{eff}

Averaging over all f_{LW} and wavelength interval

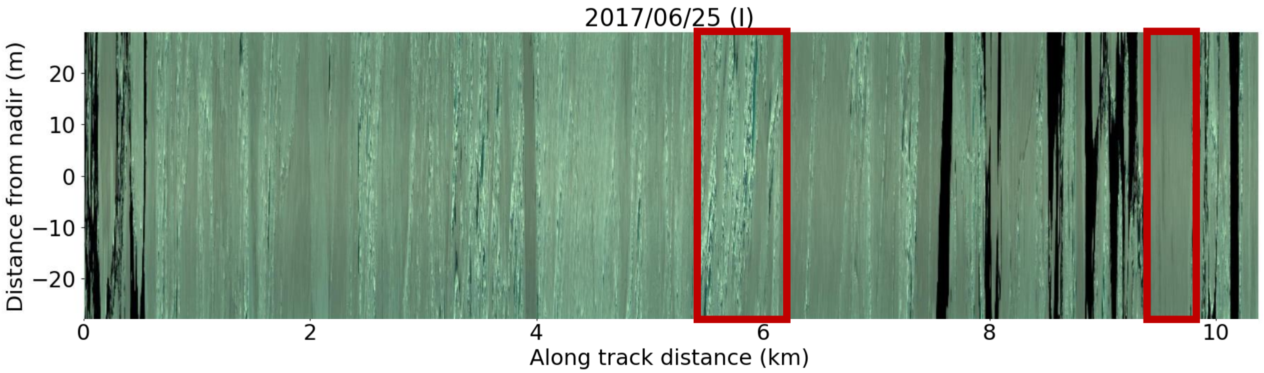
REFERENCE CURVE for r_{eff}-retrieval



Retrieval of snow layer properties

RESULTS

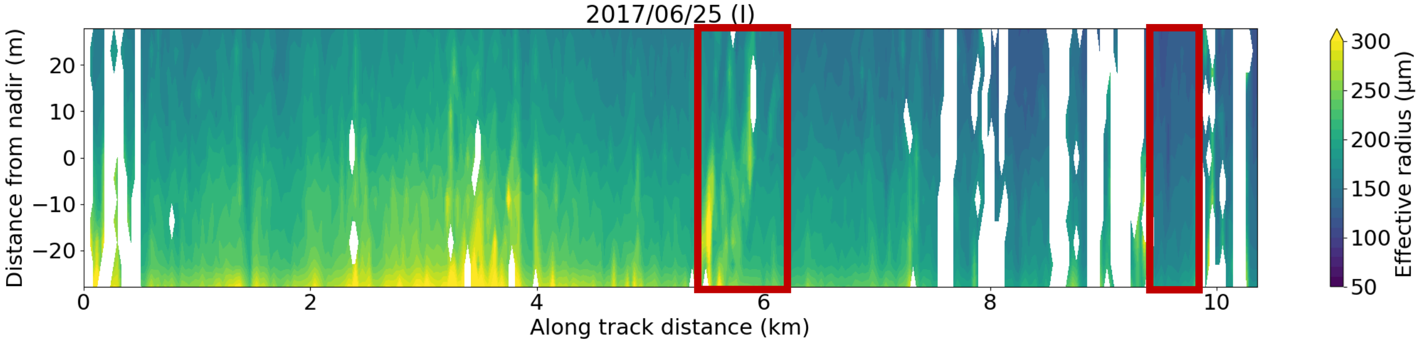
AisaEagle
RGB composite

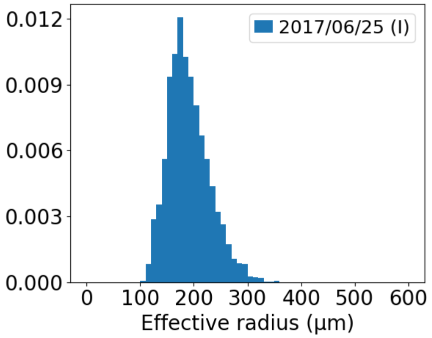


left: pressure ridges and melt ponds
right: homogeneous snow surface

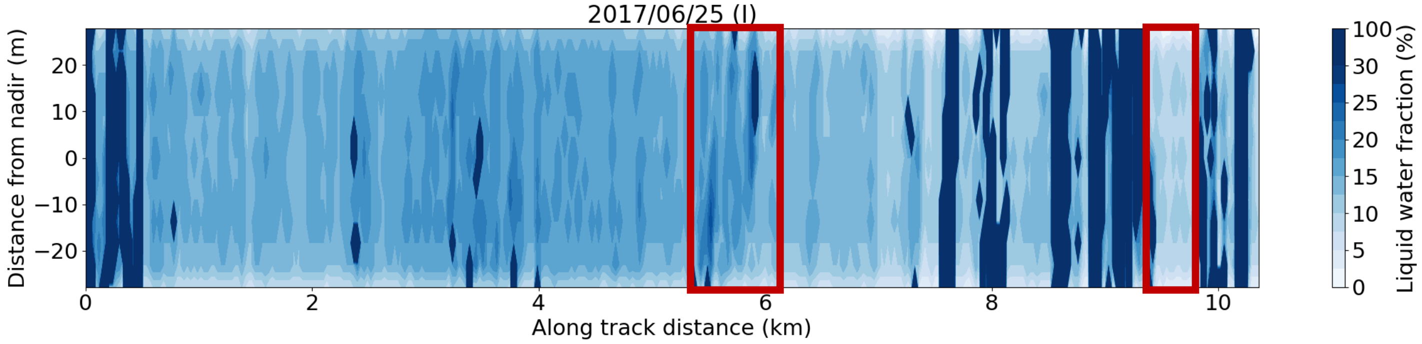
Frequency distribution

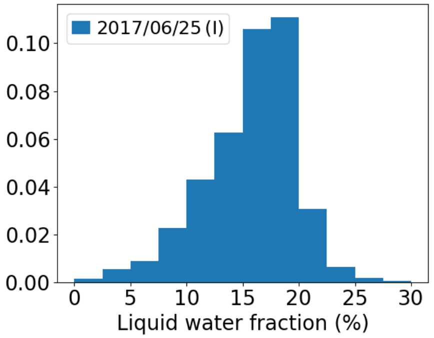
r_{eff}-map

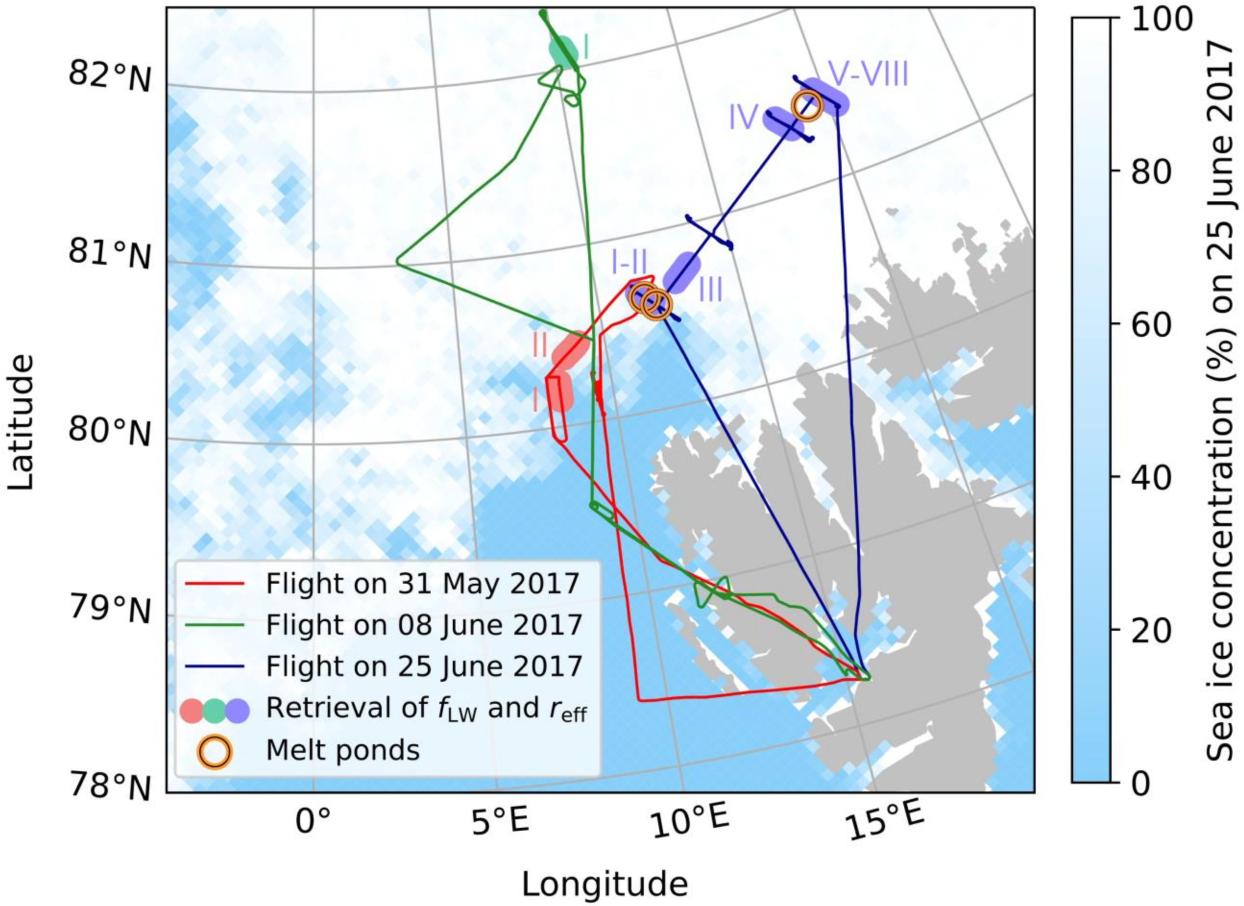




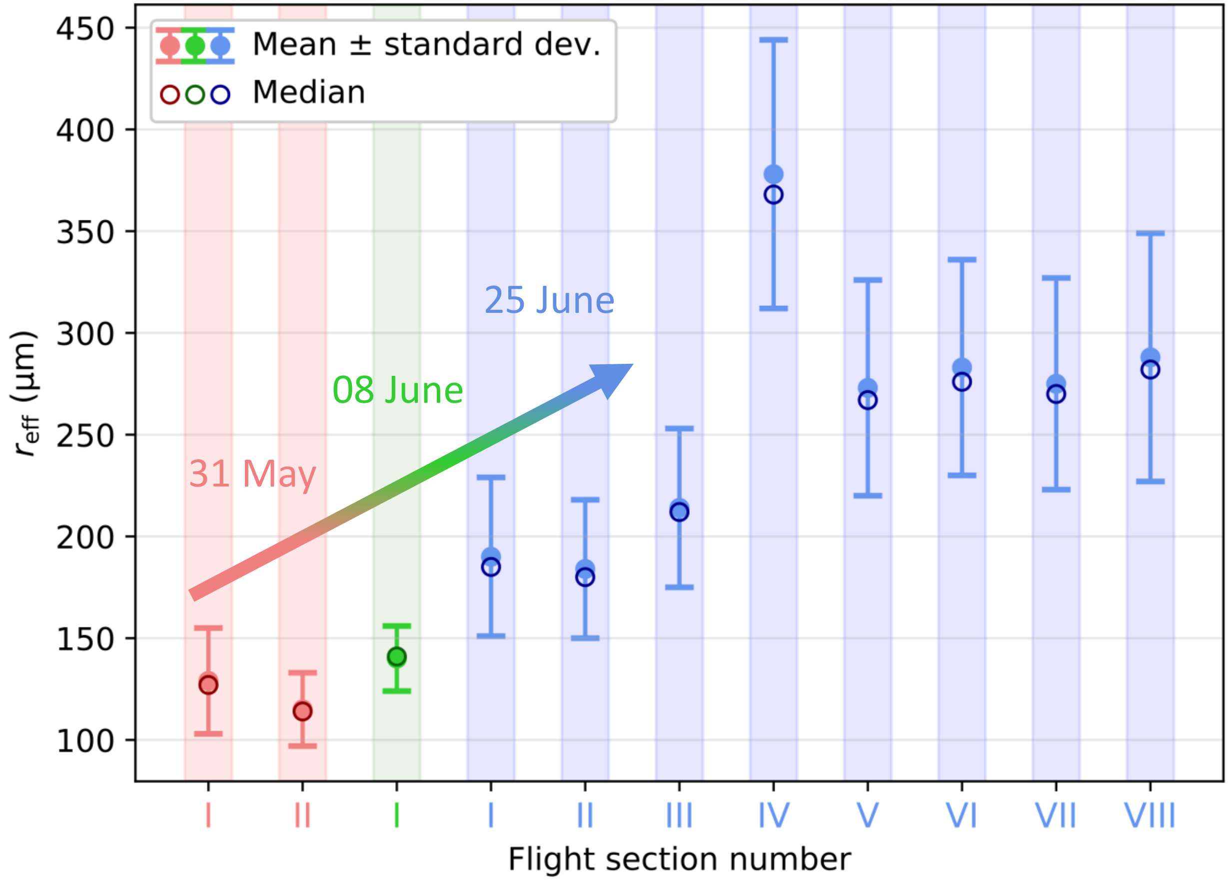
f_{LW}-map







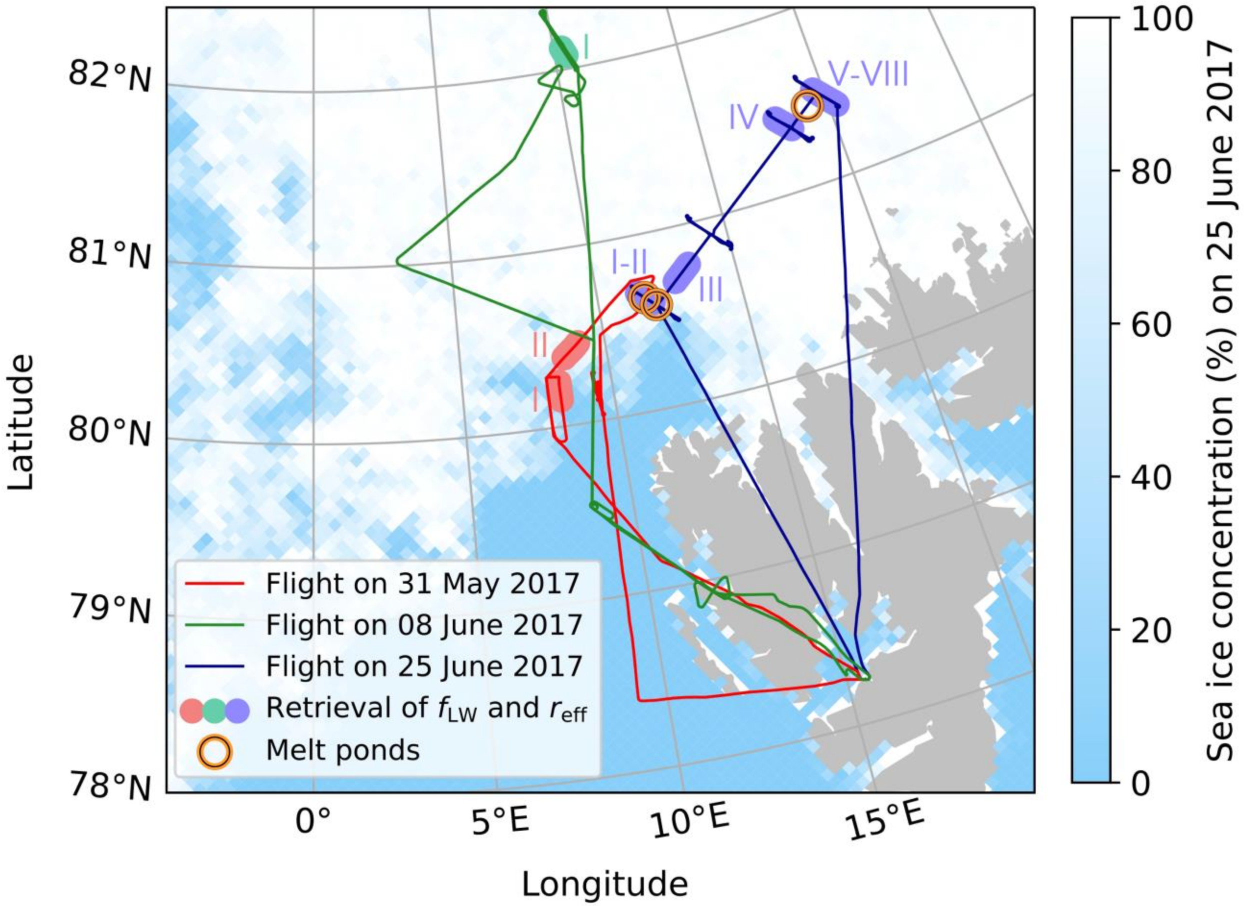
Temporal and regional variability of r_{eff}



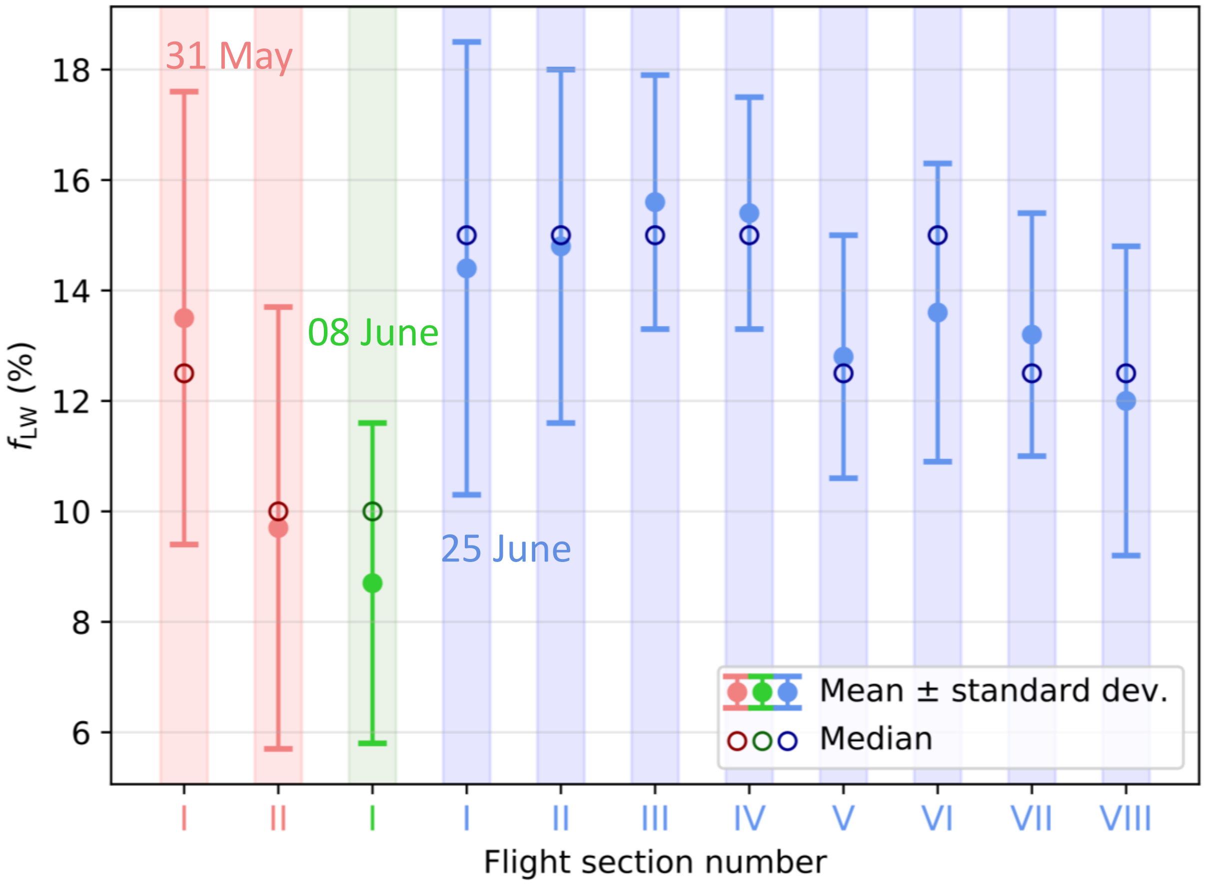
→ Overall, temporally increasing r_{eff} (snow metamorphism) but also local effects!

Retrieval of snow layer properties

RESULTS



Temporal and regional variability of f_{LW}



→ f_{LW} is strongly depending on geographical location → masked seasonal effects

Retrieval of melt pond depth

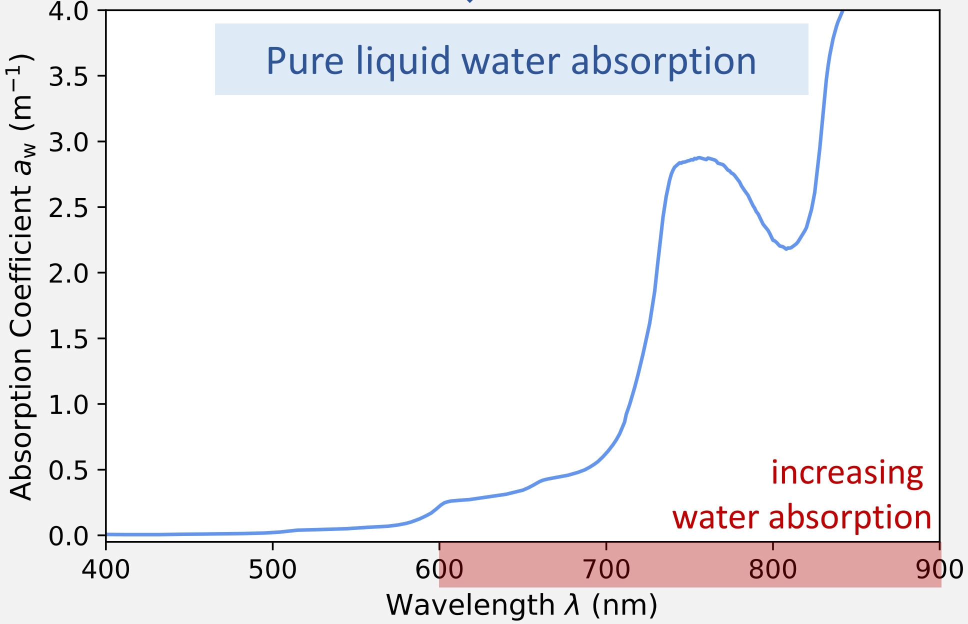
APPROACH

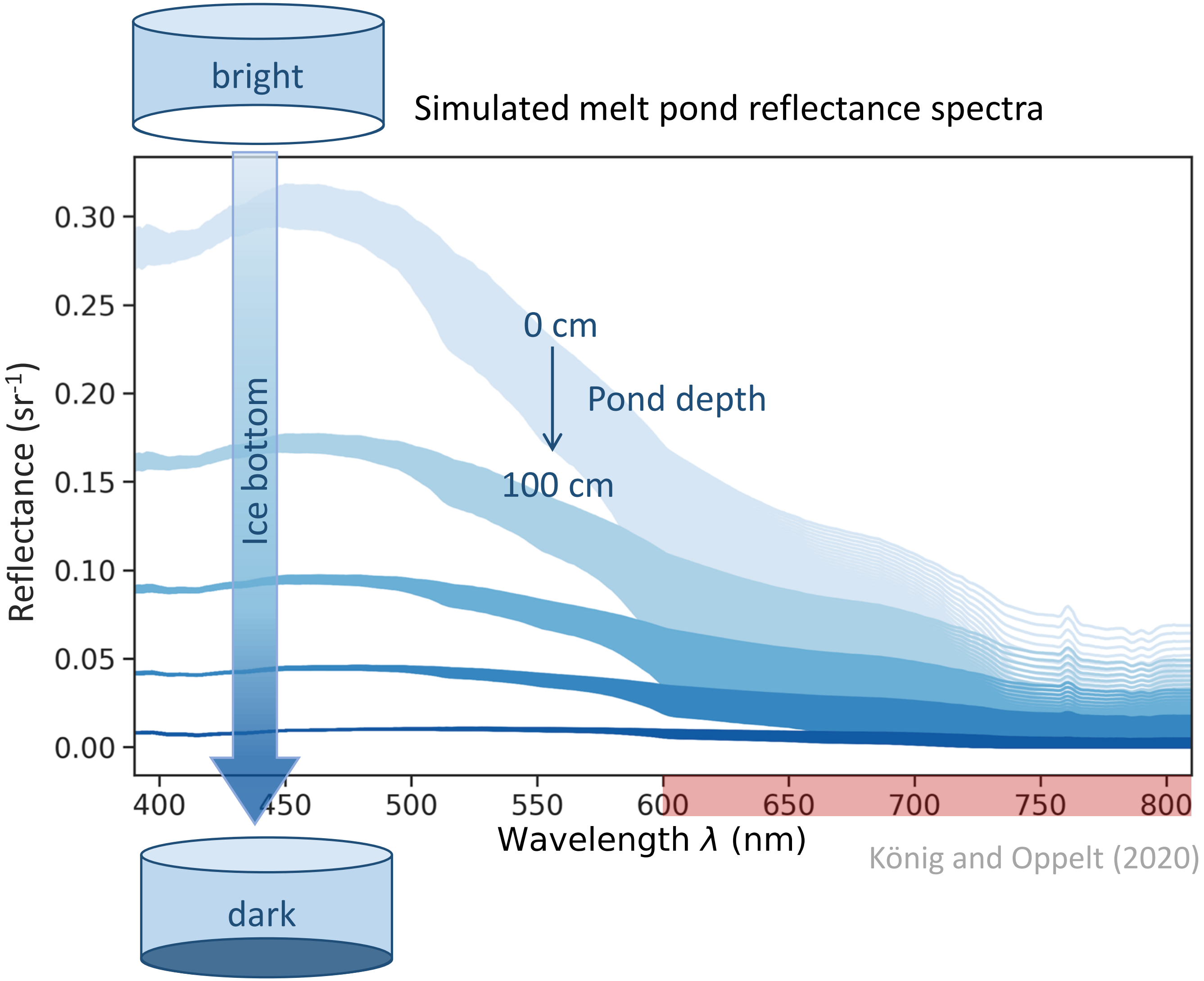
THEORY

Melt pond reflectance depending on

→ Ice bottom reflectance

→ Melt pond depth





Approach by König and Oppelt (2020)

Retrieval of melt pond depth

APPROACH

AIM

Finding reflectance property widely independent of the ice bottom reflectance

Linear model

by König and Oppelt (2020)

$$z = a(\theta_{\text{Sun}}) + b(\theta_{\text{Sun}}) \left[\frac{\partial \log(\mathcal{R}_\lambda \cdot \pi^{-1})}{\partial \lambda} \right]_{\lambda = 710\ \text{nm}}$$

Slope of log-scaled reflectance spectrum at λ = 710 nm

z Melt pond depth

θ_{Sun} Solar zenith angle

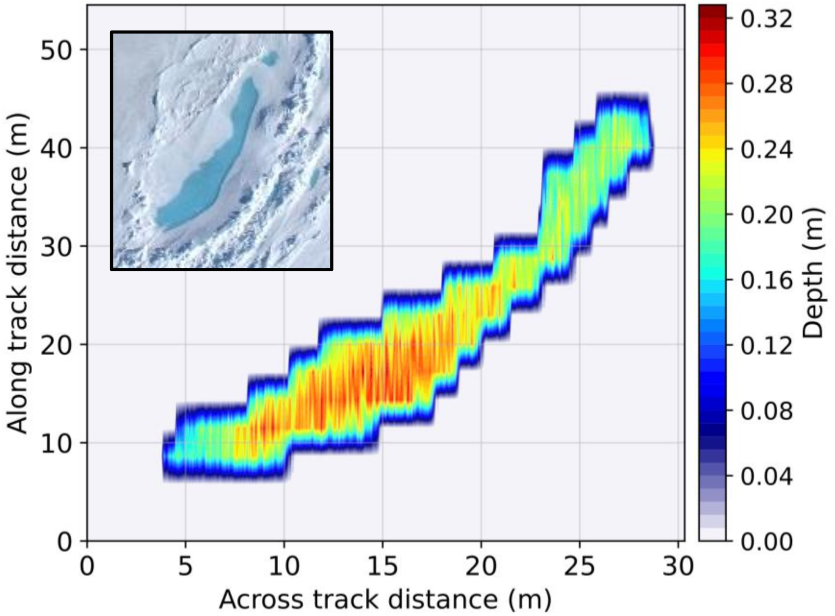
APPLICATION

Assumptions/Limitations

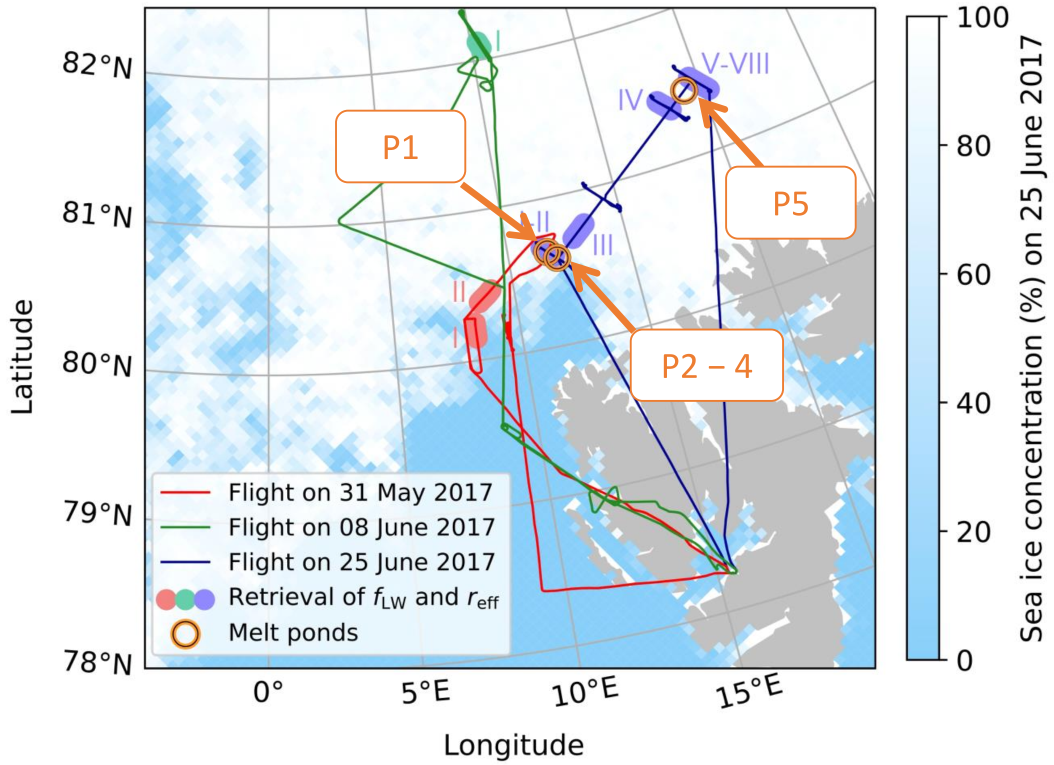
- Cloud-free conditions
- Pure pond water
- No water surface reflections
- Complete independence of ice bottom reflectance

RESULT

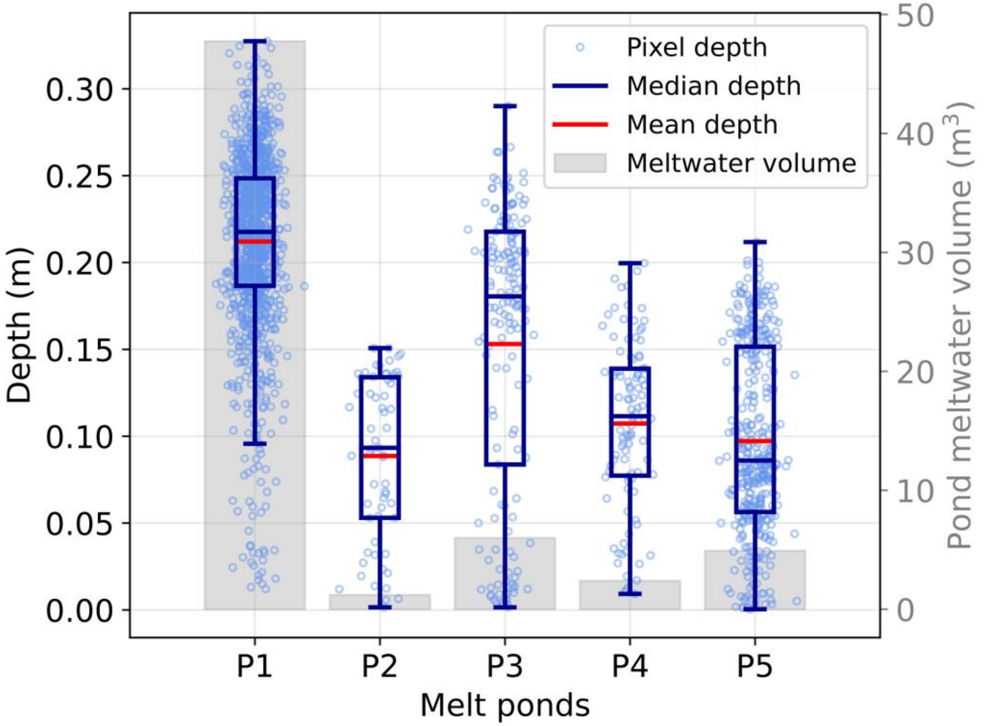
Retrieved depth for each detected melt pond pixel



5 selected melt ponds (P1 – P5)
as case studies on 25 June 2017



Depth distribution and meltwater volume



Melt pond depth → in-pond and spatial variability depending on → sea ice surface topography / meltwater availability

Potential uncertainty sources

→ No ground-based reference measurements available

Retrieval of snow layer properties	Main uncertainty sources	Retrieval of melt pond depth
AisaHawk, SMART	Measurement uncertainties	AisaEagle, SMART
Temporal averaging (aircraft heading/altitude, solar azimuth/zenith angle)	Data processing	Spectral smoothing, reflectance slope calculation
Realistic reflective behavior of snow layer in radiative transfer simulations?	Approach	Linear model RMSE = 0.03 m
$r_{\mathrm{eff}} \longrightarrow \pm 70\ \mu\mathrm{m}$ $f_{\mathrm{LW}} \longrightarrow \pm 18\ \%$	Maximum uncertainty	$z \longrightarrow \pm 0.1\ \mathrm{m}$

CONCLUSION

Potential of airborne spectral imaging
to map melting processes on Arctic sea ice

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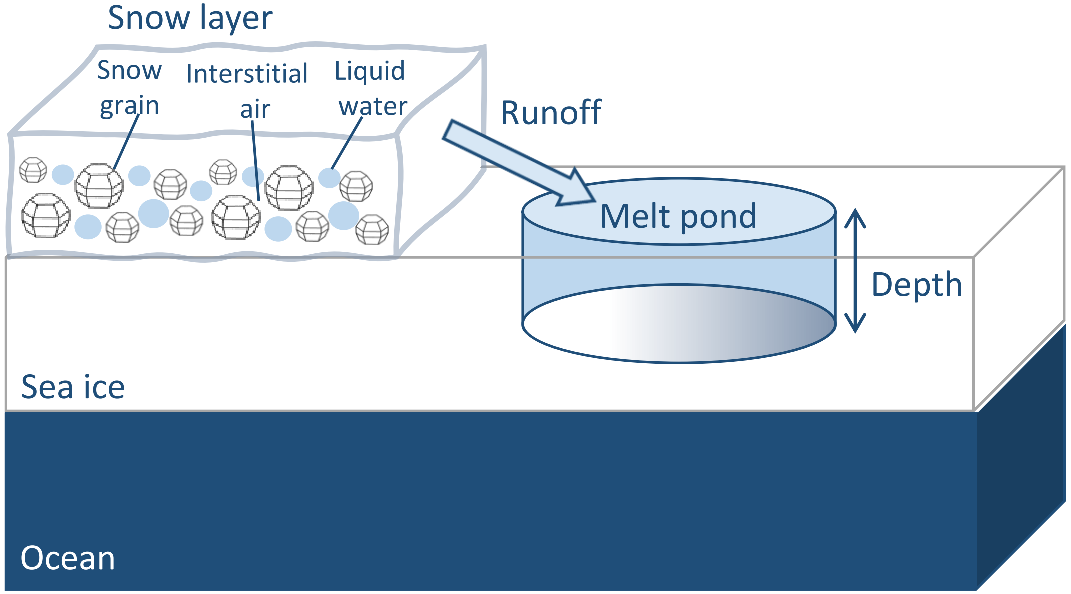

Further improvement

- Reference measurements for validation
- Spatially and temporally expanded measurements to map seasonal development

Further information

Manuscript submitted to AMT, other studies

Further information

MEASUREMENTS

Wendisch et al. (2019)

Ehrlich et al. (2019)

Wesche et al. (2016)

SIMULATIONS

Yang et al. (2000)

Emde et al. (2016)

Mayer et al. (2019)

APPROACHES

Green et al. (2002)

Donahue et al. (2022)

König and Oppelt (2020)