Verifying Snow Spectral Albedo from the Snow, Ice, and Aerosol Radiation (SNICARv3) Model

Julian B. Arnheim

Department of Climate and Space Sciences and Engineering, University of Michigan

Advisors: Dr. Mark G. Flanner, Dr. Frank J. Marsik

SCAN ME

Abstract

- Heightened interest in cryospheric change has spurred research advancements in radiative transfer schemes that account for enhanced snow grain metamorphism and the optical effects of particulates such as black carbon (BC) and dust.
- This project evaluates the third version of the Snow, Ice, and Aerosol Radiative (SNICAR) model by first gathering experimental verification of snow spectral albedo in laboratory and in situ optical analyses of snow laden with Light Absorbing Impurities (LAIs), and then manipulating key physical characteristics such as LAI content, snow grain shape and size, and solar zenith angle (SZA) to optimize agreement with observations and assess possible model biases.
- Representation of key spectral characteristics and implementation of these radiative transfer schemes into Earth System Models (ESMs) have widespread implications on climate forcing and response, affecting the timing of spring snowmelt, the impact of anthropogenic pollution on snow cover, and the strength of the global snow albedo feedback.

Snow Darkening & SNICAR

While few natural surfaces on Earth have greater reflectivities than our frozen high latitudes, common parameters such as effective grain size or the concentration of impurities (BC, mineral dust, volcanic ash) bear considerable influence on albedo reductions. SNICAR, a two-stream, multilayer radiative model, aids in understanding and quantifying cryospheric feedback mechanisms including impurity- and aging-induced feedback processes.

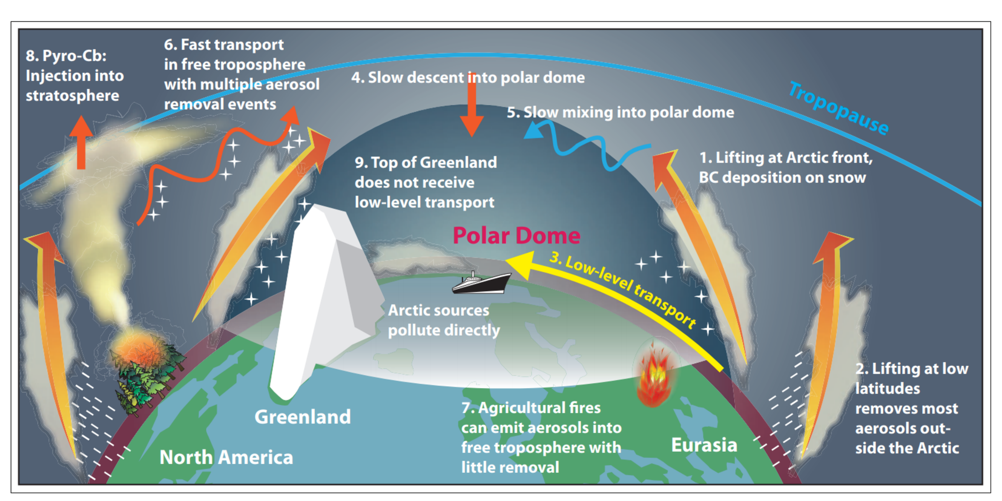

Figure 1: Schematic illustration of processes relevant to transport of BC into the Arctic [1]. In reality, the polar dome extends southernmost over Eurasia, is spatially asymmetric, heterogeneous, smaller in the summer, and temporally variable.

Snow spectroscopy in the past three decades has predominantly utilized spectro-radiometers like the Analytical Spectral Device (ASD), 'FieldSpec.' Modeling radiative transfer in pure snow has been effectively validated by spectral albedo measurements of Antarctic snow, where impurity content is marginal.

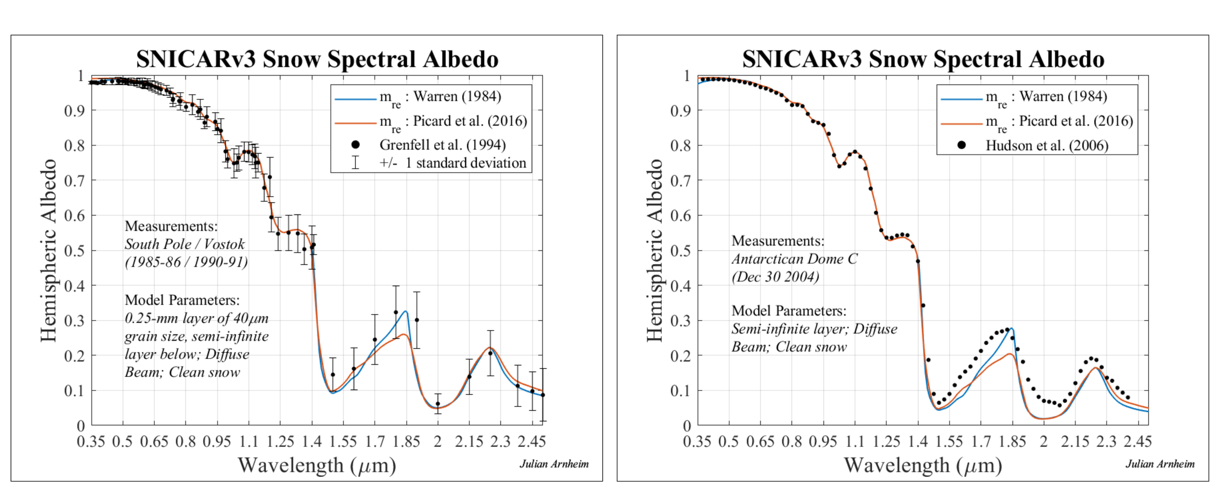

Figure 2: Averaged spectral albedos of Antarctic snow (Left: [2]; Right: [3]) and two model runs of varying ice refractive indices.

Studies have suggested that dust-dominant impurities yield visible absorption features, while BC reduces albedo in a broader manner from visible to shortwave IR (SWIR). The dominating snow reflectivity factor shifts from LAIs in the UV and visible spectrum to snow grain size in NIR/SWIR. LAI, by enhancing snow grain growth, can therefore impact the full range of snow reflectance.

In Situ Measurements

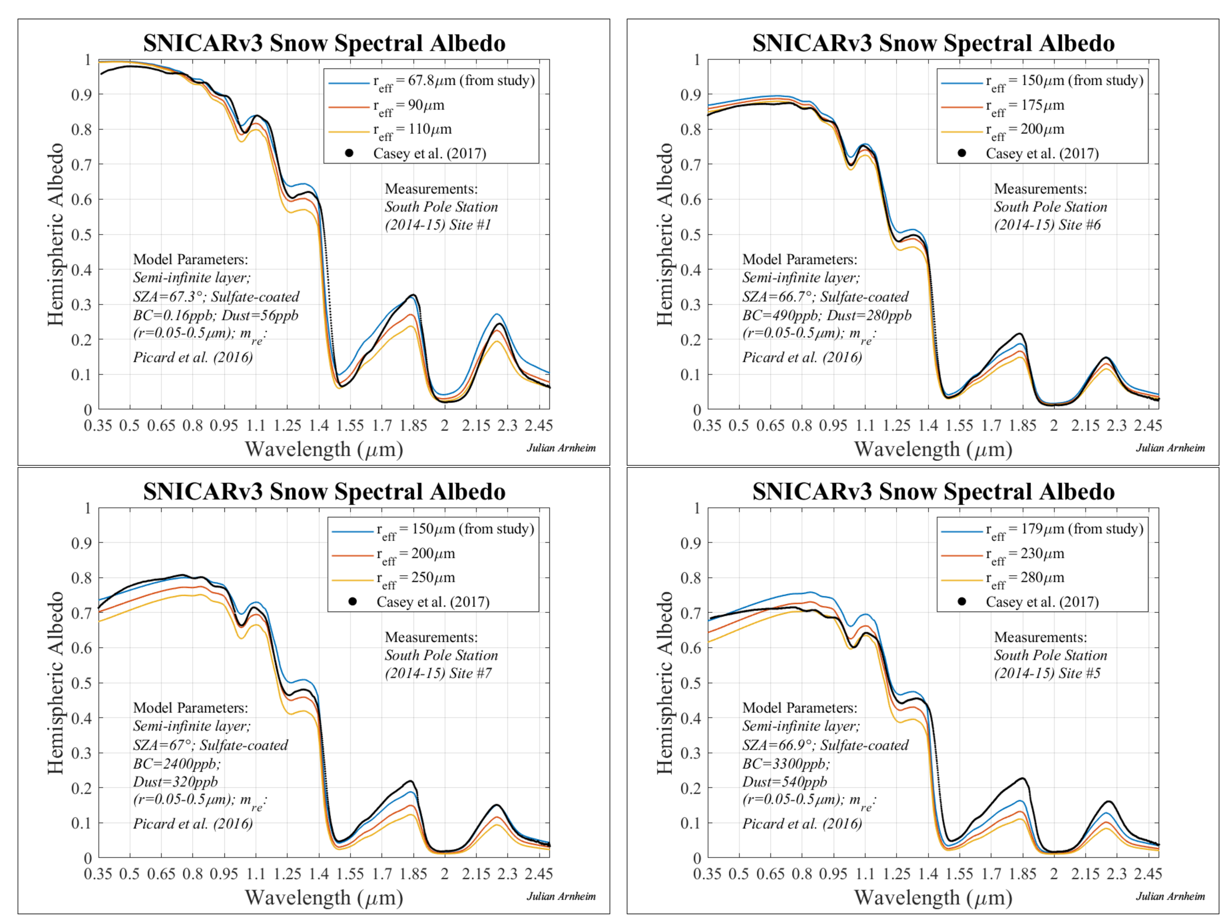

Figure 3: Antarctic snow spectral albedo data [4] from gradations of impure snow along the South Pole Station runaway. Clean Air Sector sample in the top left. Colored model runs refer to varying effective radii assumed of the sample.

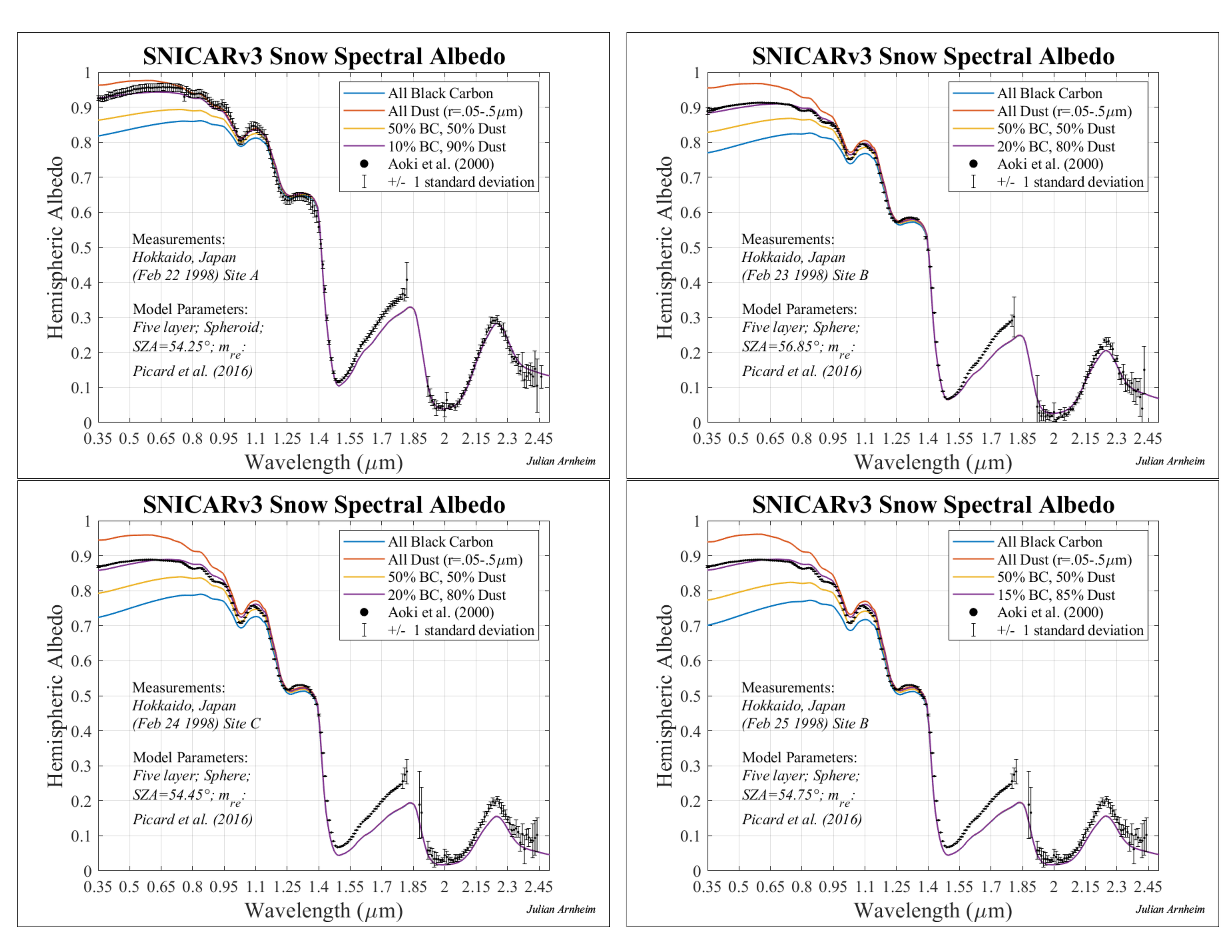

Figure 4: Japanese snow spectral albedo data [5]. Colored model runs refer to varying LAI mass ratios due to bulk value measured in the study. The most accurate model run (purple line) is prescribed via visual approximation.

Artificial Snow Measurements

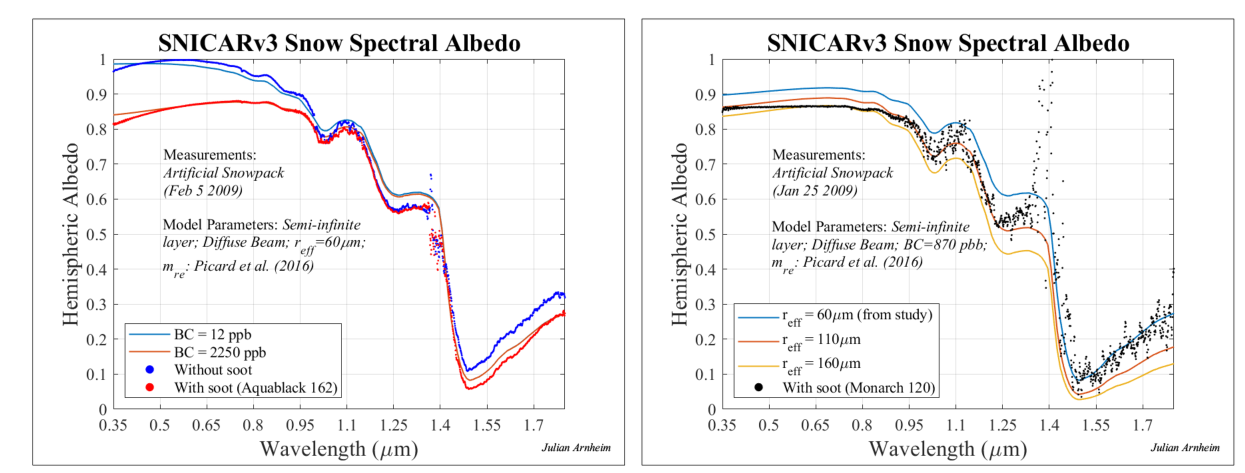

Figure 5: Artificial snowpacks with controlled soot concentrations [6]. Left: Snow without soot and snow with 'Aquablack 162' ($r_{eff} \approx 0.1$ μm) observations and model run. Right: Snow with 'Monarch 120' ($r_{eff} \approx 0.25$ μm) observations and model run. Wavelengths >1.8 μm disregarded due to measurement noise.

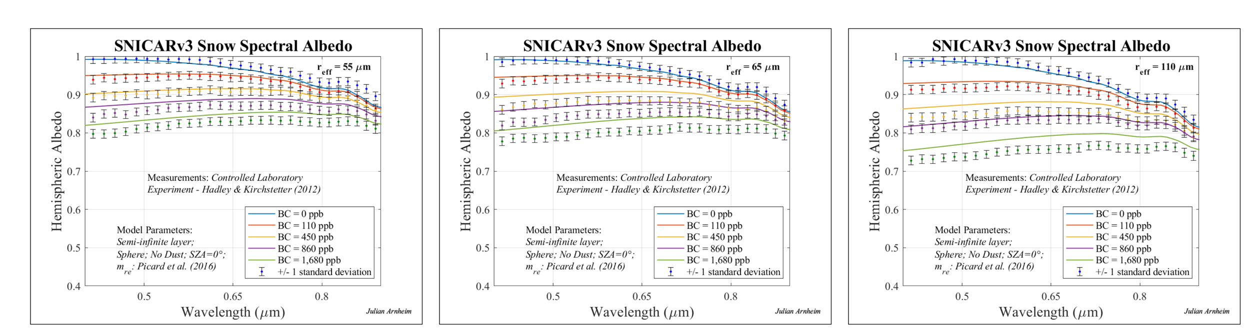

Figure 6: Laboratory measurements and model runs for pristine and BC-laden snow of various set quantities under optical effective radii of 55 (left), 65 (center), and 110 μm (right) [7]. Measurements limited to visible spectrum.

Results

- Assessment indicates model under-representation of LAI forcing, or equivalently, an overestimation of impure snow albedo.
- Consistent model underestimation of albedo at 1.8 μm. Attribution of this bias is a matter of further inquiry.
- The 2.2 μm feature is generally well represented, though occasionally overestimated in higher LAI samples.
- SNICAR modeling of Casey et al. (2014) (Figure 3) indicates a modest overestimation of albedo for wavelengths smaller than 1.5 μm, becoming more pronounced with greater LAI.
- Model-guided analysis of Aoki et al. (2000) (Figure 4) resolves a LAI composition of 10-20% BC and 80-90% dust.
- SNICAR most accurately represents albedo of snow impure from the fine 'Aquablack 162' BC of Brandt et al. (2011) (Figure 5). Overestimation in the visible spectrum arises from larger BC.
- Hadley et al. (2012) (Figure 6) uncovers a positive bias in visible albedo enlarged with increasingly impure snow. Larger effective grain sizes also amplify this model error.

Discussion & Conclusions

These results suggest a minor yet widespread overestimation of snow spectral albedo by SNICARv3, a trend amplified with increased LAI content. Dominant features in spectral albedo, particularly local minima at 1.03, 1.3, 1.5 μm and local maxima at 1.1, 1.8, and 2.2 μm, generally do not produce precise, simultaneous agreement between model and observations, though an optimal grain size greatly enhances already sufficient validation. Future work may investigate integration of larger BC particle sizes into SNICAR to diminish albedo overestimation in the visible, particularly red, portion of the spectrum, and achieve greater agreement with the 'flatter' shortwave albedo of Brandt et al. 2011 'Monarch 120' and Casey et al. 2017 Site #5.

Other underdeveloped research endeavors include improving and validating ice albedo modeling, particularly incorporating ice algae ("cryoconite" or "bioalbedo"). Expressing biological contribution to snow and ice albedo remains crucial for investigating climatic feedbacks in future climate scenarios where intensity and spatial coverage of algal blooms will likely differ from inorganic impurities.

References

[1] PK Quinn, A Stohl, A Arneth, T Berntsen, JF Burchart, J Christensen, M Flanner, K Kupiainen, H Lihavainen, M Shepherd, et al. Arctic monitoring and assessment programme. *The impact of black carbon on Arctic climate. Rep*, 2011.

[2] Thomas C Grenfell, Stephen G Warren, and Peter C Mullen. Reflection of solar radiation by the antarctic snow surface at ultraviolet, visible, and near-infrared wavelengths. *Journal of Geophysical Research: Atmospheres*, 99(D9):18669–18684, 1994.

[3] Stephen R Hudson, Stephen G Warren, Richard E Brandt, Thomas C Grenfell, and Delphine Six. Spectral bidirectional reflectance of antarctic snow: Measurements and parameterization. *Journal of Geophysical Research: Atmospheres*, 111(D18), 2006.

[4] Kimberly A Casey, Susan D Kaspari, SM Skiles, K Kreutz, and MJ Handley. The spectral and chemical measurement of pollutants on snow near south pole, antarctica. *Journal of Geophysical Research: Atmospheres*, 122(12):6592–6610, 2017.

[5] Teruo Aoki, Tadao Aoki, Masashi Fukabori, Akihiro Hachikubo, Yoshihiro Tachibana, and Fumihiko Nishio. Effects of snow physical parameters on spectral albedo and bidirectional reflectance of snow surface. *Journal of Geophysical Research: Atmospheres*, 105(D8):10219–10236, 2000.

[6] Richard E Brandt, Stephen G Warren, and Antony D Clarke. A controlled snowmaking experiment testing the relation between black carbon content and reduction of snow albedo. *Journal of Geophysical Research: Atmospheres*, 116(D8), 2011.

[7] Odelle L Hadley and Thomas W Kirchstetter. Black-carbon reduction of snow albedo. *Nature Climate Change*, 2(6):437–440, 2012.

Acknowledgements

This project was funded through a grant from the National Science Foundation's Research Experience for Undergraduates Program (Grant 1659248).

Research was conducted from May to August 2020.

SNICARv3 is operable online at http://snow.engin.umich.edu.