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

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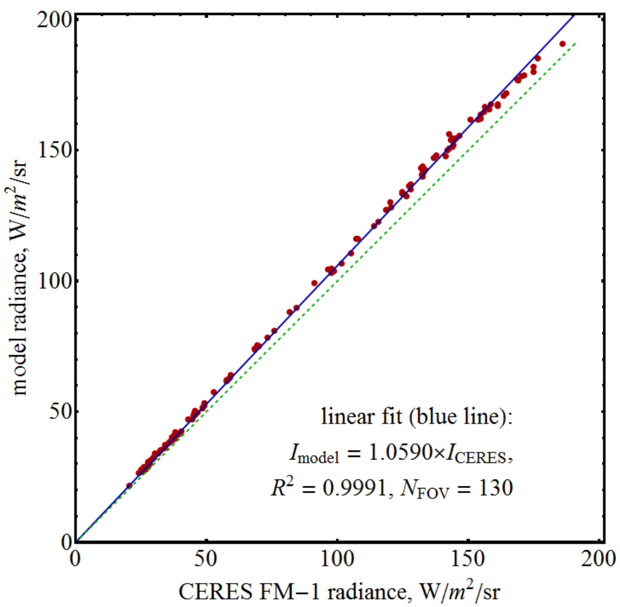
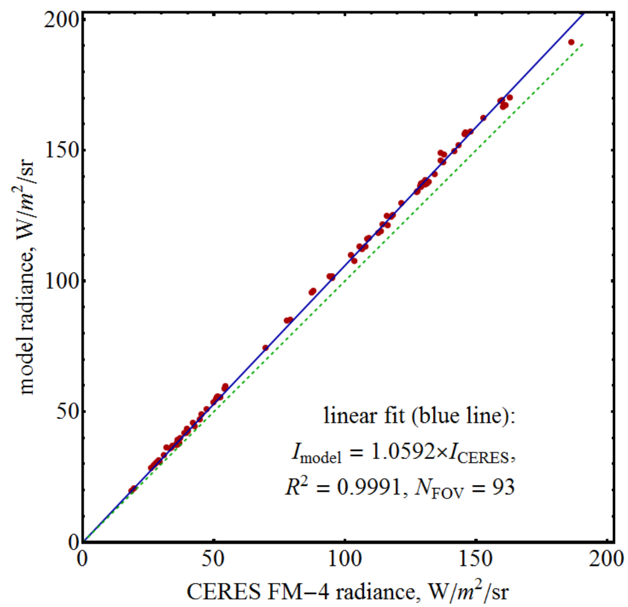
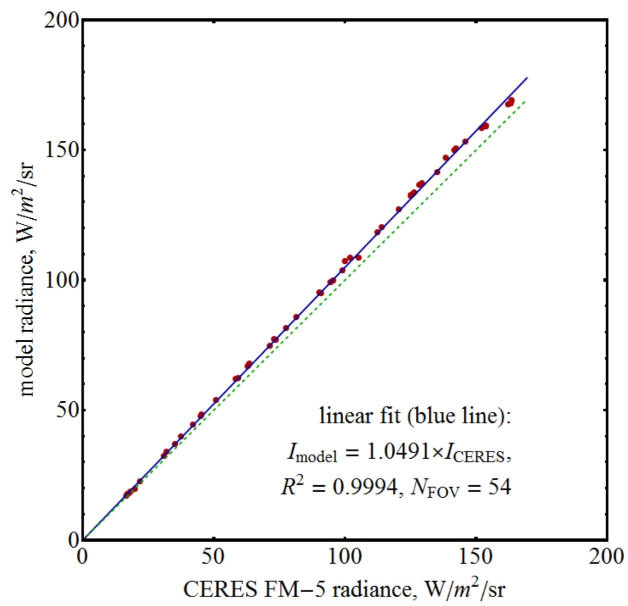
Current results of the modeling

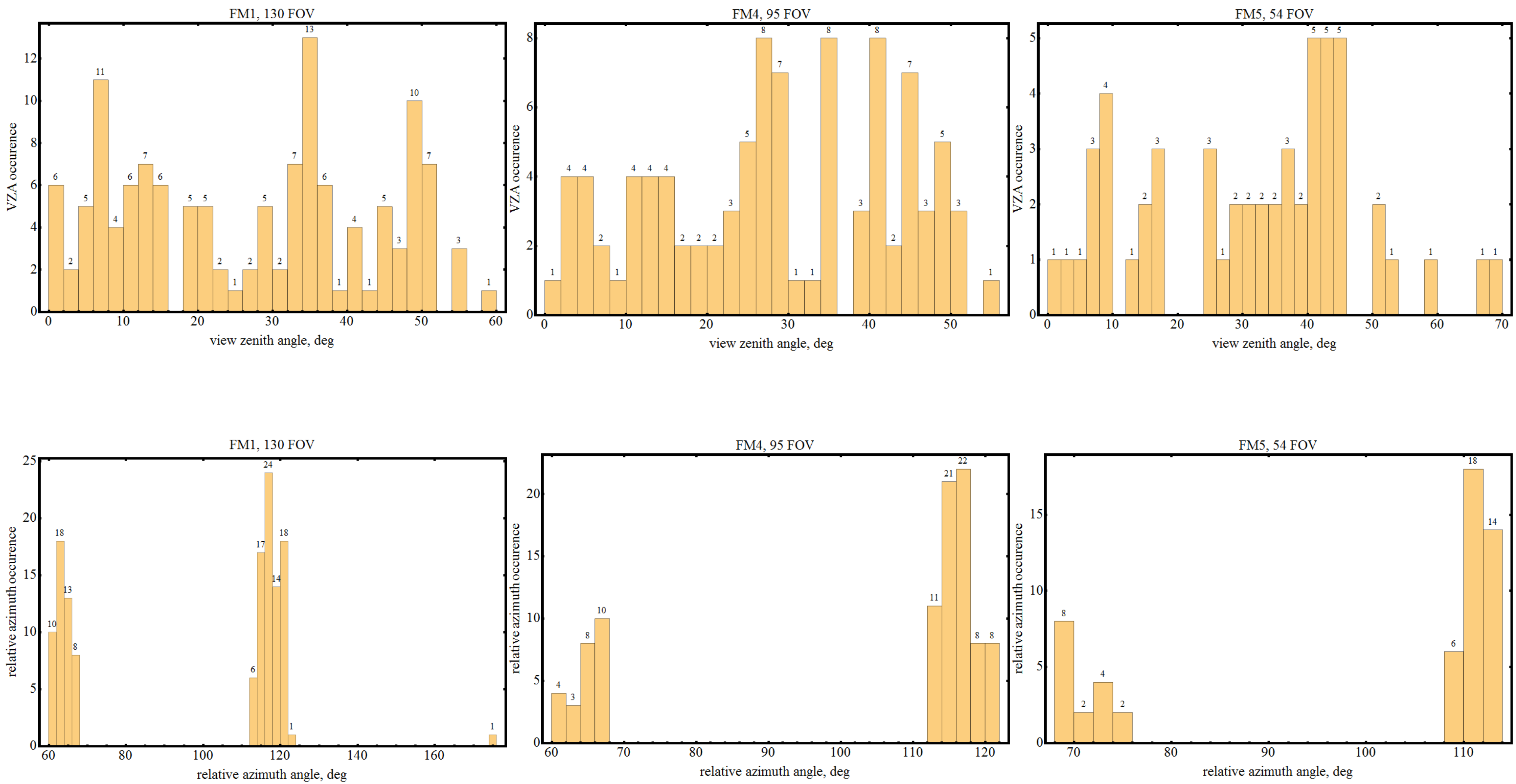






- High correlation between the model and observations.
- FM-5 sensor is known to be slightly brighter than other instruments.
- We still need to find a reason for ~5% discrepancy.

CERES viewing geometry



All observations are clustered in the relatively narrow azimuth sector.
For this reason, only results in azimuth plane $\phi = 63°$ (117°) are reported in this study.

BRDF model recap 1: what was measured in Dome C and how it was reported

Hudson, S. R., S. G. Warren, R. E. Brandt, and T. C. Grenfell. 2006. "Spectral bidirectional reflectance of Antarctic snow: Measurements and Parameterization." *JGR* 111: D18106.

- 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

$$\rho(\theta_i, \theta_r, \phi_i - \phi_r) = \frac{I_r(\theta_i, \theta_r, \phi_i - \phi_r)}{F_0(\theta_i, \phi_i)}$$ BRDF

BRDF cannot be measured under natural light illumination (blue-sky) conditions: light comes to the surface from the solid angle of 2π

$$I_r(\theta_i, \theta_r, \phi_i - \phi_r)$$ Reflected radiance

$$F_0(\theta_i, \phi_i)$$ Illuminating irradiance (incoming flux) coming from a **single** direction (θ_i, ϕ_i)

$$\boxed{\rho(\theta_i, \theta_r, \phi) = \frac{1}{\pi} \frac{\pi I_r(\theta_i, \theta_r, \phi)}{F_r(\theta_i)} \frac{F_r(\theta_i)}{F_0(\theta_i)} = \frac{1}{\pi} \Re(\theta_i, \theta_r, \phi)\, a_{black\text{-}sky}(\theta_i)}$$

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

$$\Re(\theta_i, \theta_r, \phi) = \frac{\pi I_r(\theta_i, \theta_r, \phi)}{F_r(\theta_i)}$$ True anisotropic reflection factor

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

$$R(\theta_i, \theta_r, \phi, \mathrm{atm}) = \frac{\pi I_r^{measured}(\theta_i, \theta_r, \phi)}{F_r^{measured}(\theta_i)}$$ Measured anisotropic reflection factor

BRDF model recap 2: the use of measurements in Dome C

$$\rho(\theta_i,\ \theta_r,\ \phi) \approx \frac{1}{\pi} R(\theta_i,\ \theta_r,\ \phi)\, a^{model}_{black\text{-}sky}(\theta_i)$$

Approximations:

Does not depends on atmospheric conditions

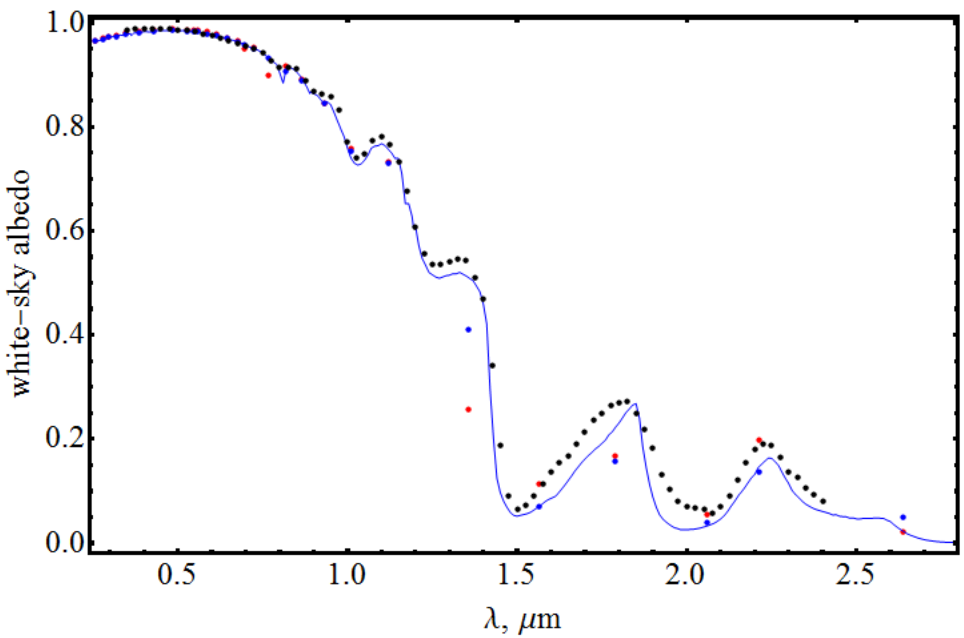
$$\Re(\theta_i,\ \theta_r,\ \phi) \approx R(\theta_i,\ \theta_r,\ \phi)$$

Depends on atmospheric conditions

$$a^{real}_{black\text{-}sky}(\theta_i) \approx a^{model}_{black\text{-}sky}(\theta_i)$$

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

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.

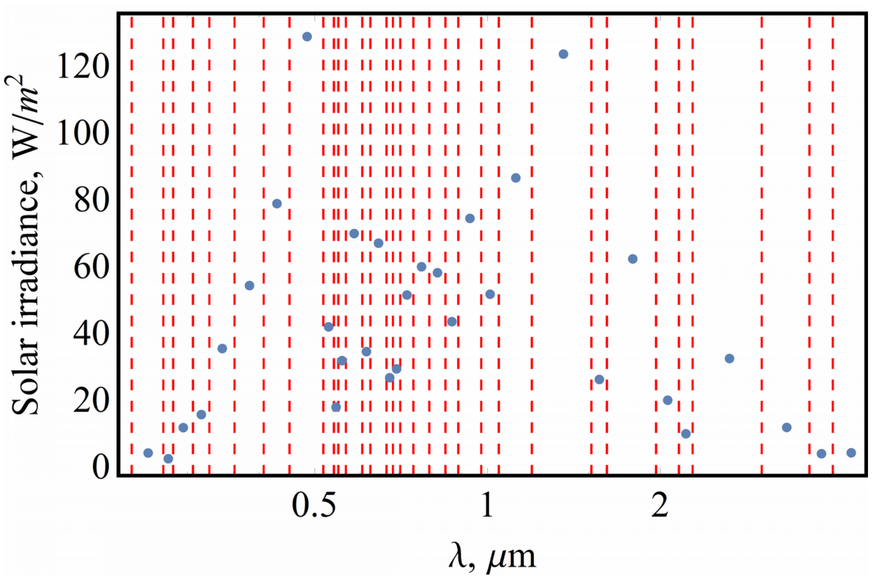


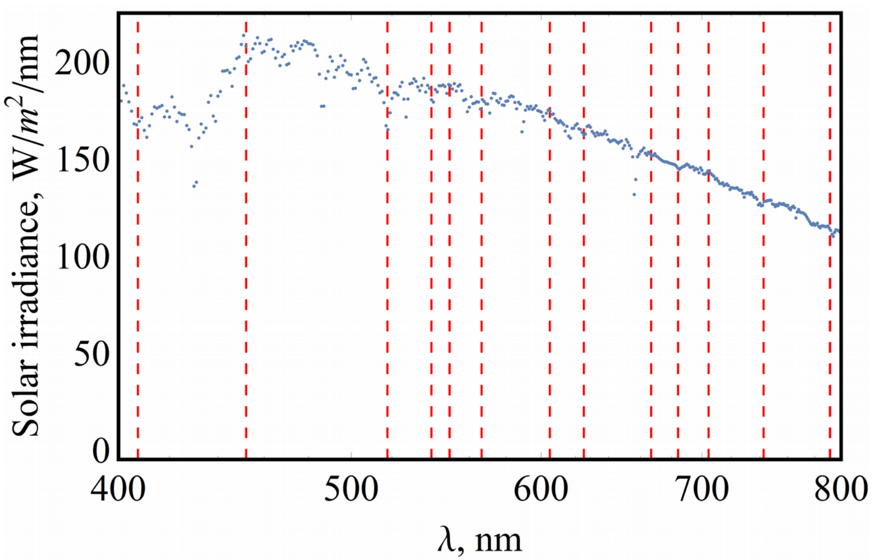
Possible problems:

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/m^2.

BRDF model recap 3: limited SZA range

Surface boundary condition to the RTE

$$I(\tau = \tau_{surf}, \theta > \pi/2, \phi) = I_0 \cos\theta_s \rho(\theta_s, \theta, \phi) \exp(-\tau_{surf}/\cos\theta_s)$$
$$+\int_0^{2\pi} d\phi' \int_0^{\pi/2} \sin\theta' d\theta' \cos\theta' \rho(\theta', \theta, \phi-\phi') I(\tau = \tau_{surf}, \theta', \phi')$$

$$\downarrow$$

BRDF $\rho(\theta_i, \theta_r, \phi)$ is needed on $0° \leq \theta_i \leq 90°$;
$R(\theta_i, \theta_r, \phi)$ was measured on $51.6° \leq \theta_i \leq 86.6°$

assumptions:

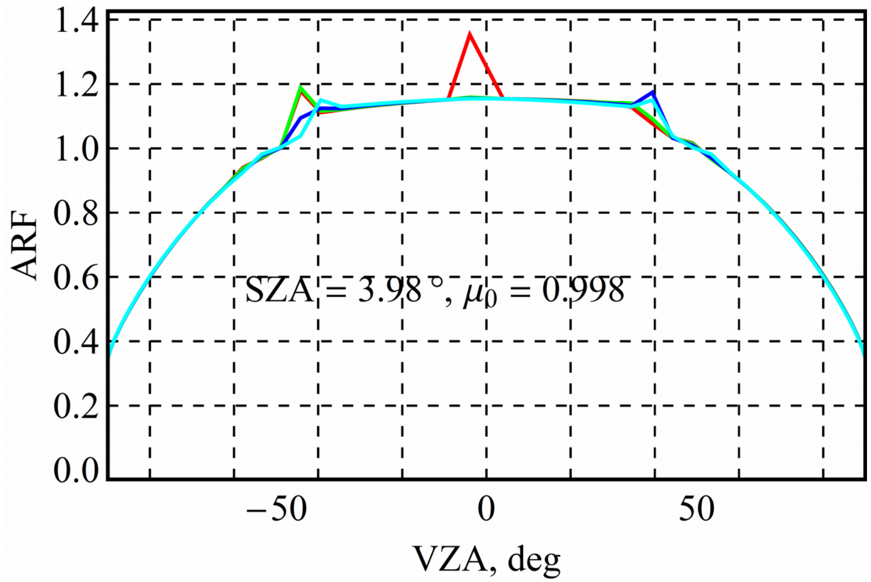
1) $\boxed{R(\theta_i = 0, \theta_r, \phi) = 1}$

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

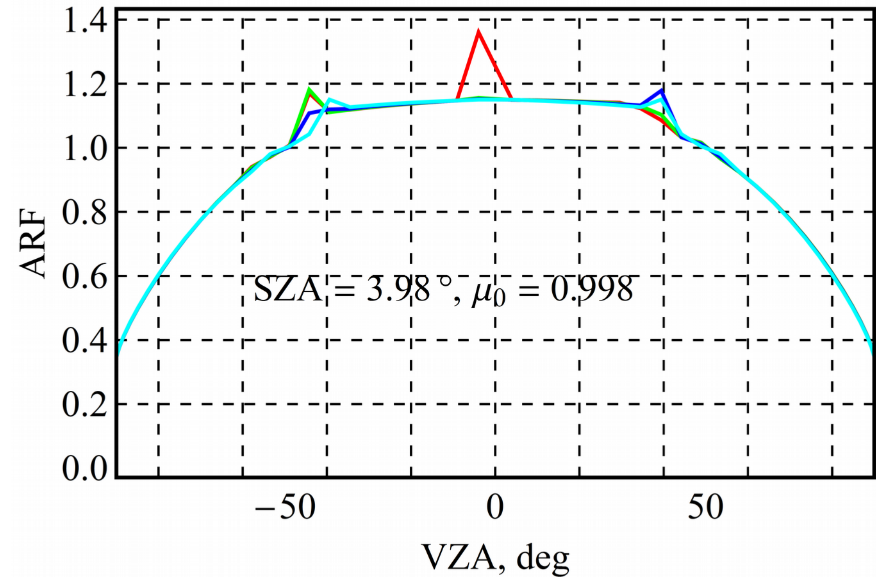
2) $\boxed{R(\theta_i > 86.6°, \theta_r, \phi) \approx R(\theta_i = 86.6°, \theta_r, \phi)}$

Is reflection isotropic under overhead sun?

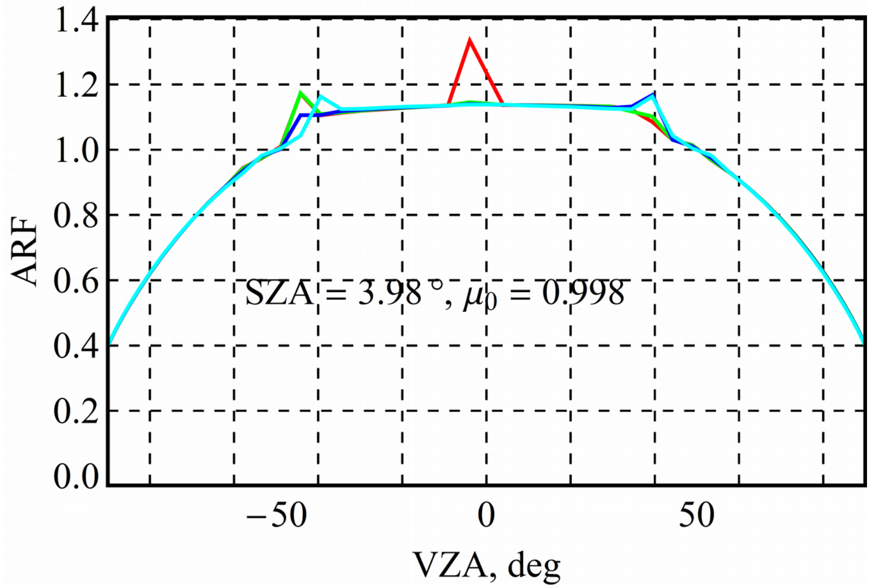
Snowpack only, wavelength 0.549 through 0.567 um



Snowpack only, wavelength 0.667 through 0.684 um



Snowpack with atmosphere, wavelength 0.8 um



$$\boxed{R(\theta_i = 0,\ \theta_r,\ \phi) = 1}$$

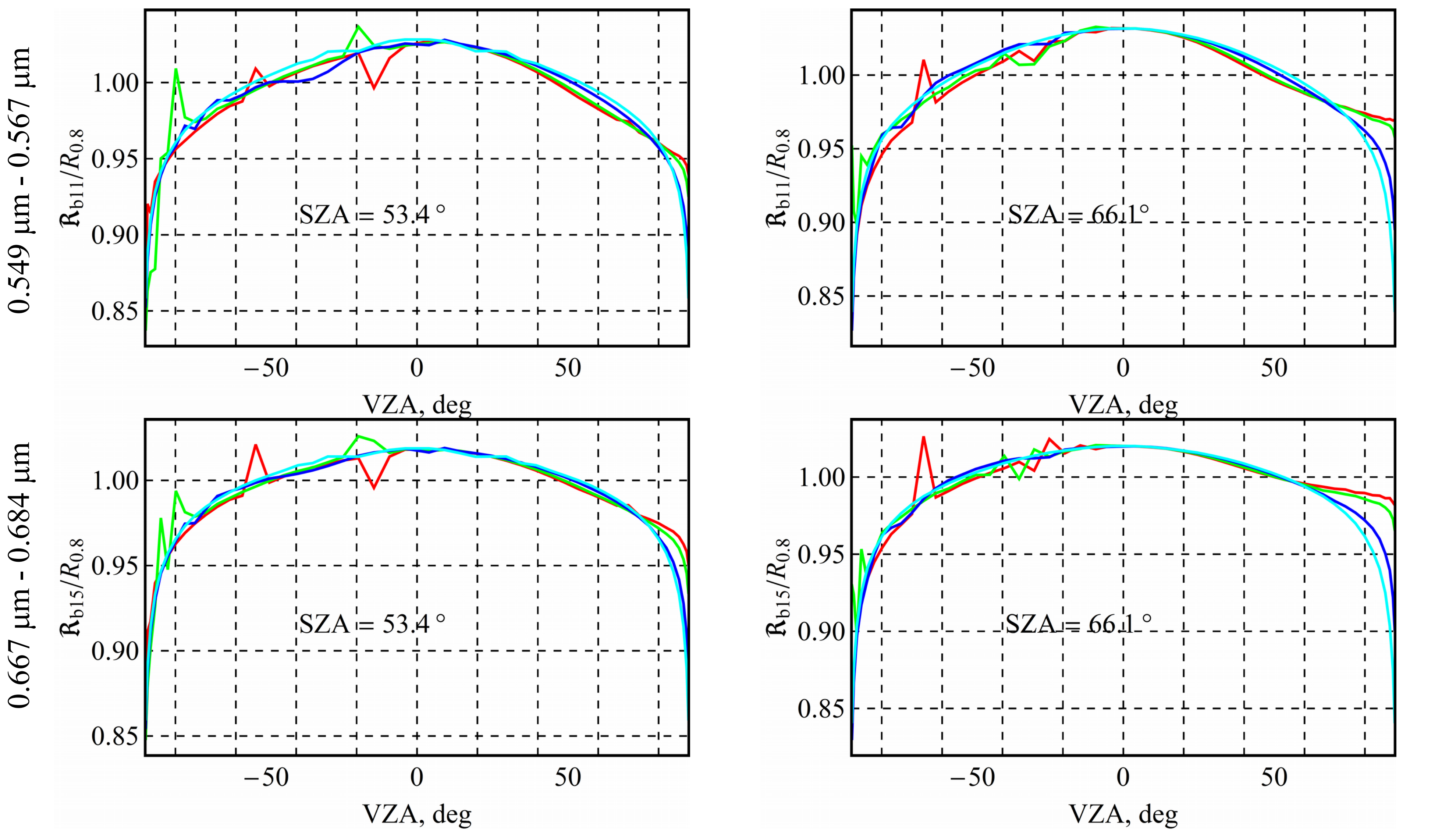
is a wrong assumption
azimuth rotational symmetry holds

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°).

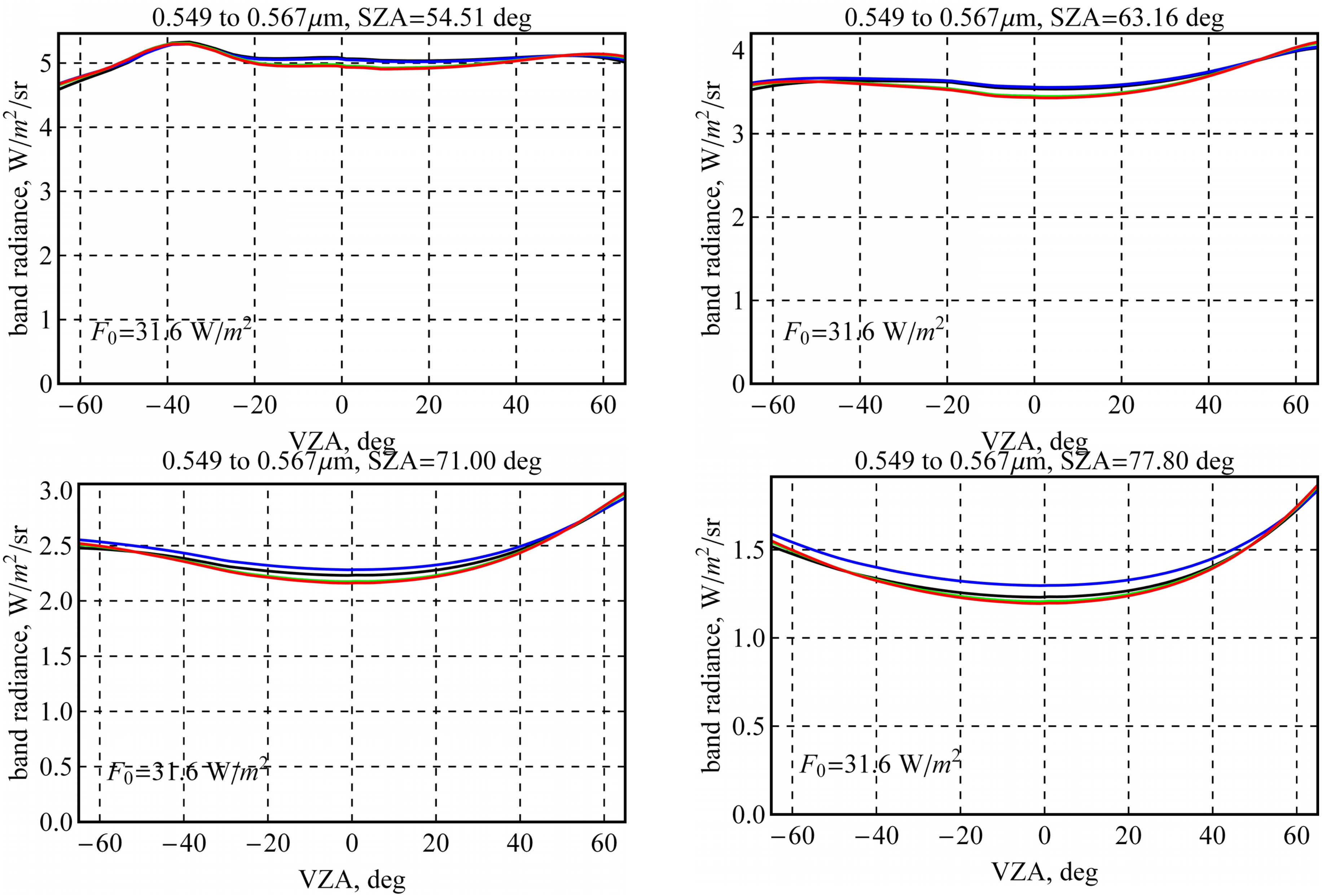
BRDF model recap 4: spectral dependence

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

$R(\lambda = 0.8\ \mu m)$ better approximates $\Re(\lambda = 0.8\ \mu m)$ than $R(\lambda = 0.5\ \mu m)$ does $\Re(\lambda = 0.5\ \mu m)$. However, $R(\lambda = 0.8\ \mu m) \neq \Re(\lambda < 0.8\ \mu m)$

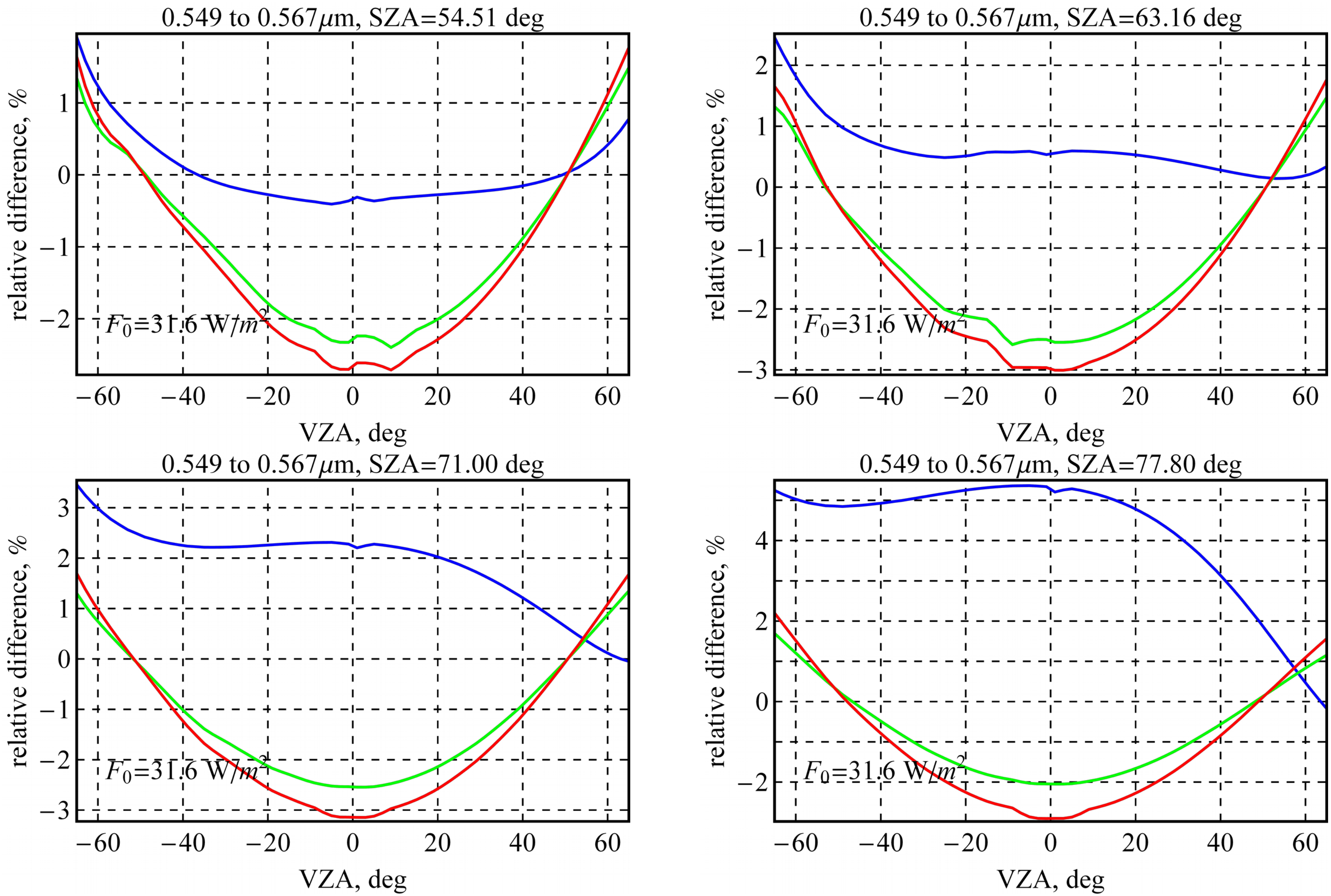


Modeling results: TOA radiance, band 11



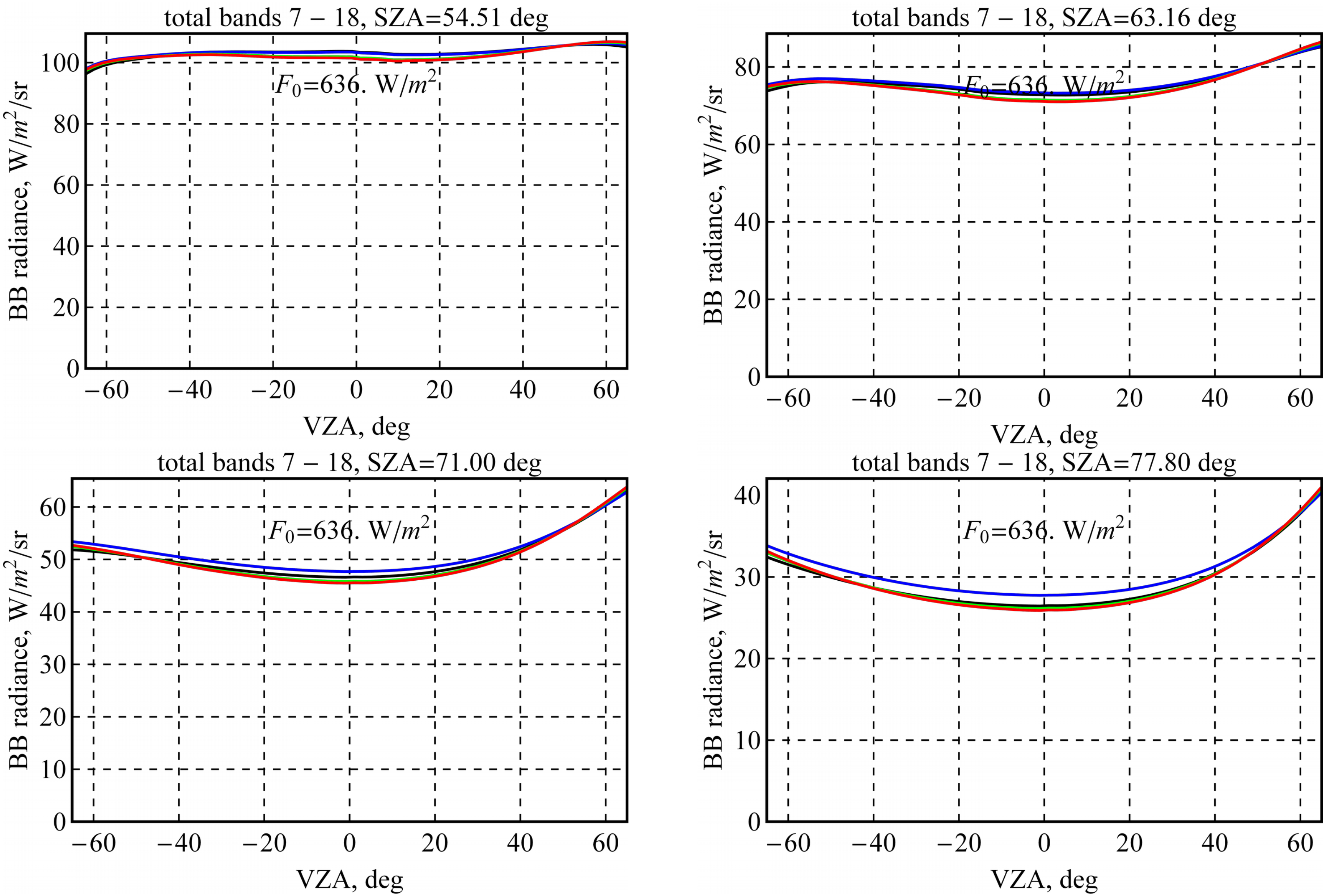
band radiance over spectral interval 0.549 μm through 0.567 μm: black – snowpack-only ARF, blue – snowpack+atmosphere ARF (model of measurable quantity), green – the same as blue but ARF at 0.8 μm, red – the same as green but with interpolation over SZA. RAA = 63° for positive VZA, RAA = 117° negative.

Modeling results: relative error, band 11



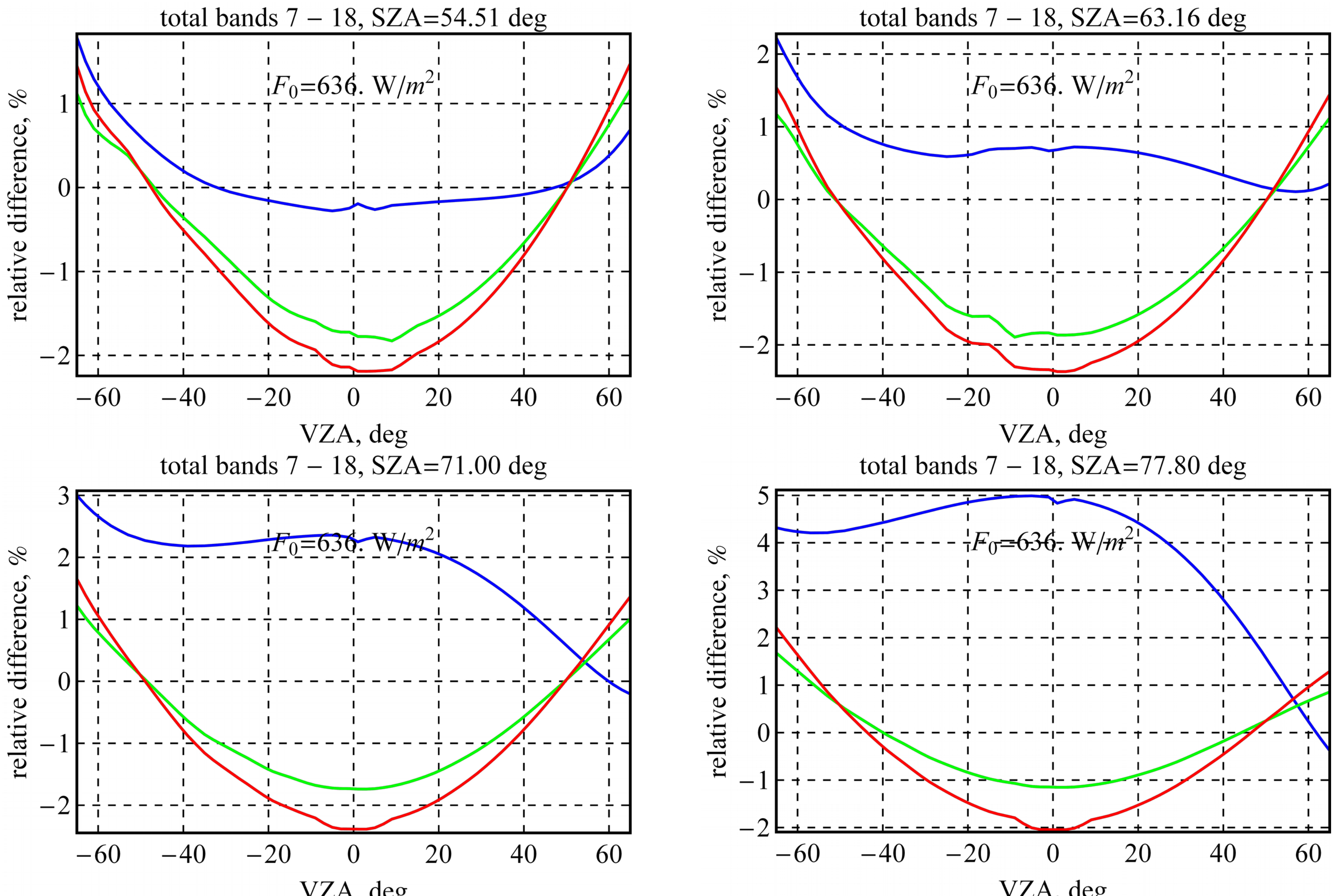
Relative error of band radiance over spectral interval 0.549 μm through 0.567 μm: blue – snowpack+atmosphere ARF (model with measurable quantity), green – the same as blue but ARF at 0.8 μm, red – the same as green but with interpolation over SZA. RAA = 63° for positive VZA, RAA = 117° negative.

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.

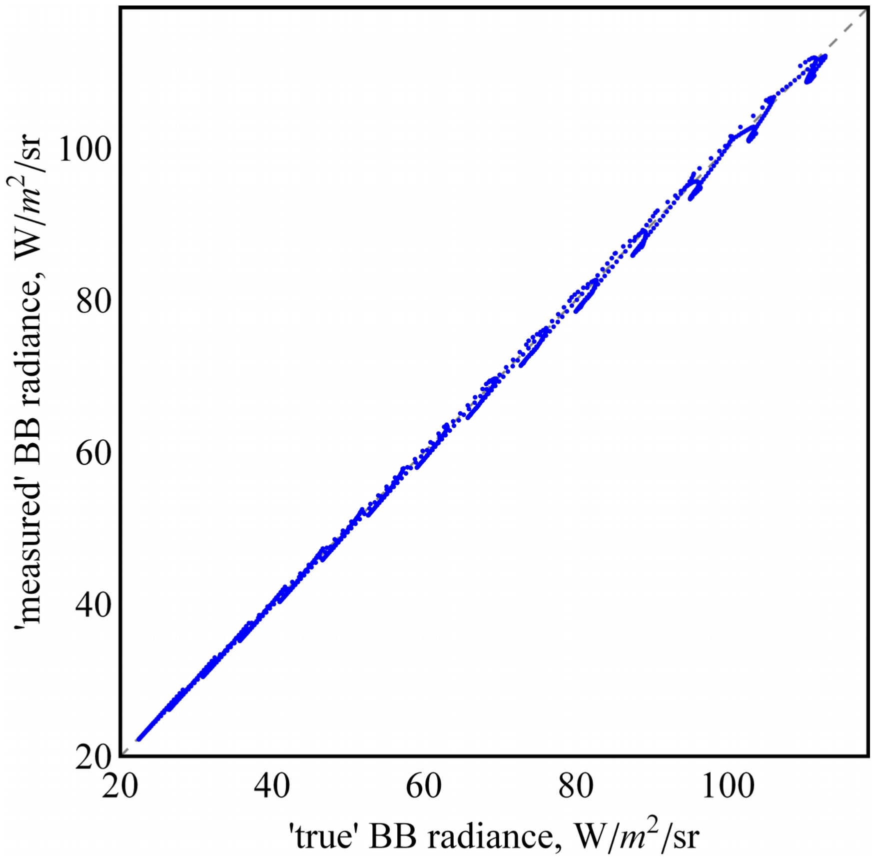
Modeling results: total radiance relative difference



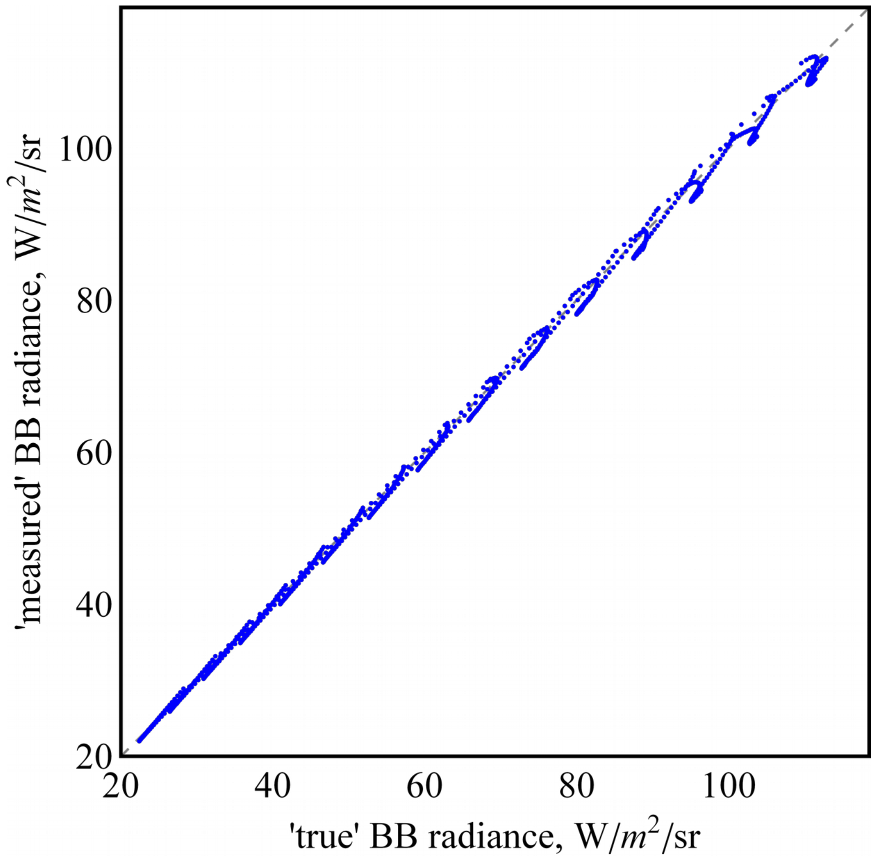
Relative error of broadband radiance over spectral interval 0.407 μm through 0.791 μm: blue – snowpack+atmosphere ARF (model of measurable quantity), green – the same as blue but ARF at 0.8 μm, red – the same as green but with interpolation over SZA. RAA = 63° for positive VZA, RAA = 117° negative.

Total TOA radiance modeled with ‘true’ and ‘measured’ ARF

“Measured” ARF: snowpack + atmosphere,
no interpolation, no spectral assumptions,
regression: $I_{measured\_ARF} = 1.0064 * I_{true\_ARF}$



“Measured” ARF: snowpack + atmosphere,
SZA interpolation, $R_{\lambda<0.8} \rightarrow R_{\lambda=0.8}$,
regression: $I_{measured\_ARF} = 0.9917 * I_{true\_ARF}$



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;

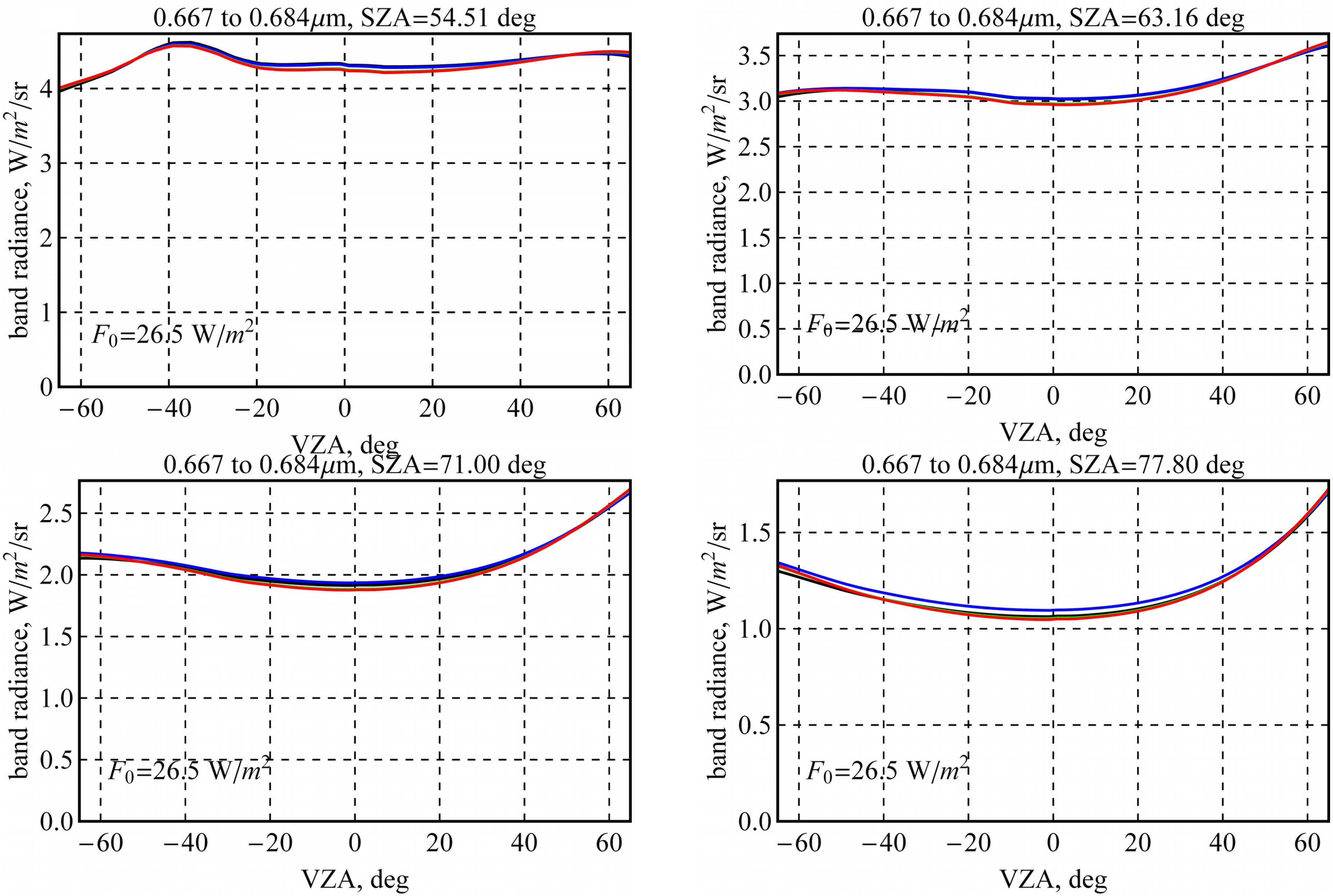
2. The algorithm requires:

   a) measured radiance (not yet available);

   b) kernel-based BRDF model, e.g. MODIS BRDF;

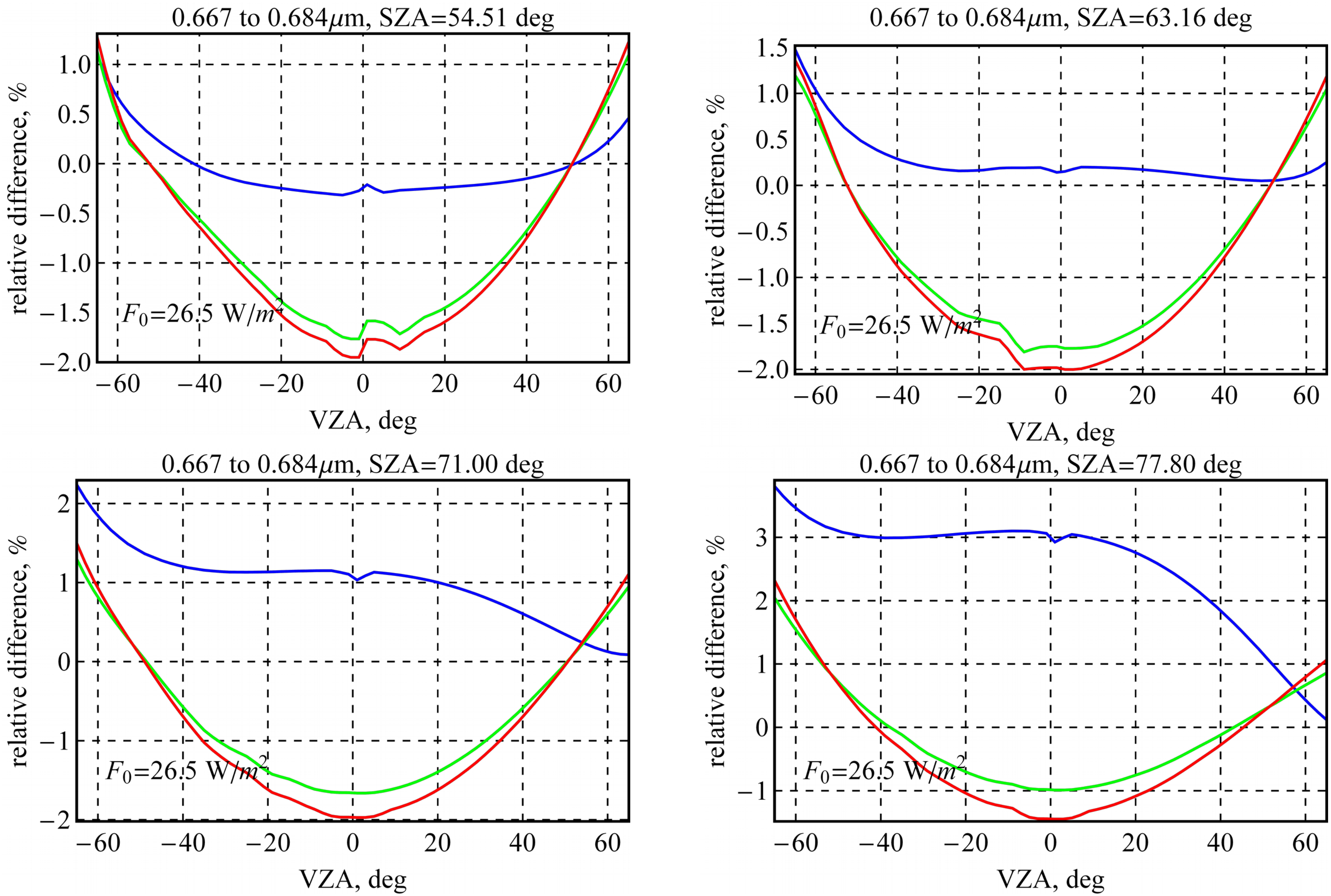
3. Once data are available some tuning of BRDF kernels may be needed to accommodate specific features of snow.

Modeling results: TOA radiance, band 15



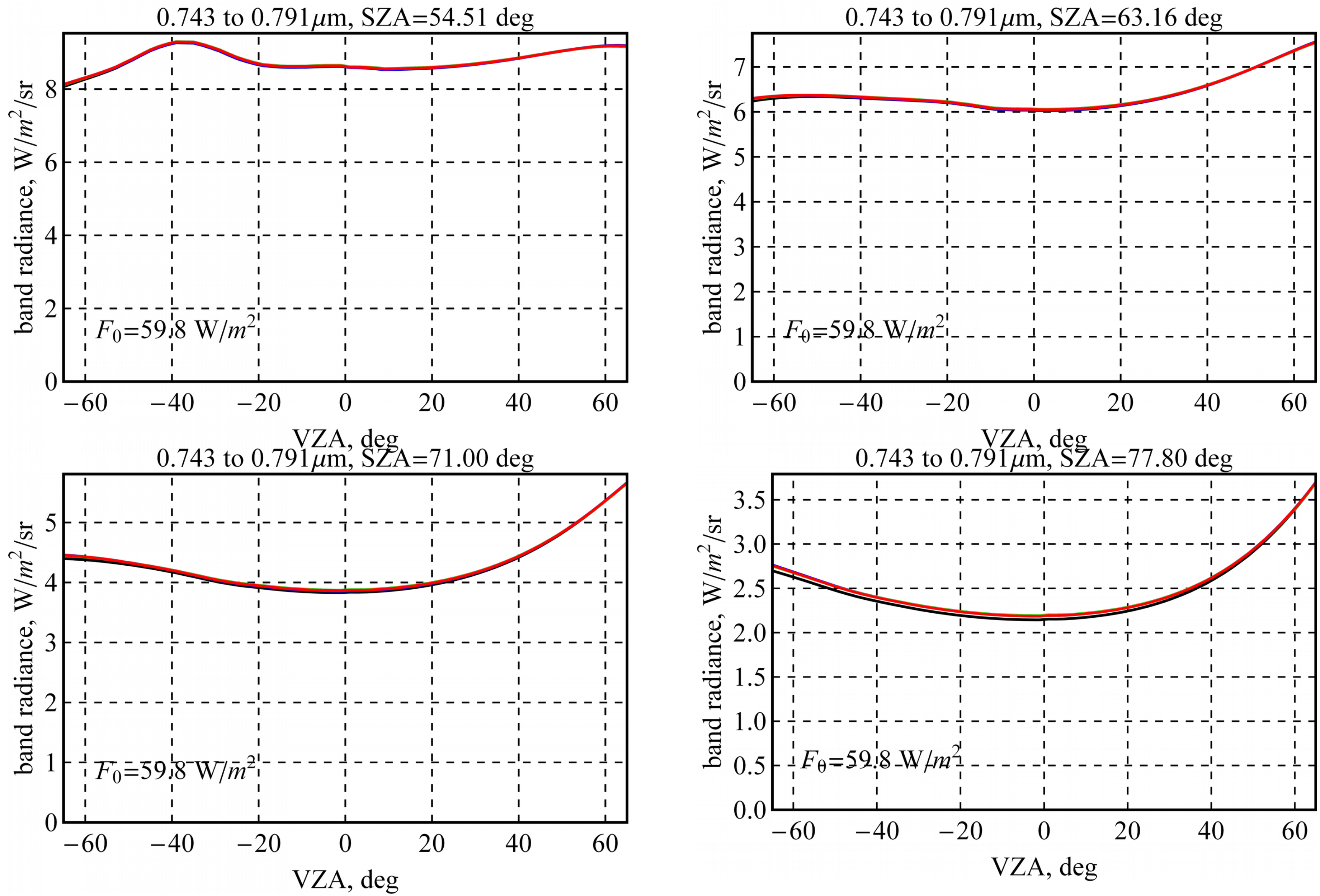
band radiance over spectral interval 0.667 μm through 0.684 μm: black – snowpack-only ARF, blue – snowpack+atmosphere ARF (model of measurable quantity), green – the same as blue but ARF at 0.8 μm, red – the same as green but with interpolation over SZA. RAA = 63° for positive VZA, RAA = 117° negative.

Modeling results: relative error, band 15



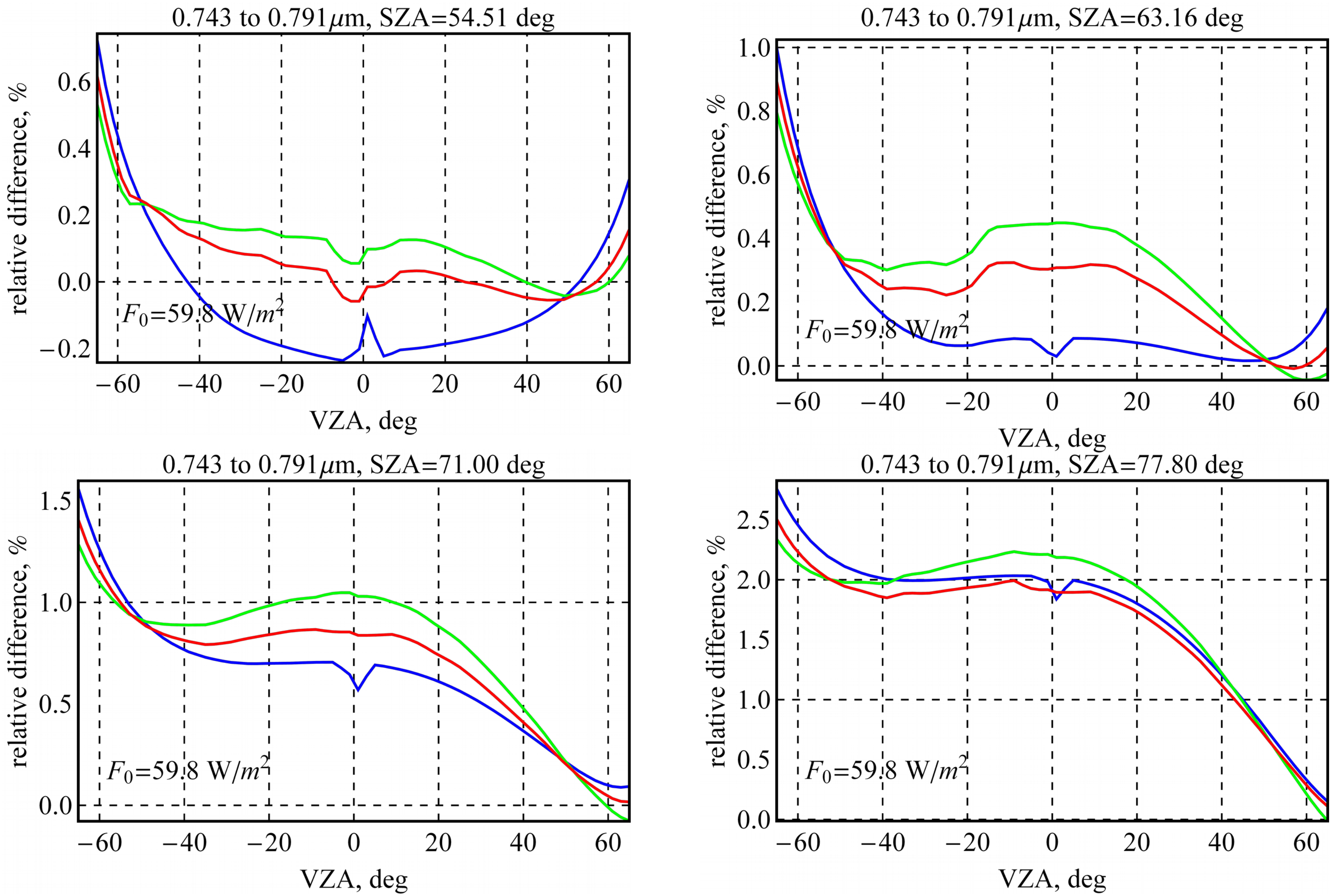
Relative error of band radiance over spectral interval 0.667 μm through 0.684 μm: blue – snowpack+atmosphere ARF (model with measurable quantity), green – the same as blue but ARF at 0.8 μm, red – the same as green but with interpolation over SZA. RAA = 63° for positive VZA, RAA = 117° negative.

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.

Modeling results: relative error, band 18



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.