CERES Top-of-atmosphere and Surface fluxes in the Arctic: A comparison with ARISE and MOSAiC measurements

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Acknowledgements: Yiyi Huang, Kyle Itterly, Brant Dodson, Joe Corbett, Sergio Sejas, Wenying Su, Dave Doelling, Seiji Kato, Anthony Bucholtz

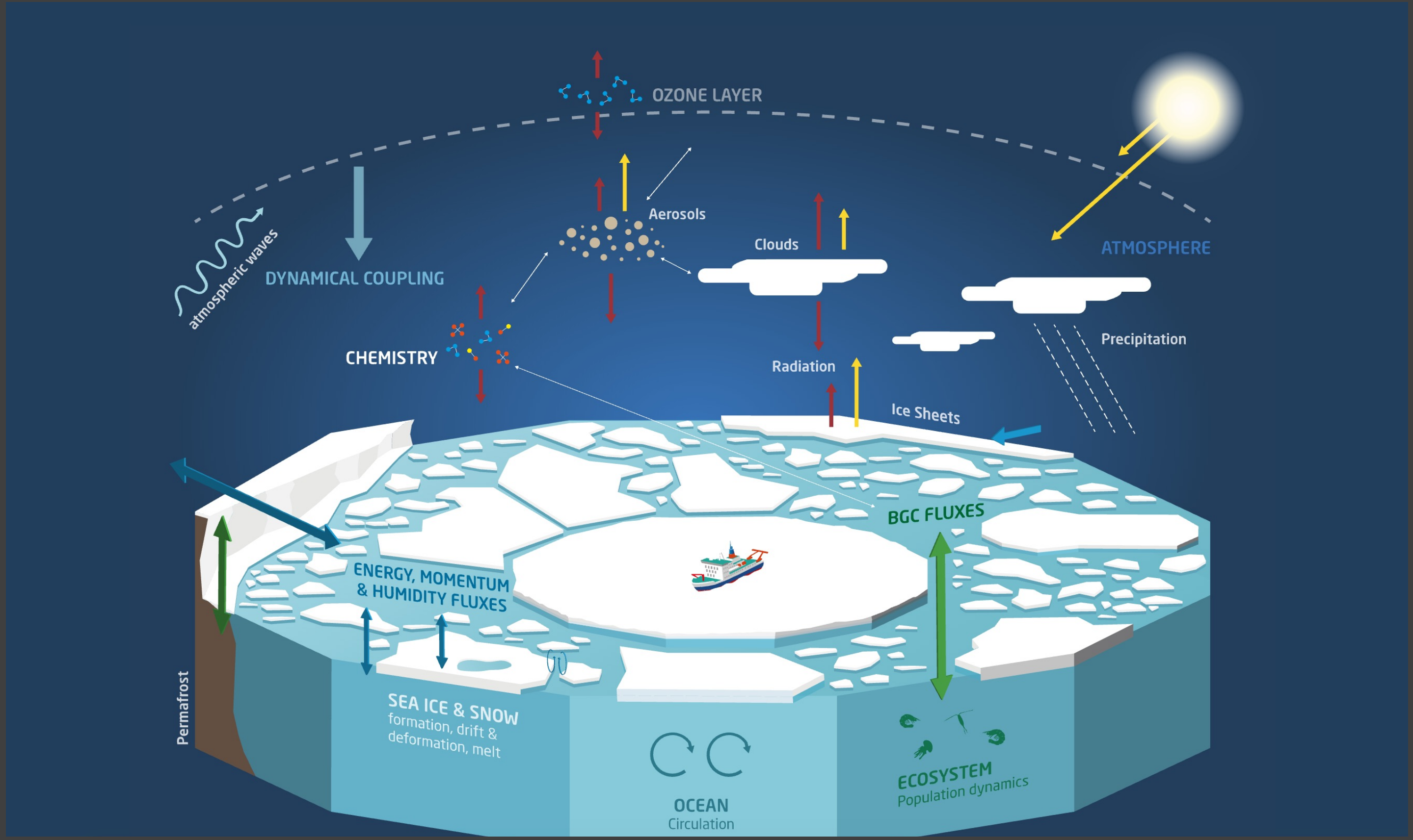
Fall 2022 CERES Science Team Meeting

October 13, 2022

The Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) field campaign

September 2019 - October 2020

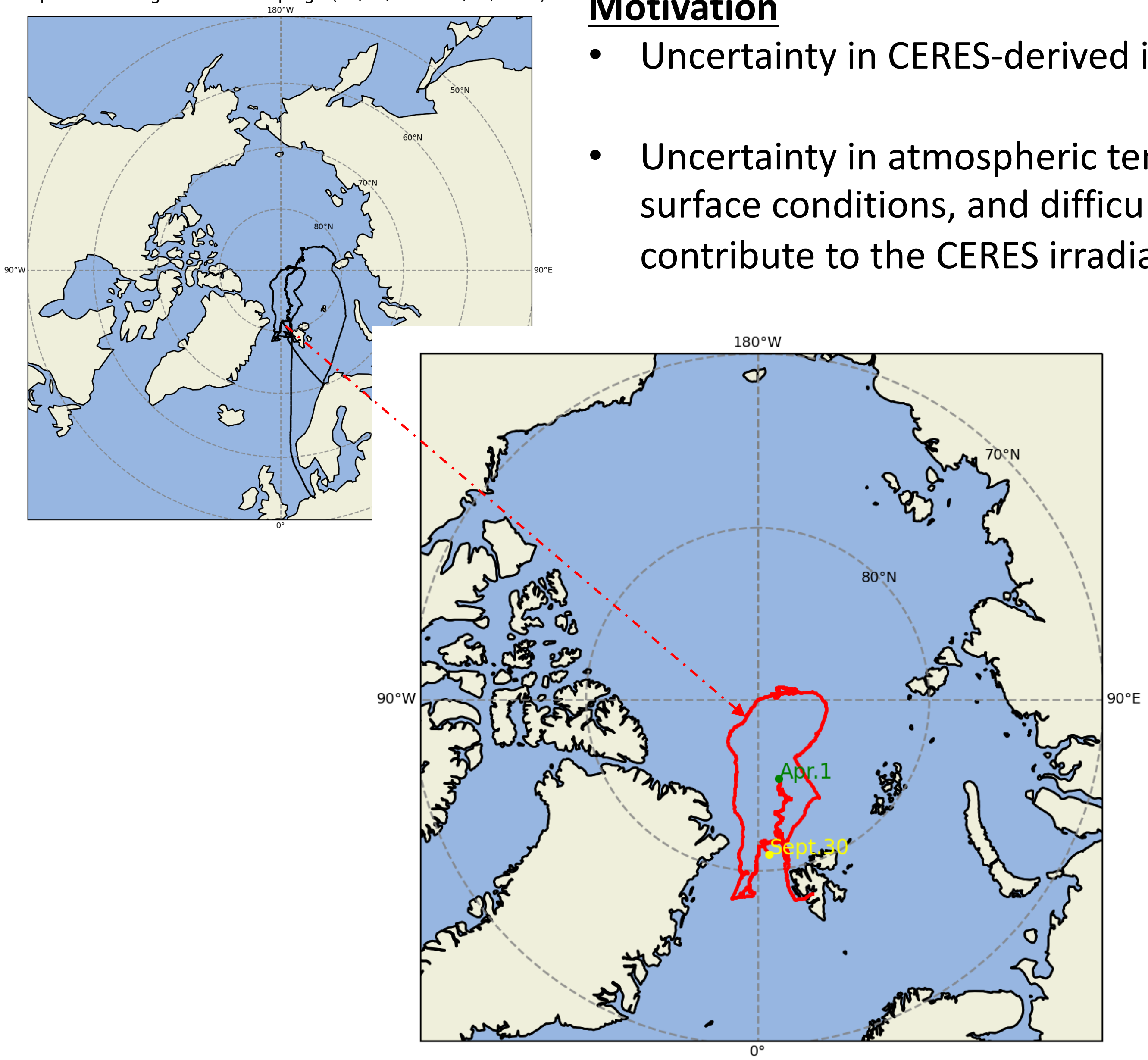
- The largest polar expedition in history; the first time in polar winter
- The goal of the MOSAiC expedition was to take the closest look ever at the Arctic as the epicenter of global warming and to gain fundamental insights that are key to better understand global climate change



https://mosaic-expedition.org/

Overview

Ship Track during MOSAiC Campaign (09/01/2019-10/31/2020)



Motivation

- Uncertainty in CERES-derived irradiances is larger over sea ice than any other scene type
- Uncertainty in atmospheric temperature and humidity from reanalysis, heterogeneity in surface conditions, and difficulties in detecting and characterizing clouds over sea ice all contribute to the CERES irradiance uncertainty

Outline

- The comparison between CERES SYN1deg and MOSAiC from April to September 2020
- The surface albedo perturbation experiments with Fu-Liou radiative transfer model

MOSAiC remote flux stations (managed by CIRES/NOAA)

- **Multiple remote flux stations**: asfs30, asfs40, asfs50
- **Temporal resolutions**: 10s
- **Location**: top of station at 2 m

Measurements at surface
solar zenith angle, solar azimuth angle, snow depth, air pressure, air temperature, relative humidity, dew point temperature, mixing ratio, absolute humidity, vapor pressure, brightness temp, surface skin temp, conductive flux, wind speed, wind direction

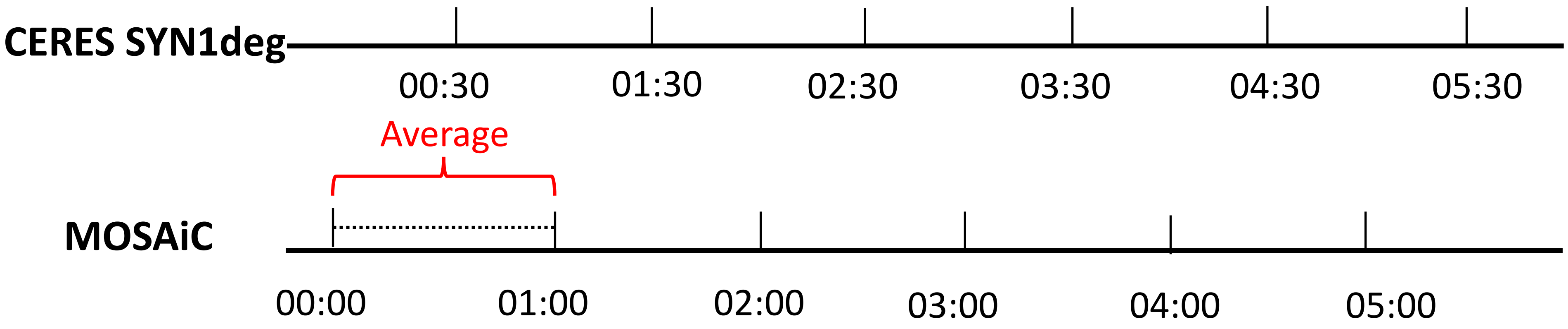
Turbulence and met tower (2m, 6m, 10m, 24m)
Latent heat flux, Sensible heat flux
Temperature

Radiation measurements

Variable	Instrument
SW_up flux	Hukseflux SR30 pyranometer
SW_down flux	Hukseflux SR30 pyranometer
LW_down flux	Hukseflux IR20 pyrgeometer
LW_up flux	Hukseflux IR20 pyrgeometer
Net radiative flux	SR30 and IR20 radiometers

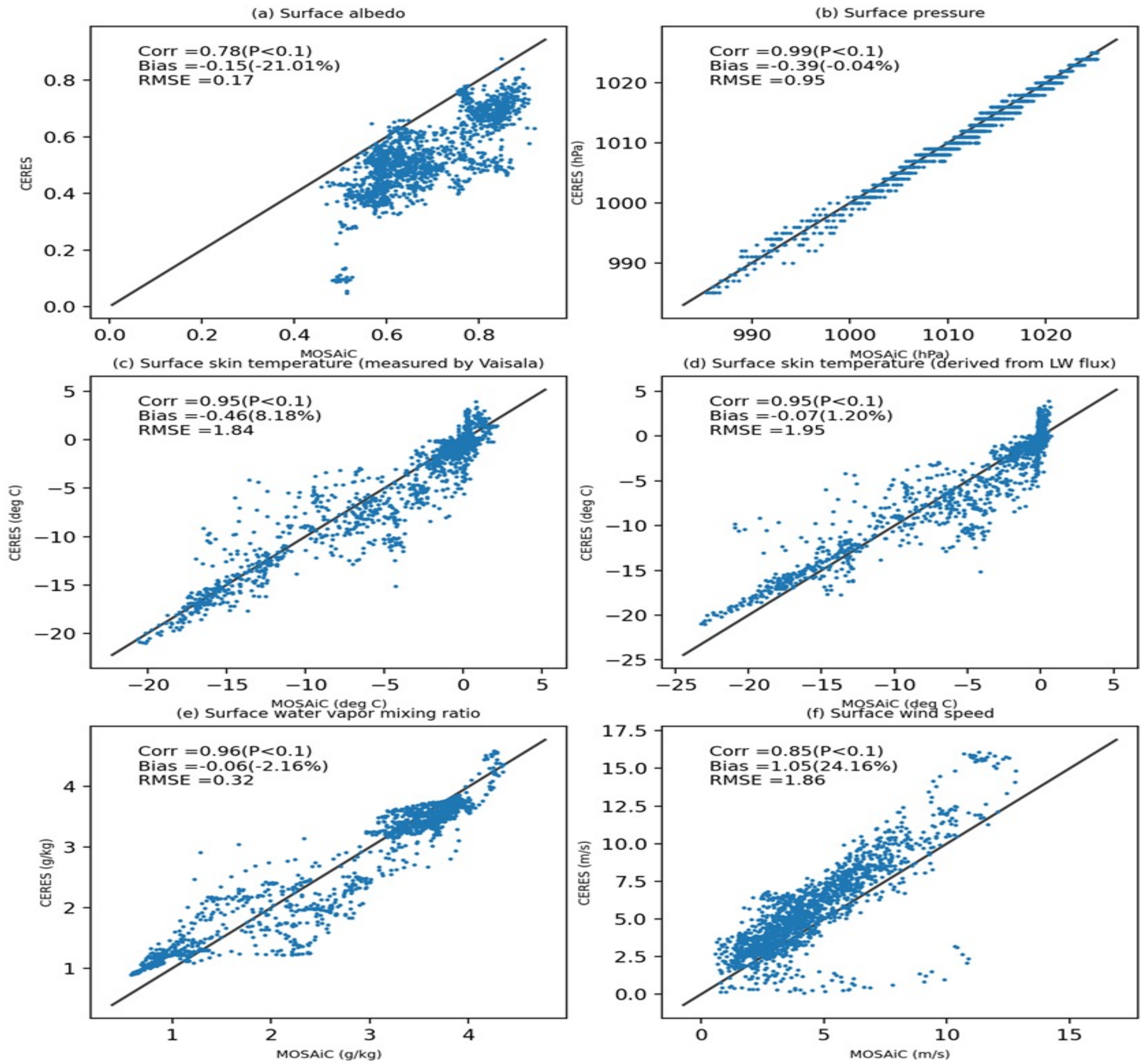
Collocation between CERES SYN1deg and MOSAiC

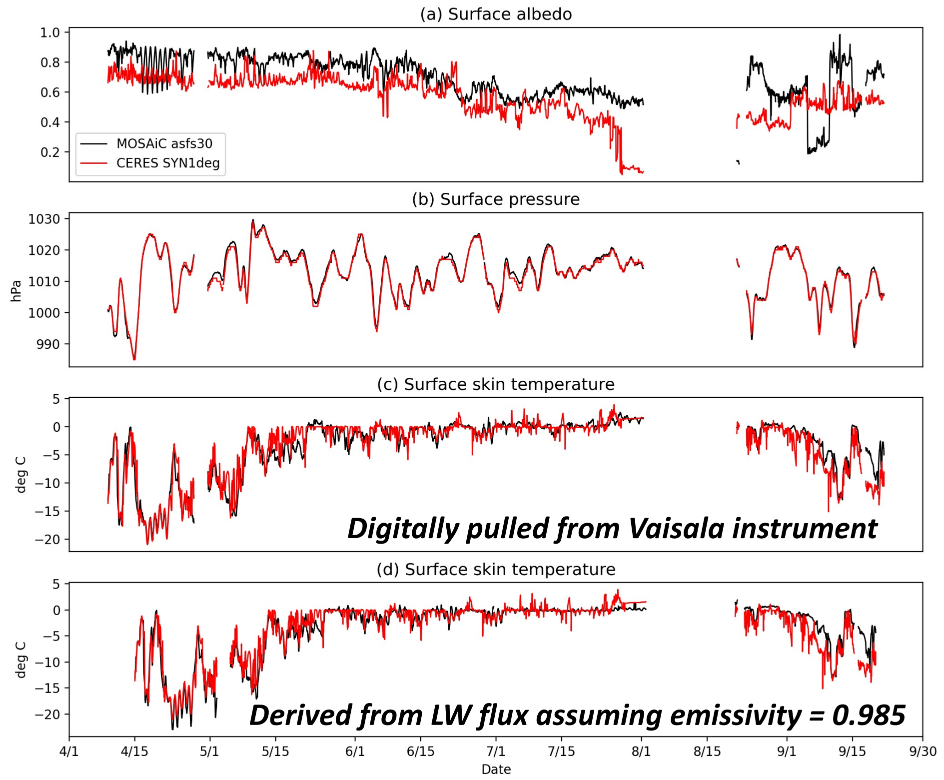
- **CERES**: CERES_SYN1deg-1H_Terra-Aqua-MODIS_Ed4.1 (Hourly)
- **MOSAiC**: mosasfsmet.level2.10min (10-min)
- Averaged 10-min MOSAiC data (location, radiative fluxes) and saved it as hourly output
- Collocated MOSAiC hourly data with CERES SYN1deg dataset by finding the closest grid box



- **"Matched" surface sites**: Subsequent analysis considers only days where at least two of the three stations collected data

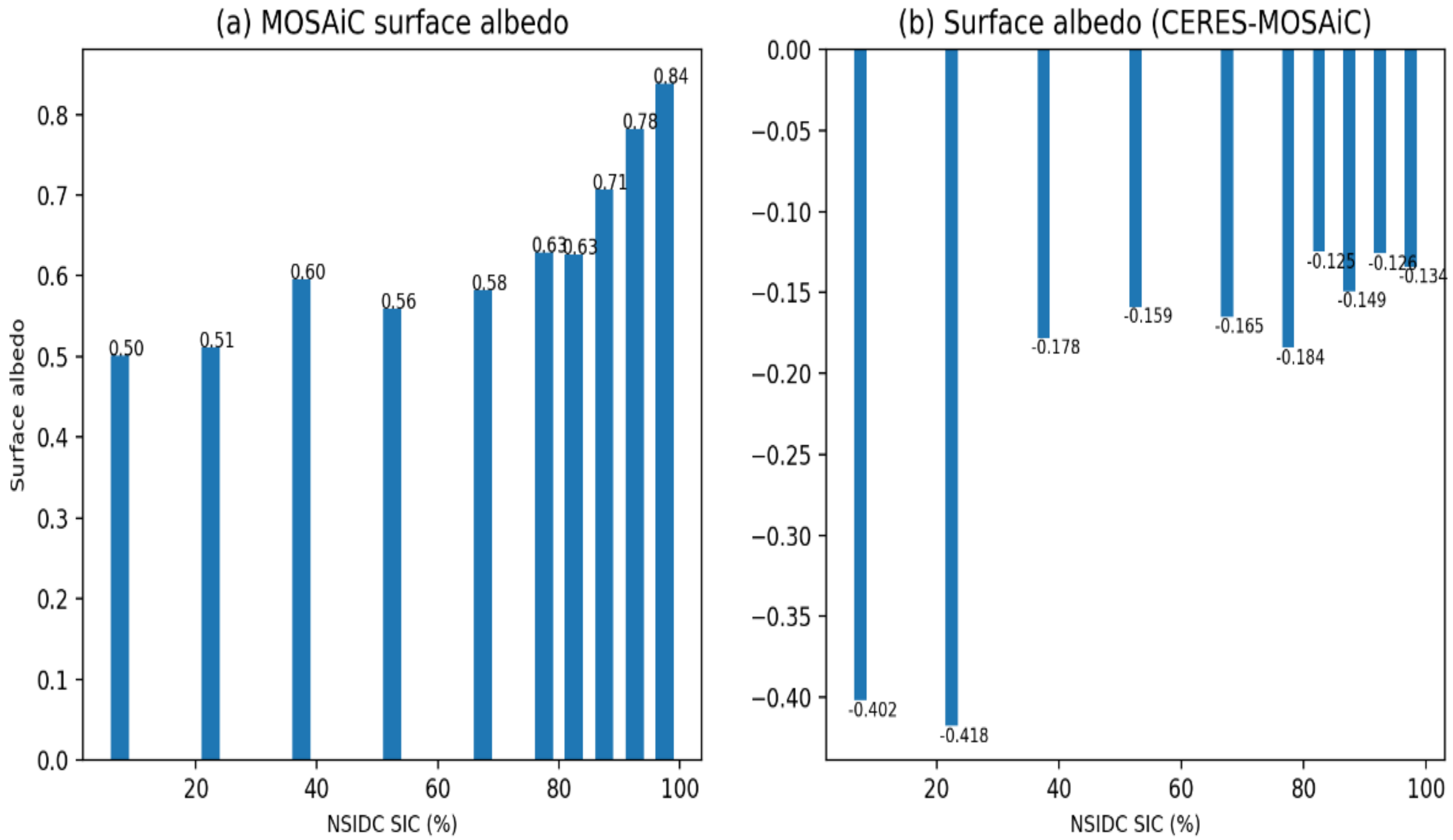
Meteorological conditions: MOSAiC and CERES SYN1deg





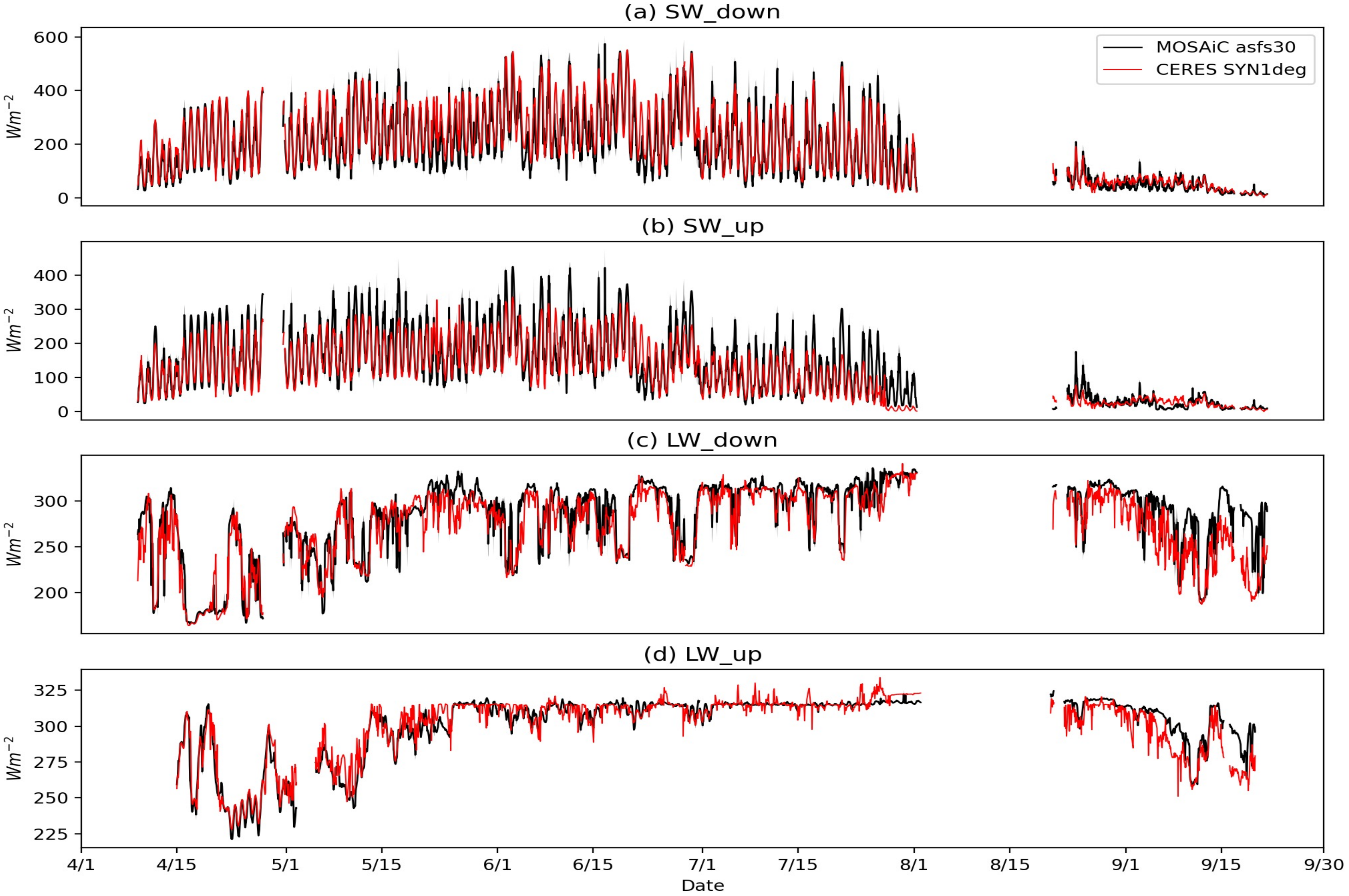
- The SYN1deg constantly underestimates the surface albedo during summertime
- Large uncertainty remains in surface skin temperature when surface reaches melting point (~0°C)

Sea ice concentration dependent albedo differences: MOSAiC and CERES SYN1deg

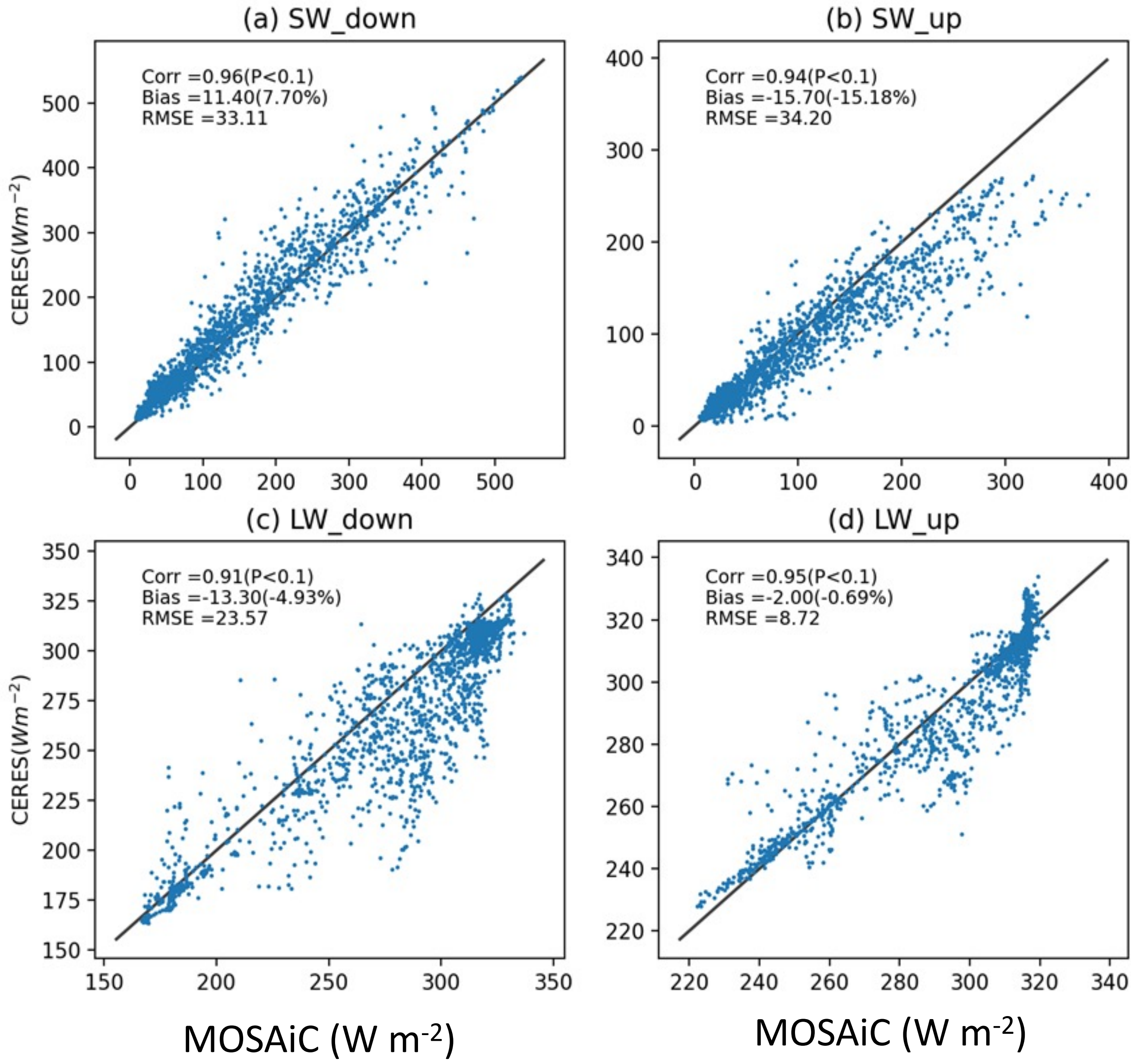


- CERES-MOSAiC differences in surface albedo are sea ice concentration dependent.
- Differences at lower sea ice concentrations is attributed to the smaller scale of the MOSAiC observations (~6 m^2 area), such that they only represent the sea ice portions of the CERES gridbox.

Radiative fluxes at the surface: MOSAiC asfs30 and CERES SYN1deg



Radiative fluxes at the surface: MOSAiC and CERES SYN1deg

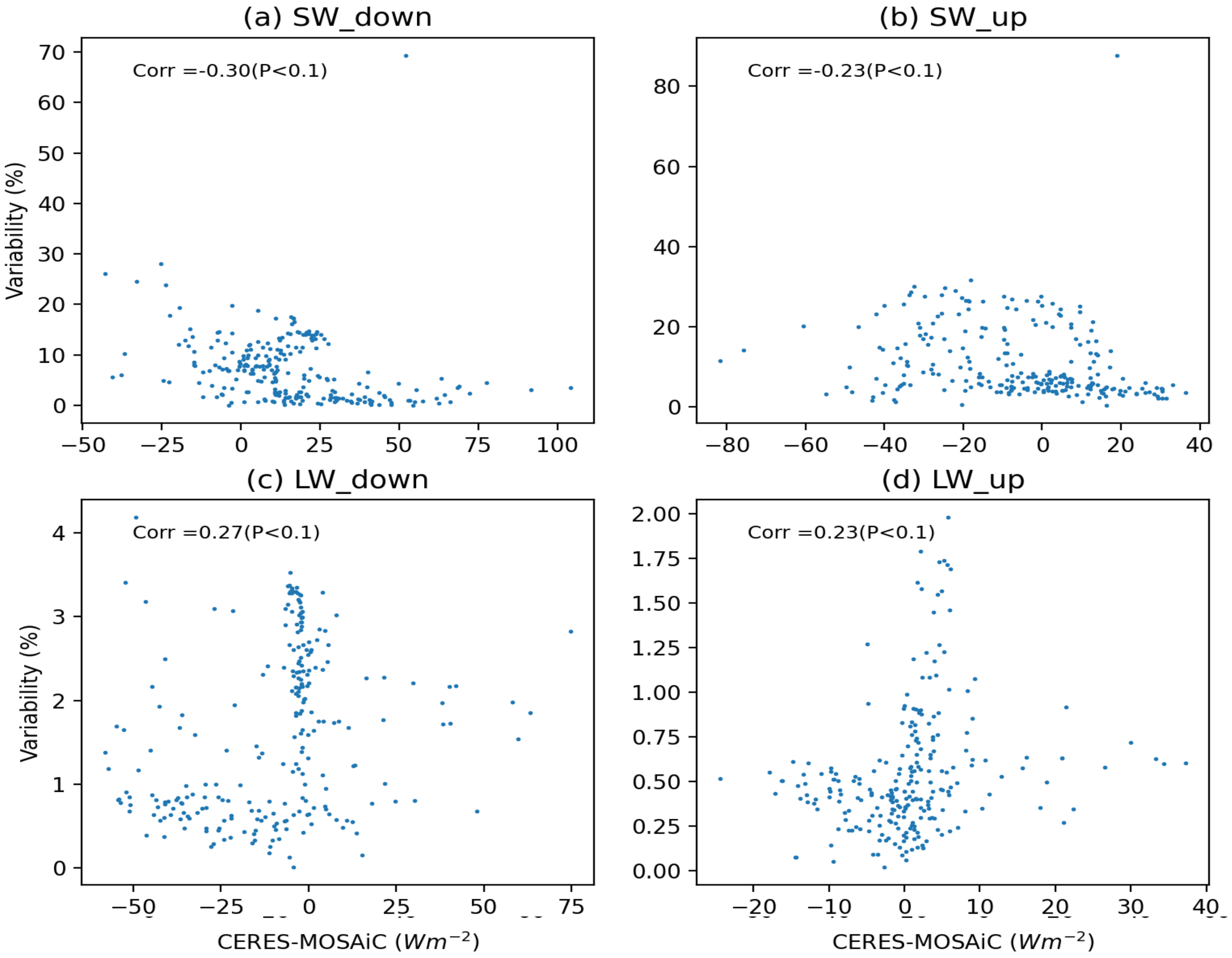


- The SYN1deg tends to overestimate SW_down flux, but underestimate SW_up and LW_down fluxes at the surface during summertime

- The SW_up flux is the most uncertain quantity

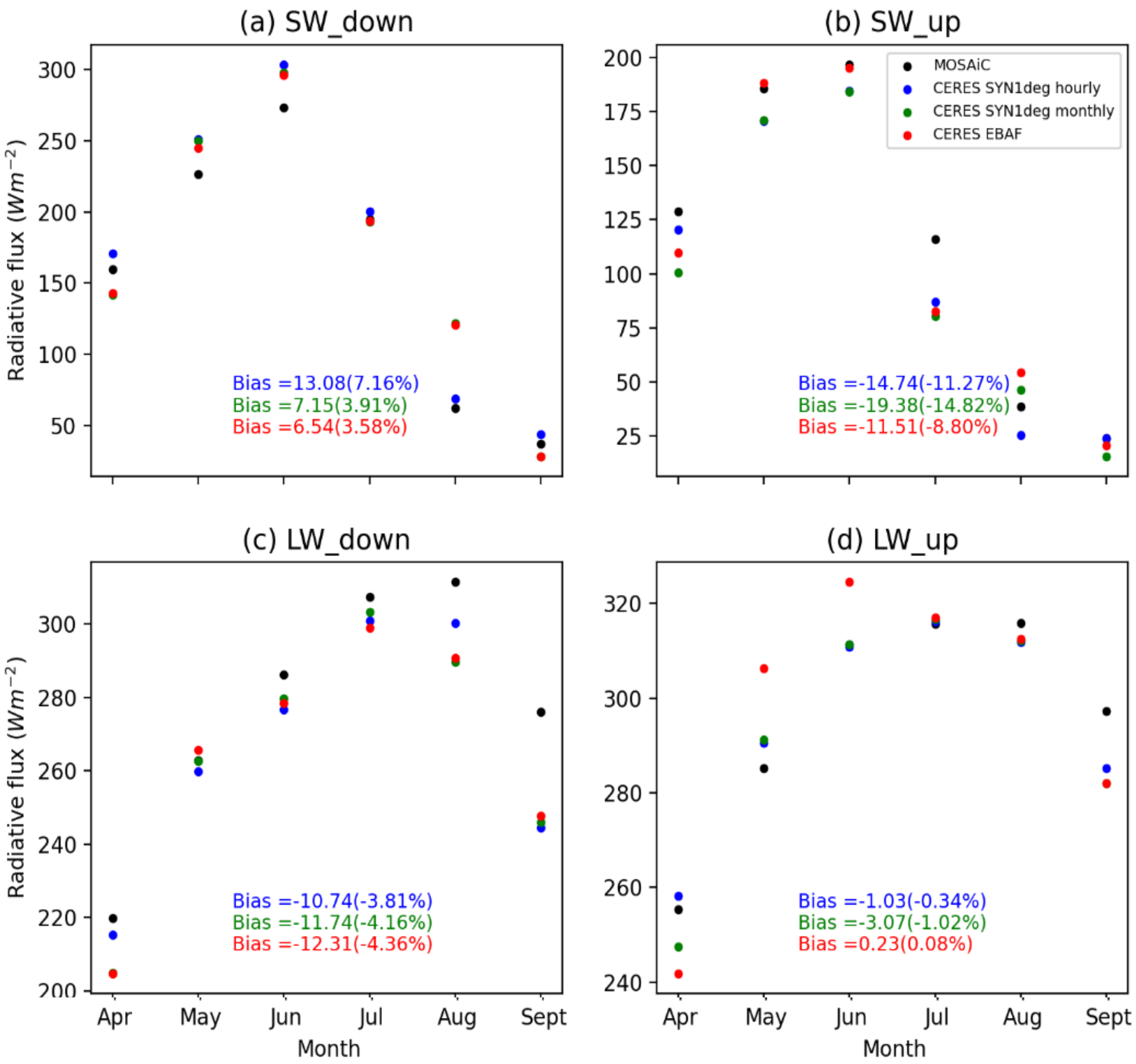
- Larger uncertainty in LW_up flux (~320W/m^2) occurs when the surface reaches melting point

Influence of spatial variability on MOSAiC and CERES SYN1deg differences



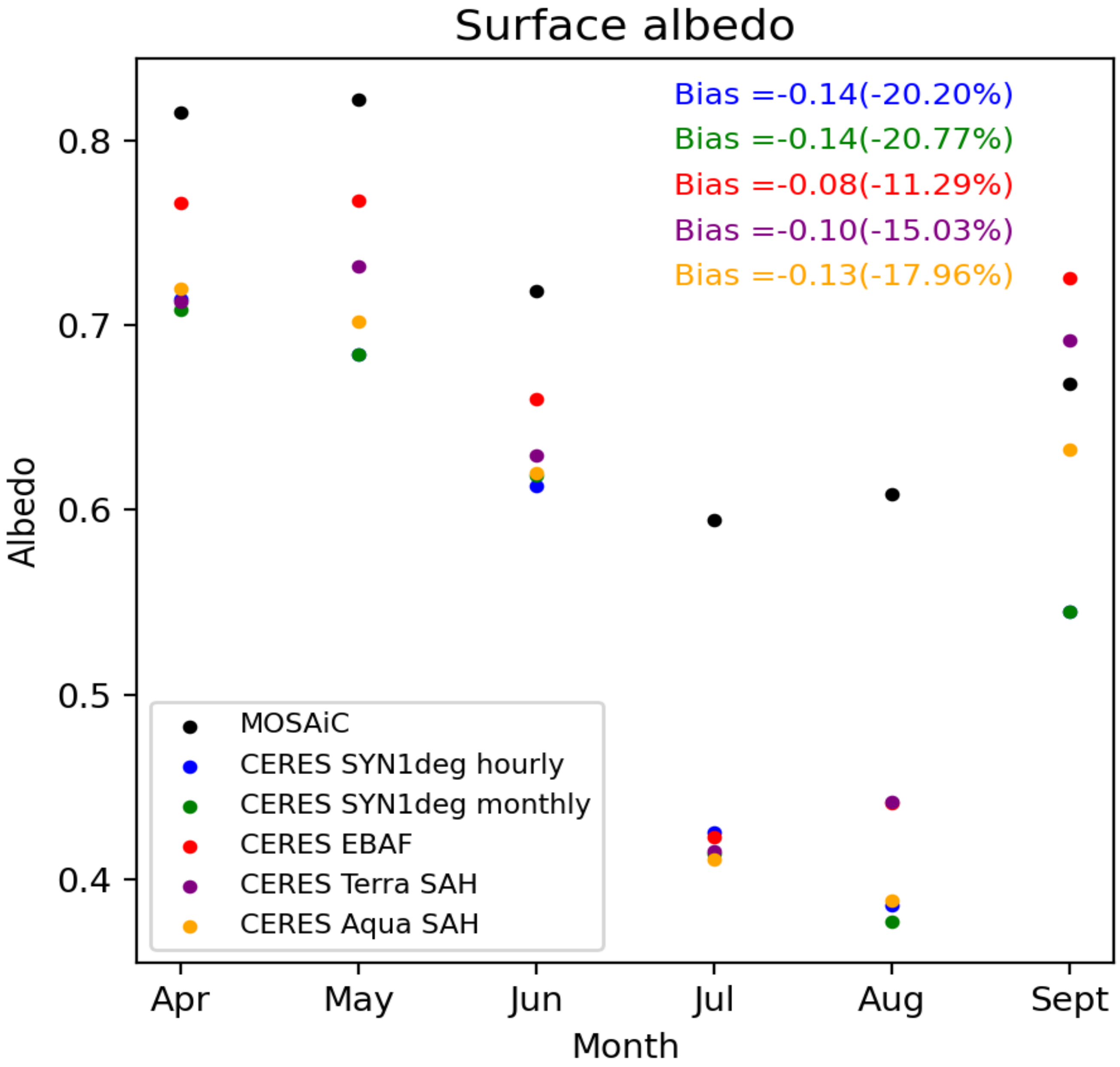
- Plots illustrate the correlation between CERES-MOSAiC differences and the magnitude of spatial variability.
- Variability (%) is quantified as the percent difference between two stations at a given hour.
- Results show a **slightly smaller** CERES-MOSAiC differences in the presence of **larger inter-surface site variability**.

Monthly Radiative Mean fluxes : MOSAiC and CERES SYN1deg



- Monthly mean CERES-MOSAiC fluxes differ between for CERES products (e.g., SYN 1deg and EBAF).
- SFC EBAF represents the smallest biases over the 6-month period but is not always the most accurate for an individual month.

Monthly Surface Albedo: MOSAiC and CERES SYN1deg

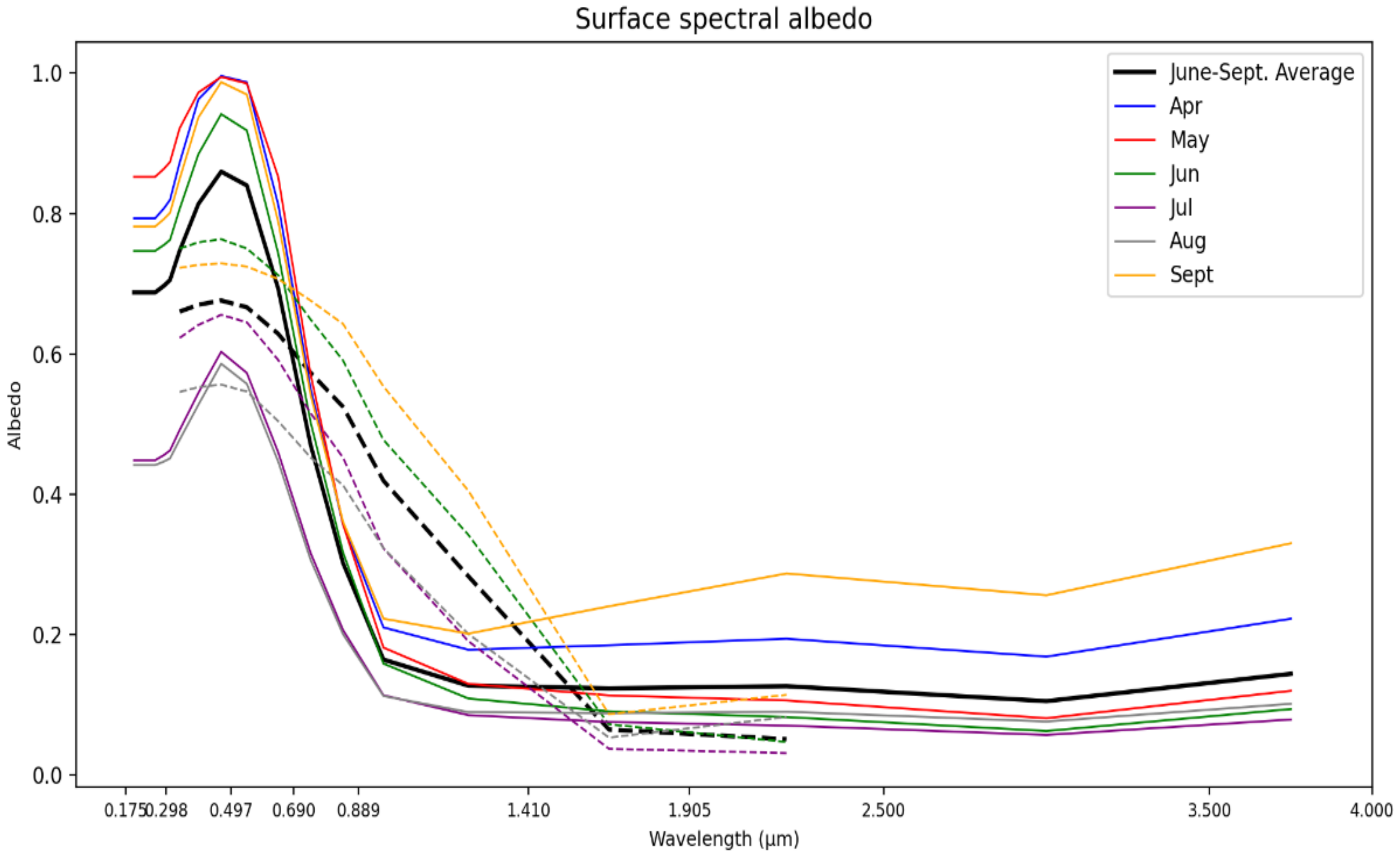


- This comparison shows the monthly mean surface albedo values over the MOSAiC domain for different CERES products and observations.
- Differences are found between the different CERES produces (e.g., SYN-1deg and EBAF)
- SFC EBAF again represents the smallest bias over the 6-month period but is not always the most accurate for an individual month.

Spectral Surface Albedo: MOSAiC and CERES SYN1deg

Solid—CERES (Jin 2004; LUT)

Dashed—MOSAiC observations (Perovich et al. 2021)



- Comparison reveals differences in the CERES surface spectral albedo shape model and the MOSAiC observations.

Understanding the contribution of surface albedo differences to CERES-MOSAiC differences

Radiative Transfer Experiments

Surface Albedo Effects

CERES-like Fu-Liou RTM calculations

Category	Variables	Sources
General model inputs	Number of model layers	4 layers
	Solar zenith angle	TSI files
	Solar insolation	Daily SORCE TSI files and earth-sun distance
	Solver method	**4-stream solver for SW and LW calculation**
	Other information (CO2,CH4,N2O, CFCs, correction to cosSZA, etc)	Values in year 2019
Atmospheric structure inputs	Pressure profile	MOA files (GEOS-5.4.1)
	Air temperature profile	
	Water vapor mixing ratio profile	
	Ozone mixing ratio profile	
	Surface skin temperature	
Cloud inputs	Cloud fraction, effective radius, optical depth, phase, particle size	TSI files (from MODIS)
Surface inputs	Spectral surface albedo	**JIN lookup table, daily sea ice concentration, and monthly Terra surface albedo history (SAH) map**
	Spectral surface emissivity	Determined by surface type
Aerosol inputs	Aerosol types and aerosol optical depth	MATCH aerosol hourly output

SYN1deg Ed4
Gamma-weighted Two-stream approximation (GWTSA)

SYN1deg Ed4
Terra/Aqua SAH monthly map

CERES-Like Fu-Liou Radiative Transfer Calculations

Obtain the ocean and sea ice spectral albedos using Jin look up tables (LUTS)

Combine ocean and ice albedo by weighting by scene fractions

Determine an approximate broadband albedo for the combined initial spectral albedo

Normalize to the SAH based hourly broadband albedo

SAH_monthly

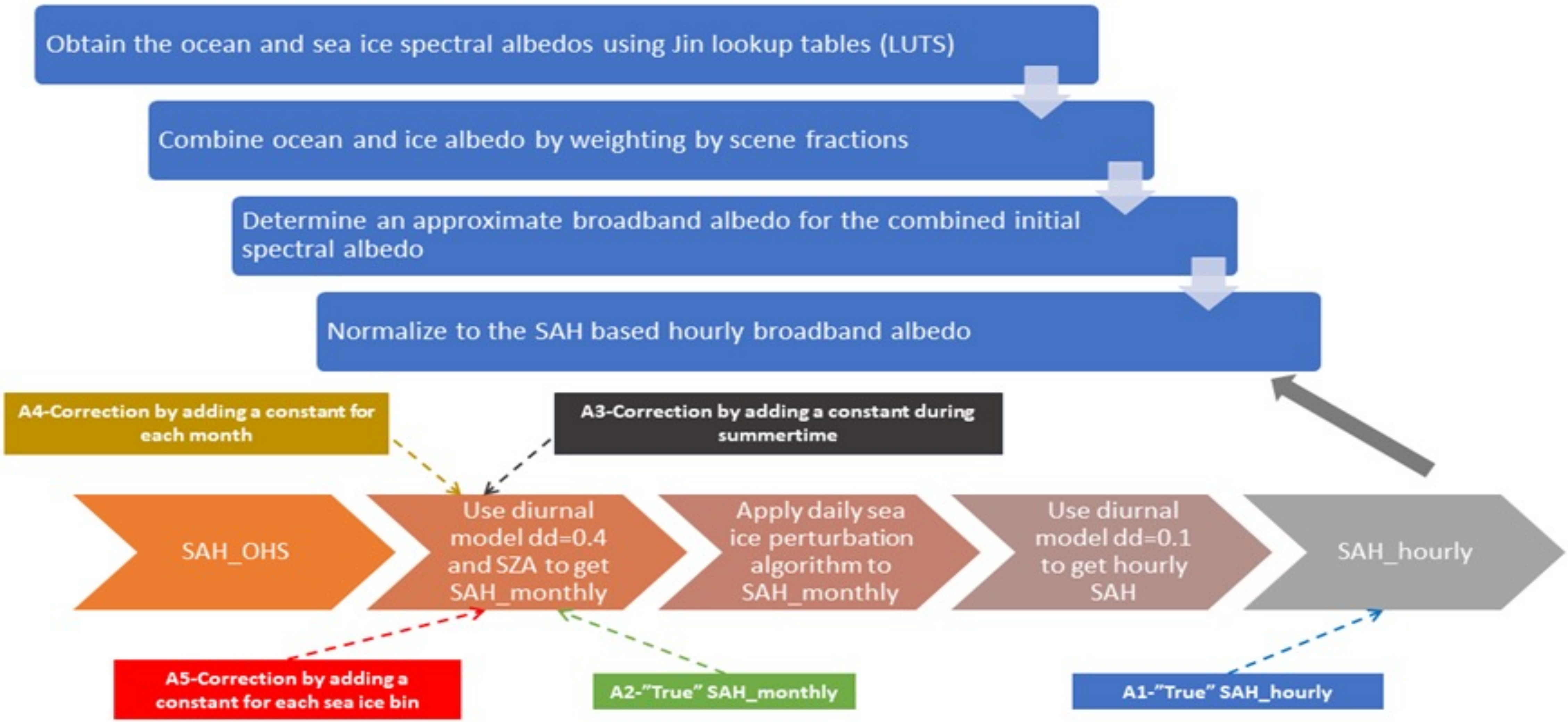
Use diurnal model dd=0.4 and SZA to get MEAN_SAH

Apply daily sea ice perturbation algorithm to MEAN_SAH

Use diurnal model dd=0.1 to get hourly SAH

SAH_hourly

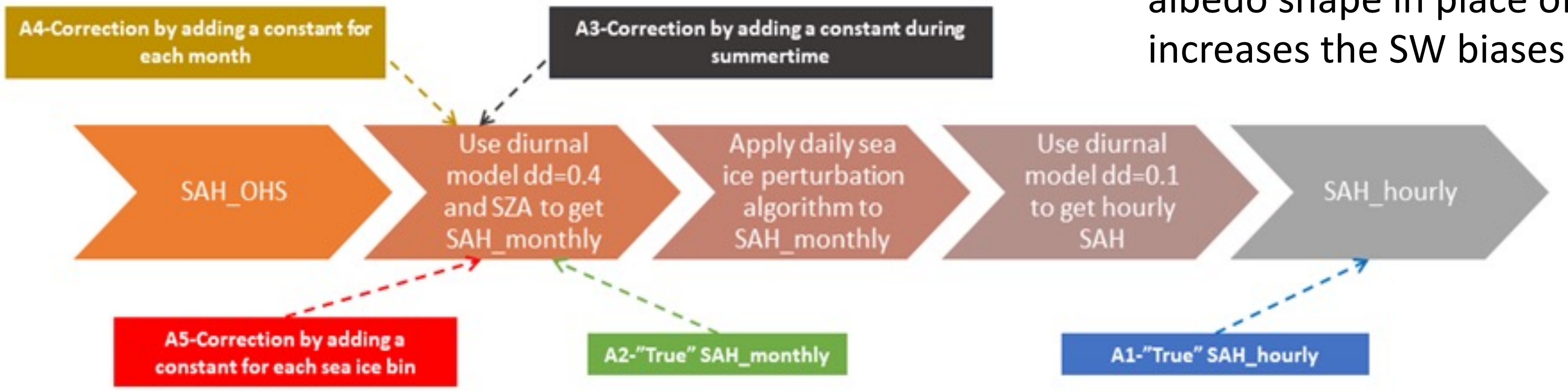
CERES-Like Fu-Liou Radiative Transfer Calculations: Perturbation Experiments



The SW differences between RTM and MOSAiC (W m^{-2})

Experiment	SW_down (RMSE)	SW_up (RMSE)
Control run	+7.88 (41.46)	-18.49 (38.31)
A1-"True" SAH_hourly	+17.51 (45.07)	+1.49 (32.61)
A2-"True" SAH_monthly	+14.37 (43.74)	-2.29 (32.27)
A3-correction by a constant in summer	+15.73 (44.52)	+2.46 (33.94)
A4-correction by adding a constant for each month	+16.22 (44.82)	+3.5 (34.48)
A5-Correction by adding a constant for each sea ice bin	+14.71 (44.00)	-0.24 (33.55)
A6-Monthly averaged spectral albedo from control run	+10.95 (44.09)	-15.11 (37.76)
A7-Monthly averaged spectral albedo from MOSAiC	+9.19 (42.88)	-18.04 (38.72)

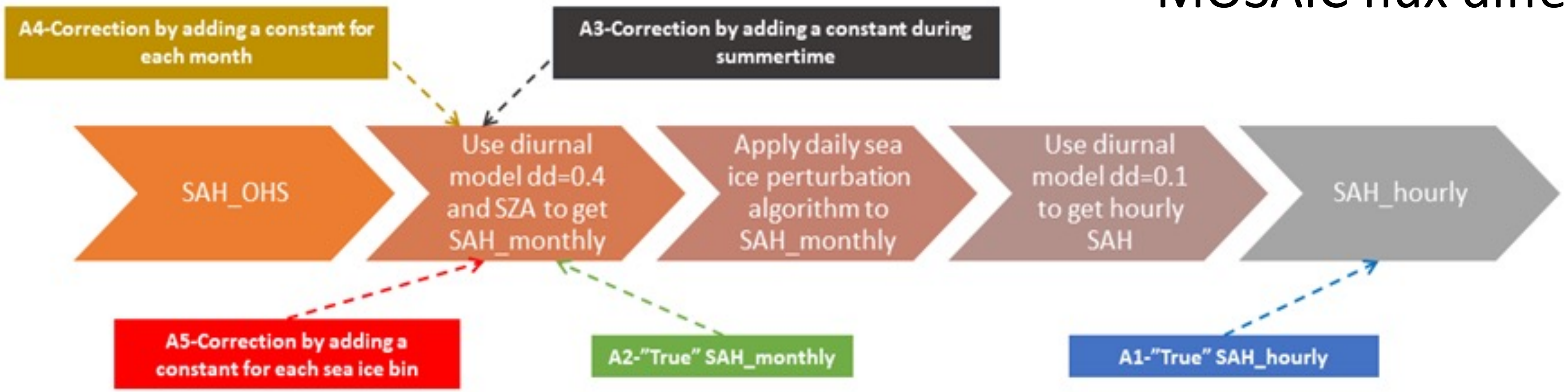
- Compared to M1 and M2, the monthly surface albedo history (SAH) bias contributes to ~**80**% of uncertainty in SW_up, while daily sea ice perturbation process accounts for ~**20%** of uncertainty
- Correcting SAH monthly map by adding a constant would be an efficient strategy to reduce SW_up biases during summertime
- The impacts of multiple reflections between clouds and highly reflective surface should be taken into consideration
- Using MOSAiC observed spectral surface albedo shape in place of the CERES-Jin LUT increases the SW biases by ~3 W m^{-2}



Summary of cloud-related perturbation experiments (Wm^{-2})

Experiment	SW_down	SW_up
Control run	+7.88 (41.46)	-18.49 (38.31)
A5-Correction by adding constant for each sea ice bin	+14.71 (44.00)	-0.24 (33.55)
C1-Increase cloud fraction by 1%	+14.23	-0.56
C2-Increase cloud fraction by 3%	+13.67	-0.93
C3-Remove the polar daytime cloud optical depth correction	+5.14	-5.51
C4-Combine C1 and C3	+4.60	-5.86
C5-Combin C2 and C3	+3.97	-6.28

- Each cloud property perturbation experiment is performed from the A5 experiment.
- Increasing cloud fraction and cloud optical depth improve the CERES-MOSAiC agreement for SW_down bias and degrade the agreement for SW_up.
- Both cloud properties and surface albedo differences make strong contributions to the CERES-MOSAIC flux differences.



Summary

- The SYN1deg tends to overestimate SW_down flux, but underestimate SW_up and LW_down fluxes at the surface during summertime
- The large negative bias in SW_up flux can be attributed to the underestimation of surface albedo in SYN1deg
- Correcting SAH monthly map by adding a constant number would be an efficient strategy to reduce SW biases during summertime
- It is important to consider the impacts of cloud biases (multiple reflection between clouds and reflective surface) when correct the surface albedo
- Larger uncertainty in LW_up flux (~320W/m^2) occurs when the surface reaches melting point (~0°C)
- The biases in surface wind and surface water vapor mixing ratio show a minor impact on SW and LW flux calculations

Photo credit: https://blogs.helmholtz.de/polarstern/en/2019/09/anchors-aweigh-for-mosaic-leg-1/

Arctic Radiation-IceBridge Sea ice Experiment (ARISE)

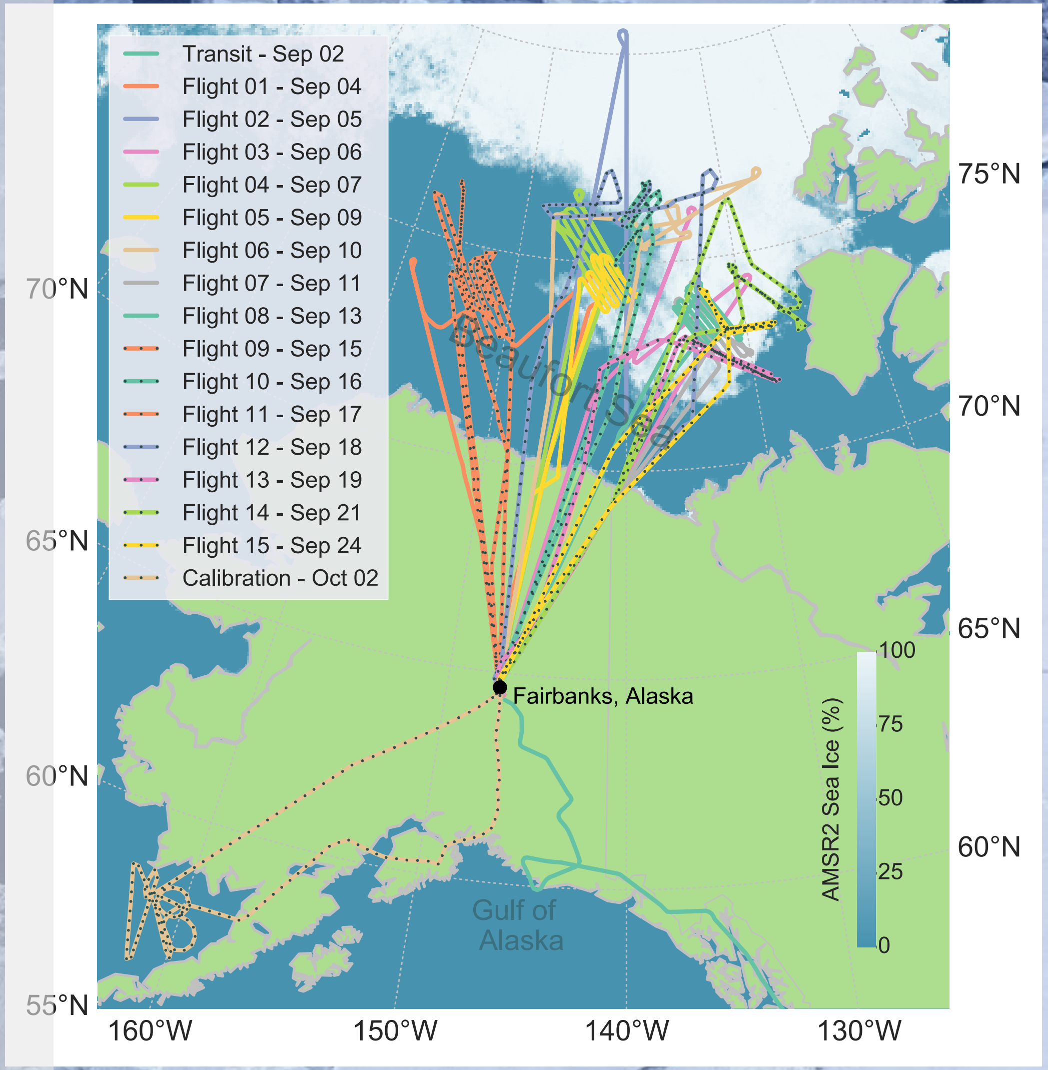
Based in Fairbanks, Alaska during September 2014

From the NASA C-130:

- Measure spectral and broadband radiative flux profiles
- Quantify surface characteristics, cloud properties, and other atmospheric state parameters under a variety of Arctic atmospheric and surface conditions
- Coincide with satellite overpasses as often as possible

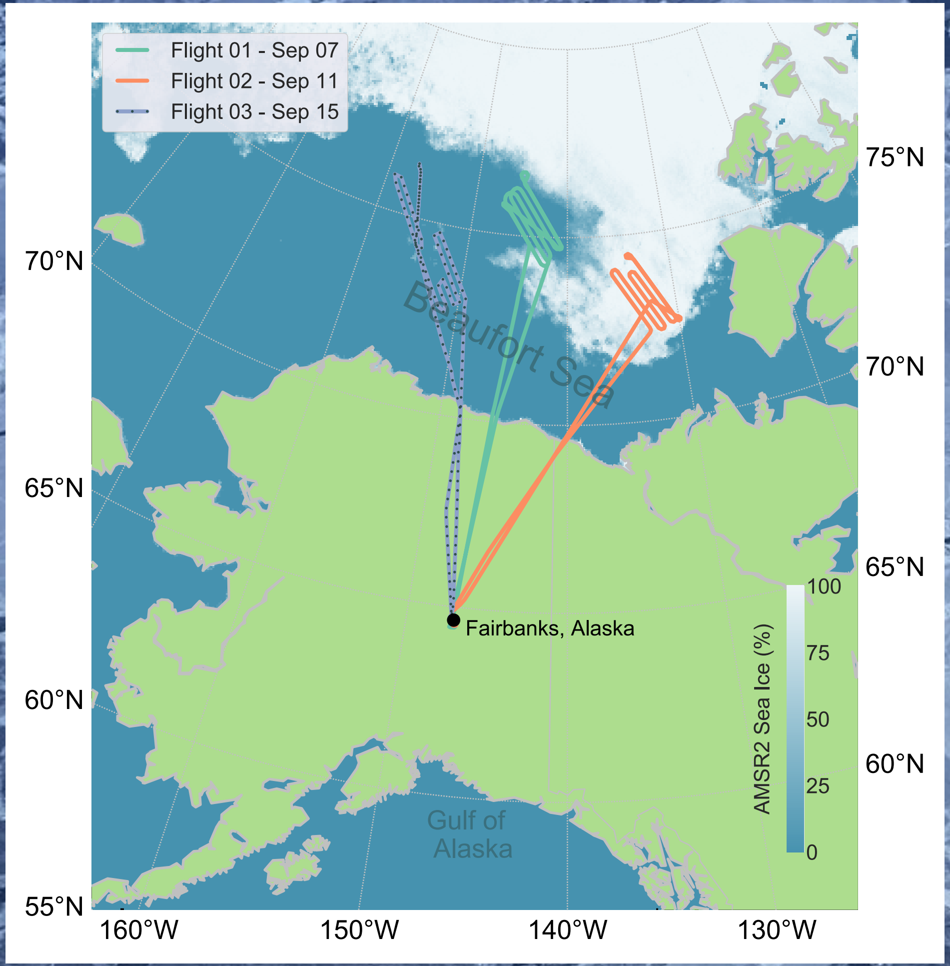
Naval Research Laboratory Broadband Radiometers (BBR):

- SW up and down – modified Kipp and Zonen CM-22 pyranometers
- LW up and down – modified Kipp and Zonen CG-4 pyrgeometers
- estimated uncertainty ~ 3-5%



NASA C-130: An airborne radiometer (thermometer) with in-situ probes and a laser altimeter to characterize the surface, atmosphere and radiative effects of sea-ice and clouds

ARISE TOA gridbox experiments:



Three flight days focus on CERES TOA gridbox experiments:

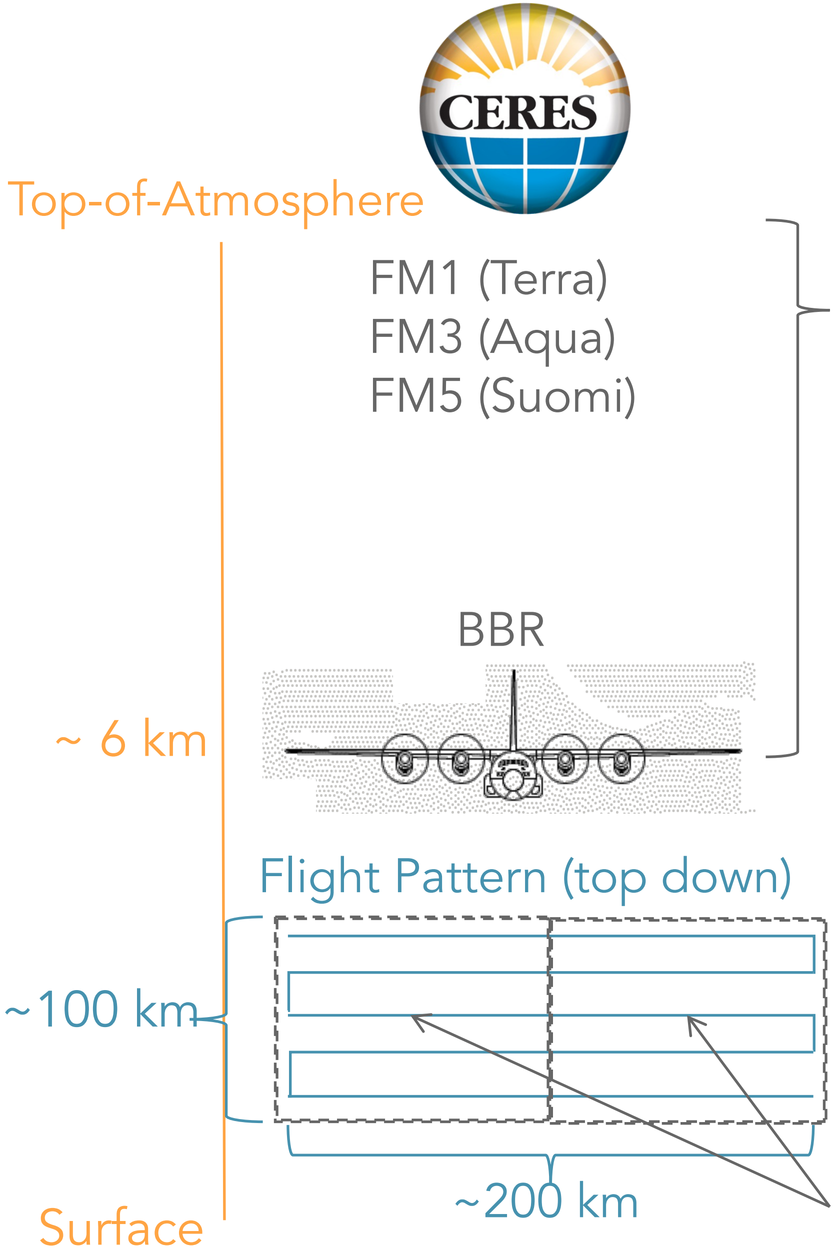
September 7, 2014: Marginal ice zone (two boxes)

September 11, 2014: High sea ice concentration (two boxes)

September 15, 2014: open ocean (one box)

A key ARISE objective was to evaluate CERES TOA and Surface data products.

CERES-Aircraft Comparison Methodology:



Need to account for:

LW - absorption

SW - scattering/absorption

Langley Fu-Liou Radiative transfer model:

- Atmospheric state information from GEOS 5.4.1
- Cloud property information from MODIS (CERES cloud group)
- Surface information from the AMSR2 ASI 3.5km sea ice concentration dataset (Uni. Hamburg)

To convert BBR from 6 km to TOA:

$$\text{BBR TOA} = (F(\text{TOA})_{\text{model}}/F(6\text{km})_{\text{model}}) \times \text{BBR}$$

Compare mean BBR TOA and mean CERES fluxes for each grid box

ARISE TOA gridbox experiments :

Overcast ocean

Partly cloudy sea ice

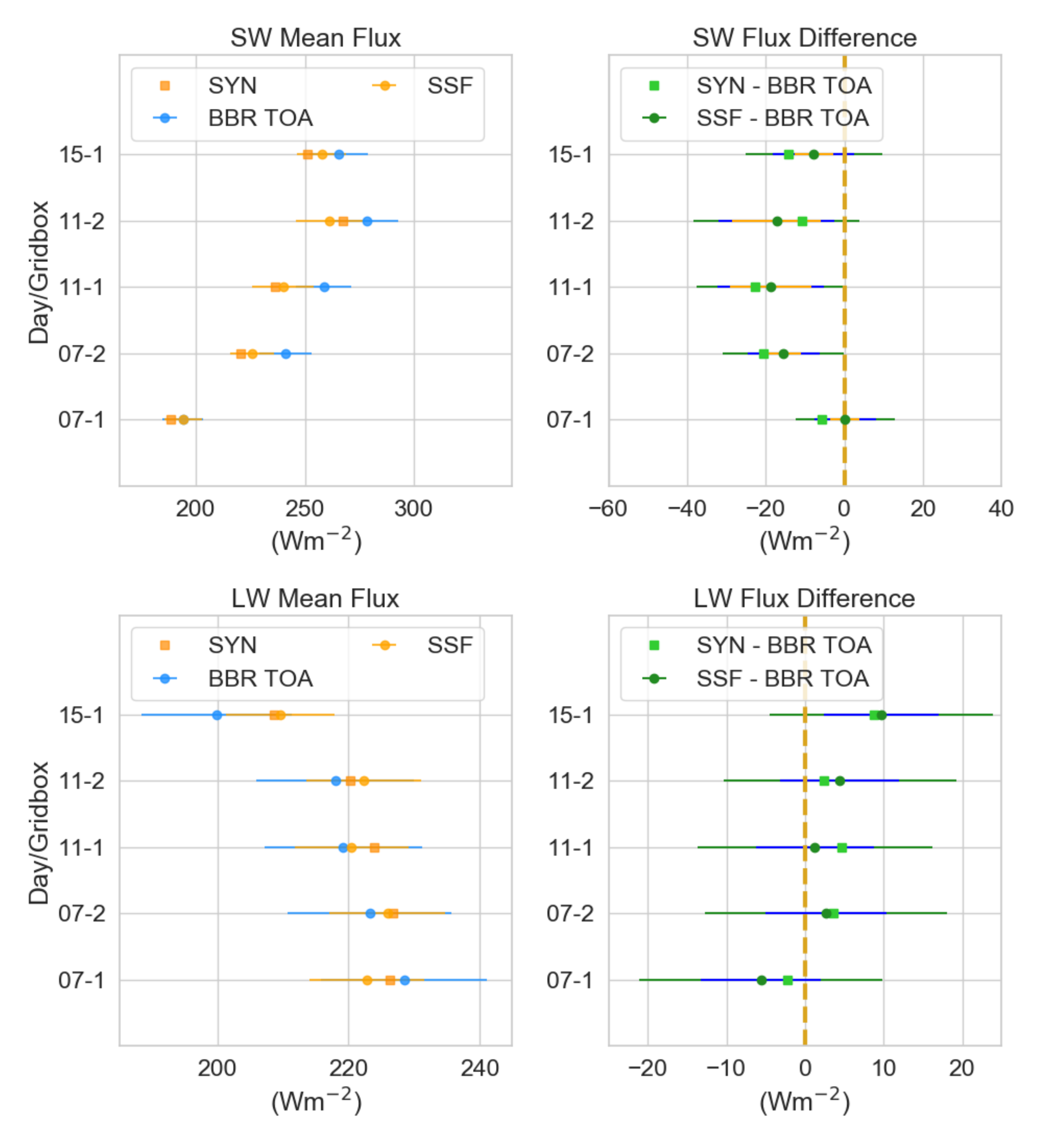
Overcast sea ice

Overcast MIZ

Overcast MIZ

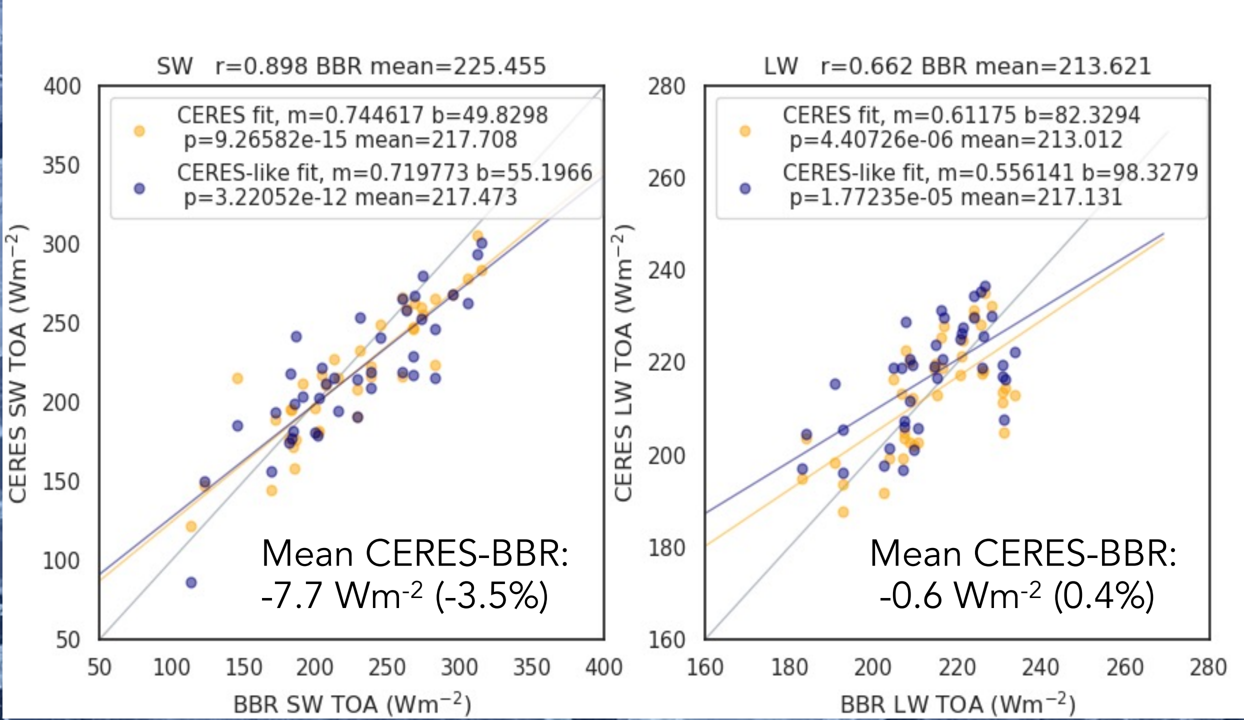
SW CERES-BBR mean difference: -13.0 Wm^{-2}
LW CERES-BBR mean difference: +2.5 Wm^{-2}

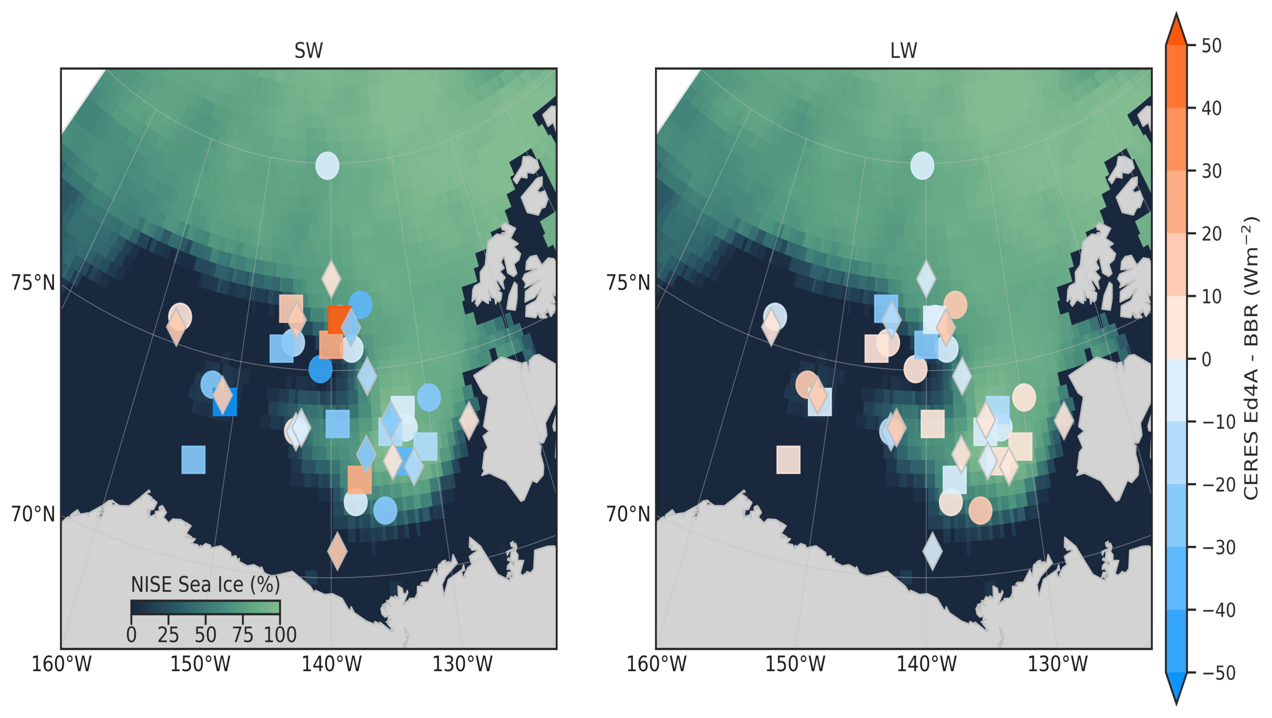
- LW shows good agreement for all grid-boxes (< +/- 2 Wm^{-2})
- SW shows agreement within uncertainty for 4/5 grid-boxes
- Cause of the negative biases?
    - Calibration
    - ADMs
    - Sampling



Instantaneous comparisons: 39 matched FOVs

- An alternative to the gridbox experiments is to compare only the instantaneous matches between aircraft and CERES FOVs
- Time match: within 15 minutes
- Despite the small number of samples, the overall results matches the gridbox experiments.





SW CERES-BBR mean difference: -7.7 Wm^{-2} (-3.5%)
LW CERES-BBR mean difference: -0.6 Wm^{-2} (0.4%)

Instantaneous comparisons: Stratifying by scene type

- An alternative to the gridbox experiments is to compare only the instantaneous matches between aircraft and CERES FOVs
- Time match: within 15 minutes
- Despite the small number of samples, the overall results matches the gridbox experiments.

ADM GROUP	N (count)	SSF-BBR SW Mean Difference (W m^{-2})	SW SSF STDEV (W m^{-2})	SSF NISE as imager –BBR Mean Difference (W m^{-2})	SW STDEV (W m^{-2})	CERES Ed4a LW Mean Difference (W m^{-2})	LW SSF STDEV (W m^{-2})
Ocean Cloudy	15	-0.8	17.6	-2.4 (12)	18.2	-1.9	11.2
Sea Ice Clear	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Sea Ice Partly Cloudy	9	-17.1	13.6	+9.2 (12)	17.1	1.9	7.4
Sea Ice Overcast	15	-9.1	29.3	-9.1 (15)	29.3	-0.9	11.0

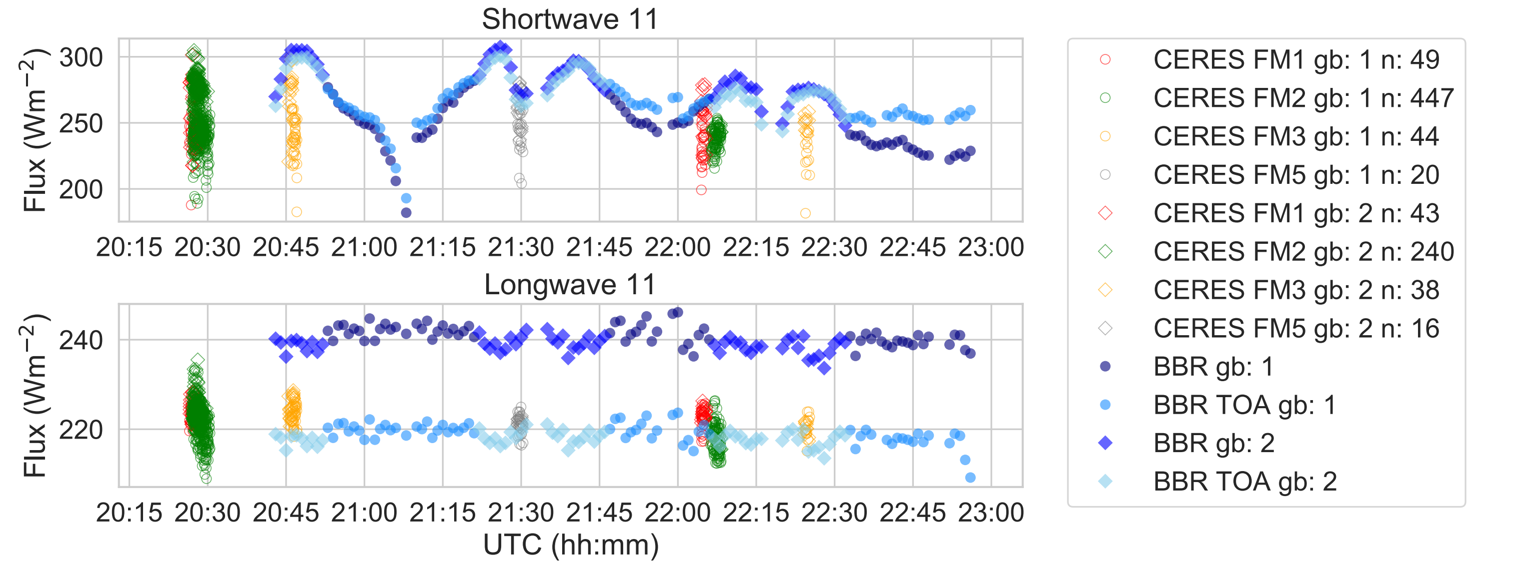
Largest difference are found in sea ice partly cloud scenes and the differences are sensitive to the choice of sea ice data set.

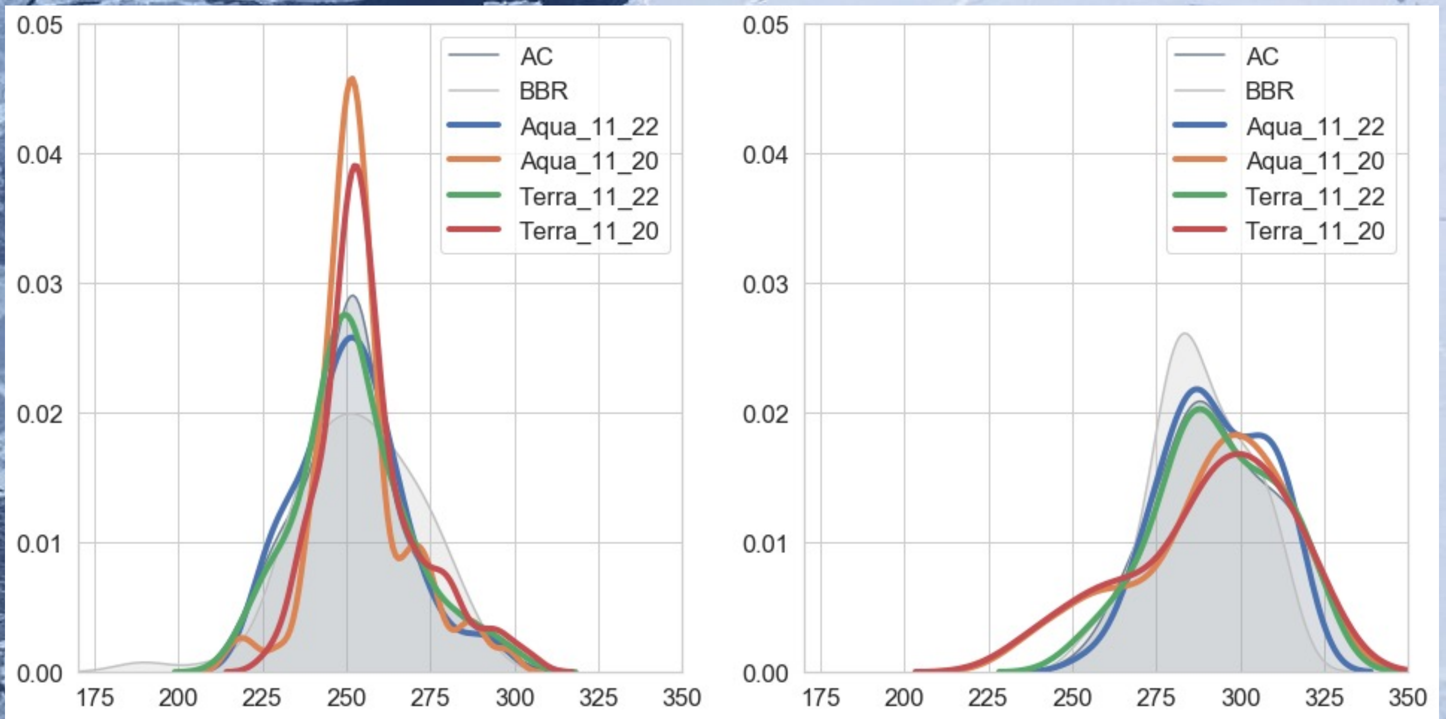
Sampling Uncertainty

Satellite sampling: grid box averages are computed from 3-4 near-instantaneous snapshots

Aircraft sampling: grid box average are computed from 2-hour continuous sampling of the grid box.

- These sampling differences could influence the CERES-BBR differences since the scenes are not static.

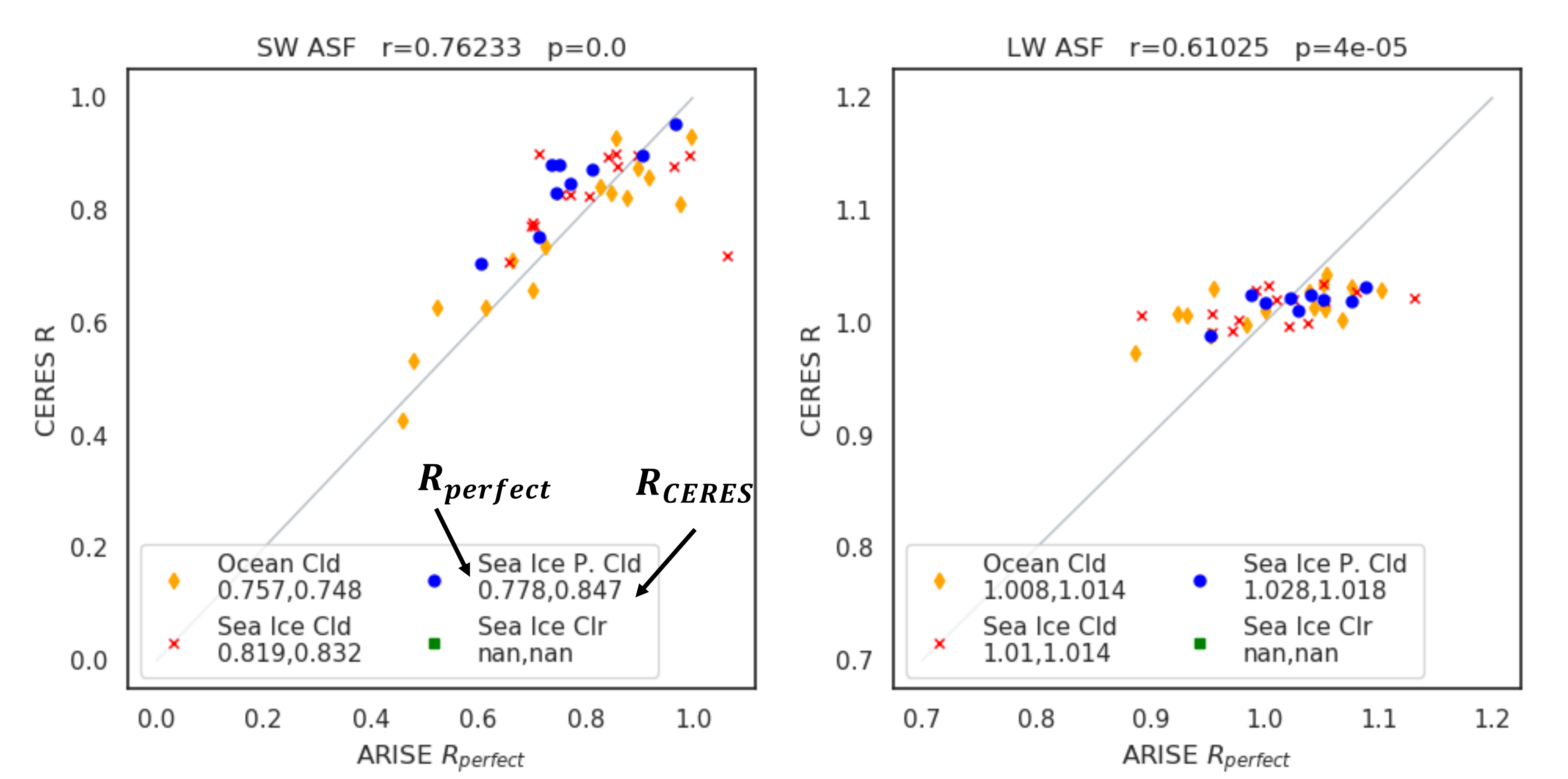




Results indicate a 1.8% and 1.7% sampling uncertainty for SW and LW, respectively.

Influence of sea ice data set: Perfect Anisotropy (R)

$$R_{perfect} = \frac{\pi ICERES}{BBR_{TOA}}$$



R_{CERES} is systematically ~0.07 larger than $R_{perfect}$ for the sea ice partly cloudy scenes indicating that the anisotropy differences contribute to the negative SSF-BBR flux differences. Using NISE as imager removes this difference.

Summary

- The gridbox sampling/validation approach proved successful during ARISE
  - LW TOA shows good agreement – all differences within the uncertainty.
  - SW TOA not quite as good – 4/5 within the uncertainty.
  - Consistent negative CERES SW difference relative to Aircraft Observations.
- Instantaneous CERES FOV and Aircraft comparison provide similar results.
- Why the negative SW bias?
  - Not Sampling differences (~1.7-1.8%)
  - Scene ID…we find substantial sensitivity of the differences to the sea ice data set
  - ADMs…evidence that sea ice partly cloud scene anisotropy could contribute
- Five data points is not enough to make strong claims about any biases – more experiments needed (in the future, leverage MOSAiC)

- Switching from imager-based to passive microwave-based sea ice data in the CERES inversion process reduces the differences in the grid box average fluxes and in the sea ice partly cloudy scene anisotropy in the instantaneously-matched footprints.

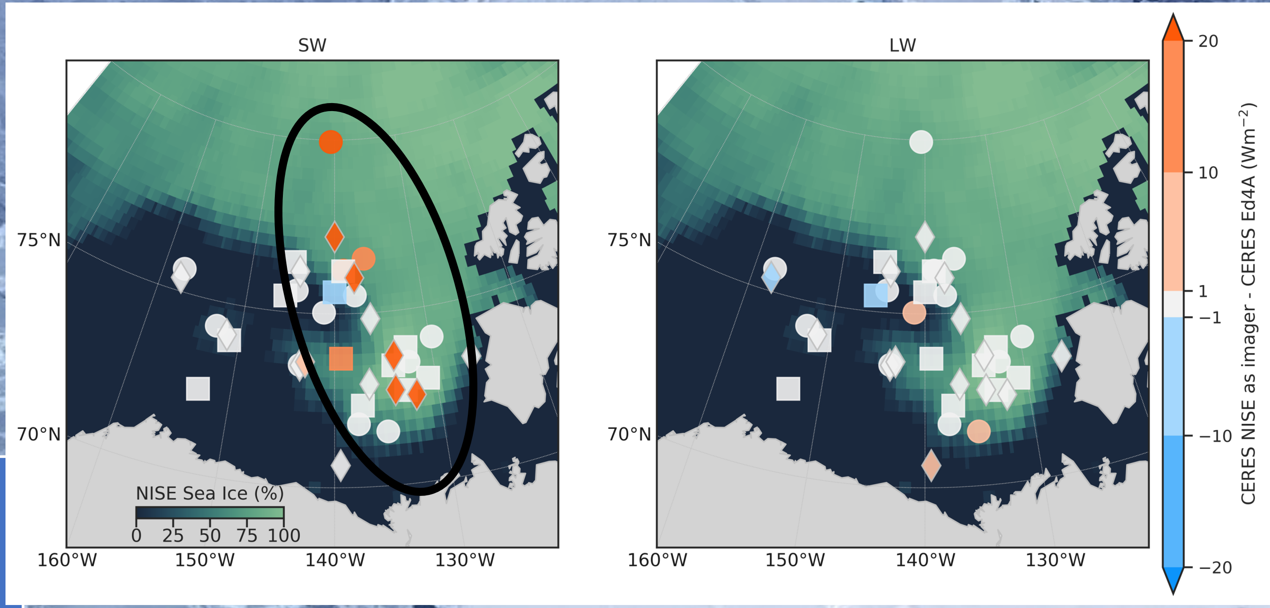
- Our analysis indicates that calibration and sampling uncertainty limit the ability to place strong constraints (<±7%) on CERES TOA fluxes with aircraft measurements.

NASA C-130 PAYLOAD

Instruments	Measurement	Characteristics	Products
Broadband Radiometers (BBR) A. Bucholtz, NRL	SW and LW fluxes (↑, ↓) SW total, direct & diffuse (↓)	SW: modified K&Z CM-22 (0.2-3.6 μm) LW: modified K&Z CG-4 (4.5-45 μm) TDDR: Delta-Devices SPN-1 (0.4-2.7 μm)	Net SW, LW Irradiance, direct/diffuse SW partitioning, absorption, heating rates Surface albedo, cloud albedo
Spectral Solar Flux Radiometer (SSFR) S. Schmidt, U. of Colo.	Spectral SW fluxes (↑, ↓)	370-2170 nm, Resolution: 8-12 nm	Spectral fluxes, albedo Cloud properties
Spectral Sun-photometer 4STAR J. Redemann, NASA ARC	Spectral radiances (↓) Modes: direct beam, sky scanning, zenith	380-1700 nm	aerosols, gases, cloud properties above aircraft
Heitronics KT-19 D. Van Gilst, NSERC/UND A. Bucholtz, NRL	IR window radiance (↑, ↓)	9.6-11.5 μm	Skin temperature, sky and cloud temperature
Land, Vegetation, and Ice Sensor (LVIS) B. Blair, M. Hofton, GSFC	Geo-located waveform vector	1064 nm Scanning: 20-minute footprint, 2 km swath from 10 km, Full waveform recorded	Surface elevation, Sea-ice freeboard, Melt-pond distribution Cloud top height

Influence of sea ice data set: Ed4a Imager-based vs. NISE

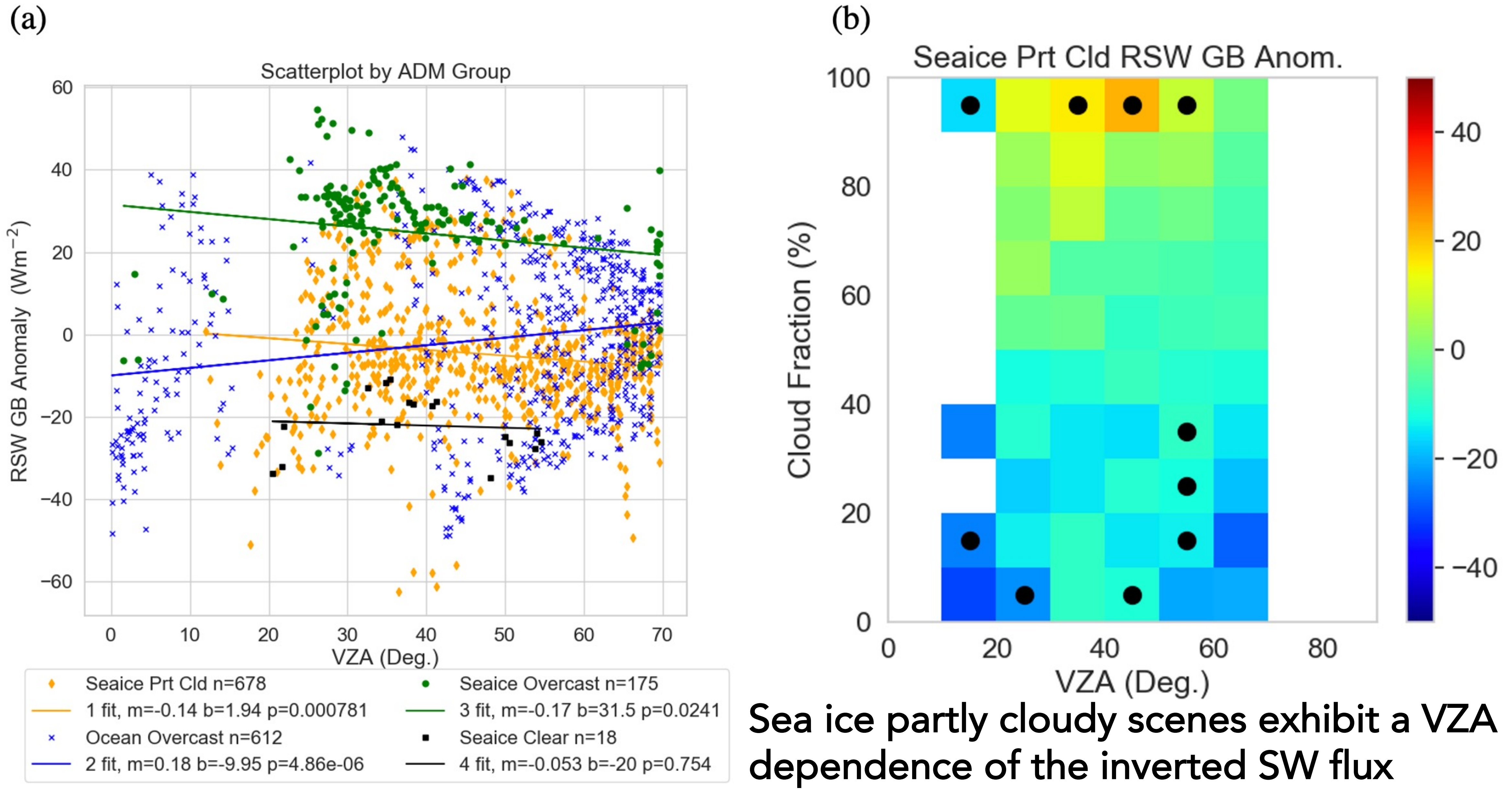
Changing the sea ice data set influenced the mean flux of 2 GBs by -3 and +10 Wm^{-2}.



GB	SIC (%)	Imager SIC (%)	CERES SSF SW (Wm^{-2})	SSF Ed4a minus NISE as SIC (Wm^{-2})	FM1: Ed4a NISE as SIC (Wm^{-2})	FM2: Ed4a NISE as SIC (Wm^{-2})
071	9.8	85.4	195.1	0.0	0.0	0.0.
072	16.9	74.2	227.0	-0.3	-0.4	-0.2
111	86.3	43.4	240.2	0.1	-30.6	+6.2
112	77.3	84.1	274.3	-12.3	-19.7	-10.9
151	0.3	99.7	257.3	0.0	0.0	n/a

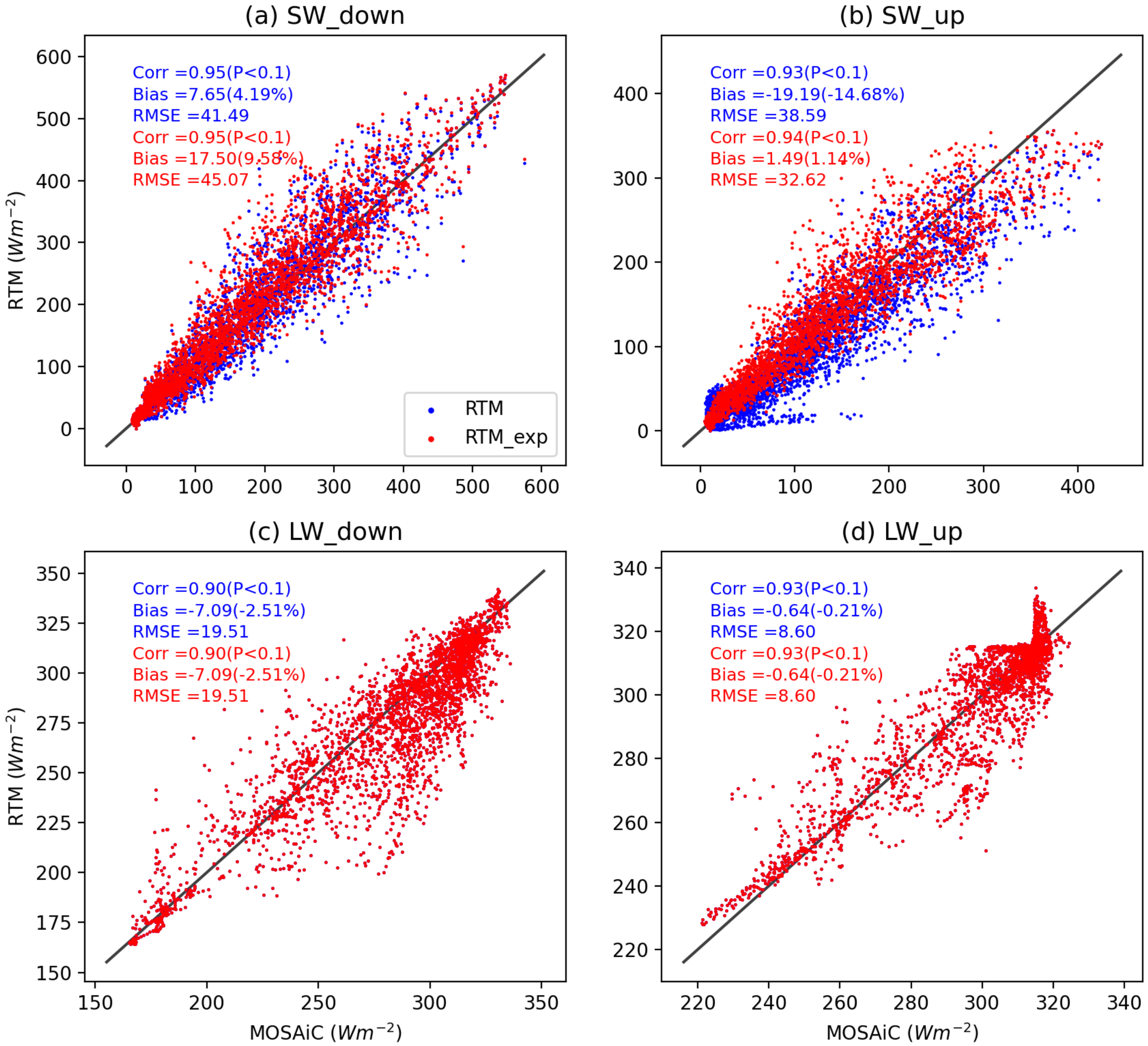
The sea ice data set changed the SW fluxes for 10 of the instant match footprints, making all but one of them more positive (ranging from -2.1 to 44.0 Wm^{-2}).

CERES Flux Inversion: VZA Dependence



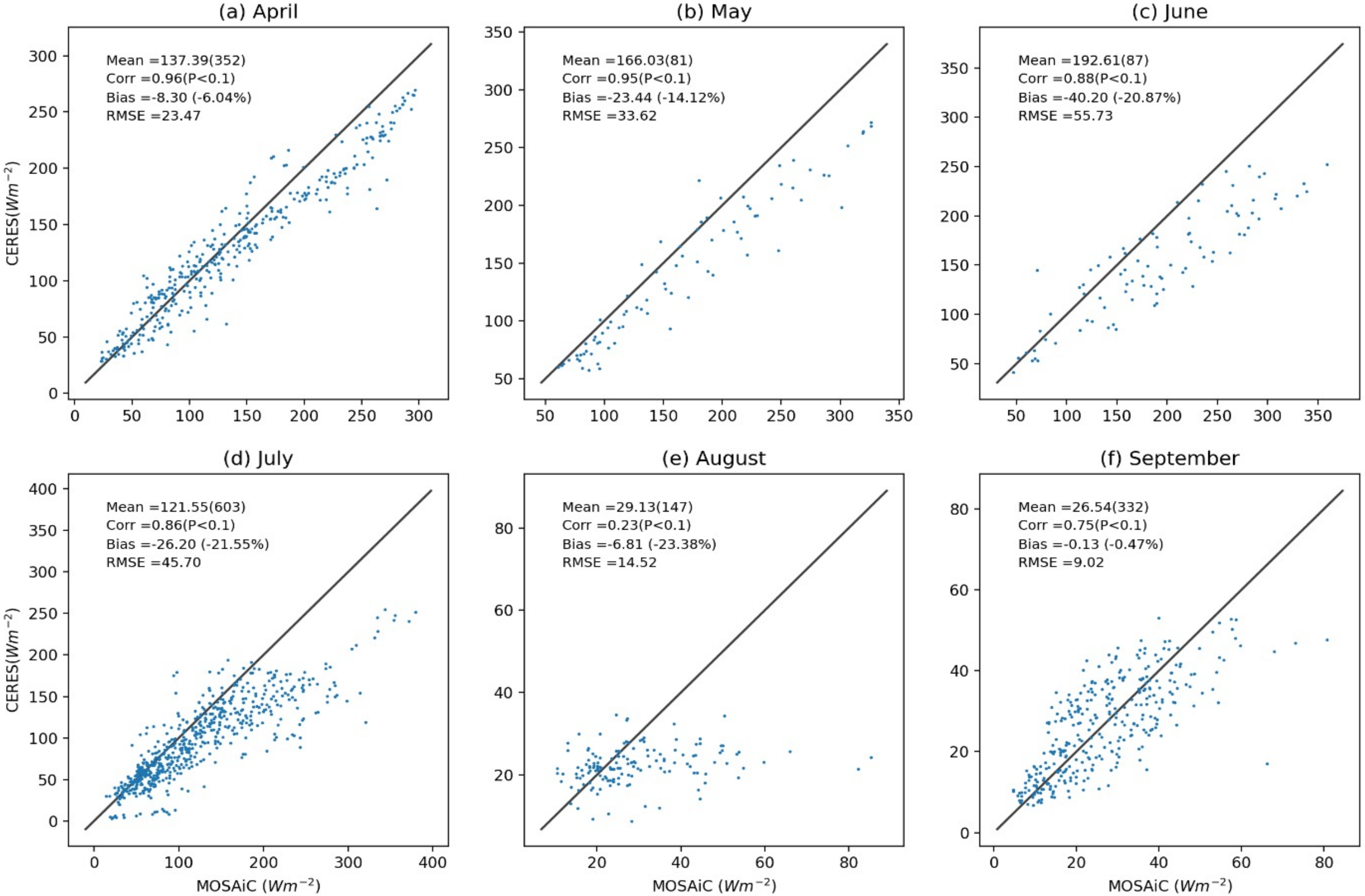
Sea ice partly cloudy scenes exhibit a VZA dependence of the inverted SW flux

Surface albedo calculations in the RTM – A1



- The uncertainty in SW_up flux was reduced by ~15%, while the uncertainty in SW_down flux was increased by ~8% (RMSE)
- No impacts on LW fluxes

Monthly SW_up fluxes at the surface: MOSAiC and CERES SYN1deg



- CERES-MOSAiC differences in SW_up vary significantly from month-to-month ranging from -0.13 to -40 W m^{-2}.
- These differences are primarily linked to the differences in surface albedo.