UNIVERSITÄT LEIPZIG

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Airborne observations of surface cloud radiative forcing over different surface types of the Arctic Ocean during late summer/early autumn

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ArctiC Amplification:
Climate Relevant Atmospheric and SurfaCe Processes
and Feedback Mechanisms (AC)³

MOTIVATION

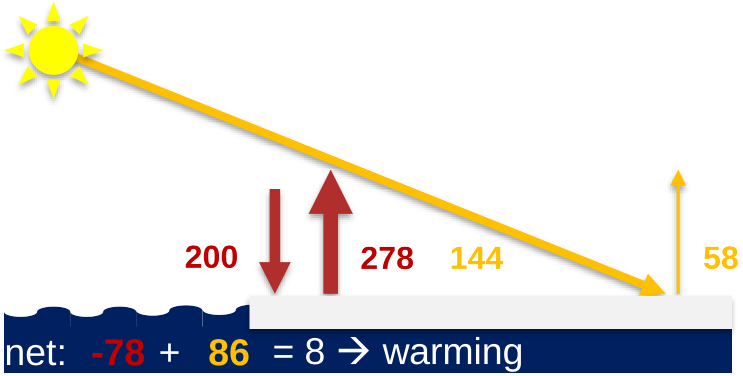
SURFACE CLOUD RADIATIVE FORCING IN THE ARCTIC

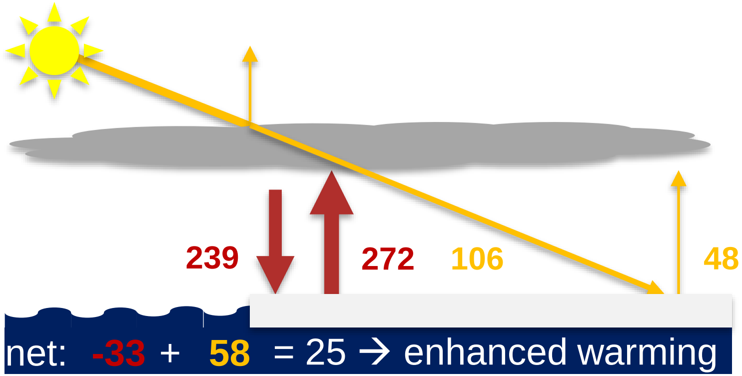
- **surface cloud radiative forcing** (CRF)**:** impact of clouds on radiative energy budget of the Earth‘s surface

$$\Delta F = F_{\mathrm{net,cld}} - F_{\mathrm{net,cf}}$$

$F_{\mathrm{net}} = F^{\downarrow} - F^{\uparrow}$ net irradiance
cld cloudy; cf cloud-free

- **solar: cooling** effect of clouds
- **terrestrial: warming** effect of clouds
- **total** effect of clouds in the Arctic: mostly **warming** in contrast to average cooling in mid and low latitudes





numbers from Sledd & L‘Ecuyer (2019) all numbers in W/m²

solar terrestrial

MOTIVATION

Why airborne observations of the surface radiative energy budget?

- ground-based: only on solid ground
- airborne: also over **open ocean**
- for fixed ground-based site:
  albedo change at most on seasonal scale
- airborne measurements over **sea ice and open ocean in close proximity**
- satellite: better suited for TOA,
  large **uncertainties of satellite products**

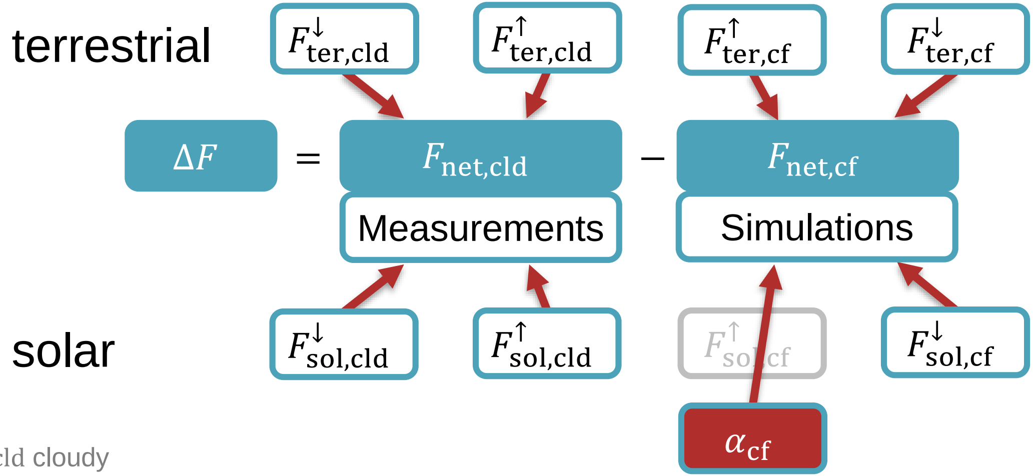
How to derive the cloud-free net irradiance?

- cloud-free observations (temporal offset)
  → atmospheric conditions change
- radiative transfer simulations
  → atmospheric conditions kept constant
- thermodynamic conditions would need adaption time to change
- **surface albedo changes instantaneously**

- here:
  radiative transfer simulations taking into account albedo changes

MEASUREMENTS & METHODS

CRF CALCULATION



cld cloudy
cf cloud-free
sol solar
ter terrestrial

α surface albedo

measurements (during low-level legs)
up- and downward-looking broadband

- pyranometers (solar)
- pyrgeometers (terrestrial)

radiative transfer simulations

libradtran input:

- temperature and RH-profiles (in situ, dropsondes, radiosondes)
- solar zenith angle (SZA)
- measured surface albedo

α_{cf} cloud-free albedo (see next slides)

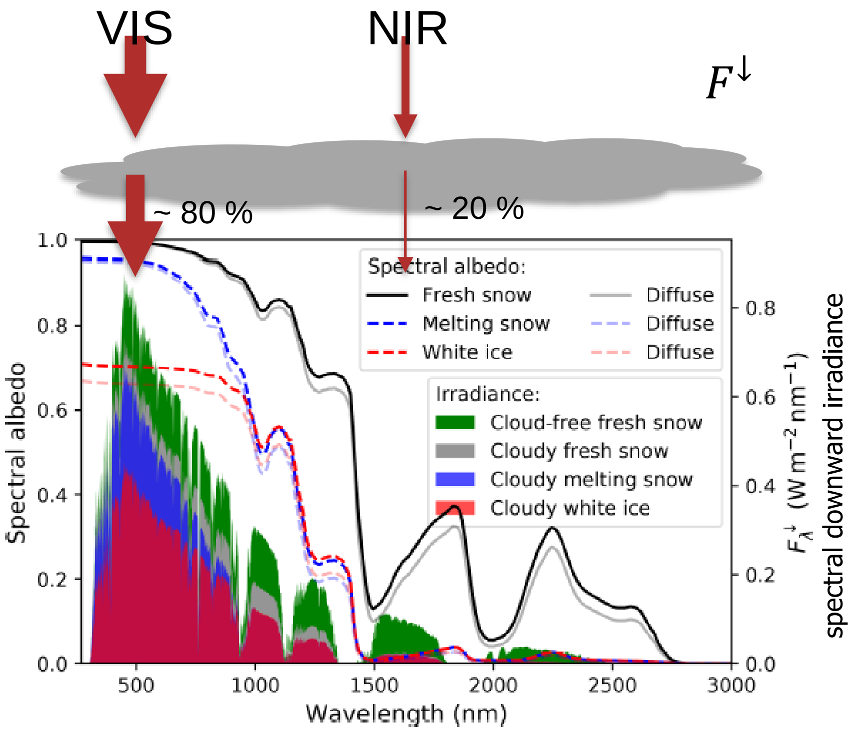
after Stapf et al. (2020)

CLOUD-SURFACE ALBEDO INTERACTIONS

SNOW & SEA ICE

two competing effects in case of clouds:

- diffuse conditions:
  decrease of „**effective**“ **SZA** to 50°
  → decrease of spectral surface albedo (especially in NIR)
- **spectral weighting effect**:
  largest attenuation of spectral downward irradiance by clouds in NIR
  → increase of broadband surface albedo
- **second effect mostly dominating**
  (at large SZA at least for optical thick clouds)



fresh snow: SSA = 80 m²/kg, 20 cm thick
melting snow: SSA = 5 m²/kg, 20 cm thick
white ice: SSA = 5 m²/kg, 1 cm thick

Stapf et al. (2020)

SSA – specific surface area (optical measure for snow grain size)
VIS – visible NIR – near infrared

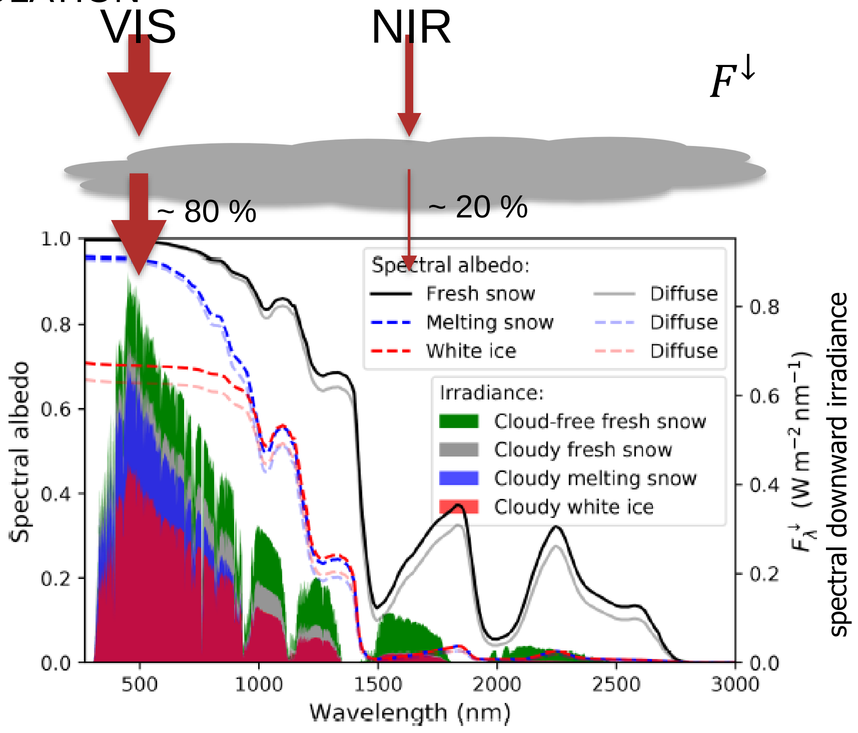
CLOUD-SURFACE ALBEDO INTERACTIONS

SNOW & SEA ICE – A SIMPLE EXEMPLARY CALCULATION

broadband albedo: $\alpha_{\mathrm{BB}} = \frac{F^{\uparrow}}{F^{\downarrow}} = \frac{\int F_{\lambda}^{\uparrow} \mathrm{d}\lambda}{\int F_{\lambda}^{\downarrow} \mathrm{d}\lambda} = \frac{\int \alpha_{\lambda} \cdot F_{\lambda}^{\downarrow} \mathrm{d}\lambda}{\int F_{\lambda}^{\downarrow} \mathrm{d}\lambda}$

assume only 2 wavelengths (VIS & NIR):

- cloud-free
  - VIS: $F_{\mathrm{VIS}}^{\downarrow} = 0.7\ \mathrm{W\,m^{-2}\,nm^{-1}}$, $\alpha_{\mathrm{VIS}} = 0.9$
  - NIR: $F_{\mathrm{NIR}}^{\downarrow} = 0.1\ \mathrm{W\,m^{-2}\,nm^{-1}}$, $\alpha_{\mathrm{NIR}} = 0.1$
  - broadband albedo: $\alpha_{\mathrm{BB}} = 0.8$
- cloudy:
  - VIS: $F_{\mathrm{VIS}}^{\downarrow} = 0.5\ \mathrm{W\,m^{-2}\,nm^{-1}}$, $\alpha_{\mathrm{VIS}} = 0.85$
  - NIR: $F_{\mathrm{NIR}}^{\downarrow} = 0.025\ \mathrm{W\,m^{-2}\,nm^{-1}}$, $\alpha_{\mathrm{NIR}} = 0.05$
  - broadband albedo: $\alpha_{\mathrm{BB}} = 0.812$
- spectral albedo decreasing everywhere, but broadband albedo can increase



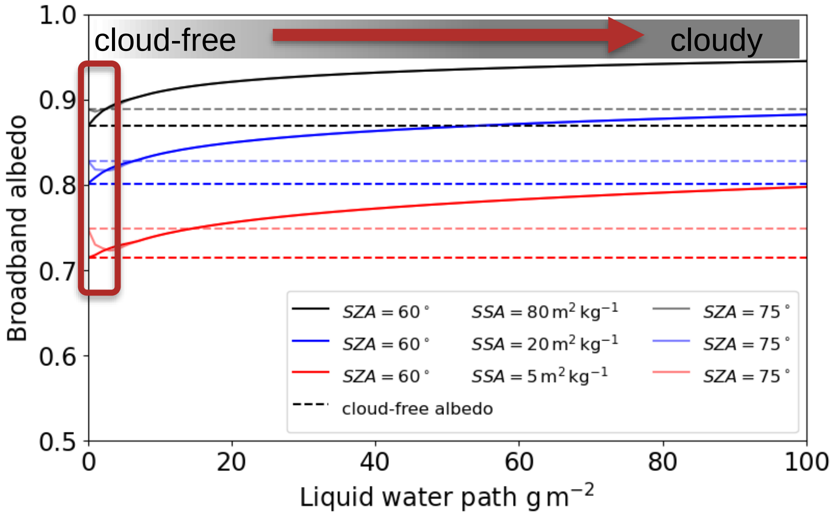
Stapf et al. (2020)

CLOUD-SURFACE ALBEDO INTERACTIONS

SNOW & SEA ICE

cloudy conditions:

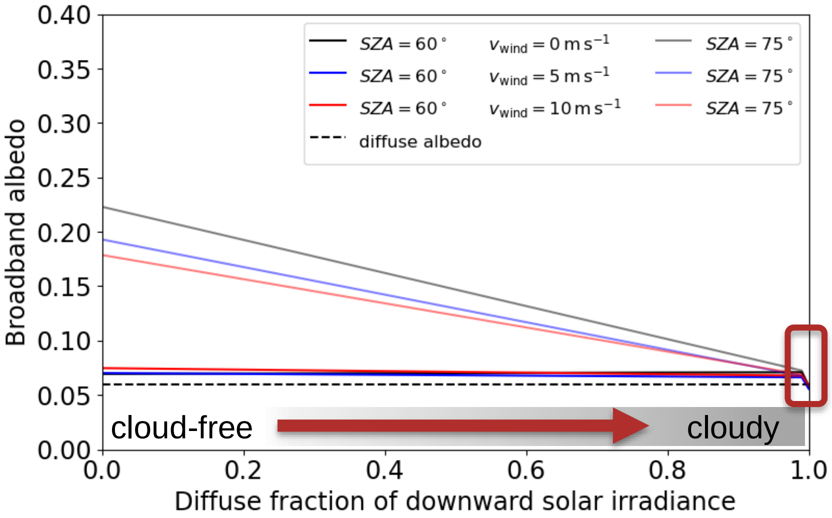
- spectral weighting effect mostly dominating (at large SZA at least for optical thick clouds)
  → **increase** of broadband surface albedo



OPEN OCEAN

cloudy conditions:

- direct albedo albedo higher than diffuse albedo (for SZA larger than ~ 60°)
  → **decrease** of broadband surface albedo



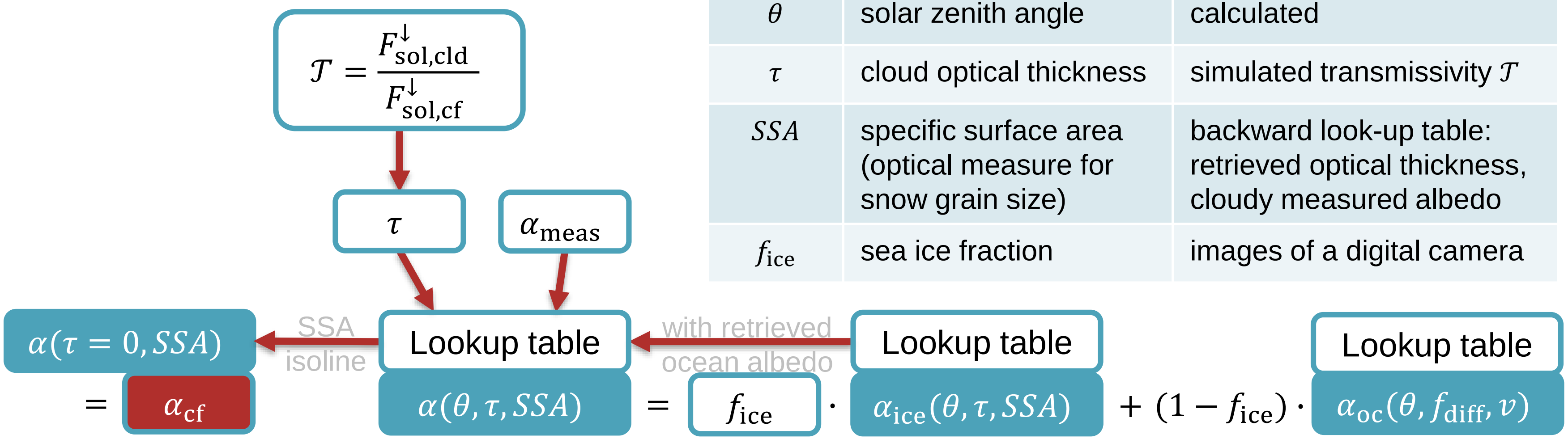
CLOUD-SURFACE ALBEDO INTERACTIONS

CALCULATION OF CLOUD-FREE ALBEDO

surface albedo parameterizations:

- sea ice α_{ice} (Gardner & Sharp, 2010)
- open ocean α_{oc} (Jin et al., 2011)

symbol	Parameter	derivation method
v	surface wind speed	measured in flight altitude, scaled to surface (log wind)
f_{diff}	diffuse fraction of $F^{\downarrow}_{\mathrm{sol,cf}}$	simulated (cloud-free)
θ	solar zenith angle	calculated
τ	cloud optical thickness	simulated transmissivity $\mathcal{T}$
SSA	specific surface area (optical measure for snow grain size)	backward look-up table: retrieved optical thickness, cloudy measured albedo
f_{ice}	sea ice fraction	images of a digital camera



cld cloudy
cf cloud-free

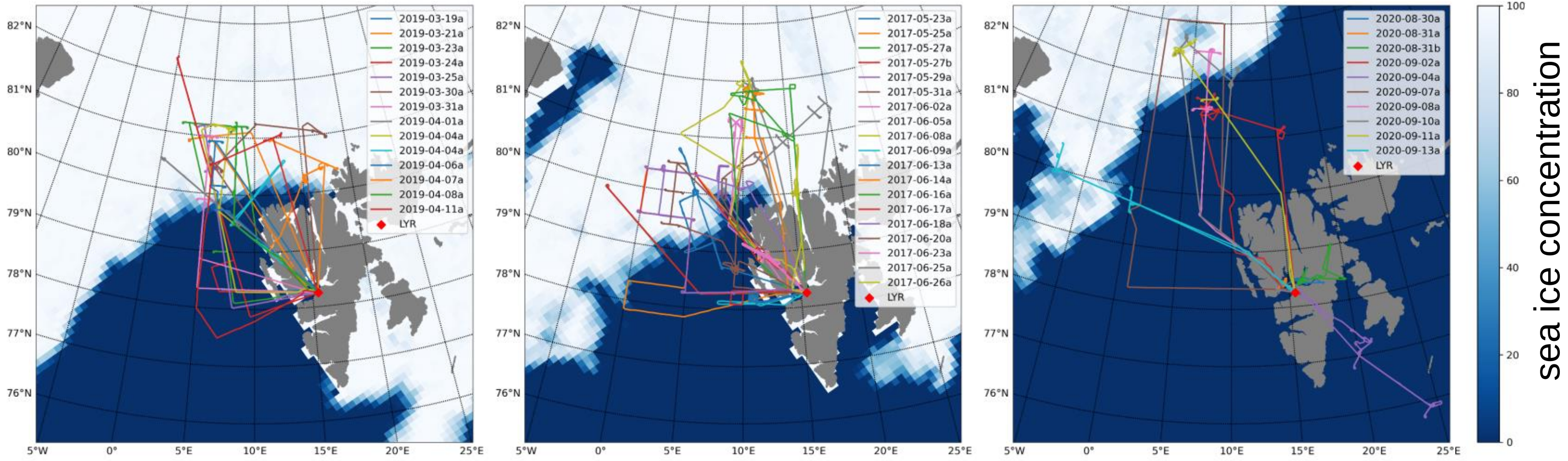
sol solar
ter terrestrial

oc open ocean
meas measured

after Stapf et al. (2020; in review, 2021)

CAMPAIGNS

AFLUX	ACLOUD	MOSAiC-ACA	
March/April 2019	May/June 2019	August/September 2020	time
Polar 5	Polar 5 & Polar 6	Polar 5 (Polar 6 for ICEBIRD*)	aircraft
272 K	859 K	98 K (only Polar 5)	low-level data points



plots: Marcus Klingebiel

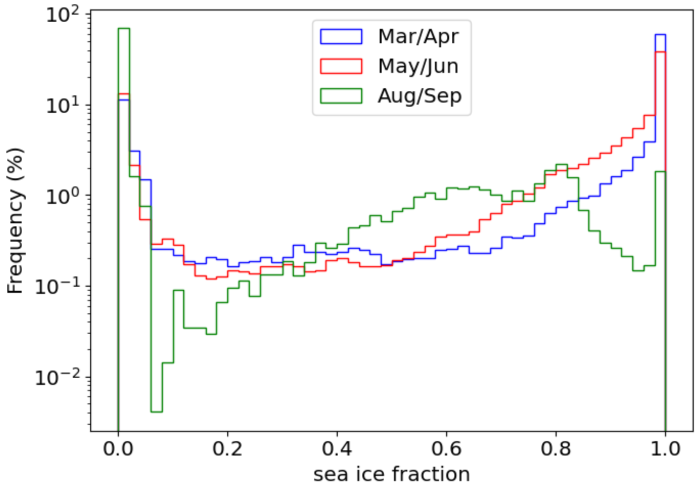
* MOSAiC Icebird campaign during the same time as MOSAiC-ACA

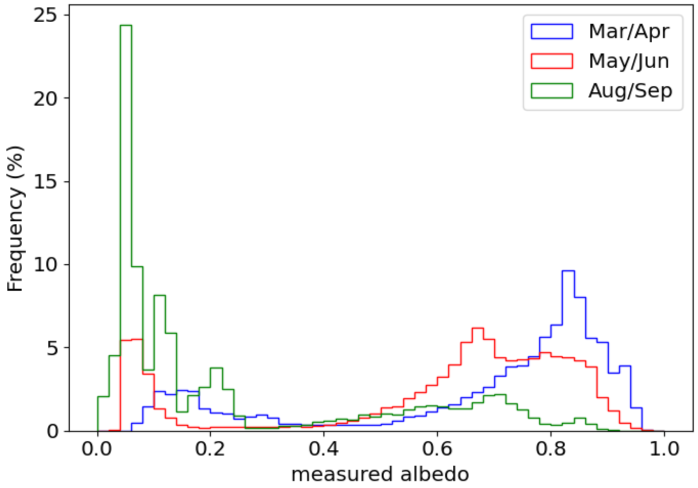
FIRST RESULTS

SEA ICE FRACTION & SURFACE ALBEDO

- AFLUX & ACLOUD dominated by sea ice
- ACLOUD MIZ dominated by sea ice
- ACA dominated by open ocean
- AFLUX larger sea ice albedo than ACLOUD

data points	Mar/Apr	May/Jun	Aug/Sep
sea ice ($f_{\text{ice}} > 0.95$)	**65.4 %**	**49.2 %**	2.1 %
MIZ ($0.05 < f_{\text{ice}} < 0.95$)	19.0 %	**35.1 %**	26.1 %
open ocean ($f_{\text{ice}} < 0.05$)	15.6 %	15.7 %	**71.8 %**





MIZ – marginal sea ice zone

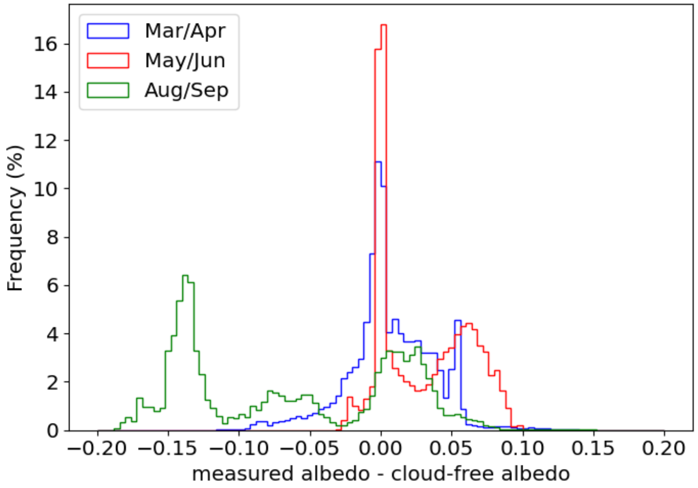
FIRST RESULTS

CLOUD-SURFACE ALBEDO INTERACTIONS

measured and cloud-free albedo difference

- $\boldsymbol{\alpha_{cf} > \alpha_{meas}}$ **for sea ice** and sea ice-dominated MIZ during **ACLOUD**
- difference of sea ice albedo weaker during AFLUX & ACA because of larger SZA ≈ 75° (*during AFLUX maybe also thinner clouds and fresher snow*)
- $\alpha_{cf} \approx \alpha_{meas}$ for open ocean during ACLOUD due to SZA ≈ 60°
- $\boldsymbol{\alpha_{cf} < \alpha_{meas}}$ **for open ocean** during **ACA** *(*should also be true for AFLUX (SZA similar to ACA), but measurements biased due to sea smoke between surface and sensor during AFLUX)*
- modes around 0 represent measurements in cloud-free conditions (no albedo change)

cloudy ($LWP > 5\ \mathrm{g\ m^{-2}}$) mean $\alpha_{meas} - \alpha_{cf}$	Mar/Apr	May/Jun	Aug/Sep
	0.01	**0.04**	**-0.07**
sea ice ($f_{ice} > 0.95$)	0.02	**0.06**	0.01
MIZ ($0.05 < f_{ice} < 0.95$)	0.01	**0.04**	0.01
open ocean ($f_{ice} < 0.05$)	-0.01*	0.00	**-0.12**

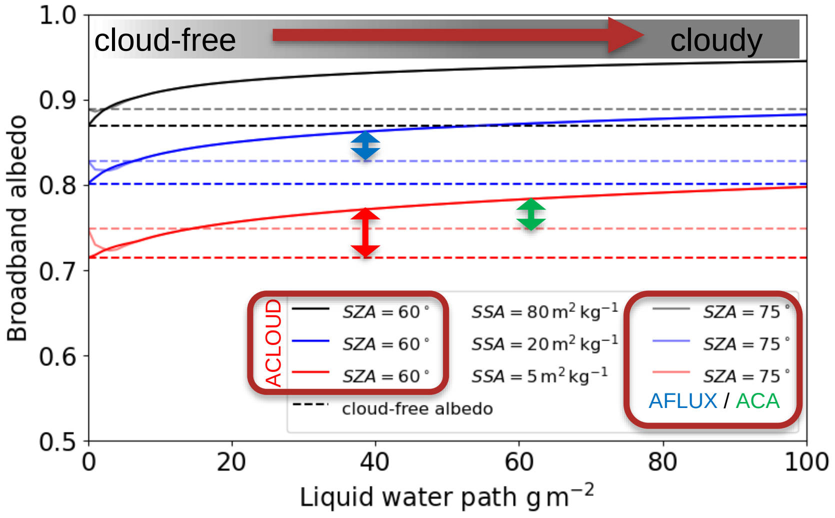


CLOUD-SURFACE ALBEDO INTERACTIONS

REMEMBER

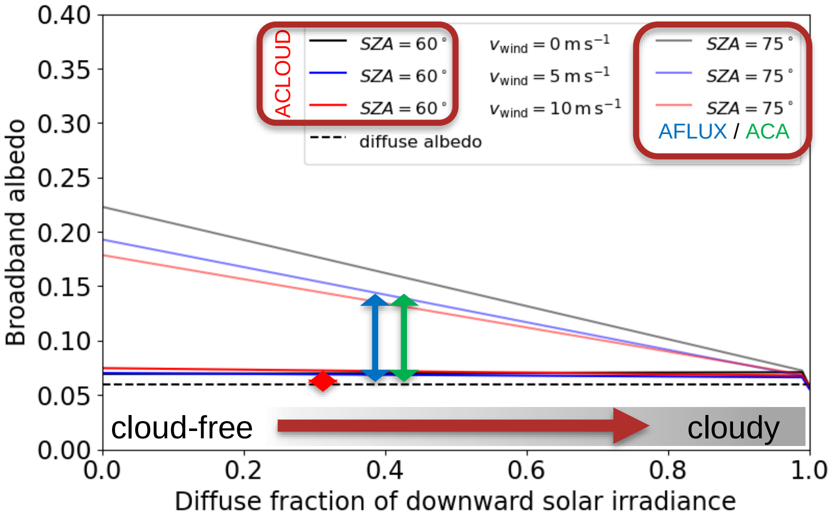
SEA ICE

– difference between cloudy and cloud-free ($LWP = 0\ \mathrm{g\,m^{-2}}$) albedo larger for SZA ≈ 60° (ACLOUD) than for SZA ≈ 75° (AFLUX/ACA), where $\alpha_{\mathrm{cf}} < \alpha_{\mathrm{meas}}$ for optical thin clouds



OPEN OCEAN

– difference between diffuse ($f_{\mathrm{diff}} = 1$) and cloudy albedo larger for larger SZA > ~ 60° (AFLUX/ACA, SZA ≈ 75°) almost no change for SZA ≈ 60° (ACLOUD)



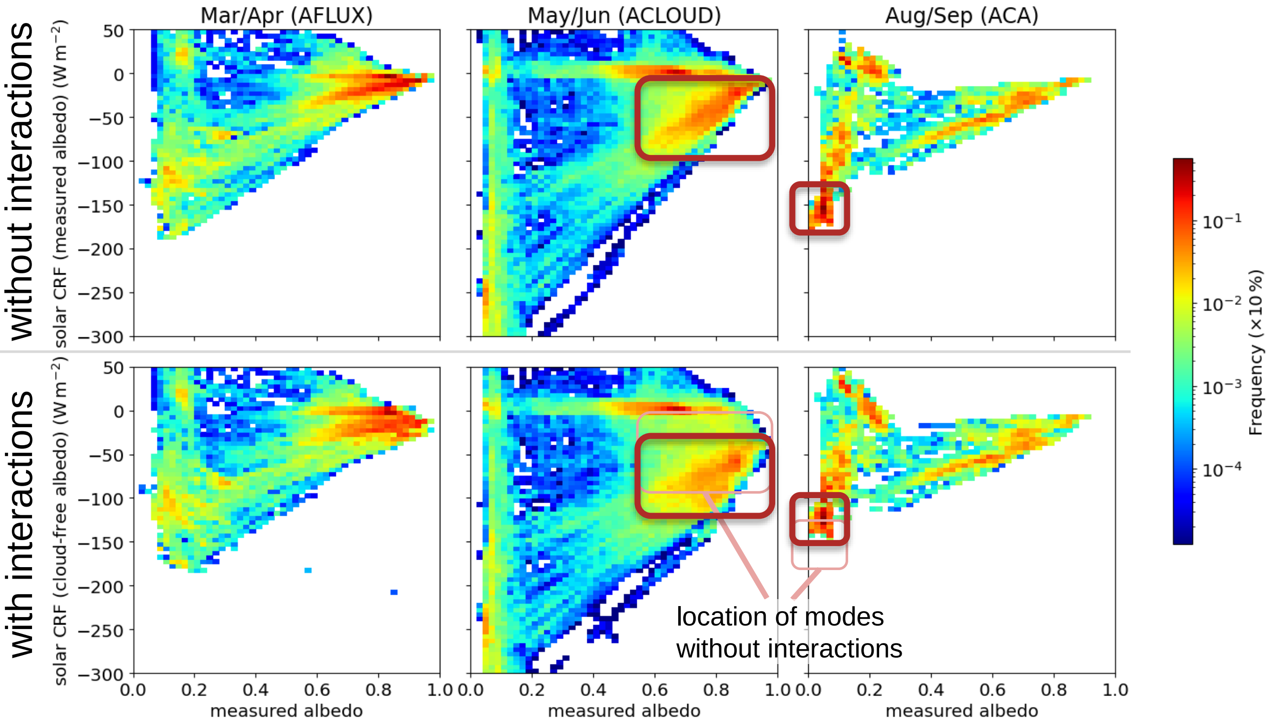
FIRST RESULTS

IMPACT OF CLOUD-SURFACE ALBEDO INTERACTIONS ON SOLAR CRF

all surface types

cloudy mean $\Delta F_{\mathrm{sol}}(\alpha_{\mathrm{meas}})$ $[LWP > 5\ \mathrm{g\,m^{-2}}]$ $(\mathrm{W\,m^{-2}})$	
Mar/Apr	-40.7
May/Jun	-96.6
Aug/Sep	-101.1

cloudy mean $\Delta F_{\mathrm{sol}}(\alpha_{\mathrm{cf}})$ $[LWP > 5\ \mathrm{g\,m^{-2}}]$ $(\mathrm{W\,m^{-2}})$	
Mar/Apr	-43.3
May/Jun	-119.7
Aug/Sep	-84.6



for explanations see next slide

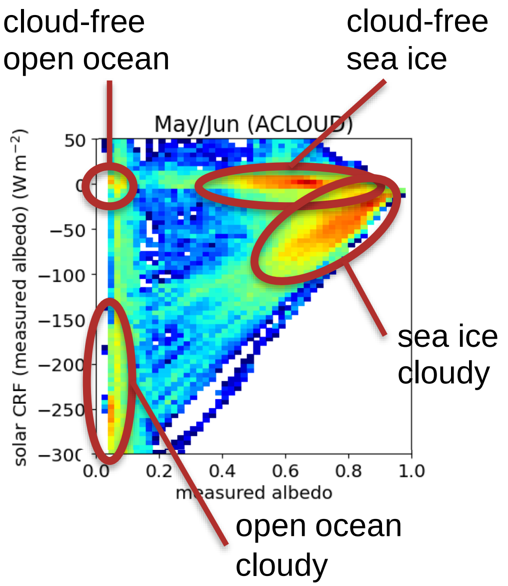
FIRST RESULTS

IMPACT OF CLOUD-SURFACE ALBEDO INTERACTIONS ON SOLAR CRF

- **4 modes** visible (see figure)
- **solar cooling** effect of clouds **stronger over open ocean** than over sea ice because of lower surface albedo
- **solar cooling** effect of clouds **stronger during solar maximum** (ACLOUD) than during AFLUX/ACA due to lower solar zenith angle
- cloud-free sea ice mode missing for ACA (lack of observations)
- ACA cloudy sea ice mode more a cloudy “MIZ mode“

Impact of cloud-surface albedo interactions

- interactions of **snow & sea ice albedo** most important during **early summer** (ACLOUD) → **stronger solar cooling** over sea ice
- interactions of **open ocean albedo** most important during **late summer** (ACA) → **weaker solar cooling** over open ocean
- *AFLUX: interactions of open ocean albedo not visible (sea smoke) → does not impact mean CRF due to small open ocean areas*



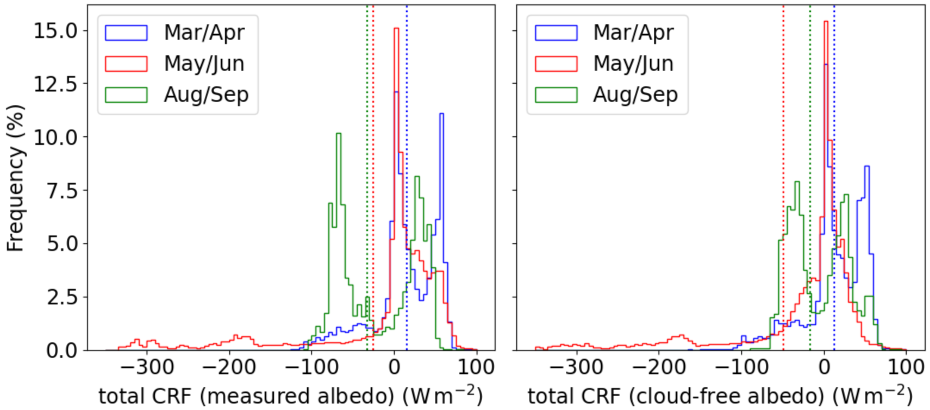
FIRST RESULTS

IMPACT OF CLOUD-SURFACE ALBEDO INTERACTIONS ON **TOTAL CRF**

all surface types cloudy mean $\Delta F_{tot}(\alpha_{meas})$ $[LWP > 5\ \mathrm{g\,m^{-2}}]$ ($\mathrm{W\,m^{-2}}$)	
Mar/Apr	15.7
May/Jun	-25.5
Aug/Sep	-32.7
cloudy mean $\Delta F_{tot}(\alpha_{cf})$ $[LWP > 5\ \mathrm{g\,m^{-2}}]$ ($\mathrm{W\,m^{-2}}$)	
Mar/Apr	13.1
May/Jun	-48.5
Aug/Sep	-16.1

- **not taking into account** cloud-surface albedo interactions: average **cooling** effect of clouds **similar during early** (ACLOUD) **and late** (ACA) **summer** (slightly larger cooling for ACA)
- **taking into account** cloud-surface albedo interactions: average **cooling** effect of clouds clearly **stronger during early** (ACLOUD) **than late** (ACA) **summer**

NB: These results hold for the average of the **entire sampled region** considering the **differences in sea ice fraction** (see slide 10) as part of **seasonal variability**



SUMMARY & CONCLUSIONS

- **cloud radiative forcing**: $\Delta F = F_{\mathrm{net,cld}} - F_{\mathrm{net,cf}}$
  cld cloudy; cf cloud-free
- clouds mostly **warm the surface in the Arctic** due to special Arctic conditions, but **cool the surface in summer**
- airborne campaigns:
  - low-level flight measurements as proxy for surface CRF
  - radiative transfer simulation of cloud-free irradiances considering **cloud-surface albedo interactions**
- cloud-surface albedo interactions lead to:
  - **increase of sea ice albedo in cloudy conditions**
    (important for large sea ice areas and relatively low SZA, **early summer**)
    → **enhanced cooling** effect of clouds
  - **decrease of open ocean albedo in cloudy conditions** for SZA > ~ 60°
    (important for large open ocean areas and relatively large SZA, **late summer**)
    → **reduced cooling** effect of clouds

→ **The importance of the cloud-surface albedo interactions and their impact on the surface cloud radiative forcing varies between different seasons.**

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Surface cloud radiative forcing (CRF ΔF): F_{net} - net irradiance

$\Delta F = F_{\text{net,cloudy}} - F_{\text{net,cloud-free}}$

$F_{\text{net,cloudy}}$: measurements

$F_{\text{net,cloud-free}}$: simulations

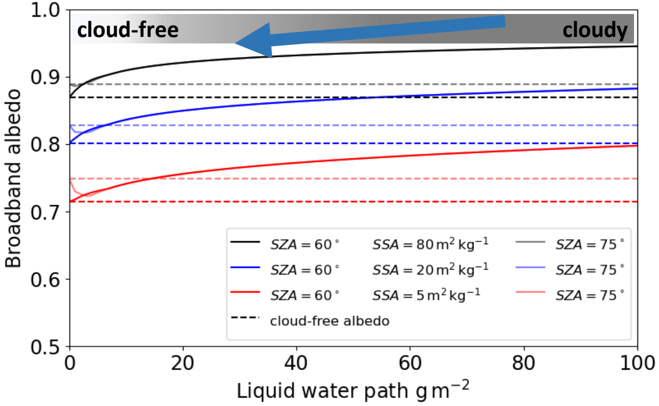
The importance of the cloud-surface albedo interactions and their impact on the surface cloud radiative forcing varies between different seasons.

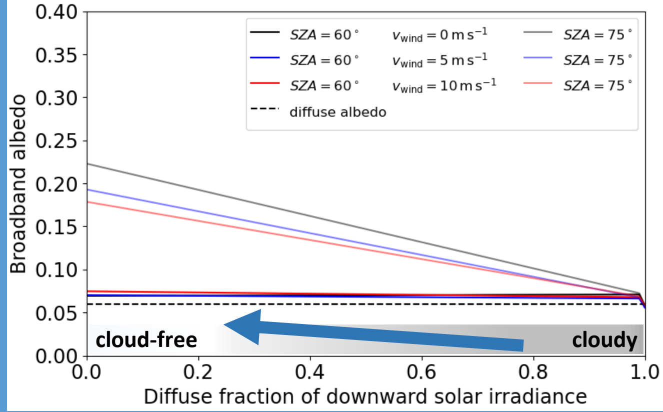
Cloud-surface albedo interactions: α - surface albedo

α_{cloudy} → **instantaneous change** → $\alpha_{\text{cloud-free}}$ **parametrizations**

snow/sea ice albedo

mostly **decreasing** in cloud-free conditions in the Arctic





open ocean albedo

mostly **increasing** in cloud-free conditions in the Arctic