Development of a two-layer snow albedo model: Preliminary results and future perspectives

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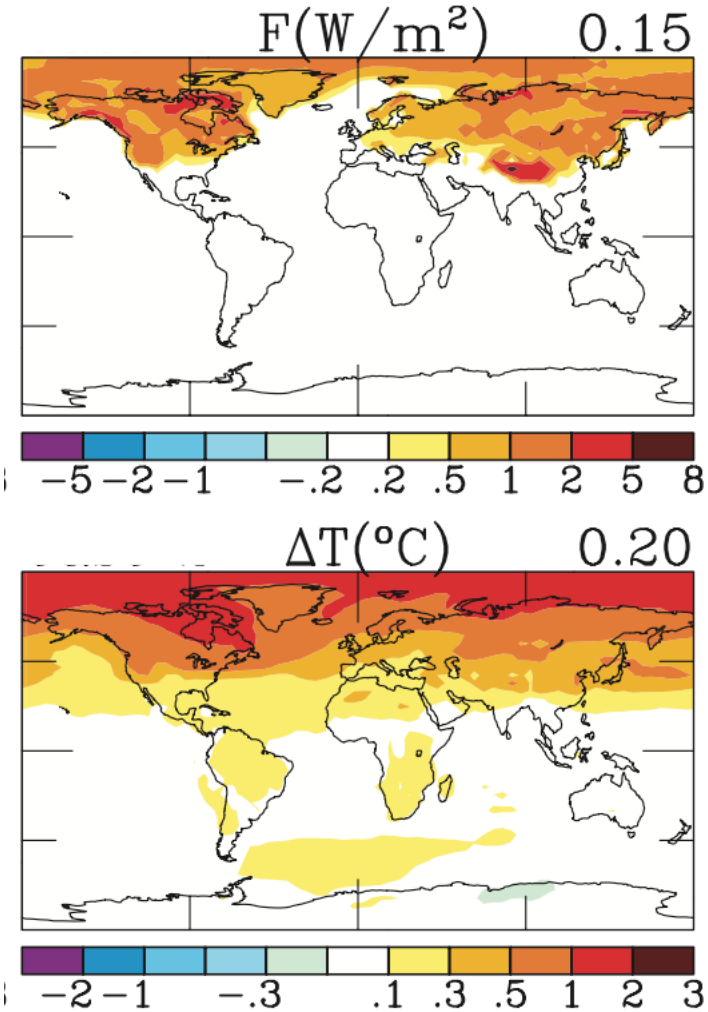
Background (1/3)

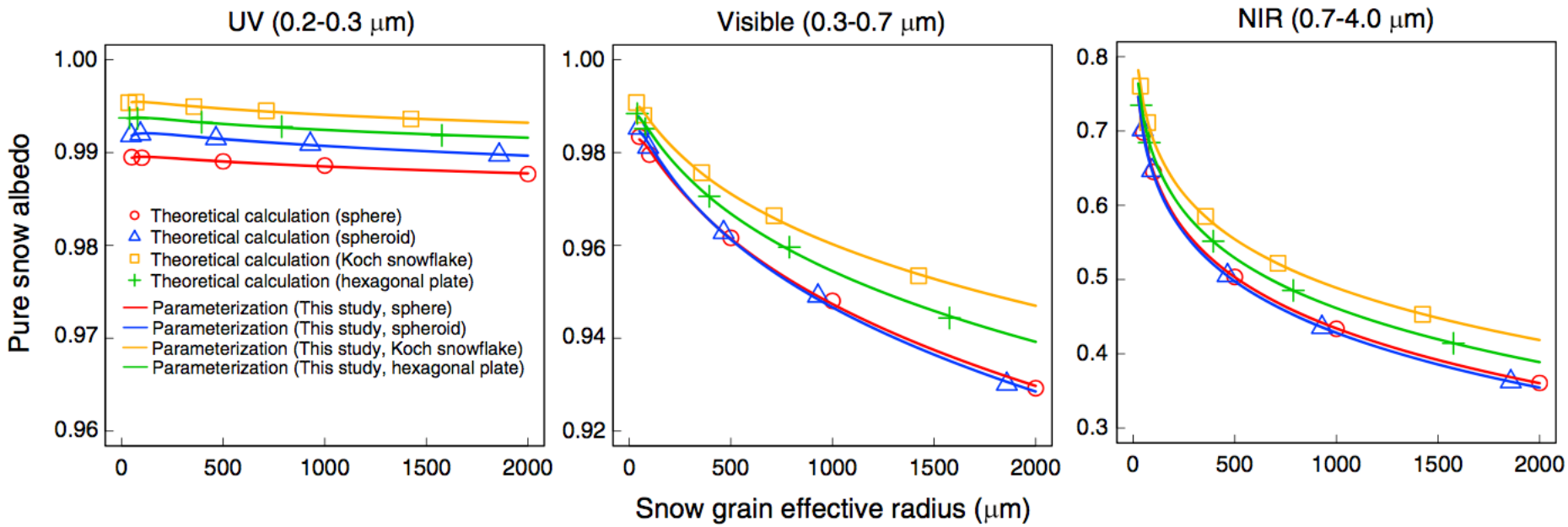
Polar regions are most sensitive to climate change



Hansen and Nazarenko, 2004 PNAS

- Large uncertainty in the climate prediction due to complex feedbacks involving the surface–atmosphere–clouds.
- **Snow albedo has significant variability and plays a key role in surface radiation budget.**
- Snow albedo depends on:
  1. Black carbon (BC) mixture
  2. Snow grain size
  3. Snow grain shape
- GCMs should properly take into account these properties in radiative transfer calculations.

Background (2/3)



He, Liou, Takano, Yang, Qi, Chen, 2018a: J. Geophys. Res.

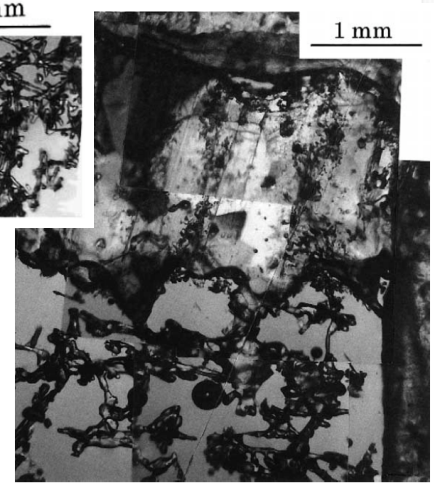
A number of snow albedo models have been developed

- External mixing of impurities (Warran and Wiscombe, 1980)
- BC internal mixing (Flanner et al., 2012)
- BC internal mixing + single nonspherical snow shape + monodisperse PSD (He et al., 2017, 2018a)

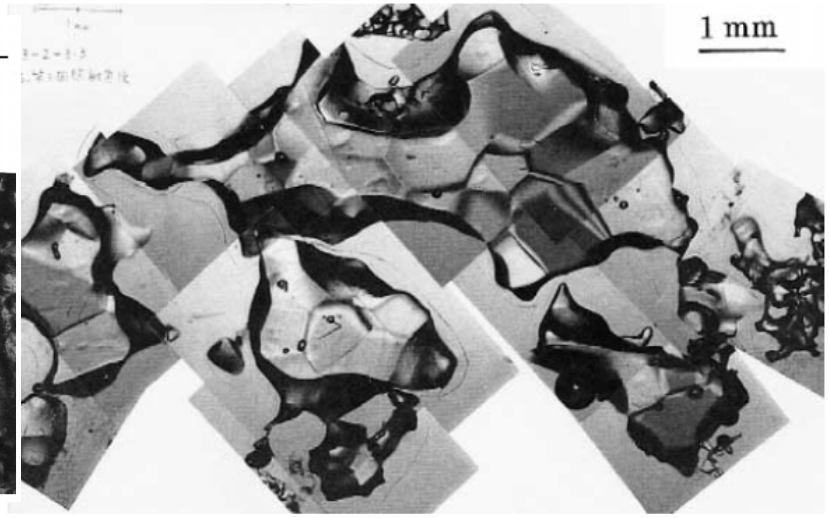
Background (3/3)

Pure Snow

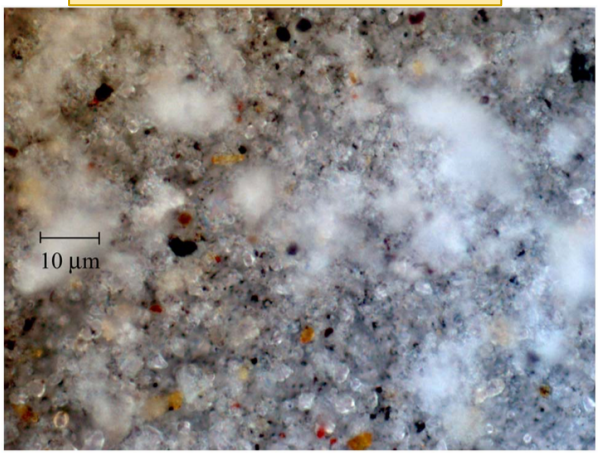
Nakamura et al., 2001



Aged Snow



Snow Impurity



Grenfell et al., 2011

- Snow grain impurities composed of black carbon and dust
- Significant variations of the size and shape distributions during snow grain aging process

Objectives

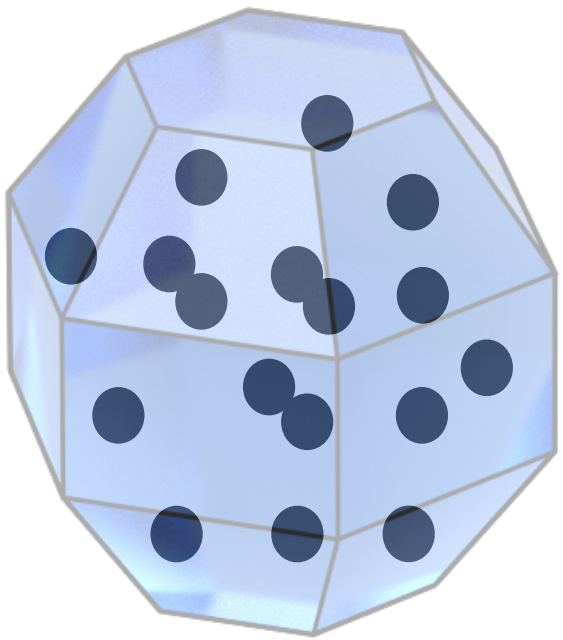
- To develop a relatively realistic snow grain model to take into account:
  1. BC internal mixture (to represent snow impurity)
  2. Snow grain metamorphosis (i.e., grain size, shape)

- To develop a two-layer snow surface albedo model based on the aforementioned snow grain model for the LaRC Radiative Transfer Model used for the CERES project.

Expected significance:

A reduction of uncertainty in estimating the surface radiation budget associated with snow surface albedo, and snow BRDF.

Black Carbon Internal Mixing (1/2)

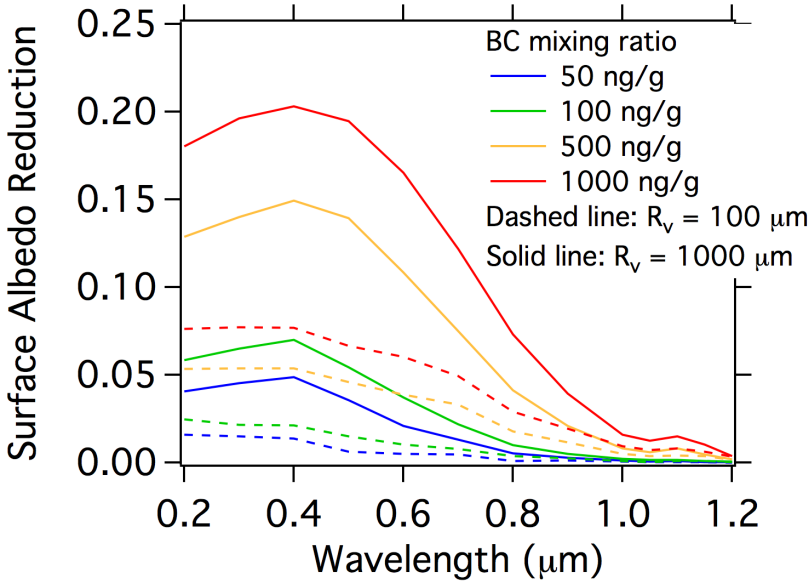


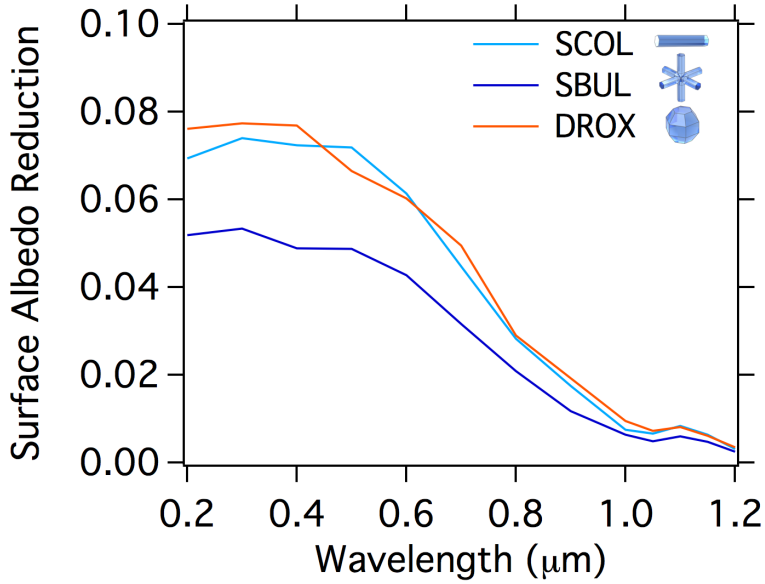
Light Scattering Simulation:

- BC volume density: 1.7 g/cm^3 (Bond and Bergstrom, 2006)
- BC optical properties (Stegmann and Yang, 2017)
- Size resolved BC internal mixing
  - Gamma distribution
  - Effective radius of 0.1 μm
  - Effective variance of 0.1

- Snow impurity treated as black carbon (BC) internal mixture
  - **BC strongly reduces snow albedo**
- IGOM (Yang and Liou, 1996; Yang et al. 2013) + stochastic spherical particle inclusions (Tang et al., 2017)

Black Carbon Internal Mixing (2/2)





Assumptions:

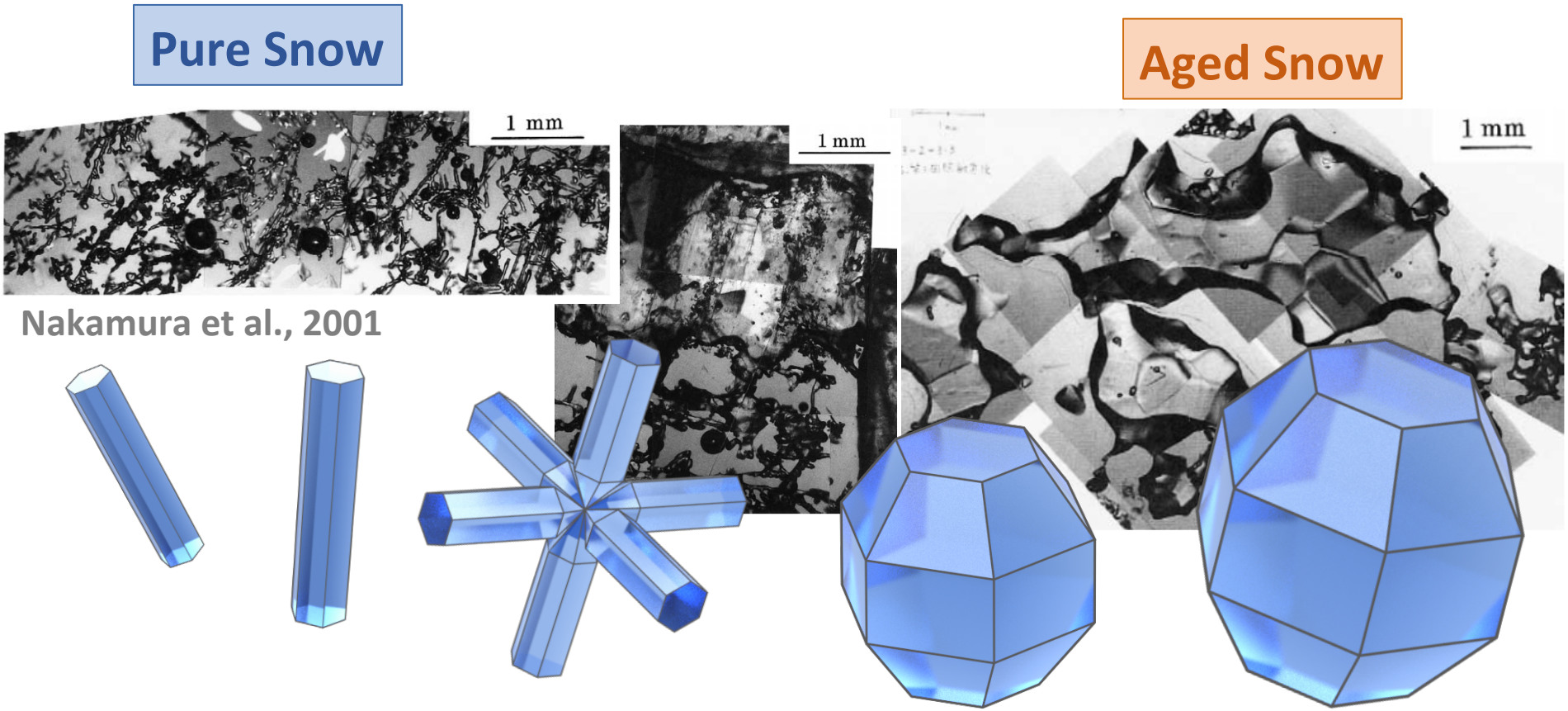
- Single snow layer
- Optical thickness: 960
- Snow habit: Droxtals
- Monodisperse PSD

Assumptions:

- Single snow layer
- Optical thickness: 960
- R_v: 100 μm
- Monodisperse PSD
- BC mixing: 1000 ng/g

- Impact of BC internal mixing on snow albedo varies with snow grain size and shape (He et al., 2018a).
- **The present results are consistent with previous findings**

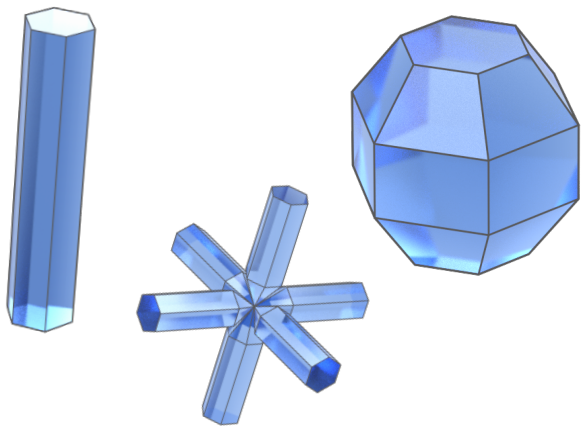
Snow Grain Habit Mixture (1/2)

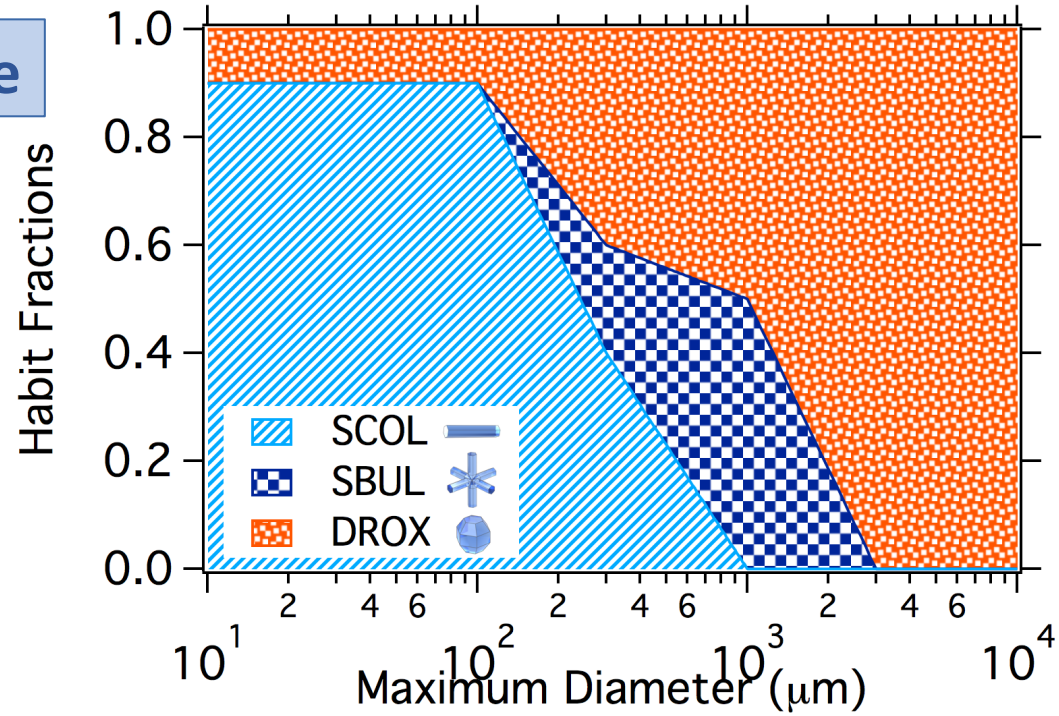


- Snow grain shape significantly changes with snow grain size in the metamorphosis process (Nakamura et al., 2001).
- Several measurements provide snow grain shape and size information, as summarized by Kikuchi et al. (2013)

Snow Grain Habit Mixture (2/2)

Snow Grain Habit Mixture

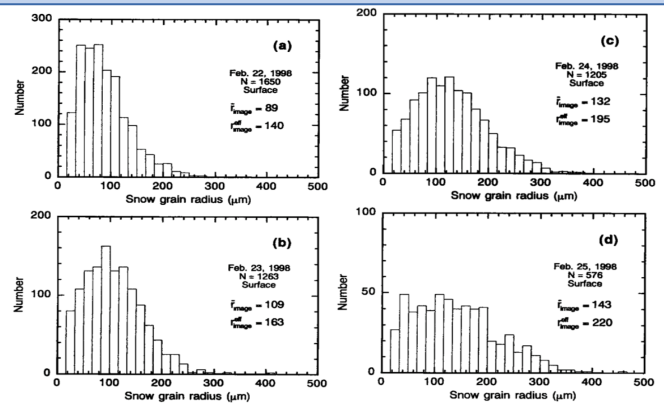




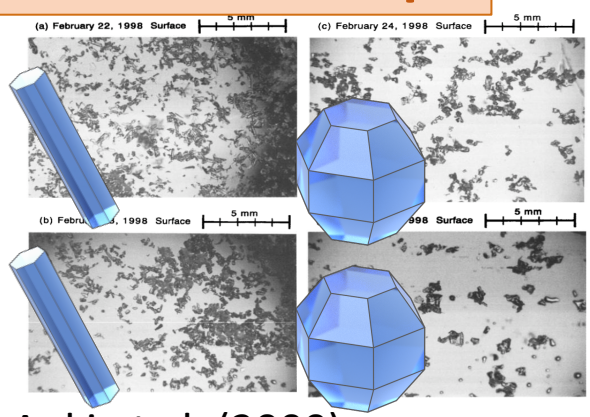
- Snow Grain Habit Mixture (SGHM) model is developed based on previous studies.
  - Needle-like snow grain is dominant in fresh snow (Aoki et al., 2000).
  - Column crystals with large aspect ratios and bullet cluster particles are often found over Antarctica (Walden et al., 2003).
  - Aged snow particles have large, compact, and granular shapes (Nakamura et al. 2001; Ishimoto et al., 2018)

Snow Grain Size Distribution (1/3)

Snow Grain Size Distribution

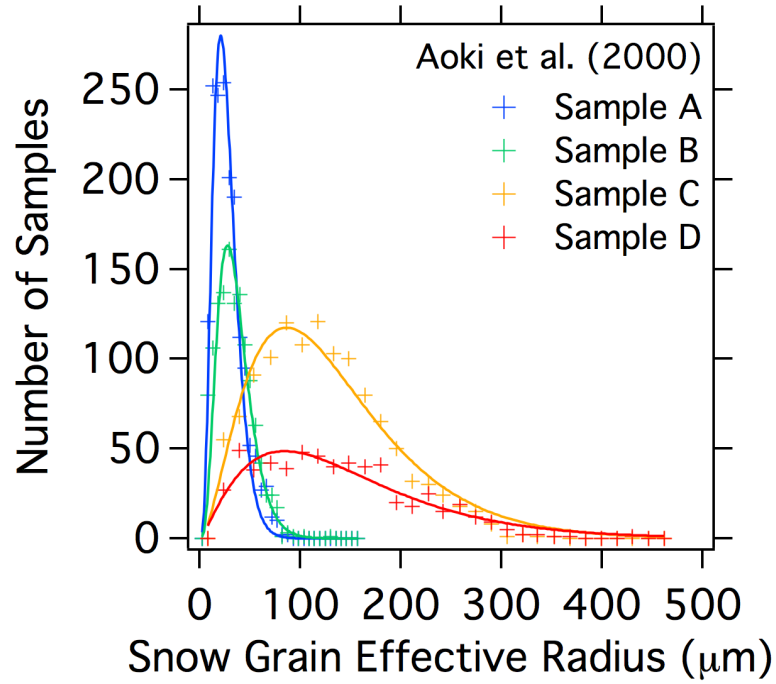


Snow Grain Shape



Aoki et al. (2000)

Fit with Gamma distribution

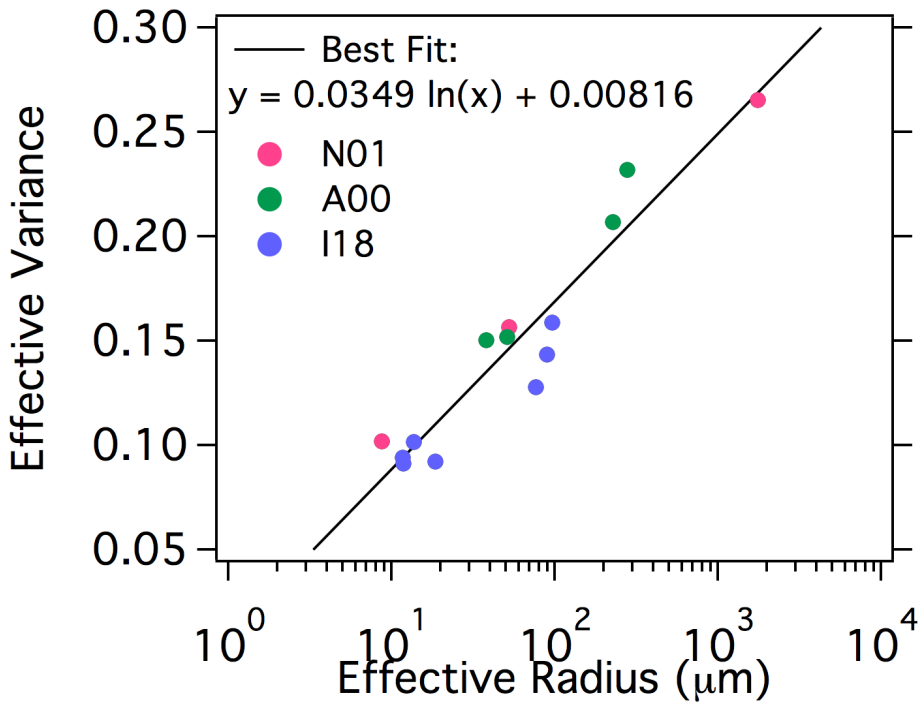


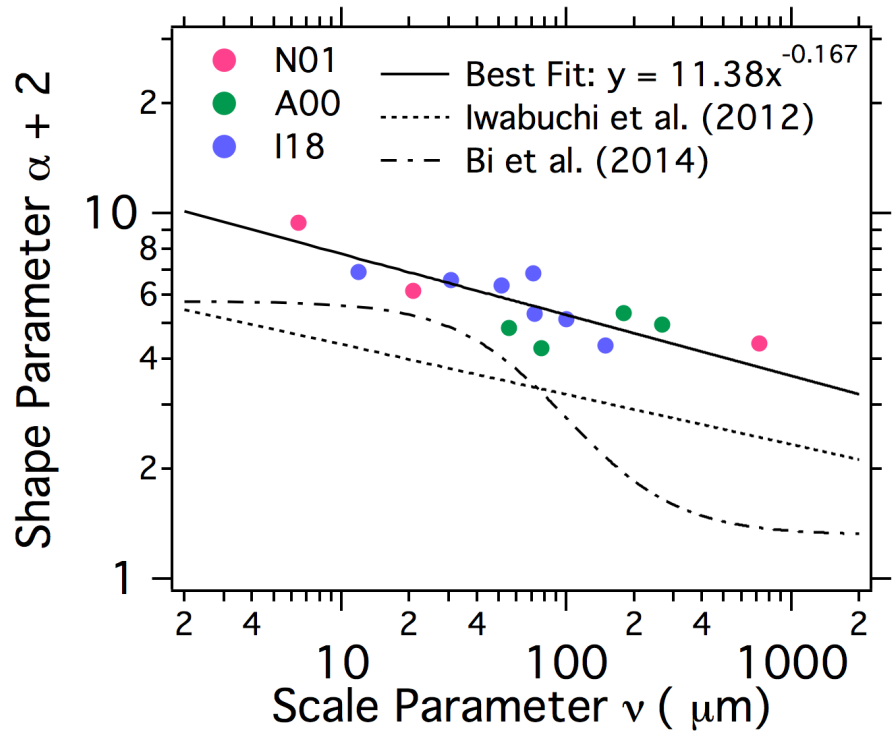
$$n(D)=N_0\left(\frac{D}{\nu}\right)^{\alpha-1}\exp\left(-\frac{D}{\nu}\right)$$

$$n(r)=N_0 r^{(1-3\nu_{eff})/\nu_{eff}}\exp\left(-\frac{r}{r_{eff}\nu_{eff}}\right)$$

- Gamma distribution is assumed to obtain scale and shape parameters of snow grain PSDs from previous studies.

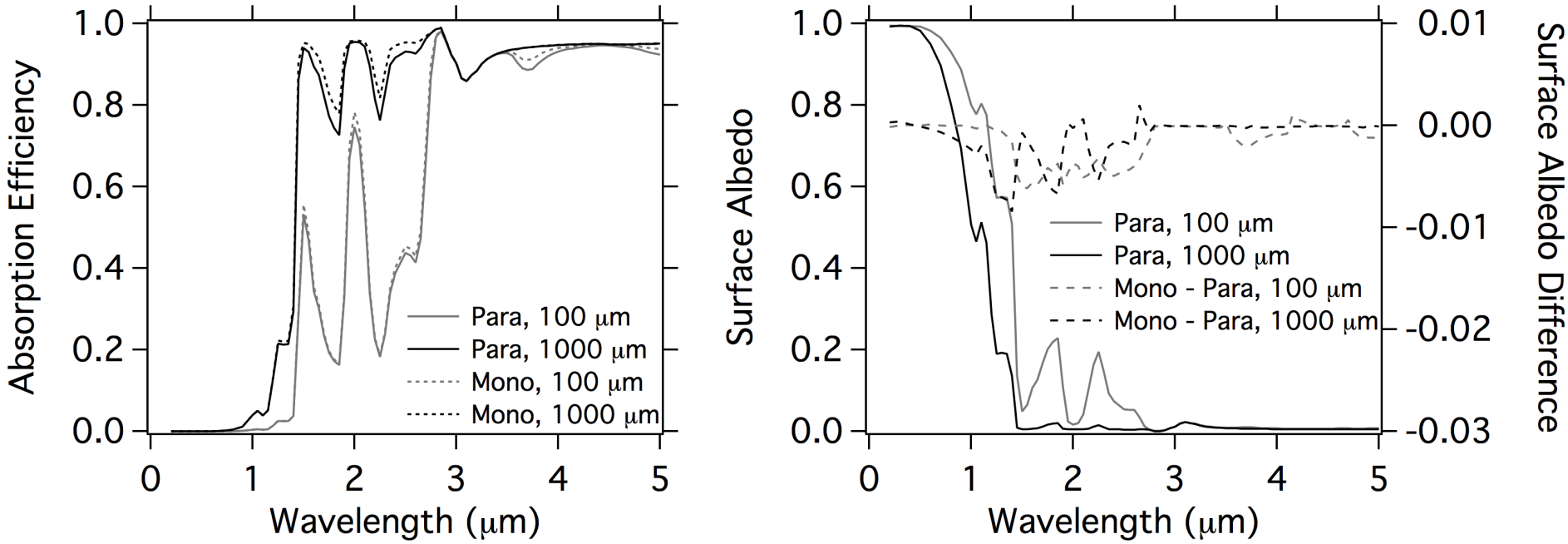
Snow Grain Size Distribution (2/3)





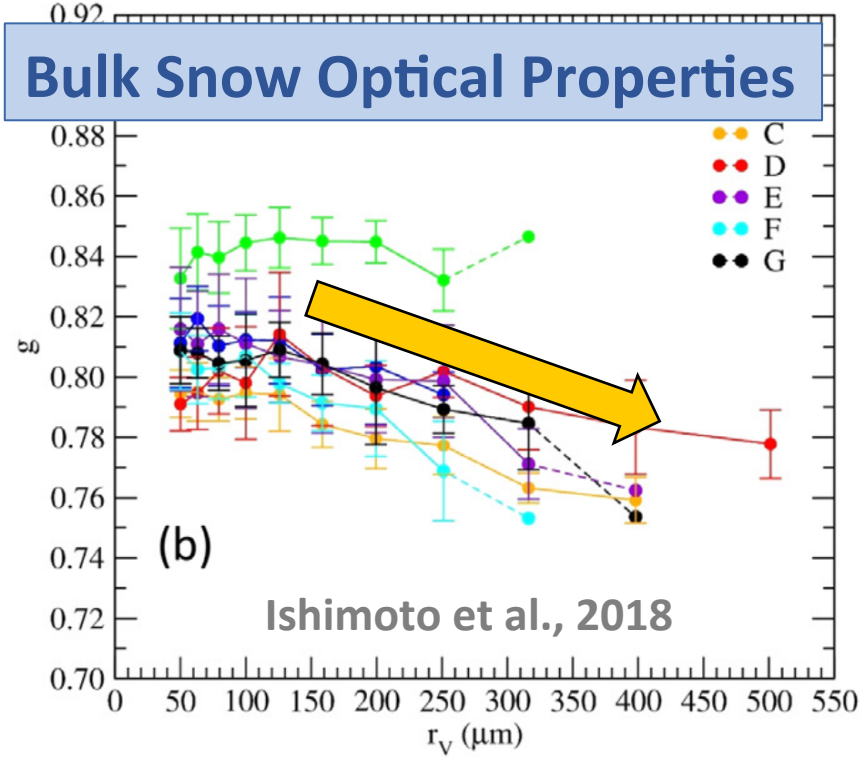
- The larger the effective snow grain radius, the larger the effective variance.
- PSD parameterization for contrails (Iwabuchi et al., 2012) and cirrus clouds (Bi et al. 2014) does not represent PSD of snow grains.
- **Does an assumption with a constant effective variance or monodisperse PSD cause biases in calculating snow surface albedo?**

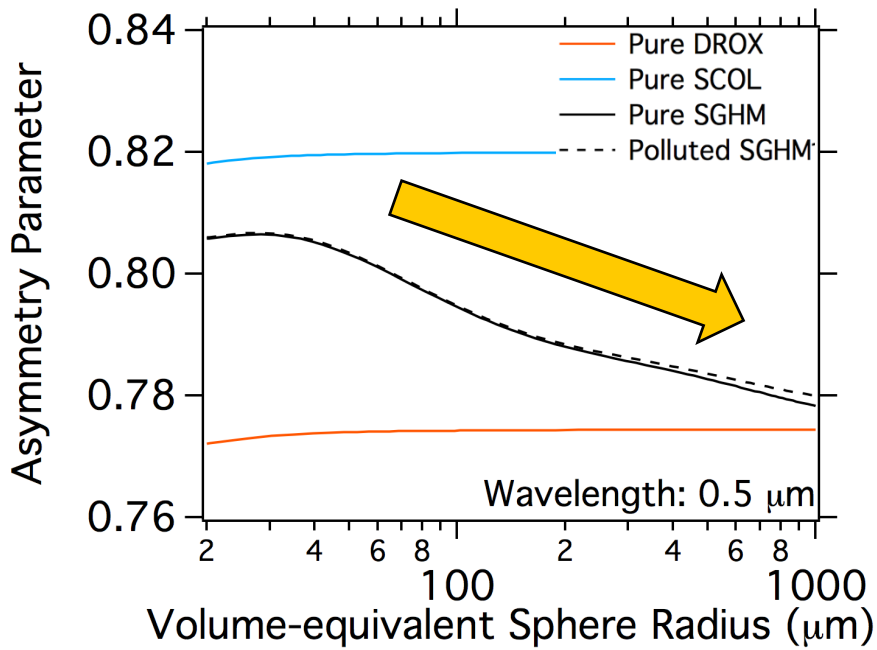
Snow Grain Size Distribution (3/3)



- Maximum difference of absorption efficiency between monodisperse and parameterized PSD is ~3% at SWIR when the effective radius is 1000 μm.
- **Snow grain PSD shape has a small effect on snow surface albedo over VIS and MWIR**.
- **Errors due to assuming monodisperse PSD are significant at 1-3 μm when snow grain size is large**.

Microphysical & Optical Consistency





- Larger snow grains have smaller asymmetry parameters with a range of 0.78–0.81 at 0.5 μm, which is consistent (0.77–0.83 at 0.532 μm) with snow grain measurements (Ishimoto et al., 2018).
- **The single snow grain habit assumption does not represent the slope in the asymmetry parameter.**

Two-layer Snow Albedo Model

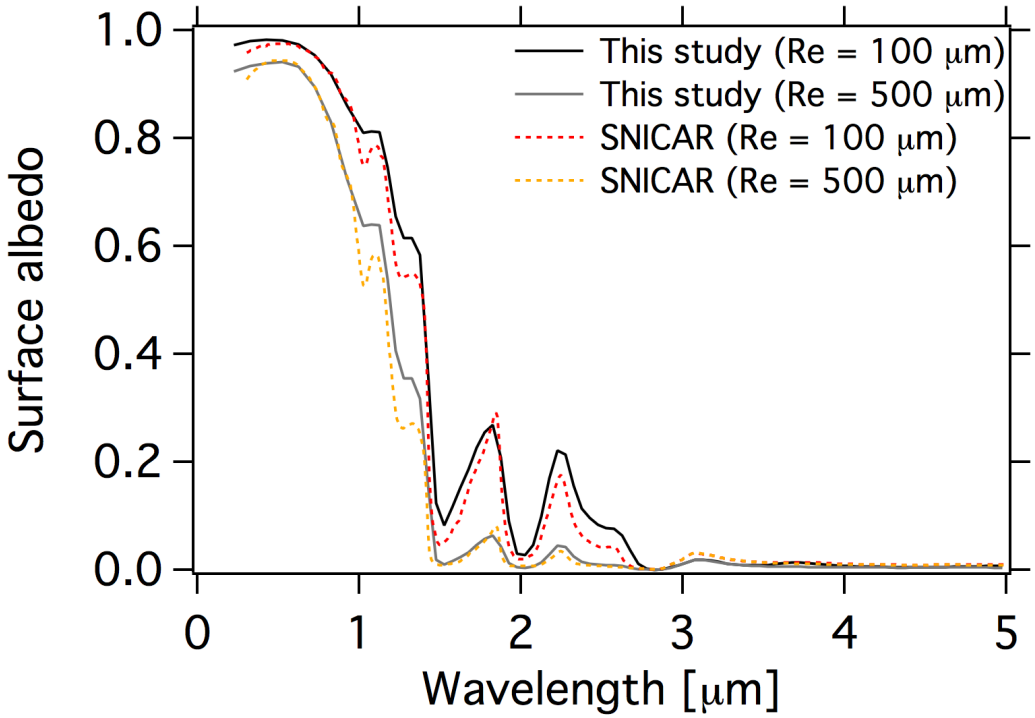
Variables: SWE, R_{eff_FL}, F_{BC}
Variables: R_{eff_SL}, F_{BC}

Snow Albedo Simulation:
- Adding-doubling RTM
- Snow water equivalent (SWE)
  - First layer (FL): Specify
  - Second layer (SL): Constant (corresponding OT = 960)

- Input parameters:
  - SWE (FL)
  - Effective radius (FL, SL)
  - BC internal mixing (the same value between FL and SL)
- **<u>Note that SGHM has not been implemented (ongoing effort)</u>.** An 8-column aggregate model + monodisperse PSD is used (as an initial version).

Comparisons (1/3)

vs SNICAR spectral snow albedo calculation



This study

- Double layer
1. Top SWE = 30 mm (To mimic a single layer)
2. The 2nd layer Re = 1000 μm
- SZA = 60˚
- BC internal mixing = 30 ng/g

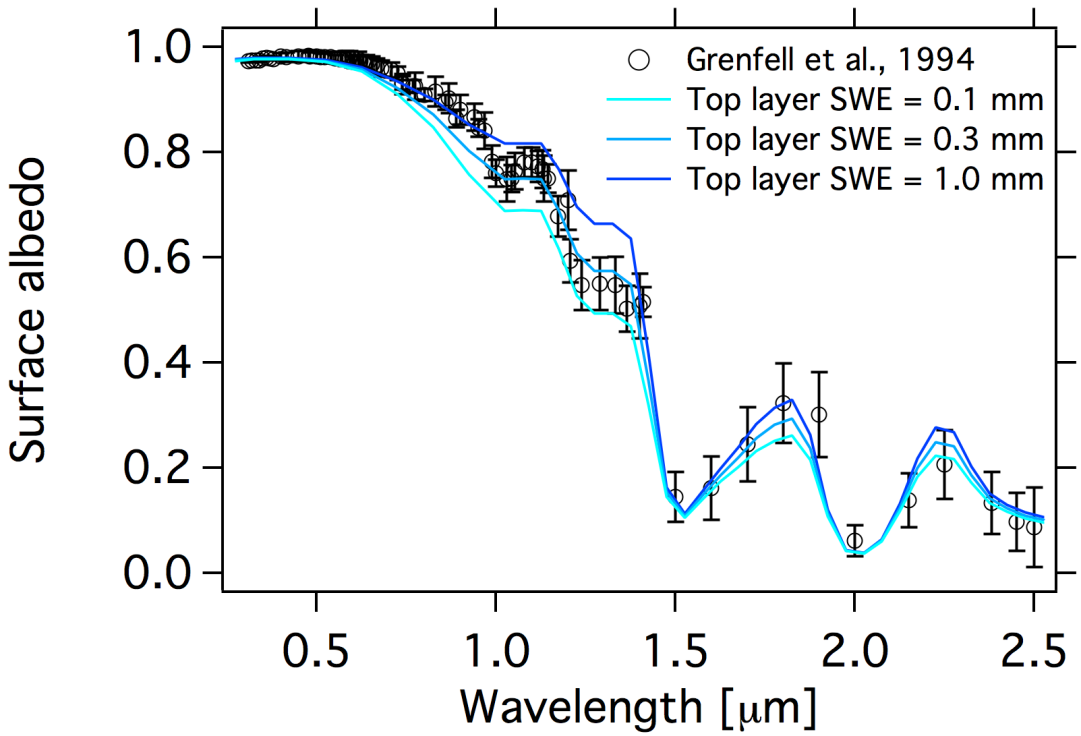
SNICAR

- Single layer
- SZA = 60˚
- BC external mixing = 30 ng/g

- Good agreement except over 1–1.5 μm wavelength (due to coarse resolution)
- Asymmetry factor has a moderate impact on snow albedo at moderately absorptive wavelengths

Comparisons (2/3)

vs Observations



This study

- Double layer

1. Top layer R_e= 70 μm
2. The 2nd layer Re = 1000 μm

- SZA = 60˚
- BC internal mixing = 1.0 ng/g

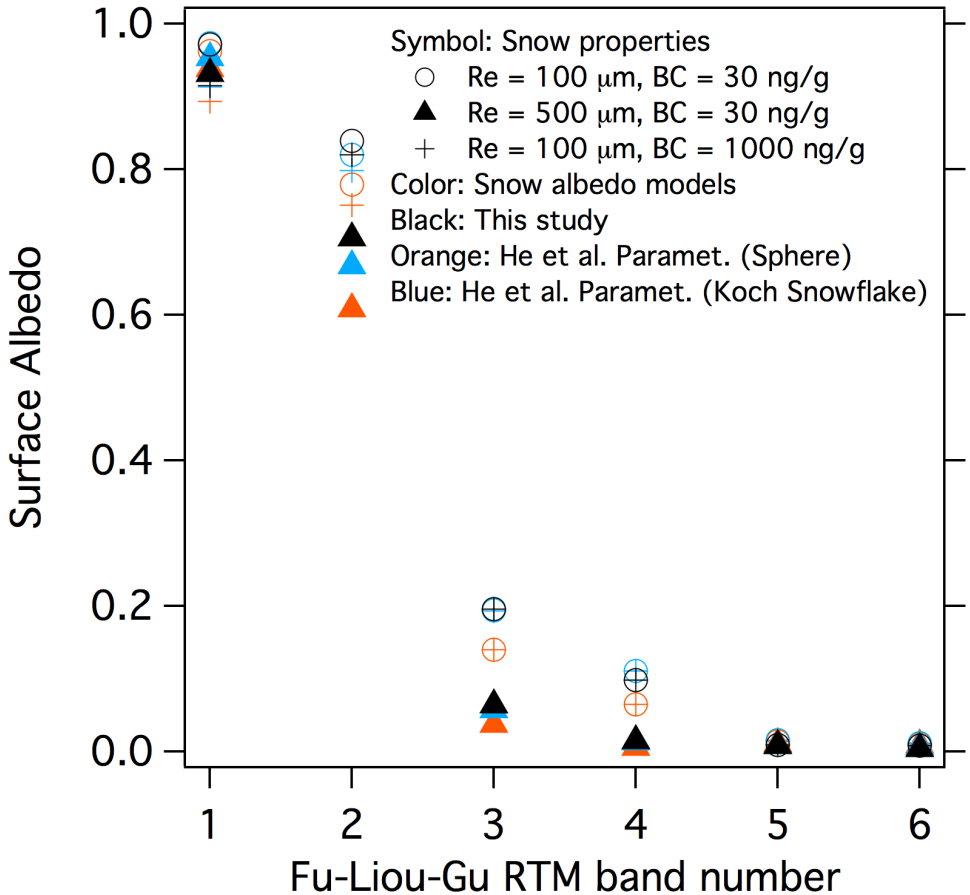
Grenfell et al. 1994

- Average top layer Re = 70 μm
- SZA = 60˚
- Low snow impurity

- The two-layer snow albedo model reproduces observed snow albedo in Antarctica (Grenfell et al., 1994).

Comparisons (3/3)

vs He et al. Fu-Liou RTM snow albedo parameterization



This study

- Double layer (top layer SWE = 30 mm; mimic single layer)
- SZA = 49.5˚
- Snowflake shape: MODIS C6

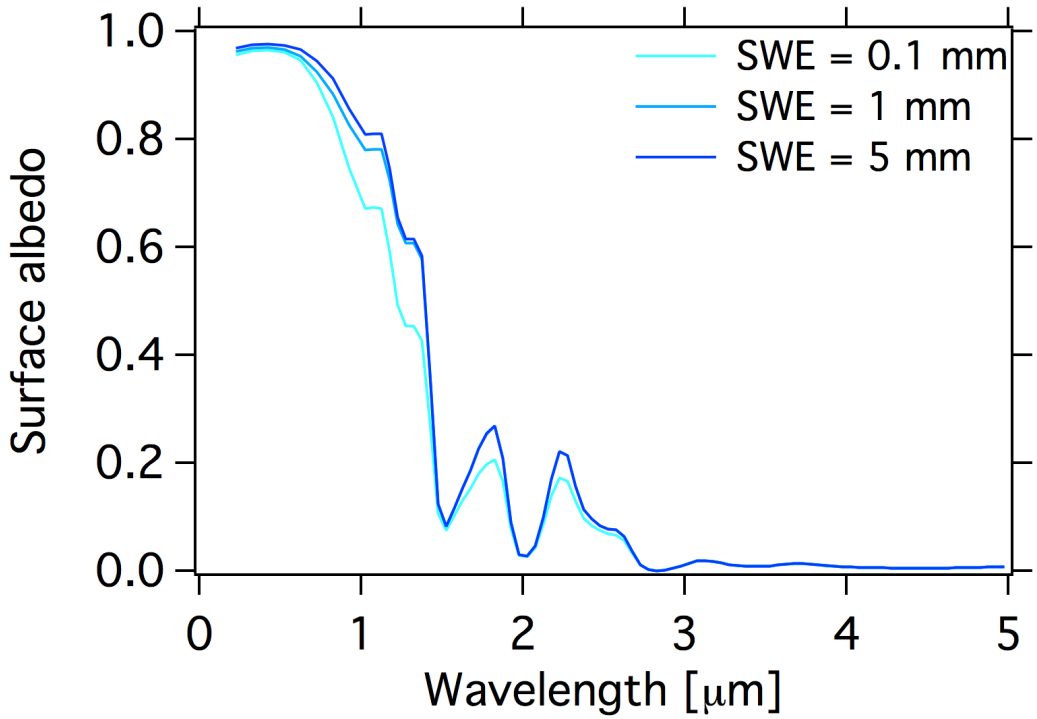
He et al. Parameterization

- Single layer
- SZA = 49.5˚
- Snowflake shape:
  1. Sphere
  2. Koch snowflake

- Consistent snow albedo with the Koch Snowflake parameterization except for band 2, which has an albedo deviation associated with a different snowflake assumption.

Results (1/2)

Top layer SWE



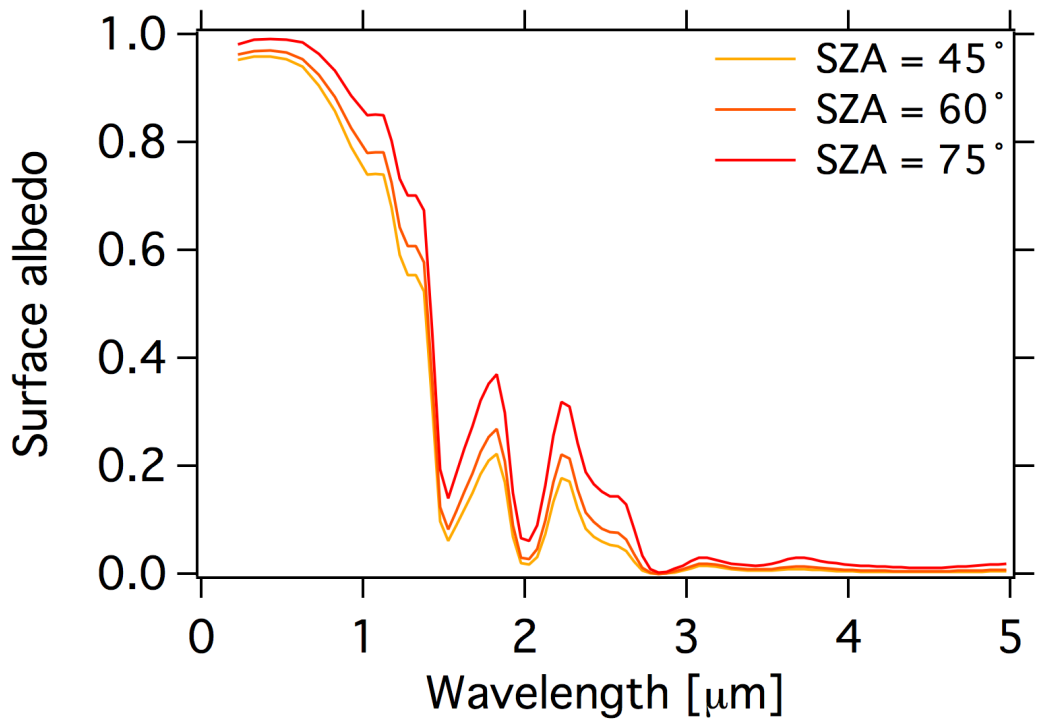
This study

- SZA = 60˚
- BC internal mixing = 30 ng/g
- Top Re = 100 μm
- Bottom Re = 1000 μm
- # of spectral bands = 88

- Top layer SWE modified (25%), and the maximum of snow albedo at NIR wavelengths (1–2.4 μm)
- Small amount of newly accumulated snow over old snow should be taken into account

Results (2/2)

Solar zenith angle



This study

- SWE = 1 mm
- BC internal mixing = 30 ng/g
- Top Re = 100 mm
- Bottom Re = 1000 mm
- # of spectral bands = 88

- Solar zenith angle (SZA) has a moderate impact on spectral snow albedo at visible to NIR wavelengths (0.2–2.7 μm)
- Large impact of SZA on snow albedo is observed at wavelengths corresponding to large asymmetry factors and relatively smaller ice absorption

Summary

- Developed a consistent snow grain model
  - BC internal mixing
  - Snow habit mixture
  - Snow grain size distribution
- Optical properties from the snow grain model are roughly consistent with observations (Ishimoto et al., 2018).

Ongoing Efforts

- Implement the Snow Grain Habit Mixture (SGHM) model to compute the snow albedo model.
- Develop parameterization of snow surface albedo.