Analysis of Errors in the modeling of CERES SW observations over Antarctica introduced by the BRDF model

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Current results of the modeling

- High correlation between the model and observations.
- FM-5 sensor is known to be slightly brighter than other instruments.
- We still need to find a reason for ~5% discrepancy.
All observations are clustered in the relatively narrow azimuth sector. For this reason, only results in azimuth plane $\phi = 63^\circ$ ($117^\circ$) are reported in this study.
BRDF model recap 1:
what was measured in Dome C and how it was reported


• spectral resolution: 25 nm; spectral range: 350 – 2400 nm;
• reflected spectral radiance was measured on a set of 6 VZA: (7.5°, 22.5°, 37.5°, 52.5°, 67.5°, 82.5°) and a number of azimuth directions;
• simultaneous measurements of reflected spectral irradiance;
• down- and up-welling irradiances under complete overcast.

The results were reported in the form of:
• the ratio of reflected radiance and irradiance under natural (blue-sky) illumination; it was called anisotropic reflection factor $R$;
• albedo under overcast conditions (it serves as a very accurate surrogate of bi-hemispherical reflection, a.k.a. white-sky albedo).
BRDF and related quantities

\[ \rho(\theta_i, \theta_r, \phi_i - \phi_r) = \frac{I_r(\theta_i, \theta_r, \phi_i - \phi_r)}{F_0(\theta_i, \phi_i)} \quad \text{BRDF} \]

\[ I_r(\theta_i, \theta_r, \phi_i - \phi_r) \quad \text{Reflected radiance} \]

\[ F_0(\theta_i, \phi_i) \quad \text{Illuminating irradiance (incoming flux) coming from a single direction (\(\theta_i, \phi_i\))} \]

\[ \rho(\theta_i, \theta_r, \phi) = \frac{1}{\pi} \frac{\pi I_r(\theta_i, \theta_r, \phi) F_r(\theta_i)}{F_r(\theta_i)} = \frac{1}{\pi} \mathcal{R}(\theta_i, \theta_r, \phi) a_{\text{black-sky}}(\theta_i) \]

\[ F_r(\theta_i) = \int_0^{2\pi} d\phi \int_0^{\pi/2} d\theta_r \sin \theta_r \cos \theta_r I_r(\theta_i, \theta_r, \phi) \quad \text{Reflected irradiance (outcoming flux) under monodirectional illumination} \]

\[ \mathcal{R}(\theta_i, \theta_r, \phi) = \frac{\pi I_r(\theta_i, \theta_r, \phi)}{F_r(\theta_i)} \quad \text{True anisotropic reflection factor} \]

\[ a_{\text{black-sky}}(\theta_i) = \frac{F_r(\theta_i)}{F_0(\theta_i)} \quad \text{Directional-hemispherical reflectance (black sky albedo, BSA)} \]

\[ R(\theta_i, \theta_r, \phi, \text{atm}) = \frac{\pi I_r^{\text{measured}}(\theta_i, \theta_r, \phi)}{F_r^{\text{measured}}(\theta_i)} \quad \text{Measured anisotropic reflection factor} \]

BRDF cannot be measured under natural light illumination (blue-sky) conditions: light comes to the surface from the solid angle of 2\(\pi\)
BRDF model recap 2: the use of measurements in Dome C

\[ \rho(\theta_i, \theta_r, \phi) \approx \frac{1}{\pi} R(\theta_i, \theta_r, \phi) a_{\text{black-sky}}^{\text{model}}(\theta_i) \]

Approximations:

- \( a_{\text{black-sky}}^{\text{real}}(\theta_i) \approx a_{\text{black-sky}}^{\text{model}}(\theta_i) \)

- \( a_{\text{white-sky}}^{\text{model}} = 2 \int_0^{\pi/2} d\theta_i \sin \theta_i \cos \theta_i a_{\text{black-sky}}^{\text{model}}(\theta_i) \)

Model BSA comes from the RT modeling of a flat snowpack providing the closest match of white-sky albedo (WSA) with the measured albedo under overcast conditions.

Possible problems:
1) Directional distribution of light reflected from a rough surface differs from that for a flat one, so matching of WSA may provide a wrong choice of the overall brightness;
2) Both true ARF and BSA are approximated, so that reciprocity of BRDF is not guaranteed: \( R(\theta_i, \theta_r, \phi) a(\theta_i) \neq R(\theta_r, \theta_i, \phi) a(\theta_r) \)
Radiative transfer model

- 32 bands covering CERES SW band;
- monochromatic calculations performed by DISORT;
- accounts for Rayleigh scattering;
- gas absorption (correlated-k (Kato et al. 1999), HITRAN 2000);
- clouds and aerosol scattering and absorption (if any);
- auxiliary data (surface pressure, O3 and water vapor concentrations, and surface elevation) come from re-analysis used in CERES production – GEOS4 (2000 – 2007), GEOS5 (2008 – present);
- accurate bottom boundary condition.

Bands 7 through 18 covering spectral range from 407 nm to 791 nm are used in this study. They are the most reflective bands accumulating total solar irradiance of 636 W/m².
BRDF model recap 3: limited SZA range

Surface boundary condition to the RTE

\[ I(\tau = \tau_{surf}, \theta > \pi/2, \phi) = I_0 \cos \theta_s \rho(\theta_s, \theta, \phi) \exp\left(-\frac{\tau_{surf}}{\cos \theta_s}\right) \]

\[ + \int_0^{2\pi} d\phi' \int_0^{\pi/2} \sin \theta' d\theta' \cos \theta' \rho(\theta', \theta, \phi-\phi') I(\tau = \tau_{surf}, \theta', \phi') \]

BRDF \( \rho(\theta_i, \theta_r, \phi) \) is needed on \( 0^\circ \leq \theta_i \leq 90^\circ \);

\( R(\theta_i, \theta_r, \phi) \) was measured on \( 51.6^\circ \leq \theta_i \leq 86.6^\circ \)

assumptions:

1) \( R(\theta_i = 0, \theta_r, \phi) = 1 \)

\[ R(0^\circ < \theta_i < 51.6^\circ, \theta_r, \phi) = \left[(1 - \cos \theta_i)R(\theta_i = 51.6^\circ, \theta_r, \phi) + (\cos \theta_i - \cos 51.6^\circ)\right]/(1 - \cos 51.6^\circ) \]

2) \( R(\theta_i > 86.6^\circ, \theta_r, \phi) \approx R(\theta_i = 86.6^\circ, \theta_r, \phi) \)
Is reflection isotropic under overhead sun?

Snowpack only, wavelength 0.549 through 0.567 um

Snowpack only, wavelength 0.667 through 0.684 um

Snowpack with atmosphere, wavelength 0.8 um

*R(\theta_i = 0, \theta_r, \phi) = 1* is a wrong assumption
azimuth rotational symmetry holds

All graphs show ARF in 4 azimuth planes:
red – \phi = 0° (180° for negative VZA),
green – \phi = 30° (210°),
blue – \phi = 60° (240°),
cyan – \phi = 90° (270°).
BRDF model recap 4: spectral dependence

\[ R(\theta_i, \theta_r, \phi, \lambda < 0.8 \, \mu m) \approx R(\theta_i, \theta_r, \phi, \lambda = 0.8 \, \mu m) \]

\[ R(\lambda = 0.8 \, \mu m) \] better approximates \( \mathcal{R}(\lambda = 0.8 \, \mu m) \) than \( R(\lambda = 0.5 \, \mu m) \) does \( \mathcal{R}(\lambda = 0.5 \, \mu m) \). However, \( R(\lambda = 0.8 \, \mu m) \neq \mathcal{R}(\lambda < 0.8 \, \mu m) \)
Modeling results: TOA radiance, band 11

band radiance over spectral interval 0.549 μm through 0.567 μm: black – snowpack-only ARF, blue – snowpack+atmosphere ARF (model of measurable quantity), green – the same as blue but ARF at 0.8 μm, red – the same as green but with interpolation over SZA. RAA = 63° for positive VZA, RAA = 117° negative.
Modeling results: relative error, band 11

Relative error of band radiance over spectral interval 0.549 μm through 0.567 μm: blue – snowpack+atmosphere ARF (model with measurable quantity), green – the same as blue but ARF at 0.8 μm, red – the same as green but with interpolation over SZA. RAA = 63° for positive VZA, RAA = 117° negative.
Modeling results: total TOA radiance

Broadband radiance over spectral interval 0.407 μm through 0.791 μm: black – snowpack-only ARF, blue – snowpack+atmosphere ARF (model of measurable quantity), green – the same as blue but ARF at 0.8 μm, red – the same as green but with interpolation over SZA. RAA = 63° for positive VZA, RAA = 117° negative.
Modeling results: total radiance relative difference

Relative error of broadband radiance over spectral interval 0.407 μm through 0.791 μm:
- **blue** – snowpack+atmosphere ARF (model of measurable quantity),
- **green** – the same as **blue** but ARF at 0.8 μm,
- **red** – the same as **green** but with interpolation over SZA.

RAA = 63° for positive VZA, RAA = 117° negative.
Total TOA radiance modeled with ‘true’ and ‘measured’ ARF

“Measured” ARF: snowpack + atmosphere, no interpolation, no spectral assumptions, regression: \( I_{\text{measured\_ARF}} = 1.0064 \times I_{\text{true\_ARF}} \)

“Measured” ARF: snowpack + atmosphere, SZA interpolation, \( R_{\lambda<0.8} \rightarrow R_{\lambda=0.8} \), regression: \( I_{\text{measured\_ARF}} = 0.9917 \times I_{\text{true\_ARF}} \)
Conclusion

1. Assumption that ARF measured at the surface under blue sky condition can replace true ARF is not valid;

2. Assumption that ARF at 0.8 um can accurately replace ARF at shorter wavelengths is not valid;

3. Assumption that reflection is isotropic under zenith Sun is not valid;

4. Altogether the assumptions above lead to “lucky” cancellation of errors;

5. Thus, the actual reason for ~5% discrepancy between modeled and CERES measured radiance remains unclear.

Future work: how to resolve the problem

1. An algorithm of BRDF retrieval from ground measured radiance was developed;

2. The algorithm requires:
   a) measured radiance (not yet available);
   b) kernel-based BRDF model, e.g. MODIS BRDF;

3. Once data are available some tuning of BRDF kernels may be needed to accommodate specific features of snow.
Modeling results: TOA radiance, band 15

Band radiance over spectral interval 0.667 μm through 0.684 μm: black – snowpack-only ARF, blue – snowpack+atmosphere ARF (model of measurable quantity), green – the same as blue but ARF at 0.8 μm, red – the same as green but with interpolation over SZA. RAA = 63° for positive VZA, RAA = 117° negative.
Relative error of band radiance over spectral interval 0.667 μm through 0.684 μm: blue – snowpack+atmosphere ARF (model with measurable quantity), green – the same as blue but ARF at 0.8 μm, red – the same as green but with interpolation over SZA. RAA = 63° for positive VZA, RAA = 117° negative.
Modeling results: TOA radiance, band 18

Band radiance over spectral interval 0.743 μm through 0.791 μm: black – snowpack-only ARF, blue – snowpack+atmosphere ARF (model of measurable quantity), green – the same as blue but ARF at 0.8 μm, red – the same as green but with interpolation over SZA. RAA = 63° for positive VZA, RAA = 117° negative.
Relative error of band radiance over spectral interval 0.743 μm through 0.791 μm: blue – snowpack+atmosphere ARF (model of measurable quantity), green – the same as blue but ARF at 0.8 μm, red – the same as green but with interpolation over SZA. RAA = 63° for positive VZA, RAA = 117° negative.