Note: Reviewer's original comments are in black text and author responses are in blue text

Anonymous (Referee #1)

Overview:

This paper presents comparisons of spectral albedos of snow surface measured at Summit in Greenland and at the Col de Porte in the French Alps with those theoretically calculated based on in situ measured snow physical and chemical parameters using a radiative transfer model. The effect of vertical profiles of specific surface area and the effect of snow impurities on the spectral albedo are quantitatively discussed. At the wavelengths shorter than 1400 nm the calculated albedos agree well with the measurements. However, the discrepancies remain at 1430 nm and around 1800 nm. The authors concluded that the discrepancies are independent of the snow properties and the instrument used, and they may be due to the uncertainties on the ice refractive index at these wavelengths.

The field works for snow SSA measurements and snow impurity analyses are well designed and the spectral measurements look fair except some procedures. Many spectral albedo data synchronized with snow pit data are valuable for the improvements of snow albedo modeling and satellite remote sensing as mentioned by the authors. However, error evaluations coming from set-up of spectral albedo measurements and theoretical discussion on volume to surface ratio equivalent sphere radius are not sufficient. There are following points to be checked before reaching the conclusion on the issues of ice refractive index.

We thank the Referee for taking the time to review and provide feedback on this paper. We have modified the text in response to all of her/his minor and major comments as detailed below.

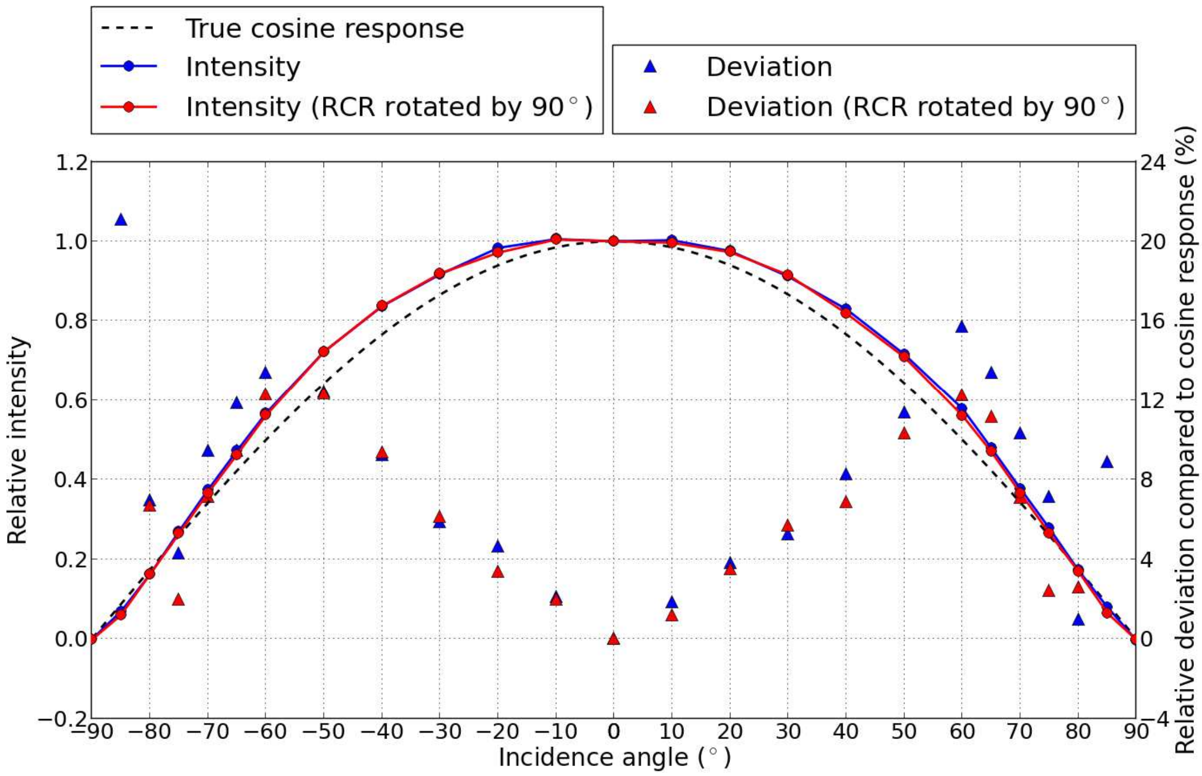
(1) The deviation factor for RCR from the perfect cosine response was not finally corrected in this study. The reason is mentioned as "The resulting albedo values were slightly higher than 1" (p.5219, L5) when the deviation factor on another RCR detector is applied. It sounds that inconvenient correction was not applied. If the deviation factor for the RCR used in this study is different from that another RCR, the actual deviation factor of RCR used in this study should be corrected. In that case, bidirectional reflectance is much anisotropic at the NIR wavelengths, that is extremely high in forward scattered direction, and thus assumption of isotropic reflectance could cause the correction error.

We completely agree with the Reviewer's comment. In the revised manuscript, the cosine collector deviation from a true cosine response has been investigated carefully and all measured albedo have been corrected accordingly (please see our reply to comment #2). Regarding the anisotropy of bidirectional reflectance at near-infrared wavelengths, it is true that assuming the measured upwelling diffuse radiation is isotropic could cause an error. This error has been evaluated and discussed in the revised manuscript (please see our reply to comment #8).

(2) My understanding for the cosine response of ASD's RCR is not so good although the RCR used in this study may differ from it. Lubin and Vogelmann (2011) reported that the RCR's deviation from perfect cosine angular response in the spectral interval 400–1000 nm increases linearly from zero at overhead illumination to approximately +10% at 60° illumination angle, then decreases to zero for larger illumination angles up to 76°, and at 1600 nm, RCR angular performance is better, with cosine error < +2% for illumination angles 0–60°, with degraded performance to an error of -10% by illumination angle 76°. In these cases the correction for RCR cannot be ignored. There are also reported the deviation of cosine response of ASD's RCR by Meywerk and Ramanathan (1999) and Malthus and MacLellan (2010) in which cosine responses at some wavelengths are shown. Please indicate the figure of cosine response of RCR in the present study as well.

Thanks for this relevant input. In the revised manuscript the angular response of the system RCR+ASD used during our field campaign at Summit has been completely characterized. The RCR sensor has been sent by D. Perovich from Hanover (US) to Grenoble (France) and its angular response has been studied at LGGE (Laboratoire de Glaciologie et Géophysique de l'Environnement) with the help of L. Arnaud and Q. Libois, who are now co-authors of the revised manuscript.

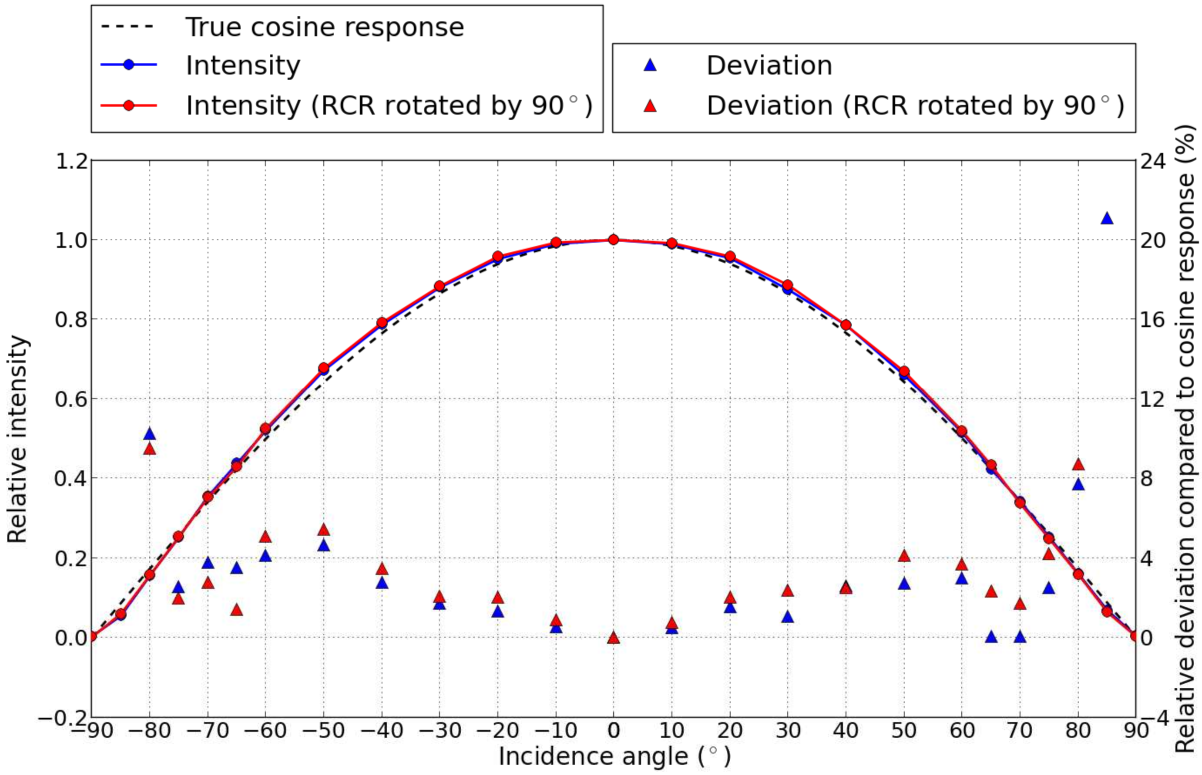
The measured response of the RCR is provided in the Figure below (Fig. 3 of the revised manuscript).



The plot shows the angular response of our RCR at 500 nm, for incidence angles ranging from -90° to 90°. Relative intensities normalized by I(0°) are represented by blue circles and compared to the true cosine response (dashed black line). Blue triangles represent absolute values of cosine collector fractional errors (ε_λ) as a function of the zenith angle of the incident light (deviation of the measured response from a true cosine response), computed as follows:

$$\varepsilon_\lambda(\theta_S) = \frac{\frac{I(\theta_S)}{I(0^\circ)} - cos\theta_S}{cos\theta_S}$$

where θ_S is the incidence angle. Note that for our albedo measurements $\theta_S \approx 50°$. The RCR response has also been measured after rotating the sensor along its axis by 90° (red circles and triangles). This gives $\varepsilon_\lambda(\theta_S)$ values different from those obtained without rotating the RCR, especially for high incidence angles. The cosine deviation used to correct our albedo measurements is the mean between blue and red values. Our RCR angular response is quite consistent with what Lubin and Vogelmann (2011) reported in their study. In the spectral interval 400-1000 nm, our RCR deviation from perfect cosine response increases linearly from zero (at θ_S=0°) to 10-14% at a 60° illumination angle; Lubin and Vogelmann (2011) found an error of approximately 10% at 60° and a similar behaviour was also described by Meywerk and Ramanathan (1999). For larger illumination angles up to 75°, $\varepsilon_\lambda(\theta_S)$ decreases to zero. At 1600 nm (see plot below), RCR angular performance is better, with cosine error <5% for illumination angles 0°–75°; Lubin and Vogelmann (2011) found an error <2% for angles 0°–60° and a degraded performance to an error of 10% by illumination angle 76°.



The spectral albedo has been then corrected taking into account this cosine collector deviation from a true cosine response (Equ. 10 of the revised manuscript):

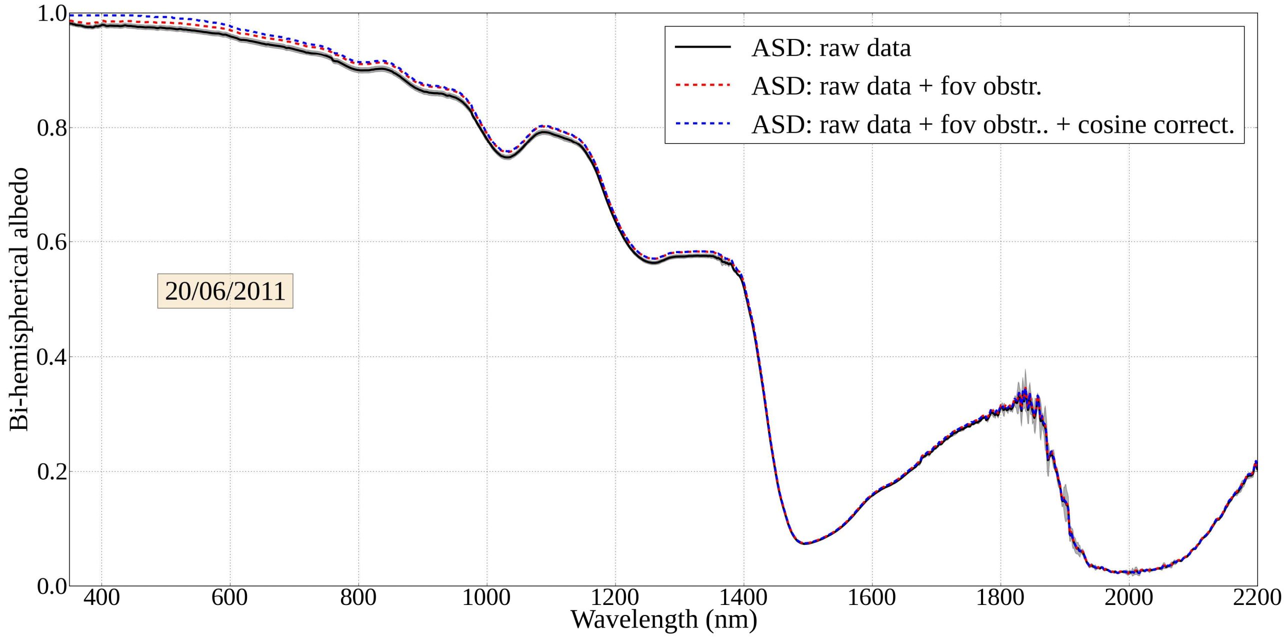
$$\alpha_{\text{true\_iso},\lambda} = \frac{C_\lambda C_\uparrow F^{\uparrow}_{\lambda,\text{dif}}}{C_\lambda C_\downarrow F^{\downarrow}_{\lambda,\text{dif}} + \frac{F^{\downarrow}_{\lambda,\text{dir}}}{1+\varepsilon_\lambda(\theta)}}$$

C_λ is the correction factor accounting for the RCR deviation, computed as follows:

$$C_\lambda = \frac{0.5}{\int_0^1 \mu(1+\varepsilon_\lambda(\mu))d\mu}$$

where μ=cosθ. The equation giving the corrected albedo has been reformulated in terms of measured albedo and downwelling direct/diffuse radiation. Since the ASD spectroradiometer was used only when taking the ratio between incident and reflected fluxes, the direct/diffuse radiation has been computed, for each day of the campaign at the time of our measurements, using a radiative transfer model (SBDART, Richiazzi et al., 1998). Averages of measurements of atmospheric parameters at Summit during the measurement period have been used as model inputs. Model results have been then compared to measurements from a Biospherical Instruments (BSI) SUV-150B scanning spectroradiometer at 350-600 nm (0.64 nm resolution, cosine corrected). This instrument is located on the roof of the Green House at Summit, approximately 1 km from the measurement site. RMSD between modelled and BSI spectra never exceed 0.04 $W/m^2/nm$.

In Sect. 2.1.3 (Radiation measurements) of the revised manuscript, we have added both a description of how we have measured the cosine deviation of our RCR and a discussion of the impact of the cosine collector correction on spectral albedo. In addition, all plots have been re-traced using ASD data corrected for the field of view obstruction due to the presence of the observer and the cosine collector deviation (see plot below). The only significant difference that we have found with respect to our previous results is in RMSD values for visible wavelengths, which are now lower. Indeed, before we obtained Δ_{alb} values ranging from 0.003 to 0.056, with median values of 0.021 for pure snow and 0.018 for snow with impurities. Now, these values range from 0.004 to 0.051, with median values of 0.018 for pure snow and 0.017 for contaminated snow. We conclude that the cosine correction has a positive, albeit very low, impact on the main results discussed in the original manuscript.



(3) Spectral albedo is calculated using spherical model for snow grains in this study. Basically I agree this approach. However, the spherical assumption is not completely verified for all non spherical snow particles. Especially for very complicated crystal such as stellar dendrites, rime, and surface hoar shown in Fig. 5 there is still room for discussion as possible cause for discrepancies in spectral albedo between calculation and measurement.

The Reviewer raises a very important question. We agree that the spherical assumption can be invoked to explain part of the discrepancies between simulated and measured albedo. However, as we have pointed out in the section "Simulations of snow albedo" (p. 5133 L9), the spherical assumption is an acceptable approximation if the aim is to model the bi-hemispherical reflectance of snow. In addition, the model used by the DUFISSS instrument in order to retrieve SSA from reflectance at 1310 nm already makes this assumption. Therefore, assuming spherical ice crystals to calculate albedo is also consistent with the way in which SSA has been obtained.

In the discussion section of the revised manuscript, we have added the spherical assumption for snow grains as a possible cause for discrepancies in spectral albedo between model and observations.

Specific comments:

(4) p. 5122, L22: "visible region (λ = 0.35-0.75 μm)" Spectral domain 0.35-0.40 μm is in general the ultraviolet region. It should be revised throughout the manuscript.

The Reviewer is correct. The spectral domain has been revised throughout the entire manuscript.

(5) p. 5123, L1: "is absorbed within the top few millimeters of snow" Please indicate the reference.

The following reference has been indicated:
Warren, S. G. *Optical constants of ice from the ultraviolet to the microwave Applied Optics*, 1984, 23, 1206-1225

(6) p. 5128, L16: "Four repeated measurements were made at each location." I recommend to plot the standard deviation calculated from those four measurements at each wavelength in Figs. 3, 8, 10, and 13.

We appreciate the Reviewer's comment and we have added the standard deviation calculated from our four daily albedo measurements to Fig. 4 of the revised manuscript. However, since standard deviation values are always lower than corrections for field of view obstruction and deviation of the RCR from a purely cosine response, we have decided not to plot them on the other figures. In the plot above, for instance, standard deviation for each wavelength is represented by the grey band around the raw ASD data. Values are lower than 0.3% of the albedo over the entire spectrum, except around 1825-1900 nm, where there is no reliable signal for the ASD (low signal/noise ratio).

(7) p. 5129, L7: "to account for the shadow of the observer and the aluminium arm of the instrument" According to Fig. 2, the aluminium arm does not affect the radiation measurements.

We thank the Reviewer for pointing out this inconsistency. The text has been modified accordingly in the revised manuscript.

(8) p. 5129, L12: "where F_upward,dif is the measured upwelling diffuse radiation, assumed isotropic," The forward bidirectional reflectance at NIR wavelengths is very strong (anisotropic). How much is the estimated error of correction factor for upward radiation due to this effect by assuming isotropic?

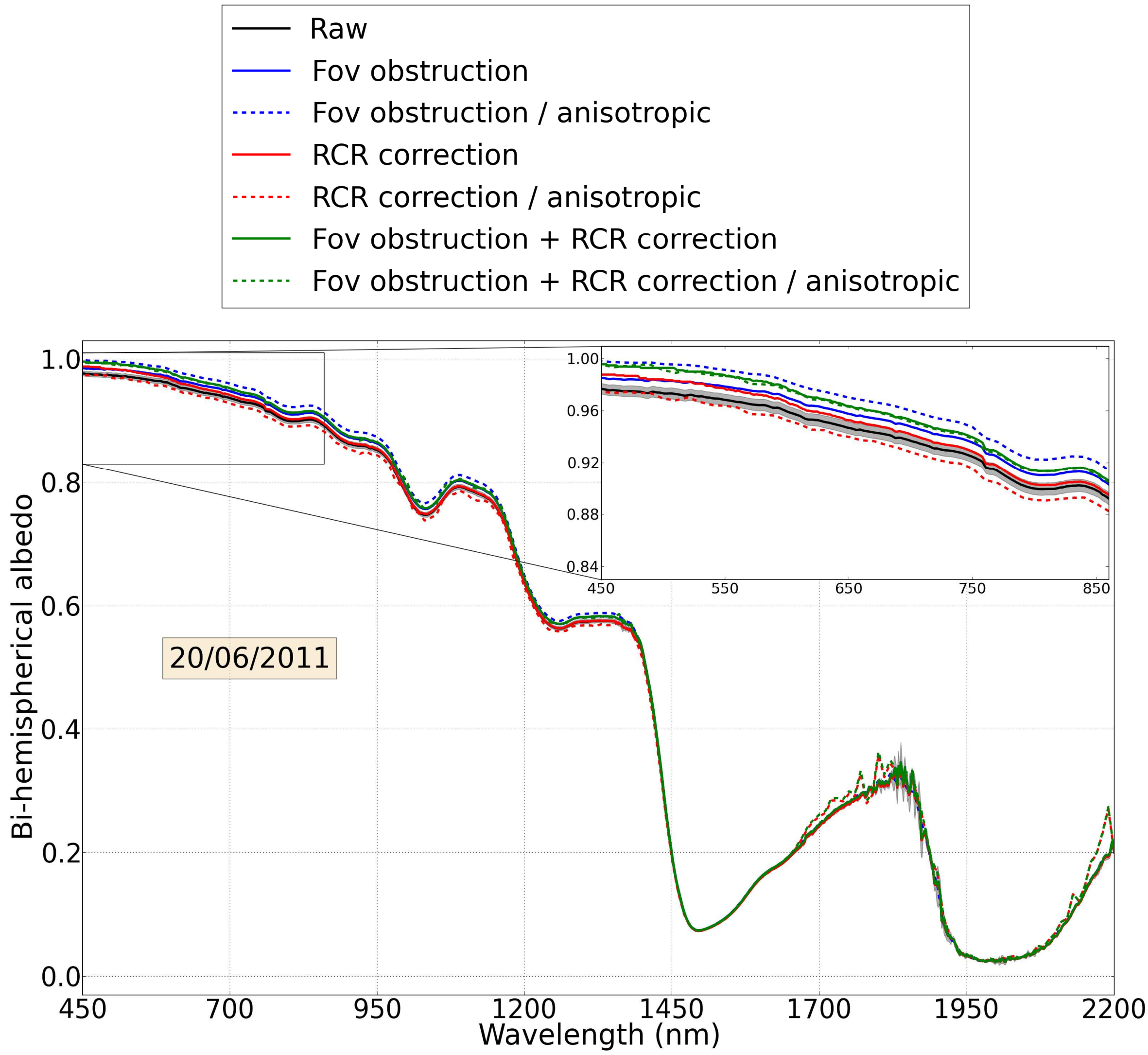
This is an excellent remark. In fact, the effect of the anisotropy was not taken into account in the original manuscript. We know, however, that assuming an isotropic reflectance over the hemisphere leads to errors, depending mostly on the incidence and measuring angles (Bourgeois et al., 2006). In particular, strong forward scattering occurs at high solar zenith angles, especially at NIR wavelength. Measurements of Hemispherical-Directional Reflectance Factors (HDRF) have been performed by Odermatt et al. (2005) at Davos Dorf (Switzerland) and by Bourgeois et al. (2006) at Summit (Greenland). Dumont et al. (2010) have measured the Bi-directional Reflectance Distribution Functions (BRDF) in a cold room for four natural snow samples, analyzing the effect of ice absorption coefficient and snow properties on the anisotropy factor at different wavelengths. During our field campaign we measured the bi-hemispherical albedo and we did not measure the bi-directional reflectance: this is the main reason why, in our work, the measured upwelling diffuse radiation is assumed isotropic.

In the revised manuscript we have estimated the effect of anisotropy on both the field of view obstruction due to the presence of the observer and the RCR cosine response. In order to do this, we have used the measured anisotropy factors R(θ,φ,λ) from Dumont et al. (2010) at an incidence angle of 60°. For the sake of simplicity and in the absence of measured spectral values of the Hemispherical-Directional Reflectance Factor, R have been used as a surrogate for the normalized HDRF. This means that we considered snow illuminated by natural light as being as anisotropic as snow illuminated by a collimated light at a 60° incidence angle. Thus, the cor rected spectral albedo can be computed as follows (Eq. 9 of the revised manuscript):

$$\alpha_{\mathrm{true},\lambda} = \frac{F^{\uparrow}_{\lambda,\mathrm{dif}}}{\left(C_\lambda C_\downarrow F^{\downarrow}_{\lambda,\mathrm{dif}} + \frac{F^{\downarrow}_{\lambda,\mathrm{dir}}}{1+\varepsilon_\lambda(\theta_S)}\right)\int_0^{\frac{\pi}{2}}\int_{\phi_{\mathrm{lim}}}^{2\pi}\frac{H(\theta,\phi,\lambda)}{\pi}\cdot\frac{I(\theta)}{I(0°)}\cdot sin\theta d\theta d\phi}$$

I(θ)/I(0°) is the normalized intensity measured by the RCR (please see our previous reply to comments #2) and describes the effect of the deviation of the RCR from a true cosine response; in case of a perfect response, this factor is equal to cos(θ). The reduction of the field of view due to the presence of the observer can be taken into account by changing the range of integration over φ. When the upward radiation is assumed isotropic, this equation reduces to the formula given in our previous reply to comments #2.

Fig. 4 of the revised manuscript (please see the plot below) shows the impact of corrections on the measured spectral albedo for 20~June 2011. Black line refers to raw ASD data obtained by averaging 4 daily spectra; the resulting standard deviation is represented in grey. The effect of the field of view obstruction by the observer is represented by blue curves, the impact of cosine collector deviation is represented by red curves and the total correction is represented by green curves. In each cases, dashed lines show the effect of taking into account the anisotropy of reflected radiation on the correction of spectral. If we consider the obstruction of the field of view by the observer (blue curves), taking into account the anisotropy gives albedo values slightly higher, at visible and NIR wavelengths, than those obtained by assuming an isotropic reflectance. The RMSD between these two curves is 0.0102 in the range 450-1400 nm. The effect on the albedo of the correction of the RCR deviation from a pure cosine response (red curves) is the opposite: between 450 and 1400 nm, albedo accounting for the fact that snow reflection is anisotropic is lower than that computed by assuming an isotropic reflection (RMSD of 0.0108). Finally, combined effects of anisotropy on both field of view obstruction and cosine response (green curves) compensate each others, leading to small differences between albedo with isotropic and anisotropic corrections (RMSD of 0.0026). Around 1800 and 2100 nm, albedo values are affected by the low signal/noise ratio of the RCR calibration. If we exclude these two spectral bands, the estimated error of assuming an isotropic reflectance ranges from 0.2 to 0.4%. These values are of the same order of magnitude of the accuracy of our spectral albedo measurements (please see our previous reply to comments #6). Even if the effect of anisotropy is not completely negligible, we want to point out once again that in our work, in the absence of knowledge on its angular distribution, the measured upwelling diffuse radiation is considered isotropic.



(9) p. 5129, L19: "and practically negligible elsewhere" Under clear sky condition F_downward,dif would be very small at NIR wavelengths and only the correction factor for upward radiation (1.31%) affects the corrected albedo, that is not negligible.

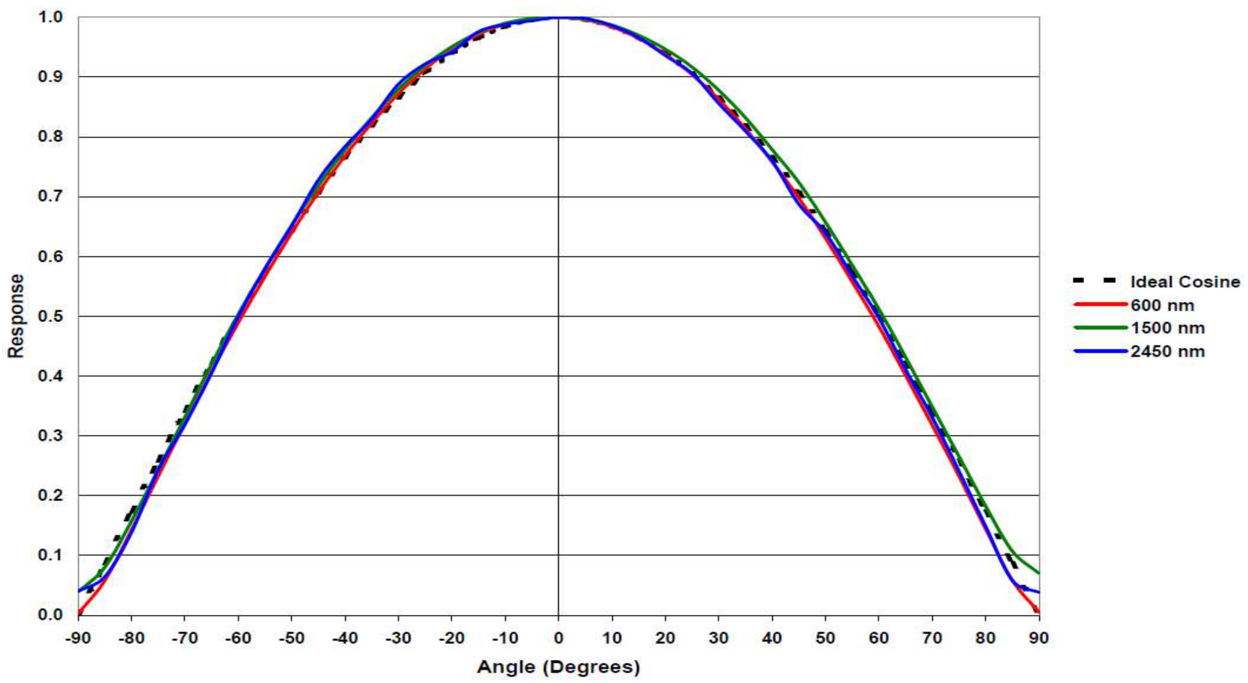
The Reviewer makes a good point. The difference between original and corrected albedo is not negligible in the NIR wavelengths. In Fig. 3 of the original manuscript, for instance, it is clear that on June 20 2011 (clear, bright sky conditions) raw ASD data and shadow corrected data differ not only in the visible, but also in the infrared until 1400 nm. In terms of albedo, this difference never exceeds 0.01. The sentence of p. 5129, L19 is not correct and has been replaced by:

"The resulting difference between corrected albedo (solid blue curve in Fig. 4) and raw albedo is less than 0.01 over the entire spectrum."

We take this opportunity to point out that the correction factor for upward radiation appearing in Eq. 2 of the original manuscript is not 1.31% but, more precisely, 1/(1-0.0131)=1.0133. Similarly, the factor for downward radiation is 1/(1-0.0155)=1.0157. The revised manuscript has been corrected accordingly.

(10) p. 5129, L24: "an integrating sphere, which eliminates the need of the RCR." Even using integrating sphere the cosine response is not perfect. If the optical fiber is horizontally connected to the side of the integrating sphere, azimuthal dependence of cosine response would occur. Please indicate the deviation factor for the integrating sphere from the perfect cosine response.

We agree with the Reviewer's point of view about the non perfect cosine response of the integrating sphere. Unfortunately, the angular response of our integrating sphere has not been characterized yet. All we have is the cosine response of the SVC sphere given directly by the manufacturer (see figure below).



That being said, we believe that this has no effect on our main results. Indeed, the main purpose of using the SVC instrument at Col de Porte was to confirm that differences between simulated and measured albedo at 1430 and around 1800 nm are independent of the snow properties and of the instrument used. At these wavelengths, the impact of the deviation factor for the integrating sphere from the perfect cosine response is negligible.

(11) p. 5135, L21: “The dust refractive indices were taken from the GEISA database.” There are many refractive indices for dust in the GEISA database. Please indicate which data base is used in this study.

In the revised manuscript, we have decided to use another refractive index for dust with a hematite content of 1.5% in volume (Balkanski et al., 2007). The reference has been added to the manuscript and all simulations have been re-run using this index.

(12) p. 5135, L29: “the fist one” Typo of “first”?

We have replaced the word “fist” with “first” in the revised manuscript.

(13) p. 5138, L7: “At Summit, the surface snow layer can display a significant horizontal variability.” This could cause of the difference in spectral albedo between calculation and observation. Please discuss it.

The Reviewer is correct. Even if we have taken great care to choose an area over the ASD field of view as spatially homogenous as possible, the horizontal variability at small scales can be responsible for part of the discrepancies between calculation and observation.

This point has been discussed in the discussion section of the revised manuscript.

(14) p. 5139, L6: “On 15 May” The date indicated in Fig. 8 is 19 May.

We thank the Reviewer for pointing out this oversight. 19 May is the right date and the text has been modified accordingly.

(15) p. 5140, L23: “whole fist cm” Typo of “first”?

We have replaced the word “fist” with “first” in the revised manuscript.

(16) p. 5140, L25: “for larger wavelengths” It is better to use “longer wavelengths”.

We have replaced the word “larger” with “longer” in the revised manuscript.

(17) p. 5144, L23: “the optical constants of BC France et al. (2012) and dust Balkanski et al. (2007) are uncertain.” The left parentheses of the years are misplaced.

This error has been corrected in the revised manuscript.

(18) p. 5147, L6: “including trace elements and black carbon (BC).” What is the trace elements, dust?

Ambiguous definition of “trace elements” has been replaced with “dust” within the entire manuscript (3 occurrences).

References:

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Meywerk, J., and V. Ramanathan: Observations of the spectral clear-sky forcing over the tropical Indian Ocean, J. Geophys. Res., 104, 24,359-24,370, doi:10.1029/1999JD900502, 1999.

Odermatt, D., Schlpfer, D., Lehning, M., Schwikowski, M., Kneubhler, M., and Itten, K.: Seasonal study of directional reflectance properties of snow, EARSeL eProceedings, 4(2), 203–214, 2005.

Ricchiazzi, P., Yang, S., Gautier, C., and Sowle, D.: SBDART: A research and teaching software tool for planeparallel radiative transfer in the earth’s atmosphere, in: Bulletin of the American Meteorological Society, October 1, 1998.

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