Replies to comments of Anonymous Referee #2

General Comments

1. Section 1: provides an excellent background literature review of snow reflectance anisotropy, snow BRDF models and verification of the models with existing BRDF measurements.

Thank you! We tried to be more rigorous in distinguishing between the BRDF and HDRF as some inconsistencies in referencing other studies slipped our attention. In case the actual measured quantity was the HDRF, we changed the term BRDF to HDRF (although stated differently in the respective publication). We further added a publication from an earlier study using airborne camera data for BRDF observations for forest classification.

Changes in text:

- Koukal, T. and Atzberger, C.: Potential of multi-angular data derived from a digital aerial frame camera for forest classification, IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens., 5, 30–43, https://doi.org/10.1109/JSTARS.2012.2184527, 2012.

2. Section 2: Methodology – the definitions of reflectance quantities are articulated well, however, the use of symbols is inconsistent. For example, in subsection 2.1, the symbol for the solar zenith angle is given as theta(i) (see Equation 1), then the subscript changes to something else, theta(0) (see Equation 3) without any explanation. In subsection 2.2, the symbol for the relative azimuth angle are different both in Equation 4 and Equation 7.

Thanks a lot for spotting these typos. We introduce the reflectance quantities and the modeling (Sects. 2.1 and 2.2) with the general illumination zenith and azimuth angles (θ_i and φ_i) as, in principle, the illumination source does not need to be the Sun. Only when referring to specific measurements (from Sect. 3 on), we use θ_0 and φ_0 as the solar zenith and azimuth angle, respectively. We changed the subscripts in Eqs. 3-11 accordingly and use the consistent symbol $\Delta\varphi$ for the relative azimuth angle in Eqs. 4-11.

Changes in text:

- Changed subscripts in Eqs. 3-11.

3. Subsection 3.2 - optical-equivalent grain size retrieval from spectral surface albedo measurements. It was reported elsewhere in the manuscript (subsection 3.4) that “the downward irradiance measurements from SMART could not be used for the calculation of the HDRF due to calibration issues.” So does this imply that the optical-equivalent snow grain size retrieved from SMART measurements may be affected by those calibration issues? It’s also odd that the “optical-equivalent snow grain size from SMART and analogous ground-based measurements were validated against grain size observations utilizing reflectance measurements with MODIS.” Which retrievals are assumed to be the "truth"?

All calibration steps for measurements of the surface albedo could be carried out, which is why the retrieval of the optical-equivalent snow grain size from SMART measurements is not affected by these calibration issues. This is different for the downward irradiance that requires an absolute radiometric calibration converting the raw signal into units of irradiance. The calibration issues were related to the radiometric calibration only. Thus, the downward irradiance measurements from SMART could not be used for the calculation of the HDRF. The other reviewer asked the same question, for more details please see our answer to Comment #2 of Reviewer #1.

As both reviewers mentioned this, we added a clarification in the manuscript.

Thank you also for the second part of your comment. It was not our intention to assume one retrieval to be the truth. We rephrased the sentence accordingly.

Changes in text:

- Page 14 Line 4: The downward irradiance measurements from SMART could not be used for the calculation of the HDRF due to calibration issues. Note that this pertains to the radiometric calibration only, which converts the digital numbers registered by the spectrometer into units of irradiance. For the albedo measurements with SMART, a relative calibration of the upper and lower sensors is sufficient and an absolute radiometric calibration is not required. Thus, the albedo measurements and the retrieval of the optical-equivalent snow grain size are unaffected by this calibration issues. For the calculation of the HDRF, the global irradiance was simulated [...] instead.

- P10 L10: The retrieved R_{opt} from SMART and analogous ground-based measurements were compared to grain size observations utilizing reflectance measurements with MODIS (Carlsen et al., 2017).

4. Subsection 3.3.2 – Radiance calibration and image post-processing. This subsection provides important details about the post processing, but there are no details about the pre-deployment calibration. Given that the flights were performed between 24 December 2013 and 5 January 2014, it may be shown that each flight need a different calibration, which would depend on the calibration stability of the digital camera Canon EOS-1D Mark III.

Thank you for your comment. Due to the problems with the integrating sphere during the campaign (compare Comment #2 from Reviewer #1), no transfer calibration in the field could be analyzed. However, unlike for SMART, there is no reason to expect a change of the camera calibration as no mechanical parts are unplugged during the deployment (laboratory vs. field). A comparison of laboratory calibrations before and after the campaign and for different temperature regimes did not show significant changes for the camera calibration.

Specific Comments

1. Pg. 1. Line 17: The study finds that “MODIS observations generally underestimated the anisotropy of the surface reflection”, but it would help to provide the degree to which MODIS underestimates the anisotropy of surface reflection.

Suggestion taken, thank you. We added the average factor of underestimation for the volumetric model weight (which is the dominant contribution to the anisotropy in the analyzed cases). The factor 10 was calculated when neglecting the possible artifacts such as the latitudinal band around 76° S with MODIS values for f_{vol} of exactly zero. We added this information in the abstract, results and discussion, and conclusions.

Changes in text:

- P1 L16: For the analyzed cases, MODIS observations (545-565 nm wavelength band) generally underestimated the anisotropy of the surface reflection. The largest deviations were found for the volumetric model weight f_{vol} (average underestimation by factor of 10).
- P24 L32: For the analyzed cases, MODIS underestimates the volumetric model weight f_{vol} on average by at least a factor of 10 compared to the airborne measurements (neglecting MODIS values of exactly zero).
- P26 L10: The airborne values for f_{vol} are larger than the corresponding MODIS retrievals (by at least a factor of 10).

2. Pg. 2, Line 4: The statement, “Satellites monitor the reflectance (i.e., reflected radiance in units of $\mathrm{Wm^{-2}sr^{-1}}$) at the top of the atmosphere (TOA). However, they are restricted in terms of the number of available observation angles and spectral bands as well as their temporal resolution." Is this in reference to polar orbiting satellites or geostationary satellites?

Thank you for this question. The statement is in reference to polar-orbiting satellites such as relevant for the MODIS instrument onboard Aqua/Terra satellites. The temporal resolution for geostationary satellites is of course much better, however the use of geostationary satellites for global surface albedo measurements comes with the drawback of less global coverage (especially missing polar regions) and the need to generate consistent estimates from different sensors. Eventually, this leads to different algorithms for surface albedo estimates for polar-orbiting and geostationary satellites. We clarified the relevance for polar-orbiting satellites in the manuscript.

Changes in text:

- P2 L4: Polar-orbiting satellites monitor the reflectance [...]
- P2 L6: The processing of measurements from polar-orbiting satellites for monitoring the broadband surface albedo [...]

3. Pg. 2, Line 8, the statement, “During the first step, the TOA reflectance is converted into a surface reflectance by means of an atmospheric radiative transfer parameterization,” need to be clarified. What is “atmospheric radiative transfer parameterization?”

With ’atmospheric radiative transfer parameterization’ we mean that the atmospheric correction algorithm has to correct for gaseous and aerosol scattering and absorption and surface-atmosphere-coupling effects (e.g. due to the anisotropic BRDF of the surface) using radiative transfer modeling. To avoid confusion in that regard, we clarified the statement in the manuscript. Thanks for this comment.

Changes in text:

- P2 L8: During the first step, the TOA reflectance is converted into a surface reflectance by correcting for gaseous and aerosol scattering and absorption applying radiative transfer modeling (e.g., Vermote and Kotchenova, 2008).

4. Pg. 2, line 10, the recommended terminology: bidirectional reflectance-distribution function (BRDF). Note the “reflectance-distribution” is a compound adjective and should be hyphenated.

Thank you for pointing this out. As this might be correct, we prefer omitting the additional hyphen for reasons of consistency applying the terminology as defined in Schaepman-Strub et al. (2006).

5. Pg. 3, line 19, change the statement, “Comparing this asymptotic model to in situ observations of the BRDF,...” to “Evaluating this asymptotic model with in situ observations of the BRDF,...”

Changed as suggested. To be more consistent with regard to the impossibility to measure the BRDF in situ, we also rephrased it to ’in situ measurements of snow reflectance’.

Changes in text:

- P3 L21: Evaluating this asymptotic model with in situ measurements of the snow reflectance, Kokhanovsky et al. (2005) found a generally good agreement but a reduced model accuracy in the solar principal plane at large observation angles.

6. Pg. 3, in the paragraph, marked by lines 8-25, various snow reflectance terms are mentioned: snow BRDF (line 10), a polarized BRDF (line 12), reflectance of snow (line18), inherent optical properties (line 22), and bidirectional reflectance (line 24). This may be confusing to readers and it would help to clarify or use consistent terms.

Thanks for pointing this out. We rephrased, where possible, some of the terms in order to make it easier for the reader. However, the terms mentioned in the paragraph are not all interchangeable and need to remain as stated in order to stay rigorous. We added some details for ’inherent optical properties’ for clarity. The bidirectional reflectance (former line 24) cannot be replaced, as Malinka (2016) calculate the BRF which is not yet defined in the manuscript and we prefer to leave it like that to avoid confusion.

Changes in text:

- P3 L14: changed ’polarized BRDF model’ to ’snow BRDF model including polarization’
- P3 L20: changed ’to model the reflectance of snow’ to ’to model the BRDF of snow’
- P3 L24: added details for ’inherent optical properties’: ’inherent optical properties (extinction coefficient, single scattering albedo, scattering phase function, and the polarization properties)’

7. Pg. 3, line 29, the use of “solar azimuth” and “azimuthal directions” in this sentence is confusing, “Kuhn (1985) observed a peak in reflectance in the azimuthal directions up to 60° to both sides of the solar azimuth that becomes more prominent with increasing solar zenith angle and snow grain size.” What is the zero azimuth in this case?

To avoid a possible confusion, we rephrased this sentence. The zero azimuth is the solar azimuth angle, the $\pm 60^\circ$ refer to the azimuth angle range of reflected radiation relative to the solar azimuth angle.

Changes in text:

- P3 L32: Kuhn (1985) observed a peak in reflectance that is contained within $\pm 60^\circ$ to both sides of the solar azimuth angle. This peak becomes more prominent with increasing solar zenith angle and snow grain size.

8. Pg. 4, line 28, change “480” to “340”. The smallest CAR wavelength is 340 nm.

Thank you for spotting this. We updated the CAR wavelength limits to 340 and 2324 nm and reference the earlier Gatebe et al. (2003) publication (instead of Gatebe et al., 2005).

Changes in text:

- P4 L30: The effective BRDFs were acquired by the Cloud Absorption Radiometer (CAR, Gatebe et al. 2003) over a 30-year period between 1984 and 2014. The CAR is a scanning radiometer covering 14 spectral channels between 340 and 2324 nm
- Gatebe, C., King, M., Platnick, S., Arnold, G., Vermote, E., and Schmid, B.: Airborne spectral measurements of surface-atmosphere anisotropy for several surfaces and ecosystems over southern Africa, J. Geophys. Res., 108, 8489, https://doi.org/doi:10.1029/2002JD002397, 2003.

9. Pg. 5, line 29, the BRDF symbol used here is not consistent with Schaepman-Strub et al. (2006) as stated/line 27.

Thank you for this comment. It is true that Schaepman-Strub et al. (2006) denote the BRDF with $f_\mathrm{r}(\theta_\mathrm{i},\varphi_\mathrm{i};\theta_\mathrm{r},\varphi_\mathrm{r})$, the BRF with $R(\theta_\mathrm{i},\varphi_\mathrm{i};\theta_\mathrm{r},\varphi_\mathrm{r})$, and the HDRF with $R(\theta_\mathrm{i},\varphi_\mathrm{i},2\pi;\theta_\mathrm{r},\varphi_\mathrm{r})$. To better distinguish between the reflectance functions $f()$ (in units sr^{-1}) and the dimensionless reflectance factors R, we changed the notation for the BRF and HDRF to R_BRF and R_HDRF. This is more consistent with Schaepman-Strub et al. (2006), however we decided to keep the acronyms in the indices of the reflectance factors as the difference in notation between the BRF ($R(\theta_\mathrm{i},\varphi_\mathrm{i};\theta_\mathrm{r},\varphi_\mathrm{r})$) and HDRF ($R(\theta_\mathrm{i},\varphi_\mathrm{i},2\pi;\theta_\mathrm{r},\varphi_\mathrm{r})$) is only marginal and hard to identify, especially for someone not familiar with the details.

Changes in text:

- We changed the notation throughout the manuscript from f_{BRF} and f_{HDRF} to R_{BRF} and R_{HDRF}, respectively.

10. Pg. 5, line 30, the statement "the reflected radiance for all reflection angles..." is unclear. The entire definition of the spectral BRDF need to be clarified.

Thanks, we clarified the definition of the spectral BRDF by including the definition of the direction of reflection.

Changes in text:

- P5 L33: The spectral BRDF (f_{BRDF}, unit of sr^{-1}) provides for each solar zenith (θ) and azimuth angle (φ) of incident direct irradiance $F_{\mathrm{i}}\left(\theta_{\mathrm{i}},\varphi_{\mathrm{i}};\lambda\right)$ the reflected radiance $I_{\mathrm{r}}\left(\theta_{\mathrm{i}},\varphi_{\mathrm{i}};\theta_{\mathrm{r}},\varphi_{\mathrm{r}};\lambda\right)$ for all directions of reflection (defined by the reflection zenith and azimuth angles θ_{r} and φ_{r}) by [...]

11. Pg. 13, line 14, the location of each pixel is given by x and y, but "x" and "y" are not defined elsewhere in the manuscript.

x and y define the location of each pixel in terms of rows and columns on the sensor. We added this detail when first defining x and y in Sect. 3.3.2 right before Equation (16).

Changes in text:

- P13 L6: The calibration factor k_{c} is defined at each pixel location on the sensor (row x, column y) as [...]

12. Pg. 6, the derivation of Equation (3) is not clear.

Thanks for pointing this out. However, the derivation of Equation (3) is lengthy and beyond the scope of this manuscript. We refer to Schaepman-Strub et al. (2006) for details.

Changes in text:

- P6 L13: The second step in Eq. 3 assumes that the incident diffuse radiation is isotropic (for details, see Schaepman-Strub et al., 2006).

13. Pg. 13, line 19, the author need to show how “...the viewing angles are corrected" using the “the roll, pitch and yaw angles of the aircraft at the time of measurement.”

So far, the correction of the viewing angles was explained earlier in the text. However, to avoid this potential confusion, we decided to provide all information about the aircraft attitude correction in one paragraph.

Changes in text:

- P13 L25: The camera viewing angles are calculated from the geometric calibration for each pixel (x, y). As the camera is fixed to the aircraft frame, a correction for the aircraft attitude was implemented to obtain the reflection angles θ_r and φ_r. Thus, beside the geometric calibration, the observed reflection angles are determined by the attitude angles of the aircraft. Utilizing the data from the internal navigation system (INS) and the global positioning system (GPS) on Polar 6, the viewing angles are corrected depending on the roll, pitch and yaw angles of the aircraft at the time of measurement. In this regard, Euler rotations are applied as described in Ehrlich et al. (2012).

14. Pg. 13, Equation 18, the viewing and illumination geometry variables need to be defined taking into account the aircraft orientation. The downward flux F should also be described here immediately after the equation is listed, unless it’s previously defined.

Thank you for this comment. The reflection geometry is obtained from the viewing geometry by means of the aircraft attitude correction. We believe in moving the aircraft attitude correction paragraph to directly above Eq. 18 (see comment #13 above), the illumination and reflection geometry are now sufficiently defined. We added the illumination angles θ_0 and φ_0 to Eq. 18. The downward flux $F^{\downarrow}$ is already defined in Sect. 3.2, but we added a description for clarity.

Changes in text:

- P13 L30: Finally, the observed HDRF is calculated by:

  $$R_{\mathrm{HDRF}}(\theta_0, \varphi_0; \theta_\mathrm{r}, \varphi_\mathrm{r}) = \frac{\pi\,\mathrm{sr} \cdot I(\theta_\mathrm{r}, \varphi_\mathrm{r})}{F^{\downarrow}(\theta_0, \varphi_0)}\,.$$

  $F^{\downarrow}(\theta_0, \varphi_0)$ denotes the downward solar irradiance at the time of measurement (with solar zenith and azimuth angles θ_0 and φ_0).