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

Masanori Saito, Guanglin Tang

Ping Yang

Texas A&M University
Background (1/3)

Polar regions are most sensitive to climate change

- 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.

Hansen and Nazarenko, 2004 PNAS
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)
• 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)

- 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)

**Light Scattering Simulation:**
- BC volume density: 1.7 g/cm³ (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
Black Carbon Internal Mixing (2/2)

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

- 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 (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)

- Gamma distribution is assumed to obtain scale and shape parameters of snow grain PSDs from previous studies.
• 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?
• Maximum difference of absorption efficiency between monodisperse and parameterized PSD is \(~3\%\) at SWIR when the effective radius is 1000 \(\mu m\).

• **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 \(\mu m\) when snow grain size is large.**
• 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: $SWE$, $R_{\text{eff_FL}}$, $F_{BC}$

Variables: $R_{\text{eff_SL}}$, $F_{BC}$

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)

Note that SGHM has not been implemented (ongoing effort). An 8-column aggregate model + monodisperse PSD is used (as an initial version).
Comparisons (1/3)

• 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

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
Comparisons (2/3)

vs Observations

This study
- Double layer
  1. Top layer $R_e = 70 \, \mu m$
  2. The 2nd layer $R_e = 1000 \, \mu m$
- SZA = 60°
- BC internal mixing = 1.0 ng/g

Grenfell et al. 1994
- Average top layer $R_e = 70 \, \mu m$
- 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

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

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
Results (1/2)

Top layer SWE

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

This study
- SZA = 60°
- BC internal mixing = 30 ng/g
- Top Re = 100 µm
- Bottom Re = 1000 µm
- # 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.