Supporting data for the Near-Infrared Emitting and Reflectance-Monitoring Dome

Adam Schneider Mark Flanner

1 Introduction

The Near-Infrared Emitting and Reflectance-Monitoring Dome (NERD) is an instrument designed to obtain snow specific surface area (SSA). We obtain snow SSA by measuring 1.30 µm and 1.55 µm bidirectional reflectance factors (BRFs) of natural snow. Natural snow was collected after snowfall events in the winters of 2015, 2016, and 2017 in Hanover, New Hampshire. Provided below is documentation for the data used by Schneider, Flanner, and De Roo (2018). In reference to these data, please cite Schneider and Flanner (2018).

2 Research methodology

Figure 1 Spectral snow albedo data was generated from the online version of the Snow, Ice, and Aerosol Radiation (SNICAR) model available at `http://snow.engin.umich.edu/` with the following input parameters (Flanner, Zender, Randerson, & Rasch, 2007):

1. *a. Incident radiation* Direct
   b. Solar zenith angle, if incident radiation is direct: 0 degrees
2. *Surface spectral distribution:* Mid-latitude winter, clear sky
3. *Snow grain effective radius:* 55 µm (blue curves), 164 µm (red curves)
4. *Snowpack thickness:* 1 m
5. *Snowpack density:* 200 kg m^{-3}
6. *Albedo of underlying ground:*

   Visible: 0.2

   Near-infrared: 0.4
7. *Black carbon concentration:*

Uncoated: 0 ppb (solid curves), 100 ppb (dashed curves)

MAC scaling factor: 1.0

Sulfate-coated: 0 ppb

8. *Dust concentration:*

   Size 1 (0.1–1.0 μm diameter): 0 ppm

   Size 2 (1.0–2.5 μm diameter): 0 ppm

   Size 3 (2.5–5.0 μm diameter): 0 ppm

   Size 4 (5.0–10.0 μm diameter): 0 ppm

9. *Volcanic ash concentration:* 0 ppm

10. *Experimental particle 1 concentration*: 0 ppb

Figure 3 Snow images were processed using X-ray micro-computed tomography (microCT) at the U.S. Army Corps of Engineers' Cold Regions Research & Engineering Laboratory. Snow samples were scanned in a cold lab to minimize snow melt. Output tiffs generated by Bruker microCT instrumentation and software (`https://www.bruker.com/products/microtomography/micro-ct-software.html`) were then analyzed to calculate snow SSA. Small *volume of interest* (VOI) subsamples were then selected to generate triangulated models used in surface rendering. These models enable the visualization of microscopic features across different snow samples shown in Figure 3 (Schneider et al., 2018).

Figure 4 Snow BRFs were measured using the NERD. Snow SSA was measured using Bruker microCT instrumentation and analysis software. Snow BRFs were modeled for varying ice particle radii and shape habits using the Monte Carlo method for photon transport. Monte Carlo input data pertaining to the ice particle single scattering properties was provided by Yang et al. (2013).

Figure 5 Snow albedo data was generated from the SNICAR-Online model (`http://snow.engin.umich.edu/`) (Flanner et al., 2007) and from Monte Carlo modeling. SNICAR input parameters are the same used in Figure 1 (Schneider et al., 2018), with the exception of the solar zenith angle of 15 degrees for 1.55 μm, and with the following array of input effective radii (μm): $[327, 164, 109, 82, 65, 55, 47, 41, 36]$. Narrow-band albedo plotted in Figure 5 was calculated from SNICAR spectral output arrays for each grain size using Gaussian weighting functions centered around 1.30 μm and 1.55 μm (Schneider et al., 2018).

Figure 6 Calibration curves were fit to data using least squares regression analysis.

Figure 7 Snow BRFs were measured throughout the day on February 14, 2017 and converted to snow SSA using an exponential calibration function.

A complete account of the research methodology is detailed in the manuscript published in The Cryosphere Discussions (Schneider et al., 2018).

3 Data

fig01/ SNICAR output arrays saved by snow grain effective radius (μm) and black carbon (BC) concentration (ng g^{-1}). The spectral albedo arrays are provided in each text file:

- re_164um_0bc.txt
- re_164um_100bc.txt
- re_55um_0bc.txt
- re_55um_100bc.txt

fig03.tar.gz MicroCT database. Top directories are named after unique samples labeled with approximate time and dates. Samples with *bc* or *sand* in their names indicate snow with added black carbon or dust particles. For exact microCT scan times and reconstruction settings, please see the log files located in each sample subdirectory. Snow samples listed below correspond to the following sample type described by Schneider et al. (2018).

1. *Fresh samples from 2016:*
   - snow_fresh_mar2016_John/
   - snow_fresh_mar2016_hotel/
2. *Artificial ice crystals grown in a cold lab:* snow_artificial_2016/
3. *Old sintered samples from 2015:*
   - snow_old_2015_clearbin/
   - snow_old_2015_largebin/
4. *Fresh needles collected during the March 14 snow storm:*
   - snow_fresh_14mar17_2/
   - snow_fresh_14mar17_3/
   - snow_fresh_14mar17_4/
5. *Fresh samples collected shortly after February (10-16) 2017 snow fall events:*
   - snow_10feb17_natural_6am/

- snow_10feb17_bc_6am/
- snow_10feb17_natural_3pm/
- snow_14feb17_natural_9am/
- snow_14feb17_bc_9am/
- snow_14feb17_sand_9am/
- snow_14feb17_natural_5pm/
- snow_14feb17_bc_5pm/
- snow_14feb17_sand_5pm/
- snow_17feb17_natural_8am/
- snow_17feb17_bc_8am/
- snow_17feb17_sand_8am/

6. *Samples collected after apparent metamorphosis on February 17 2017*
    - snow_17feb17_natural_1pm/
    - snow_17feb17_bc_1pm/
    - snow_17feb17_sand_1pm/
7. Other samples not included in Schneider et al. (2018):
    - ice_17feb17_sand_1pm/
    - snow_outside_15mar17_12pm/
    - snow_storage_15mar17_12pm/

Images from Schneider et al. (2018) are provided as PNGs in the following sample directories:

a. snow_fresh_mar2016_John/snow_fresh_mar2016_John.png

b. snow_artificial_2016/snow_artificial_2016.png

c. snow_old_2015_clearbin/snow_old_2015_clearbin.png

d. snow_fresh_14mar17_4/snow_fresh_14mar17_4_rec_voi_2.png

e. snow_outside_15mar17_12pm/snow_outside_15mar17_12pm_rec_voi_2.png

f. snow_17feb17_bc_1pm/snow_17feb17_bc_1pm_1.png

Subdirectories contain various stages of data:

raw_tiffs/ Contain output tiffs generated from X-ray transmission measurements.

SAMPLE_ID_Rec/ Contain vertically resolved cylindric sections reconstructed from raw output using Bruker microCT software.

VOI/ *Volume of interest*; smaller subsamples used for 3D visualization.

VOI/Binary Contain binarized voxel data indicating the presence of either air or ice. These data are used for 3D morphometry from which SSA is calculated.

fig04/

- nerd_xct_snow_ssa.py

  This file contains NERD snow BRF measurements and X-ray microCT snow SSA calculations displayed in Figure 4 of Schneider et al. (2018). These Python data structures are used in plotting snow 1.3 μm ("wvl13.") and 1.5 μm ("wvl15.") BRFs versus snow SSA. Generally, each microCT scan is accompanied by 4-8 NERD BRFs. Also within the metadata are labels used in the figure key, time (in hours) between NERD measurements and microCT scans, and *sa_type*, indicating which parameters were used in accounting for isothermal snow metamorphism corrections described by Ebner, Schneebeli, and Steinfeld (2015). BRFs are specified by their wavelength and viewing zenith angle, defined in the functions nerd_ssa_cal_30 (30 degrees) or nerd_ssa_cal_60 (60 degrees).

- monte_carlo_data.py

  This file processes Monte Carlo output data stored in mc_ssa_cal.tar.gz and plots BRFs versus snow SSA. To reproduce Figure 4 (Schneider et al., 2018) with Monte Carlo results, untar mc_ssa_cal.tar.gz and run nerd_xct_snow_ssa.py with input −−top_data_dir set to the location of the unpacked database (use "python nerd_xct_snow_ssa.py −−help" for help).

fig05/

- mc_albedo_ssa.py

  This file reads in Monte Carlo data and calculates and plots directional-hemispherical reflectance as a function of snow SSA for various ice shape habits used in Figure 5 of Schneider et al. (2018).

- snicar_out.py

  This file contains narrow-band albedo calculations derived from SNICAR output. In the function get_snicar_data, the following variables are defined:

  particle_re Input effective radii array.

  particle_ssa Snow SSA array.

  rho_13 Nadir black-sky albedo at 1.30 μm.

  rho_15 15 degree black-sky albedo at 1.55 μm.

  rho_15b 15 degree black-sky albedo at 1.55 μm calculated with a broadened Gaussian weighting function (see Schneider et al. (2018) for discussion).

- monte_carlo_data.py

This file processes Monte Carlo output data stored in mc_ssa_cal.tar.gz and plots BRFs versus snow SSA. To reproduce Figure 5 (Schneider et al., 2018) with Monte Carlo results, untar mc_ssa_cal.tar.gz and run mc_albedo_ssa.py with input −−top_data_dir set to the location of the unpacked database (use “python mc_albedo_ssa.py −−help” for help).

fig06/
- nerd_calibration_curves.py

  This file contains NERD snow BRF measurements and X-ray microCT snow specific surface area calculations displayed in Figure 6 of Schneider et al. (2018).

fig07/
- feb14_data.py

  Raw data from February 14, 2017 soot-in-snow experiment

mc_ssa_cal.tar.gz Monte Carlo output database. These raw output files contain photon exit angles used to calculate reflectances. monte_carlo_data.py, in fig04/ and fig05/, import these data, calculate reflectances, and plot results in Figures 4 and 5 (Schneider et al., 2018).

4 Acknowledgements

- This work is funded by the National Science Foundation, reward number ARC-1253154.
- We thank colleagues at the Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire for their generous support. In particular, thanks to Zoe Courville and John Fegyveresi for their hospitality and guidance navigating the facilities at CRREL. We also thank Ross Lieblappen for sharing his microCT expertise and providing a thorough tutorial for running and analyzing snow scans. Finally, thanks to Alden Adolph for facilitating travel accommodations and welcoming Adam to Hanover, New Hampshire in 2016 and 2017.

References

Ebner, P. P., Schneebeli, M., & Steinfeld, A. (2015, July). Tomography-based monitoring of isothermal snow metamorphism under advective conditions. *The Cryosphere*, *9*(4), 1363–1371. Retrieved 2017-10-22, from `http://www.the-cryosphere.net/9/1363/2015/` doi: 10.5194/tc-9-1363-2015

Flanner, M. G., Zender, C. S., Randerson, J. T., & Rasch, P. J. (2007, June). Present-day climate forcing and response from black carbon in snow. *Journal of Geophysical Research*, *112*(D11). Retrieved 2017-10-27, from `http://doi.wiley.com/10.1029/2006JD008003` doi: 10.1029/2006JD008003

Schneider, A., & Flanner, M. (2018). *Supporting data for the Near-Infrared Emitting and Reflectance-Monitoring Dome* [dataset]. University of Michigan. Retrieved 2018-10-31, from `http://deepblue.lib.umich.edu/data/concern/generic_works/79407x76d` doi: 10.7302/Z23F4MVC

Schneider, A., Flanner, M., & De Roo, R. (2018, October). Measuring Snow Specific Surface Area with 1.30 and 1.55 µm Bidirectional Reflectance Factors. *The Cryosphere Discussions*, 1–23. Retrieved 2018-10-25, from `https://www.the-cryosphere-discuss.net/tc-2018-198/` doi: 10.5194/tc-2018-198

Yang, P., Bi, L., Baum, B. A., Liou, K.-N., Kattawar, G. W., Mishchenko, M. I., & Cole, B. (2013, January). Spectrally Consistent Scattering, Absorption, and Polarization Properties of Atmospheric Ice Crystals at Wavelengths from 0.2 to 100µm. *Journal of the Atmospheric Sciences*, *70*(1), 330–347. Retrieved 2015-12-10, from `http://journals.ametsoc.org/doi/abs/10.1175/JAS-D-12-039.1` doi: 10.1175/JAS-D-12-039.1