Application of a two-layer snow model to shortwave surface energy budget calculations

Ping Yang, Masanori Saito
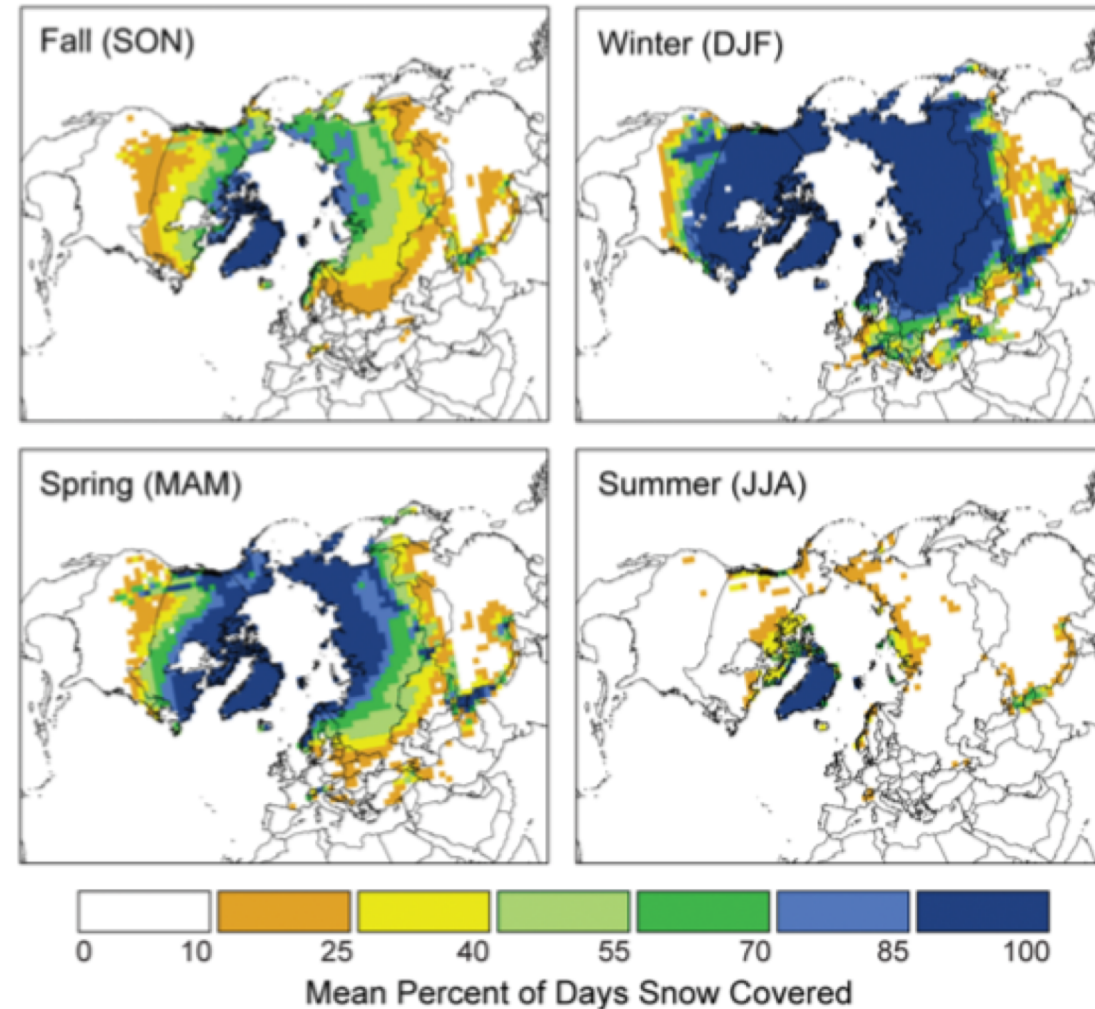
Texas A&M University

in collaboration with

N. Loeb, W. Smith Jr., S. Kato, P. Minnis

Snow Cover

Seasonal Northern Hemisphere SCE Climatologies 1981-2010

Fall (SON) — Winter (DJF) — Spring (MAM) — Summer (JJA)

Mean Percent of Days Snow Covered
0 10 25 40 55 70 85 100

- Large snow-cover areas in the Northern Hemisphere

- Significant seasonal variability

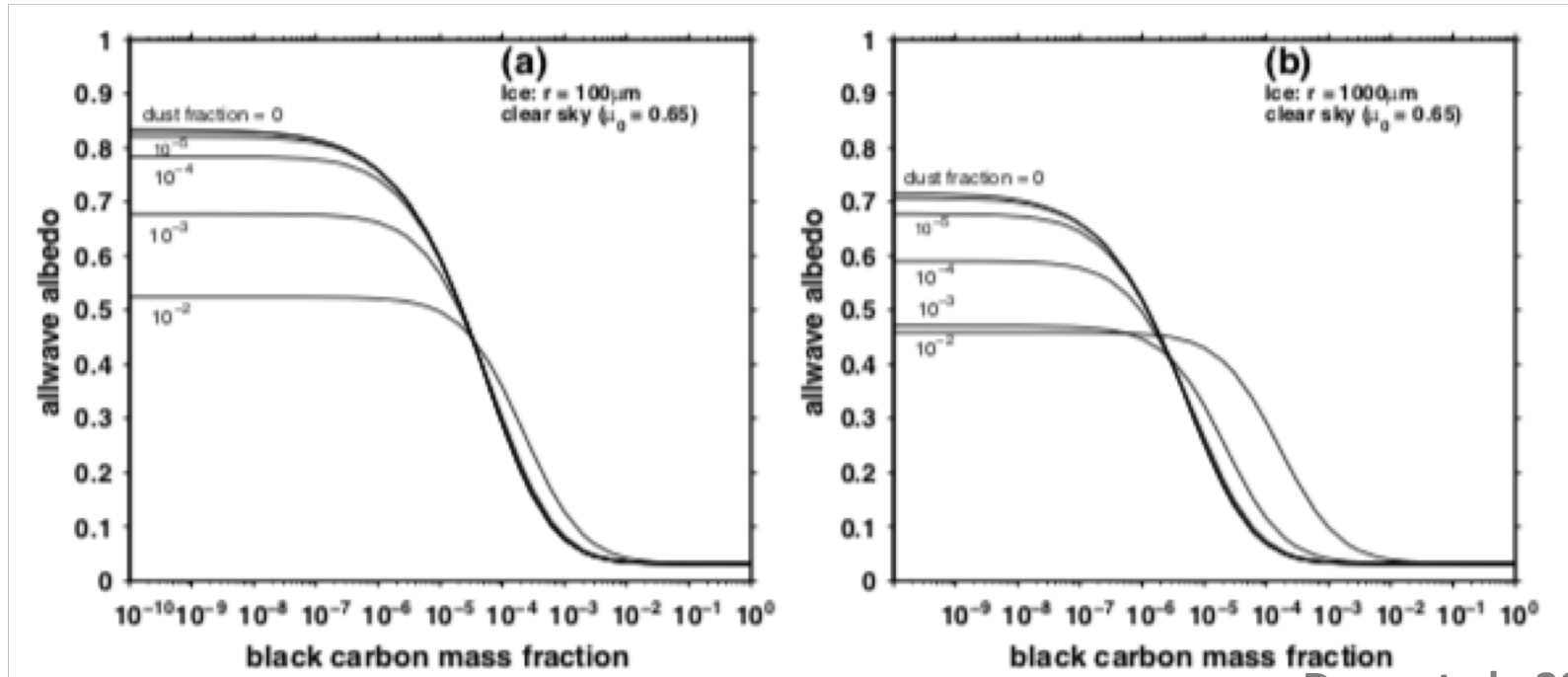- Snow albedo plays a critical role in surface radiation budget

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Snow Albedo Reduction
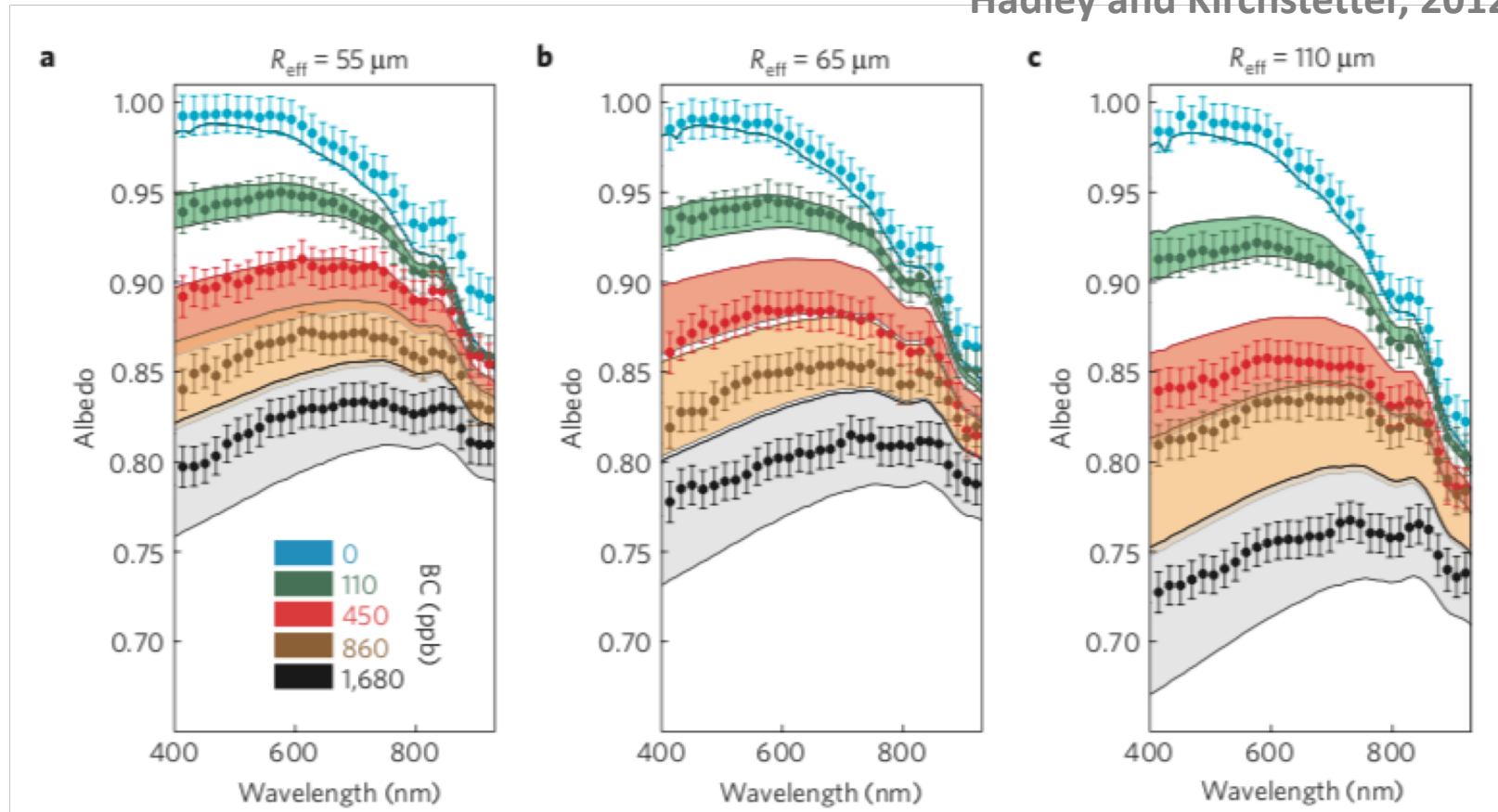
- Large variability of snow albedo depending primarily on:
    1. Black carbon (BC) mixture
    2. Snow grain size
- → Rigorous snow albedo modeling is essential in GCMs

# "Simple" Snow Albedo Parameterization

Dang et al., 2015 JGR

- External mixing of impurities (Warren and Wiscombe, 1980)

- BC internal mixing considered via the use of the effective index of refraction (Flanner et al., 2012)

- BC internal mixing + single nonspherical snow shape + mono-disperse PSD for BC (He et al., 2017, 2018)

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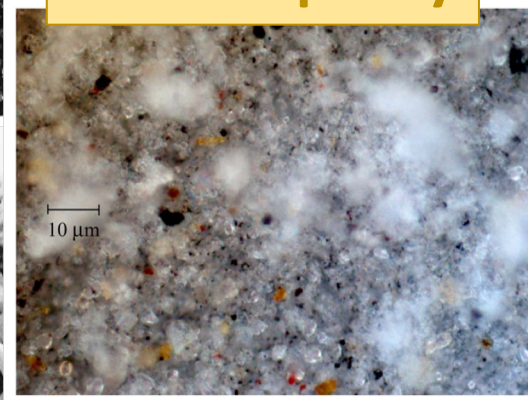# Complex Shapes & Snow Structure

Actual surface snow is more complex!

Fresh Snow
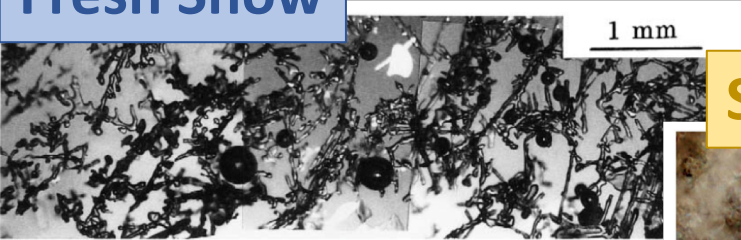
Aged Snow

Snow Impurity

Grenfell et al., 2011

Nakamura et al., 2001

z, mm	r, μm
0	52
10	122
20	171
50	169
100	192
150	138
200	195
250	196
350	247
450	208
550	189
650	209

Grenfell et al., 1994

- Snow particles have various shapes and sizes

- Surface snow has a vertically inhomogeneous structure

➔ Consider snow layering

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New Snow Particle Model

Saito, Yang, Loeb, and Kato (2019): A novel parameterization of snow albedo based on a two-layer snow model with a mixture of grain habits, *J. Atmos. Sci.*, in press
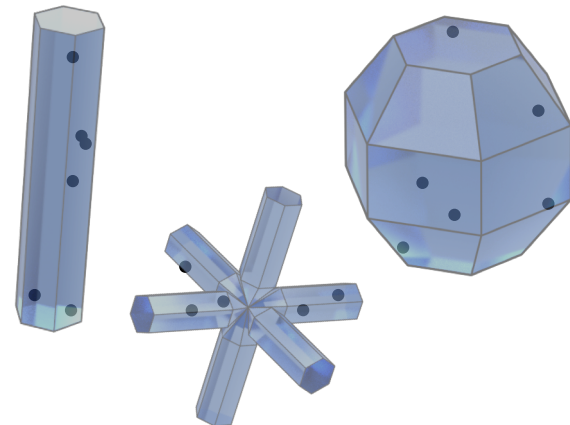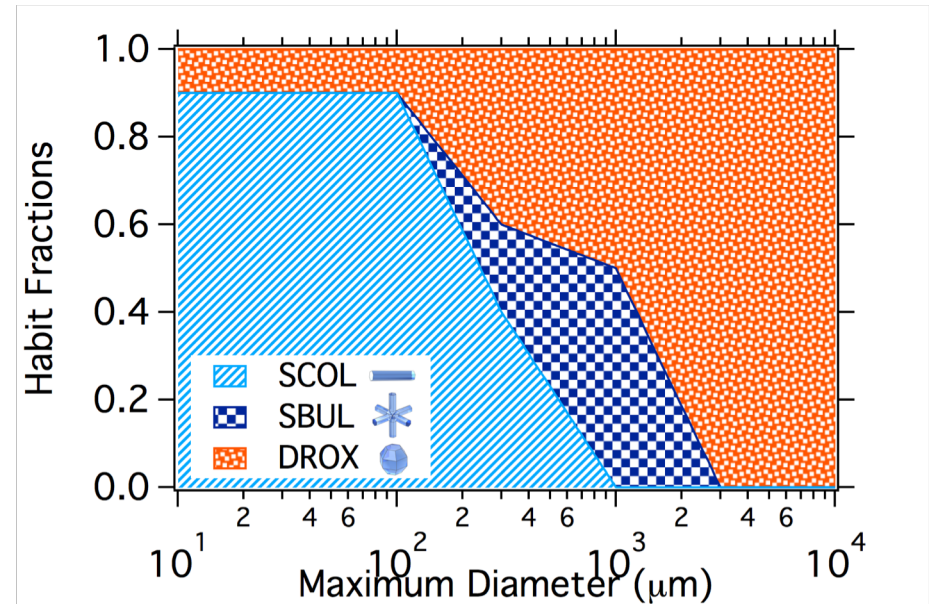
Snow Particle Model

- Mixture of three snow particle habits/shapes

- Inclusion of BC particles with a gamma PSD with $r_{eff} = 0.1$ µm

Snow Particle Size Distribution (PSD)

- PSD is parameterized based on in-situ snow measurements

→ **Characterize complex snow properties**

Objectives

- Evaluate potential biases of snow albedo due to neglecting snow layering.

- Investigate a potential bias in the surface SW net flux due to neglecting snow layering by using the Ed4 Langley Fu-Liou model in conjunction with the present two-layer snow albedo parameterization.

Expected significance:

A reduction of uncertainty in estimating surface radiation budget associated with snow albedo variability.

Ed4 Langley Fu-Liou RTM

Radiative transfer solver

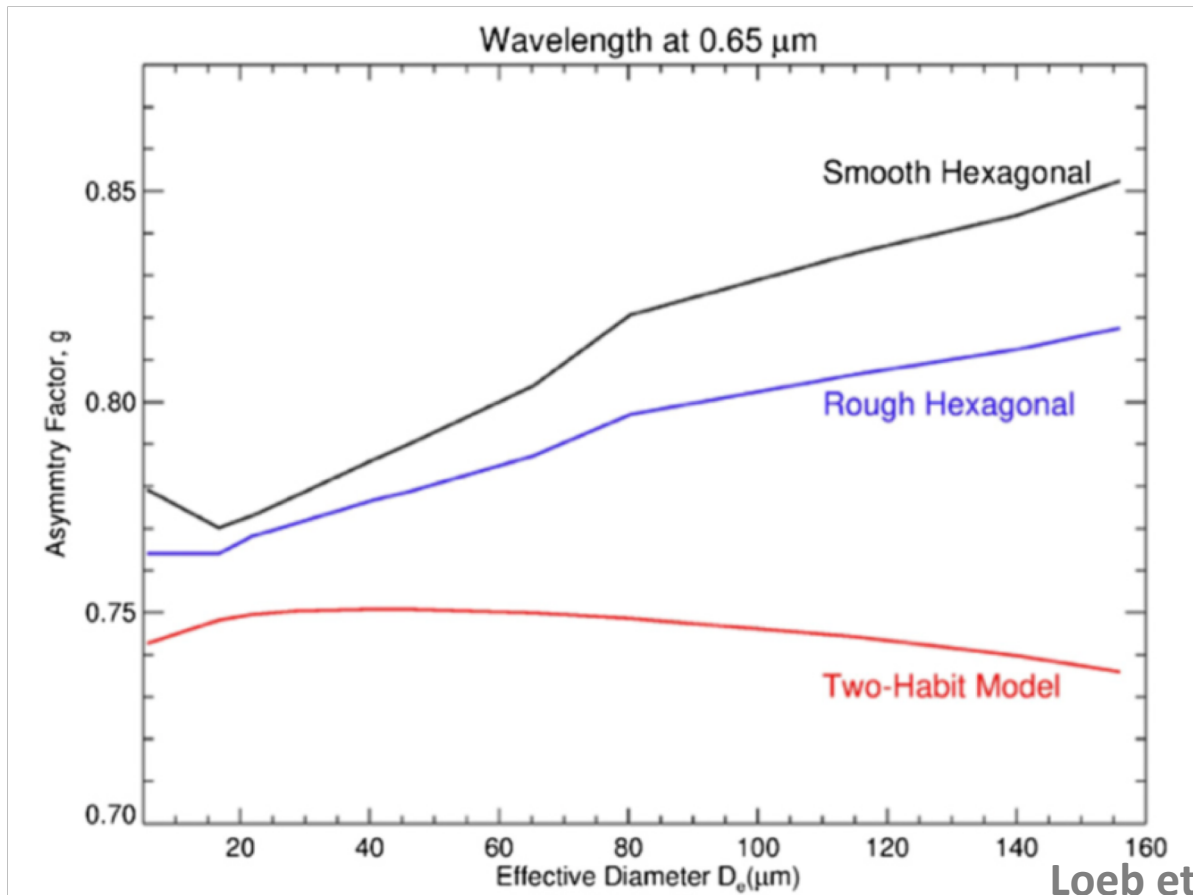- Gamma-weighted two-stream approximation (GWTSA) (Kato et al., 2001; 2005) for shortwave flux calculations

Broadbands

- 18 bands (UV to 4 μm)

Major Updates for Shortwave Flux Calculations

- **Two-habit model (THM) ice radiative parameterization**
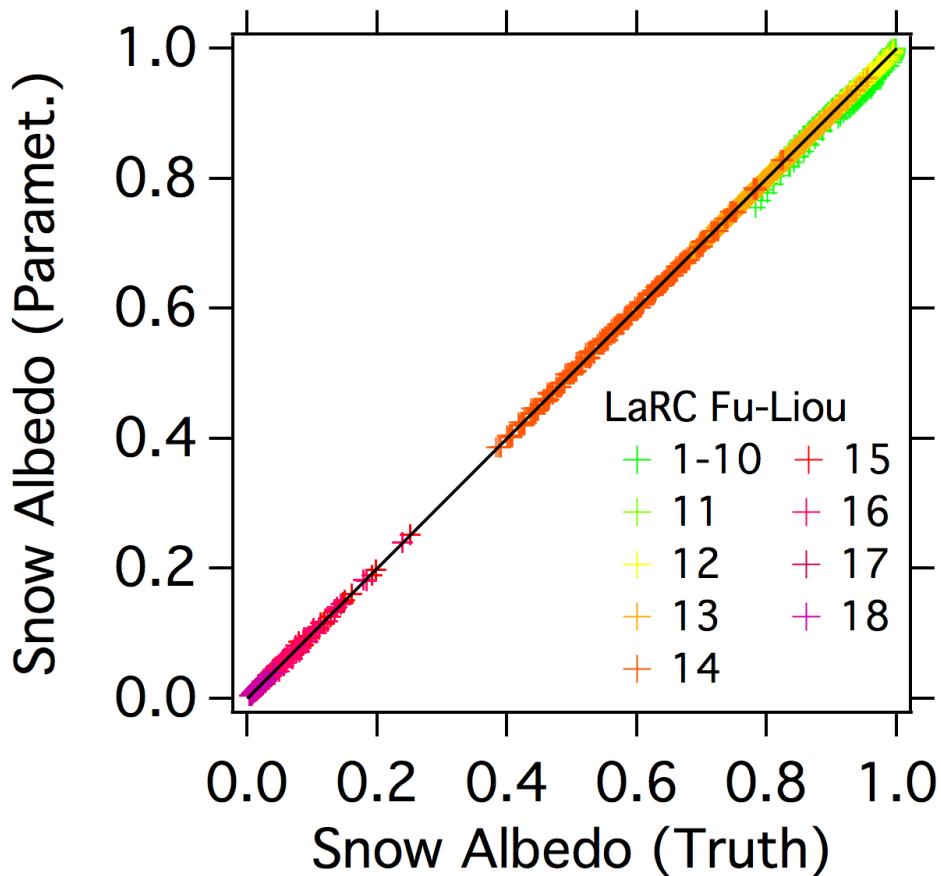- **Single & Two-layer snow albedo parameterizations**

Updates: THM Parameterization

Loeb et al., 2018 JClim

- A new THM has lower asymmetry factor

- Ice clouds are more reflective based on THM

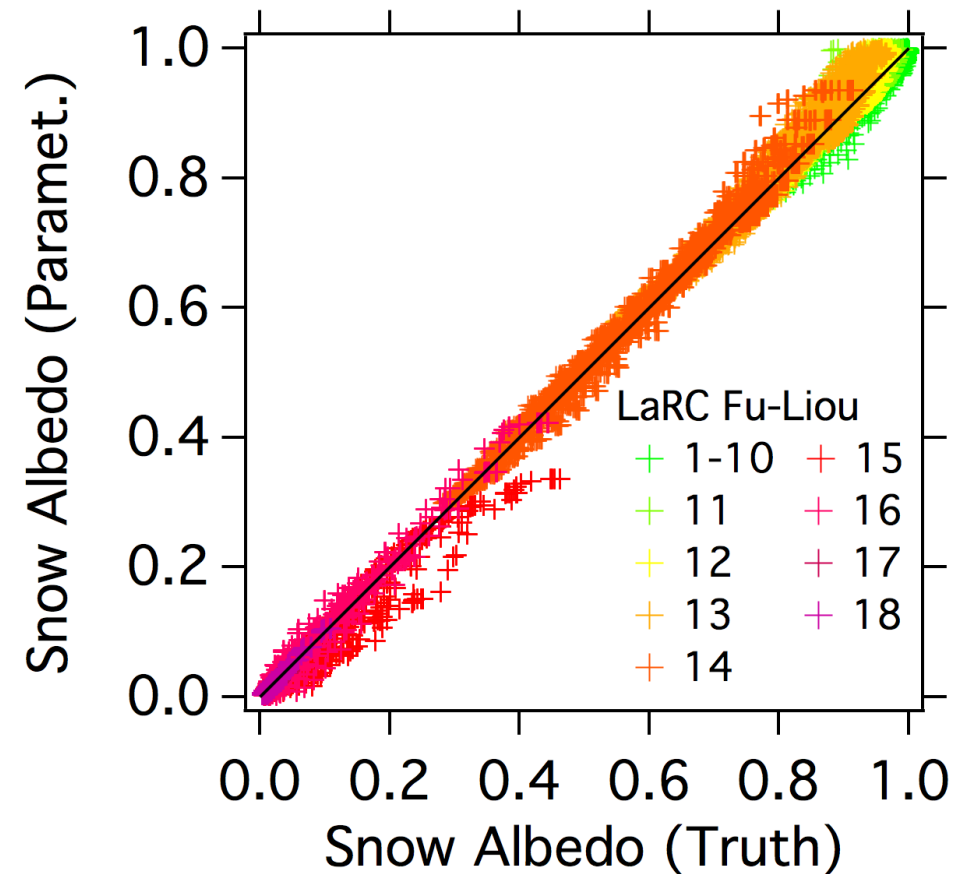- Developed a bulk THM radiative parameterization

Updates: Single layer Snow Parameterization

Broadband snow albedo is a function of:

- Snow effective radius

- Internal BC mass fraction

- Solar zenith angle (SZA)

Updates: Two-layer Snow Parameterization

Broadband snow albedo is a function of:

- Snow effective radii for top and second layers

- Top-layer snow water equivalent (SWE)

- Internal BC mass fraction

- SZA

→ **Implemented these two snow albedo parameterizations into 18 bands in the Langley Fu-Liou RTM**

Evaluation Method: THM

Cloud Radiative Forcing

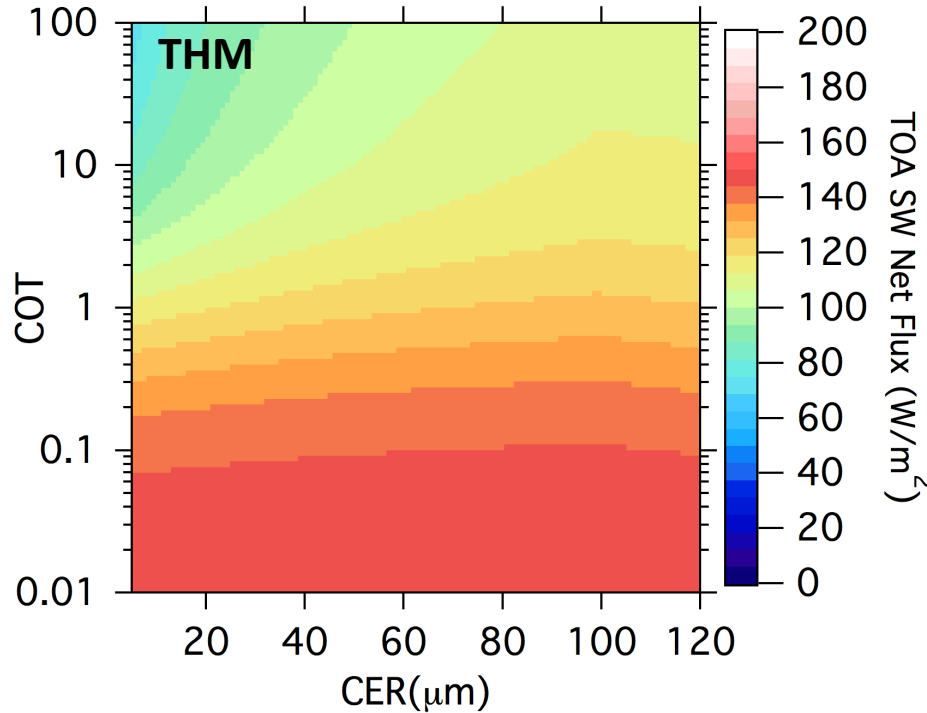$$CRF = \left(F_{tot}^{\downarrow} - F_{tot}^{\uparrow}\right) - \left(F_{clr}^{\downarrow} - F_{clr}^{\uparrow}\right). \quad (W/m^2)$$

## Net SW CRF difference

$$CRF_{THM} - CRF_{other} \quad (W/m^2)$$

Experiments

- Single layer ice clouds
    - Various cloud optical thicknesses (COTs) and cloud-particle effective radii (CER)
    - Cosine of SZA (μ_0): 0.3
- Atmospheric profile: midlatitude winter
- Surface type: Snow

THM: TOA SW Flux CRF

- CERES Ed2 and Ed4 have a positive TOA SW CRF bias due to higher values of the asymmetry parameter than the THM counterpart.
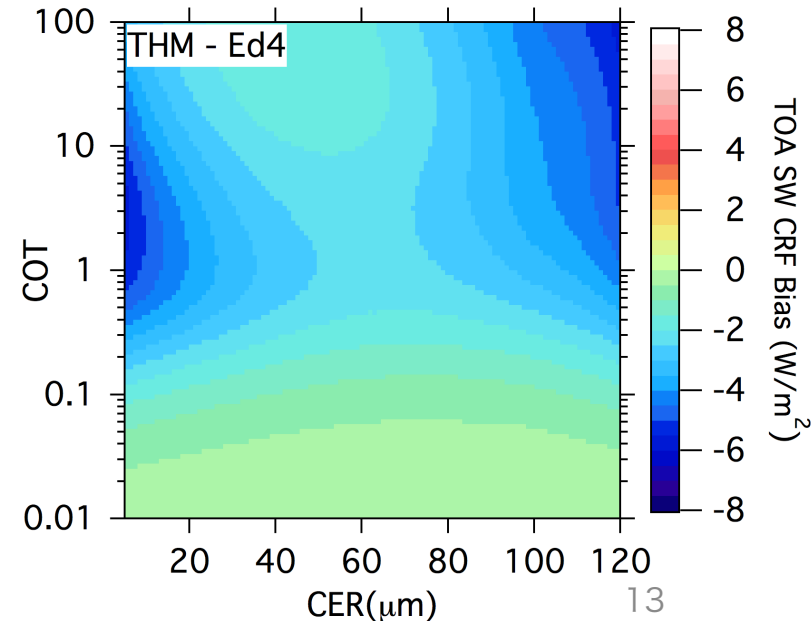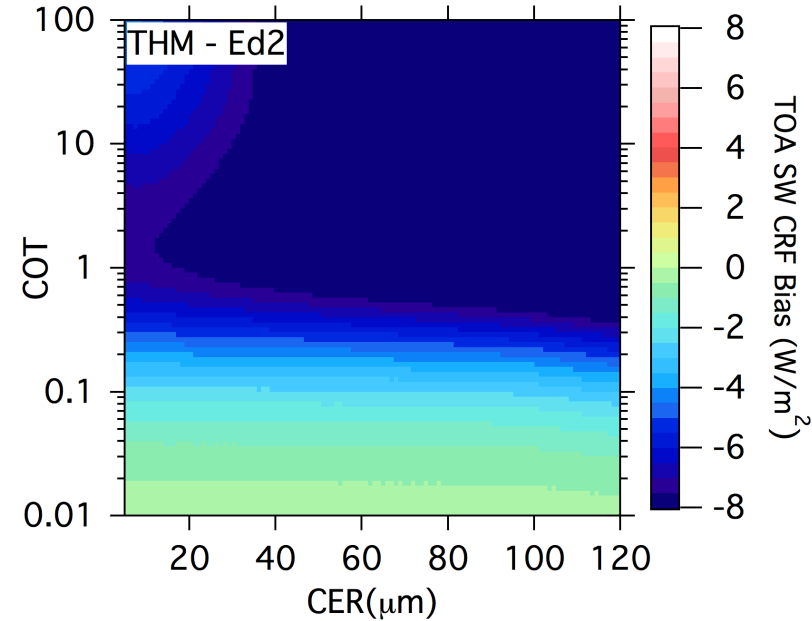
Findings by Loeb et al. (2018): radiative fluxes derived using a consistent ice particle model assumption throughout provide a more robust reference for climate model evaluation compared to existing ice cloud property retrievals.

In other words, the same ice model must be consistently used in forward remote sensing implementation (look-up tables) and downstream radiative forcing assessment.

Evaluation Method: Two-layer Snow

Snow Albedo Bias

$$\frac{\alpha_{Single} - \alpha_{TwoLay}}{\alpha_{TwoLay}} \times 100 \ (\%)$$

Net SW Flux Bias

$$\left(F^{\downarrow}_{Single} - F^{\uparrow}_{Single}\right) - \left(F^{\downarrow}_{TwoLay} - F^{\uparrow}_{TwoLay}\right). \ (W/m^2)$$
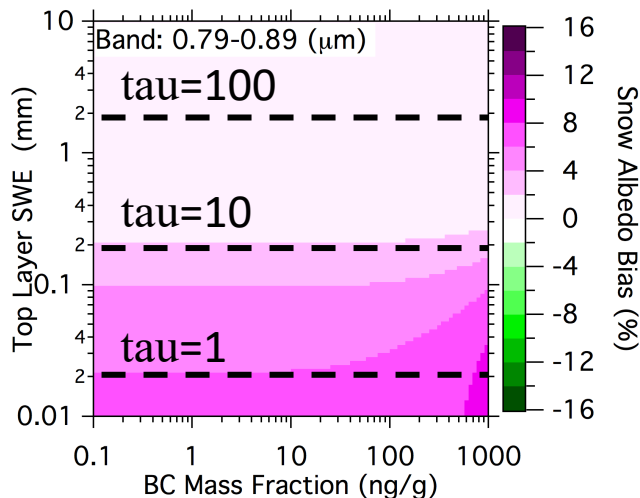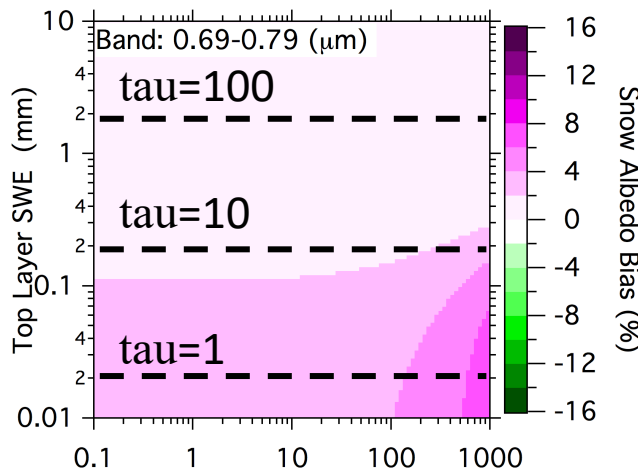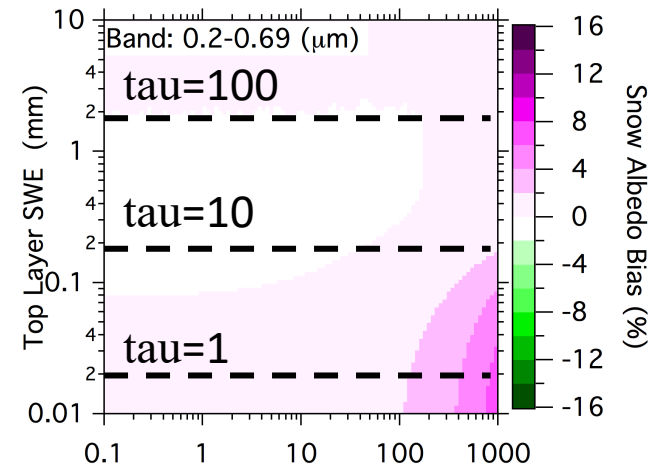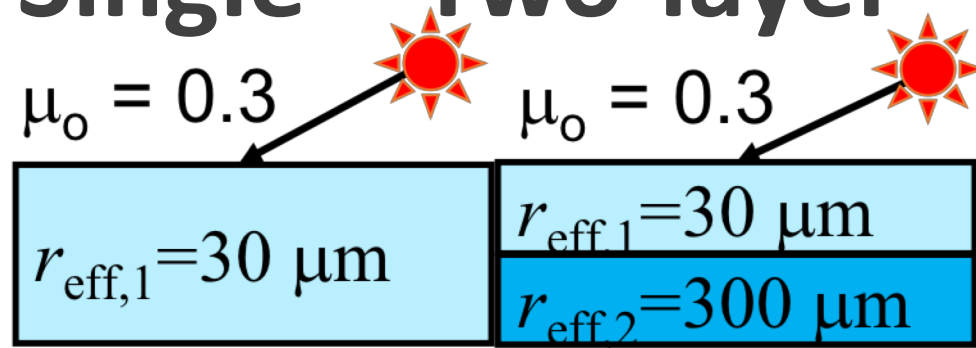
Experiments

- Clear sky
  - $\mu_0 = 0.3, 1.0$
  - Fresh and aged snow
- Cloudy sky
  - Warm cloud: COT = 10, r_{eff} = 10 μm

In the present snow model, the second snow layer is optically infinite
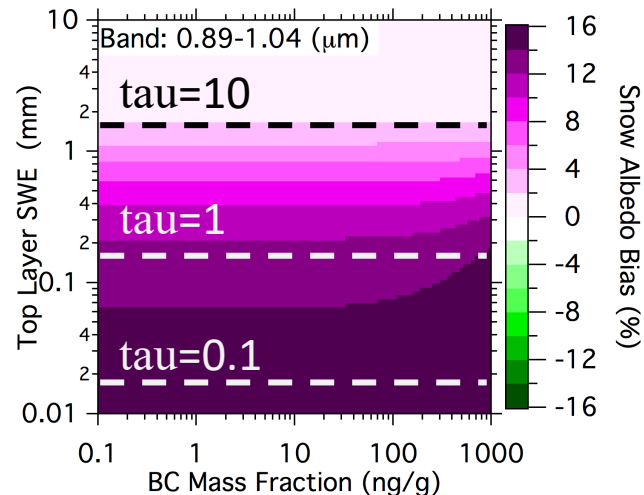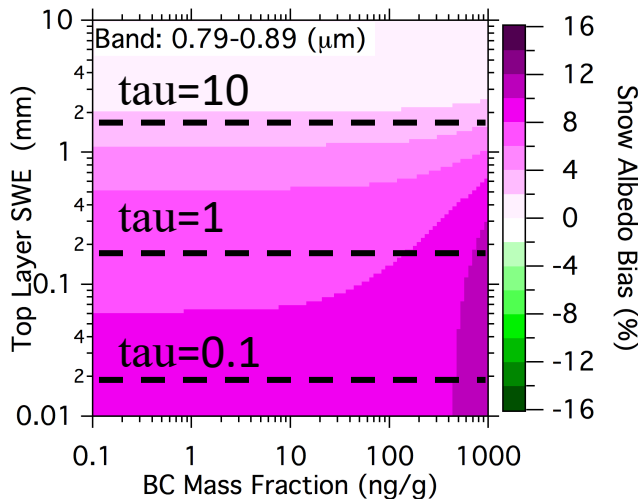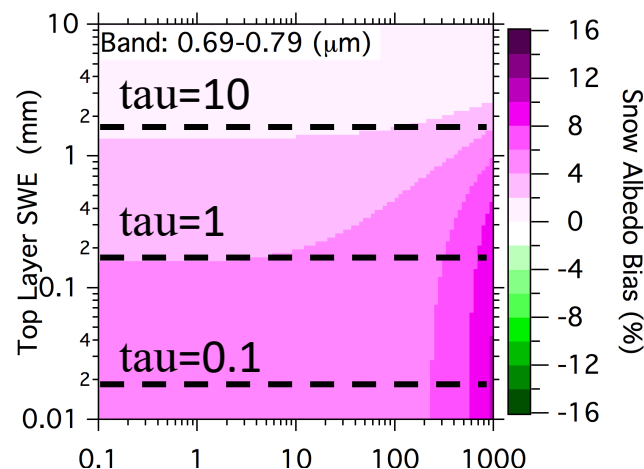
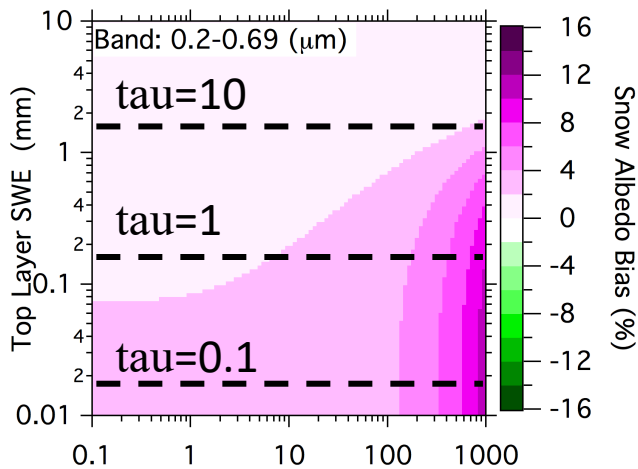# Snow Albedo Bias: Single – Two-layer

Fresh Snow

$\mu_o = 0.3$ $\mu_o = 0.3$

$r_{\text{eff},1} = 30\ \mu m$

$r_{\text{eff},1} = 30\ \mu m$

$r_{\text{eff},2} = 300\ \mu m$

Band: 0.2-0.69 (μm)

Band: 0.69-0.79 (μm)

Band: 0.79-0.89 (μm)

Band: 0.89-1.04 (μm)

tau=100
tau=10
tau=1

Top Layer SWE (mm)

BC Mass Fraction (ng/g)
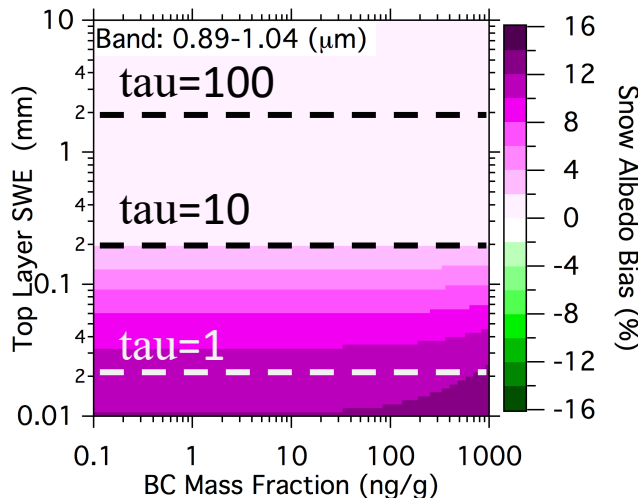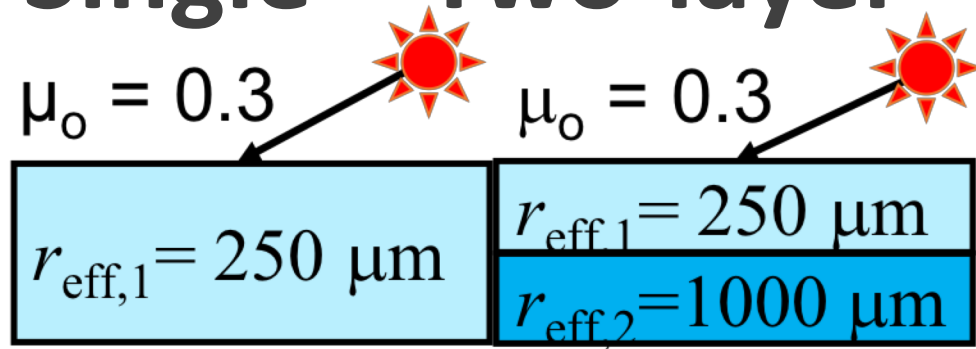
Snow Albedo Bias (%)

Positive biases depending on:

- BC Fraction (0.2–0.89 μm bands)

- Snow water equivalent (SWE) (0.79–1.04 μm bands)
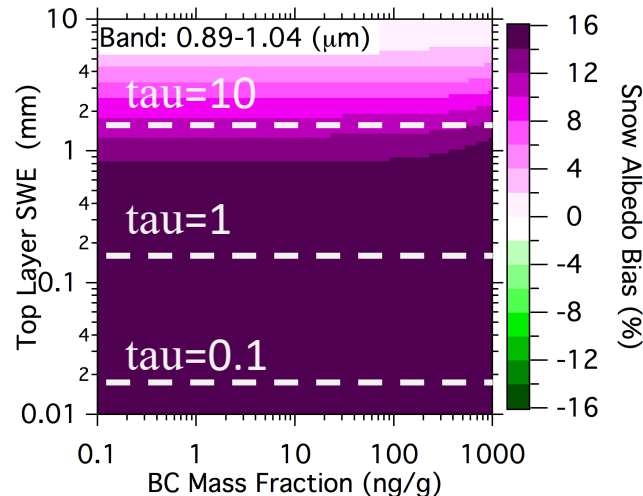
Snow Albedo Bias: Single – Two-layer

Aged Snow

$\mu_o = 0.3$ $\mu_o = 0.3$

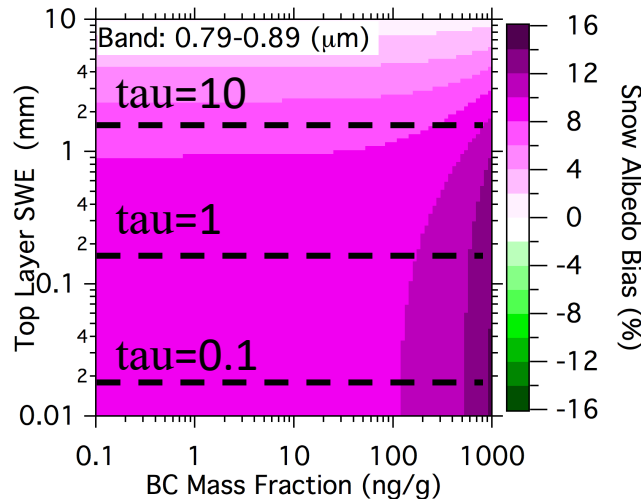$r_{eff,1} = 250\ \mu m$
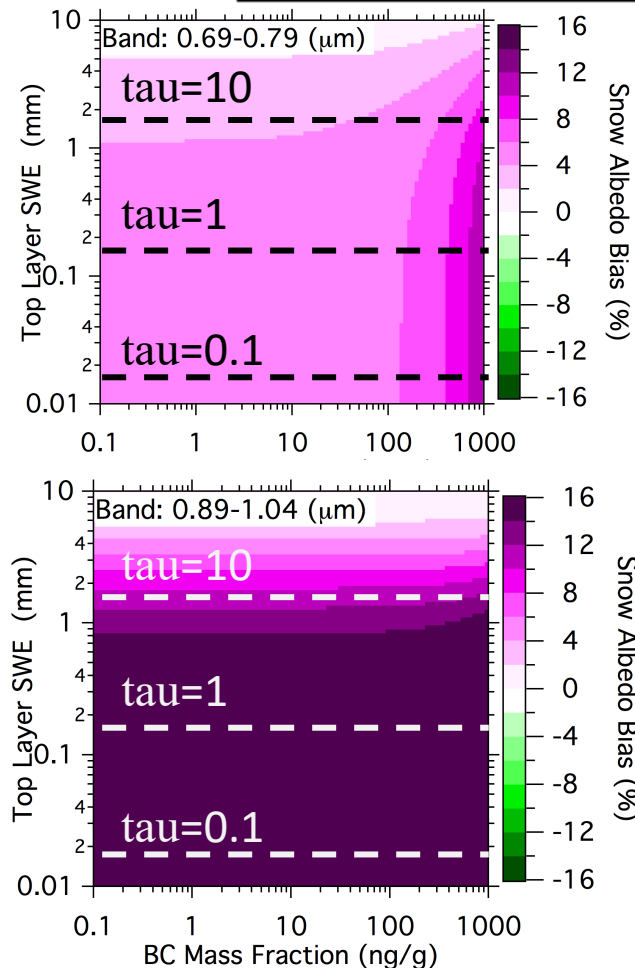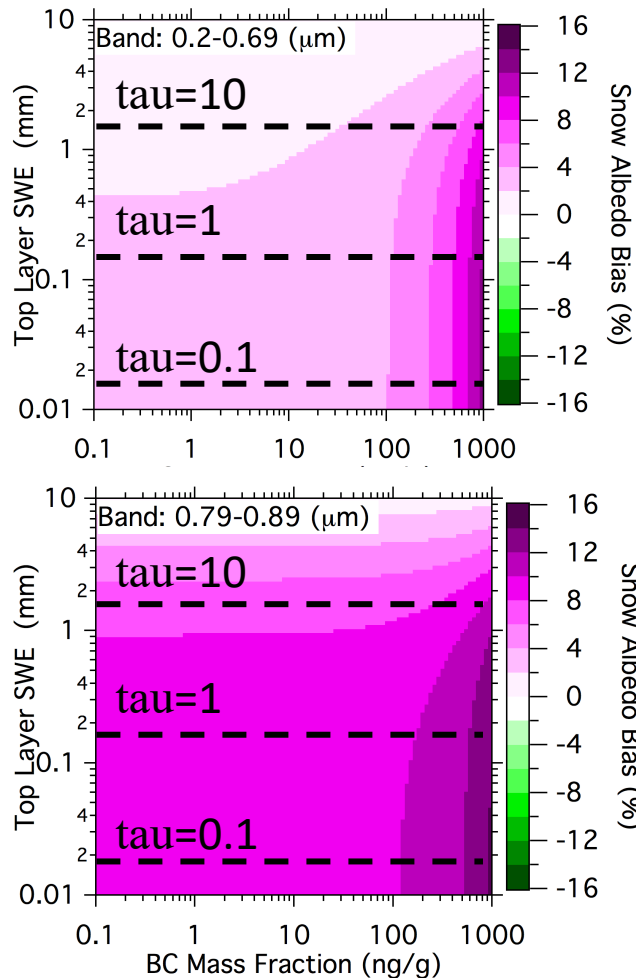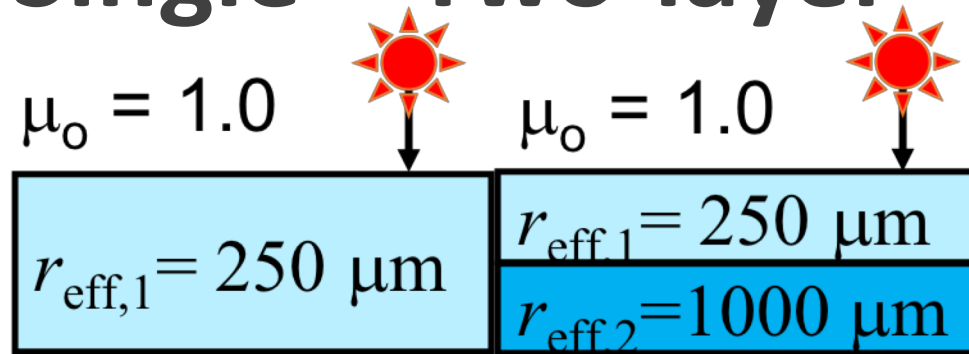
$r_{eff,1} = 250\ \mu m$

$r_{eff,2} = 1000\ \mu m$

Enhanced positive bias by aged snow due to a larger snow particle size

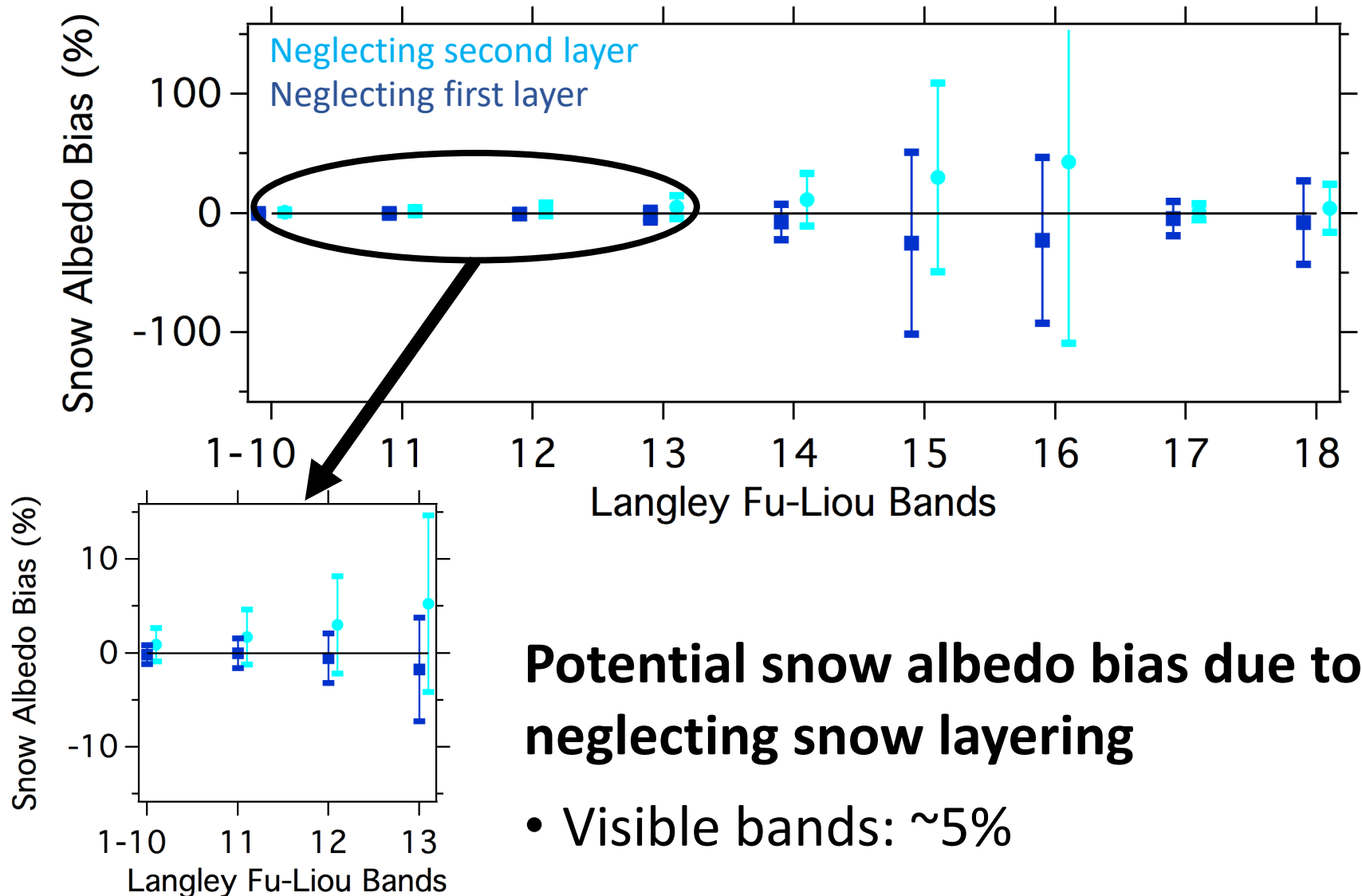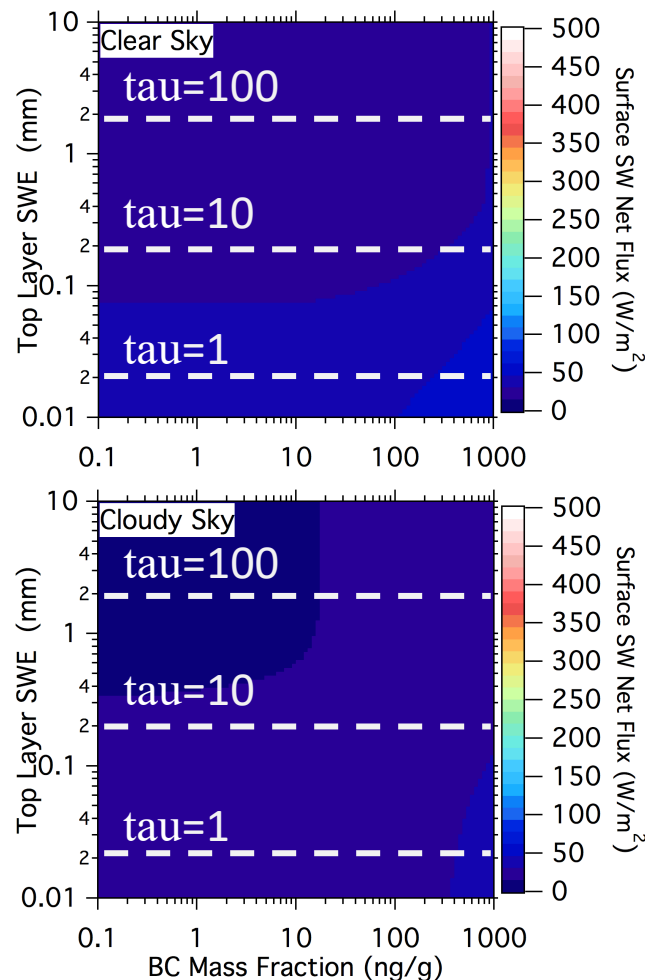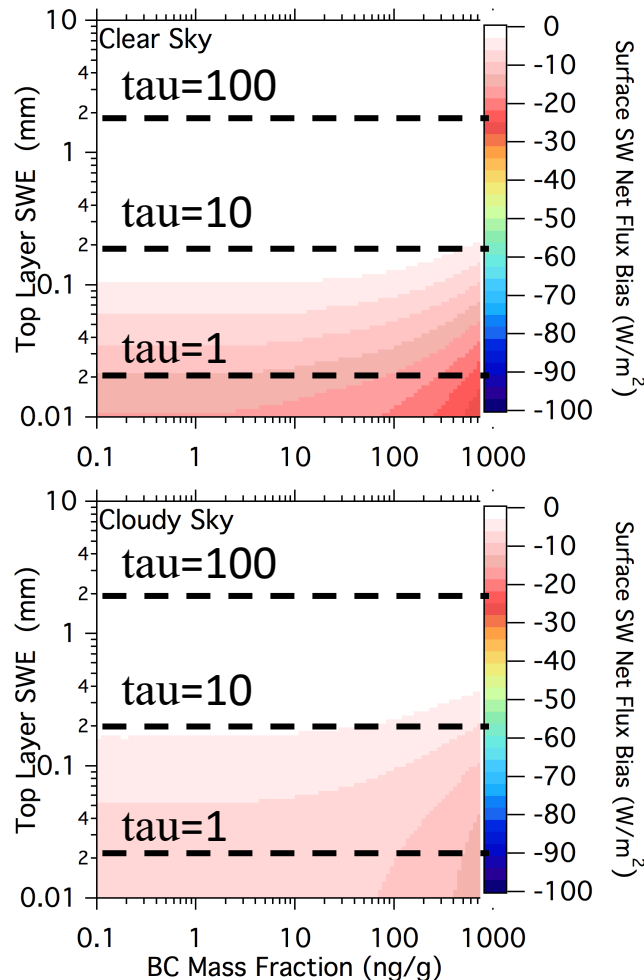# Snow Albedo Bias: Single – Two-layer

Aged Snow

$$\mu_o = 1.0 \qquad \mu_o = 1.0$$

$$r_{eff,1} = 250 \ \mu m$$

$$r_{eff,1} = 250 \ \mu m$$
$$r_{eff,2} = 1000 \ \mu m$$

Enhanced positive bias due to a small solar zenith angle

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Snow Albedo Bias and Std. dev.

Potential snow albedo bias due to neglecting snow layering

- Visible bands: ~5%

- Near infrared bands: 10–50%

Surface Net SW Flux Bias: Single – Two-layer

Fresh Snow

$\mu_o = 0.3$ $\mu_o = 0.3$

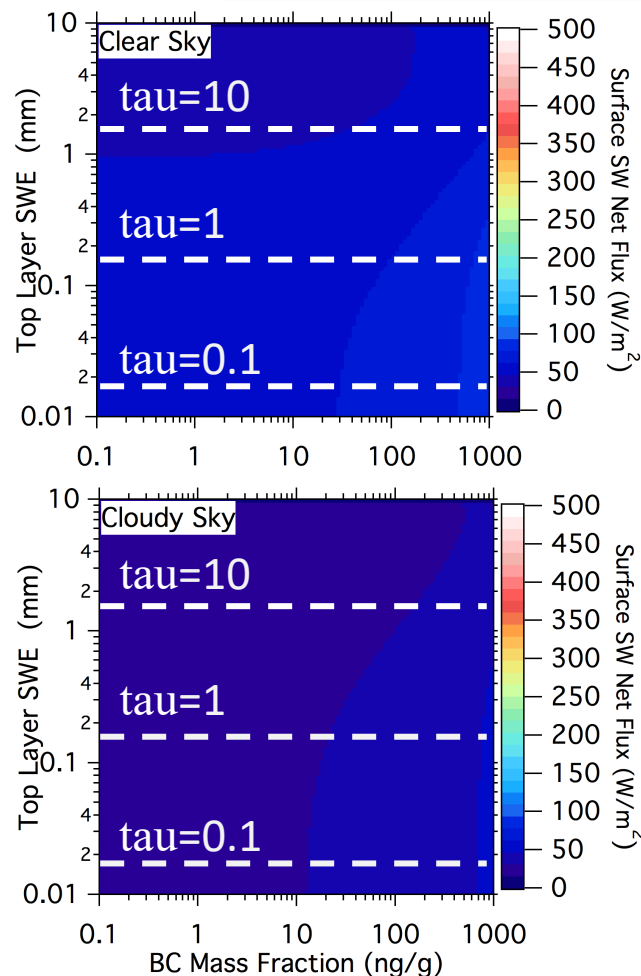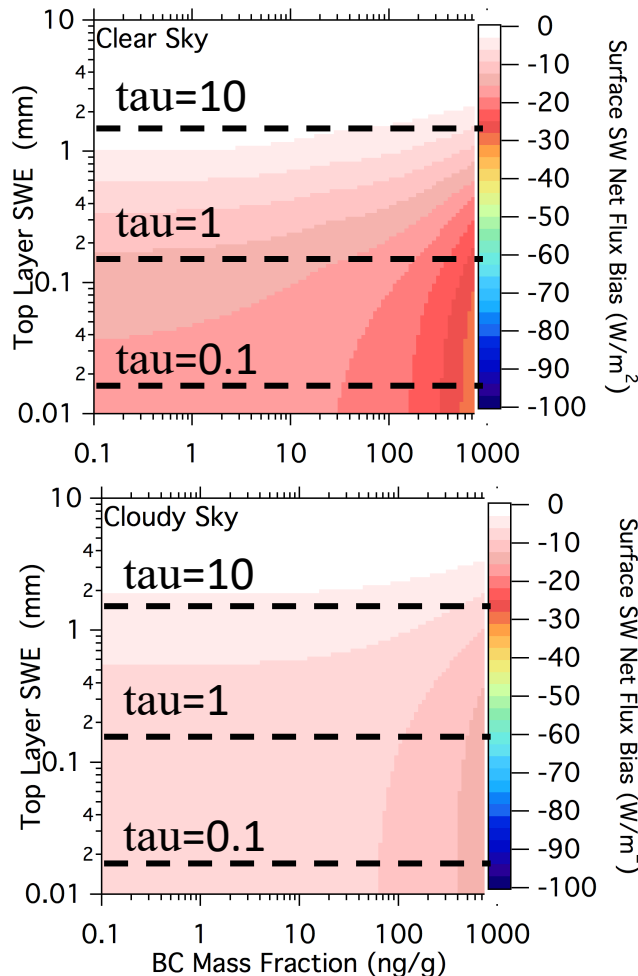$r_{eff,1} = 30\ \mu m$ $r_{eff,1} = 30\ \mu m$
$r_{eff,2} = 300\ \mu m$
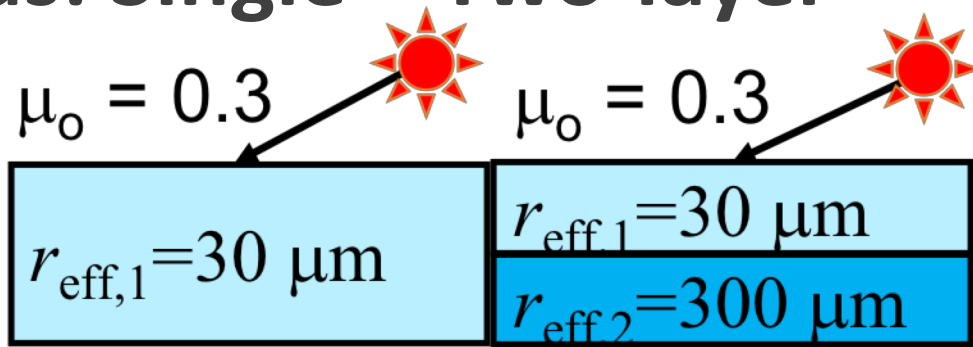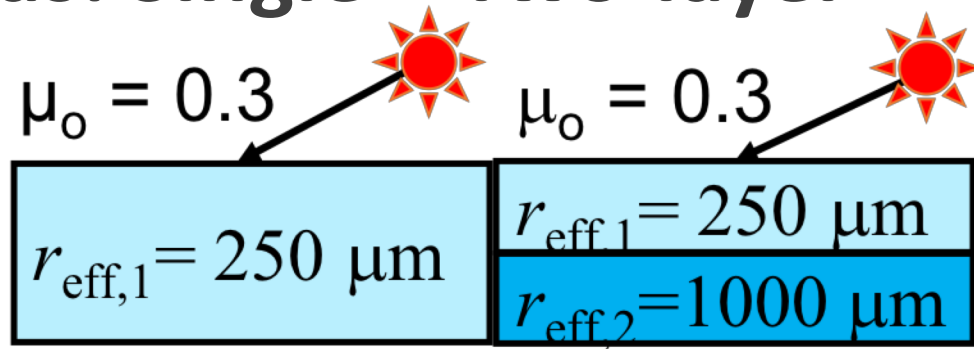

Net SW flux bias is small for typical fresh snow

Surface Net SW Flux Bias: Single – Two-layer

Aged Snow
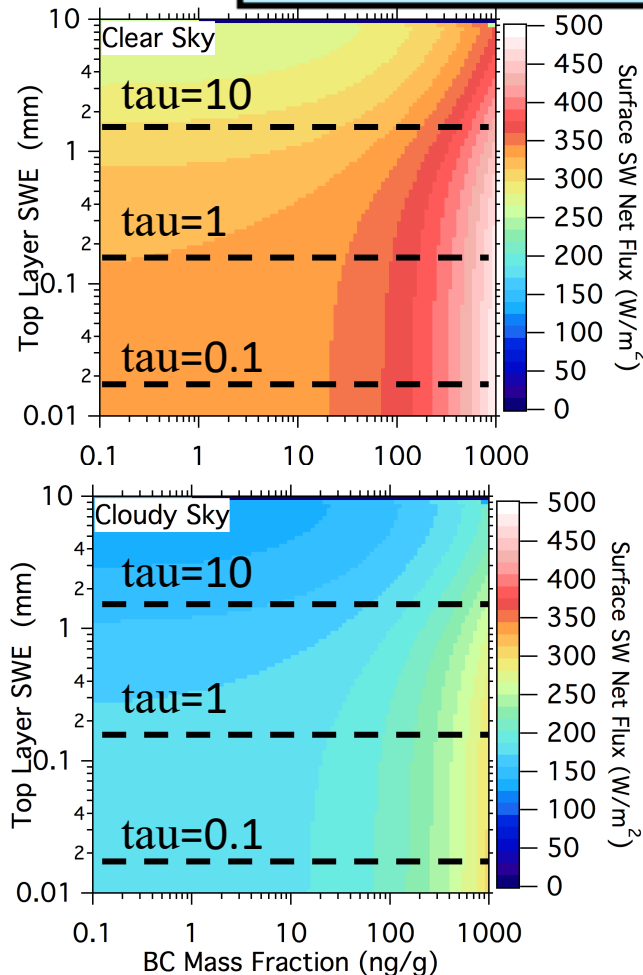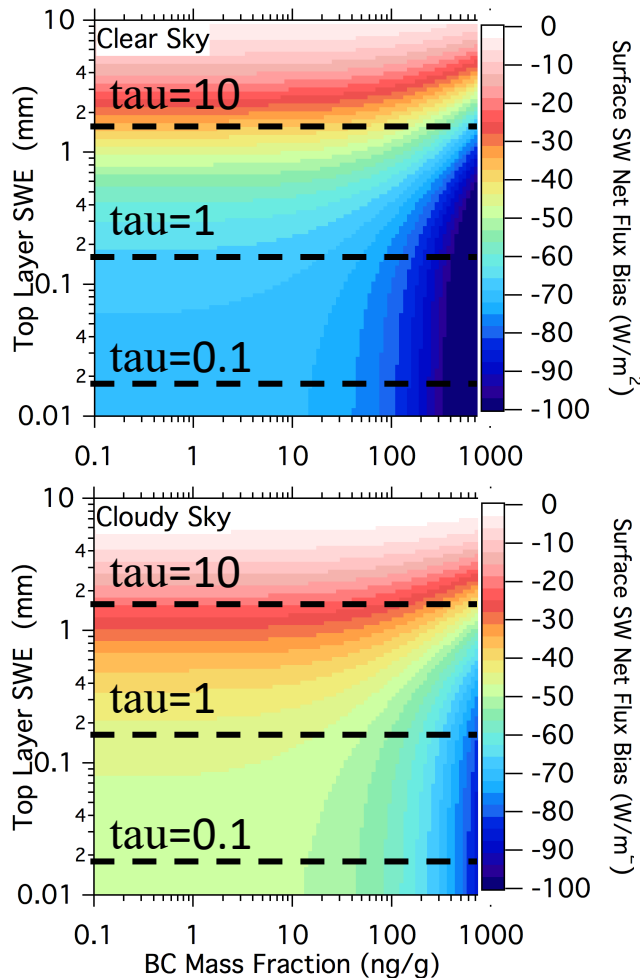
$\mu_o = 0.3$

$\mu_o = 0.3$

$r_{eff,1} = 250\ \mu m$

$r_{eff,1} = 250\ \mu m$

$r_{eff,2} = 1000\ \mu m$

Aged snow has non-negligible impacts on net SW flux.

Surface Net SW Flux Bias: Single – Two-layer

Aged Snow

$\mu_o = 1.0$ $\mu_o = 1.0$

$r_{eff,1} = 250\ \mu m$ $r_{eff,1} = 250\ \mu m$

$r_{eff,2} = 1000\ \mu m$
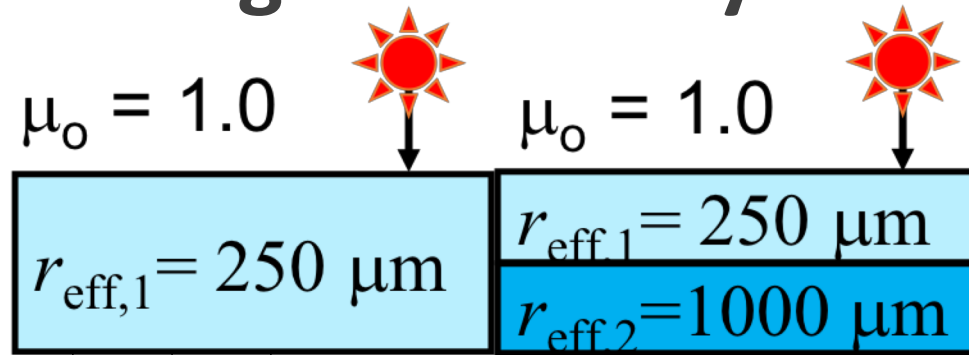
The impact on net SW flux increases with decreasing SZAs.

An example of the regions with high SZAs: Tibetan Plateau during the summer

Summary & Future Effort

Major updates in the Langley RTM

- THM ice radiative parameterization
- Single and Two-layer snow albedo parameterizations

Net surface SW flux bias due to neglecting second layer

- Less than a few W/m^2 under typical fresh snow conditions
- Up to ~20 W/m^2 under typical aged snow conditions
- Some low-latitude, snow-covered mountainous area might cause more significant net surface SW flux bias.

Future Work in support of CERES

**Bidirectional Reflectance Distribution Function (BRDF)**

Regional and Seasonal BRDF differences

1. Pollution by BCs is different among locations
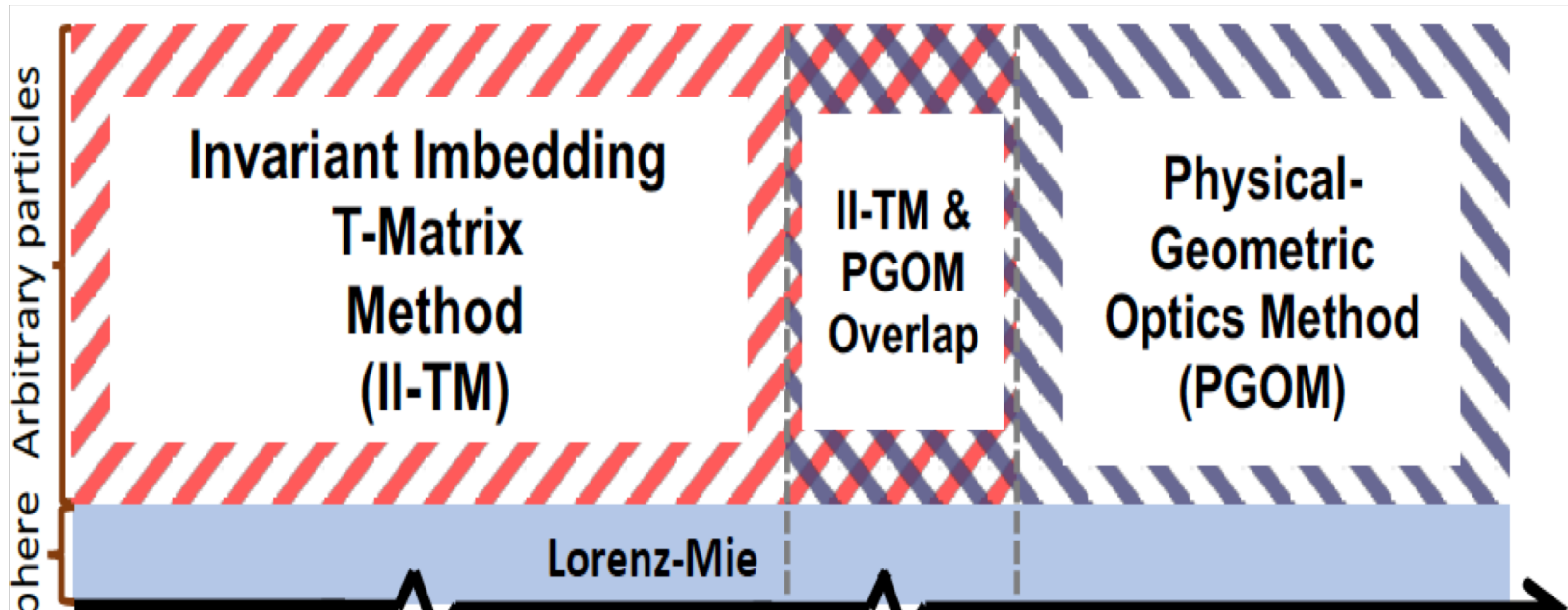2. Aged snow is dominant during summer

Consistency of the snow particle model between albedo and BRDF modeling

→ **Support operational cloud property retrievals**

# Applicability of Light-Scattering Computational Methods
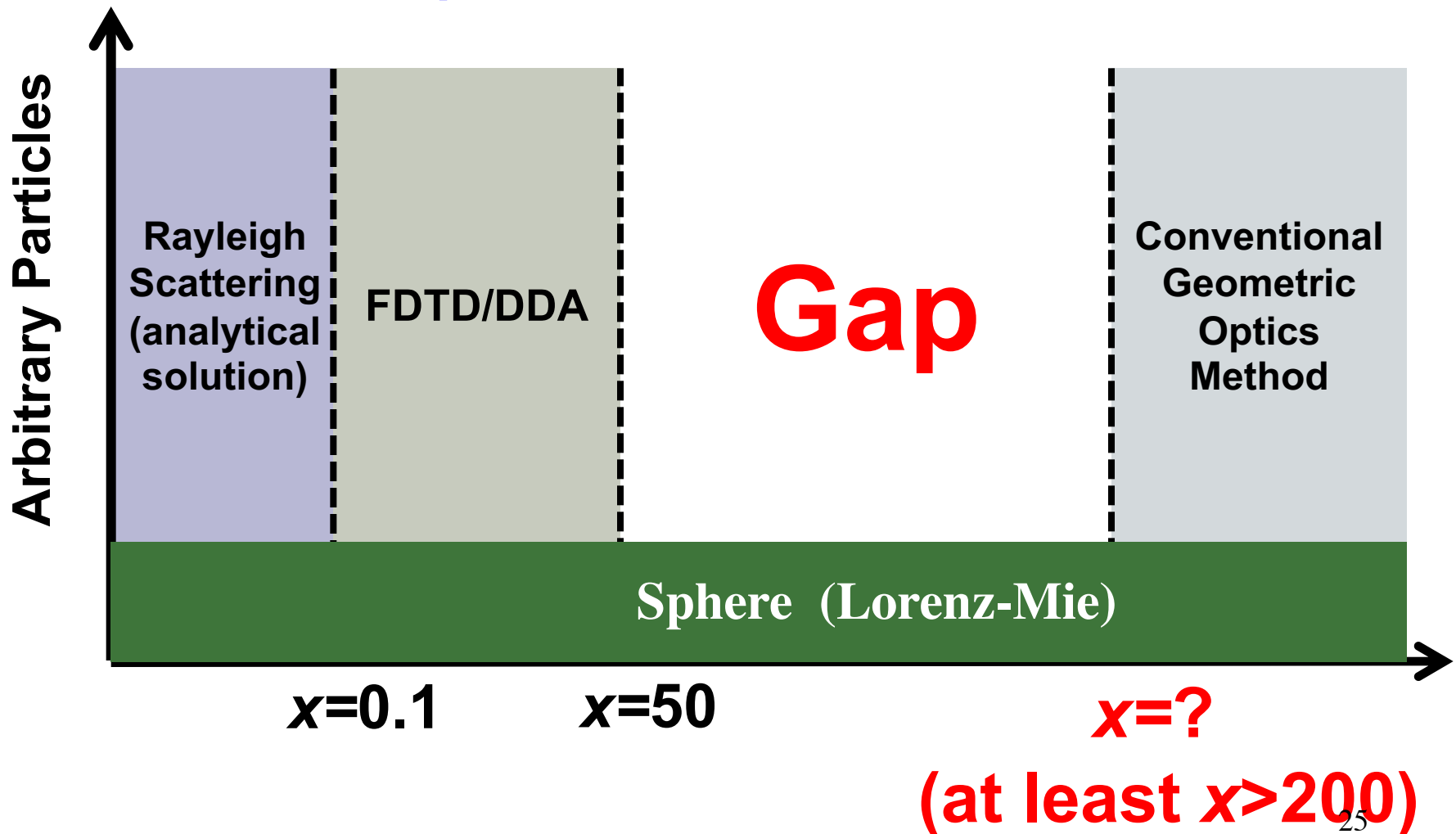
# A novel computational methodology for light-scattering computation (Yang et al. 2019)

Schematic diagram shows the seamless transition of II-TM to PGOM. Note that II-TM is an exact method for small and moderate particles while PGOM is applicable for moderate and large particles. For size parameters between 100-150, the two methods converge.

Convergence of II-TM and PGOM
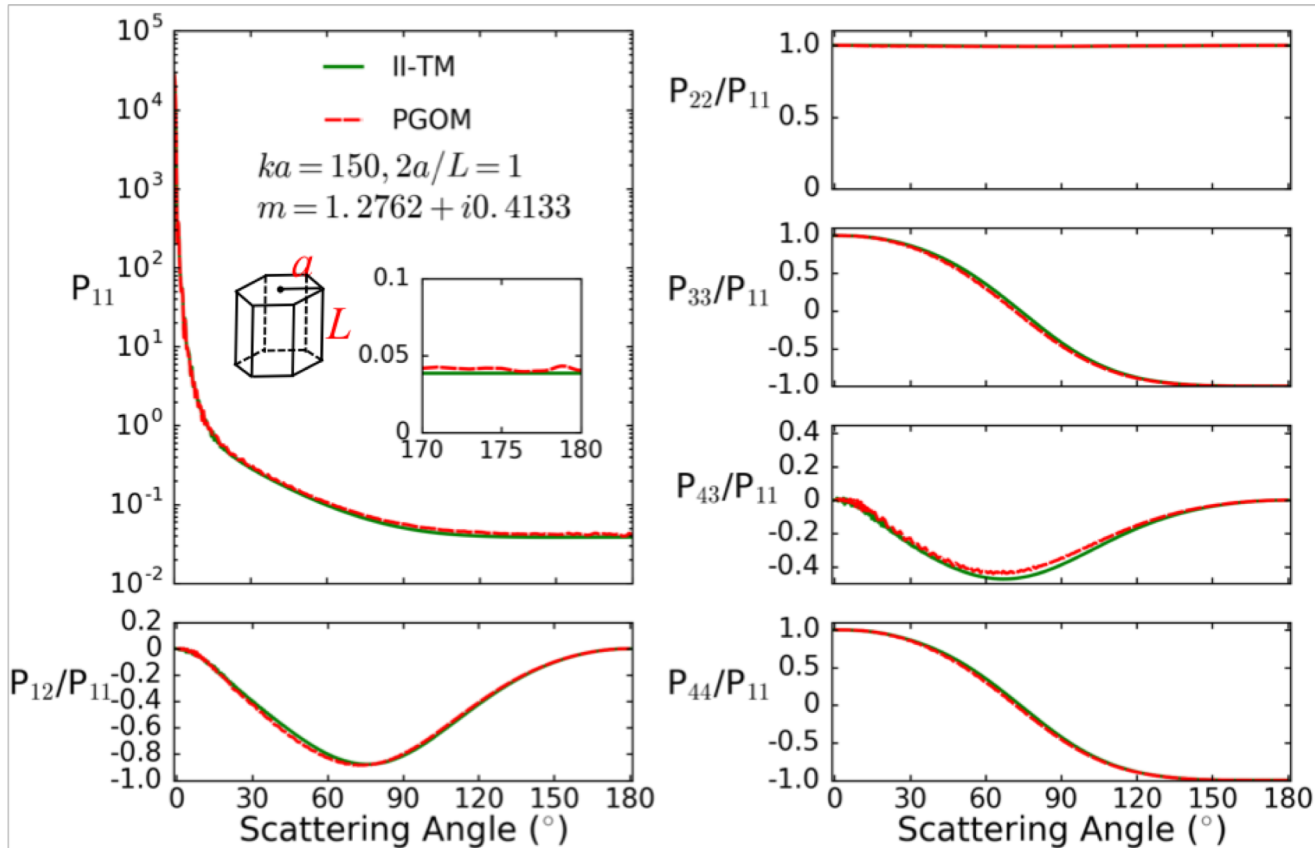
Comparison of the phase matrix elements computed by PGOM and II-TM. The particle is a hexagonal column with aspect ratio 1 with size parameter *ka*=150. the refractive index is 1.2762+*i*0.4133 the ice refractive index at 12 μm wavelength.

The conventional ray-tracing method leads to singularity (particularly in backscatter)
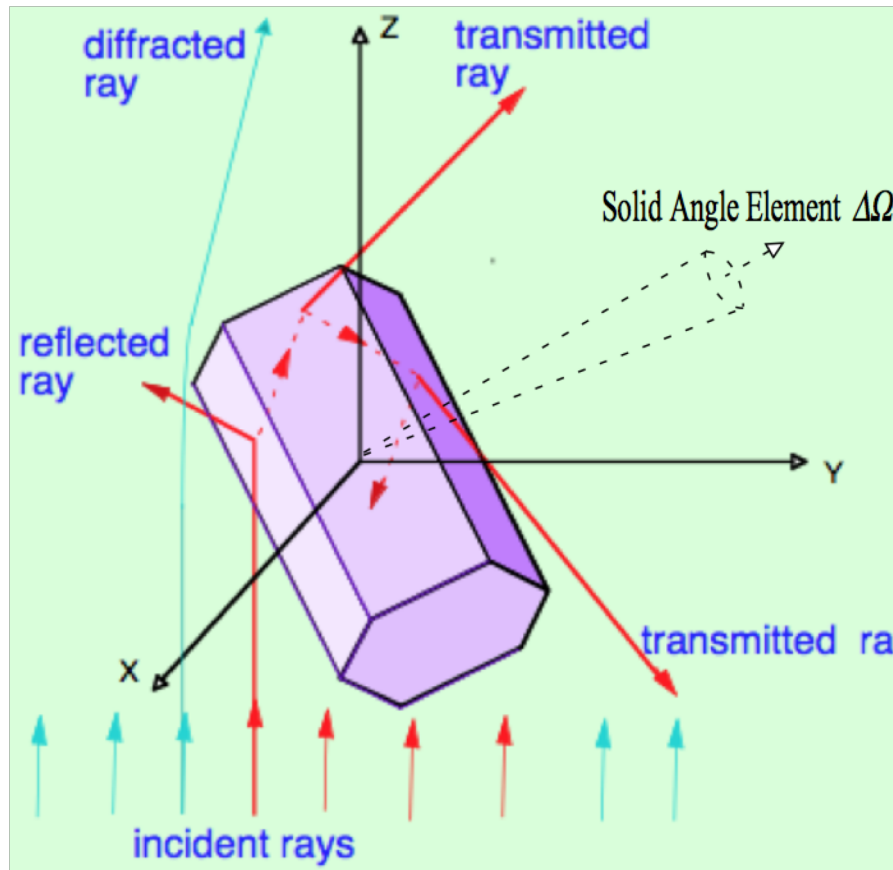
$$P = a\frac{\Delta E}{\Delta \Omega}$$

Comparison between observed modified polarized reflectance product values and the simulations based on the two-habit and CERES Edition 2 ice cloud models in comparison with the POLDER observations.
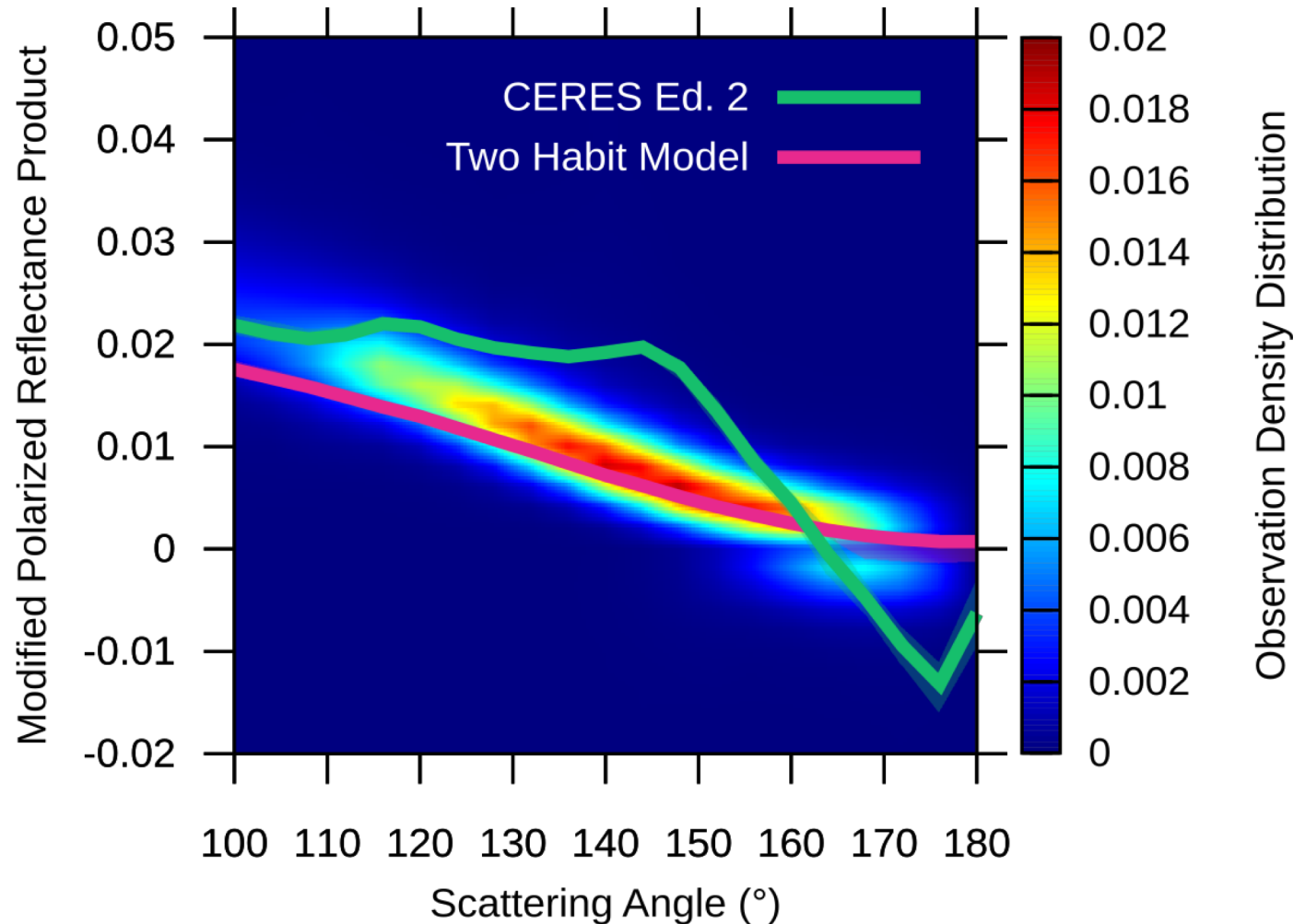
Use the new light-scattering capability to improve the two-habit ice cloud property model

- SW and LW consistency

- Consistency for passive and active remote sensing applications

- Consistency for scalar and polarimetric remote sensing

- Consistency for cloud property retrievals and broadband flux computations

The CERES ice cloud optical property model will be The Ice Cloud Model for remote sensing, RT simulations, and radiation parameterizations in GCMs concerning ice clouds.