RC2: Anonymous Referee #2

In this paper the authors - as of the title - want to investigate the pitfalls of topographic influence when analyzing snow signatures in mountaineous areas. However, the paper does not focus on this topic but rather gives an overview of how to perform a combined retrieval of snow parameters and atmospheric quantities and terrain influences. This work is of considerable importance and the paper's title should be changed accordingly. The pitfall of not considereing topography when analyzing hyperspectral data be it snow or other applications is well known and is of much less interest than the capability of retrieving the broad variety of paparameters from imagery in an optimization procedure simultaneously. However, for the latter the validation presented in the paper is not really sound and would need to be improved to make a convincing case about the accuracy of the such retrieved parameters. It is recommended to focus the paper on the parameter retrieval algorithm and describe the applied processing steps and the validation of the outputs more concisely.

We thank the referee for the feedback and the constructive review. Our general feeling of the significance of the work has always been in-between investigating the influence of topography and the combined retrieval of atmosphere and snow parameters. Therefore, we are in line with what the referee identified and changed the title of the manuscript to:

"Do we still need reflectance? From radiance to snow properties in mountainous terrain: a case study with EMIT"

We also revised the abstract to reflect the modified focus of the manuscript:

"Accurate retrievals of snow surface properties, including grain size, liquid water content, as well as concentration of mineral dust and algae, require a precise, ideally joint accounting for atmospheric, topographic, and anisotropic effects in the reflected radiance. However, previous methods either neglect physical effects of the surface or utilize the surface reflectance as an intermediate non-physical quantity, in part without proper error propagation from the atmospheric modeling and obtained from statistical modeling. In this contribution, we present a novel surface-atmosphere radiative transfer model that couples the MODTRAN code with a physics-based snow surface reflectance model that utilizes the multistream DISORT program. Our model allows to omit the intermediate retrieval of surface reflectance, and to estimate snow surface and atmosphere properties directly from measured radiance. We apply the approach to EMIT images from Patagonia, South America, and compare our results to the EMIT L2A products that model surface reflectance from statistical priors, excluding topography. We find discrepancies in snow grain size of up to 200 μm and in dust mass mixing ratio of up to 75 μg g^{-1}. Furthermore, we demonstrate differences in instantaneous LAP radiative forcing of up to 400 W m^{-2} in cases of LAP concentration inaccurately quantified from surface reflectance."

Likewise, the introduction needed a few modifications to align with the updated focus of the manuscript:

"Recent work has demonstrated that a simultaneous inversion of atmosphere and surface state using optimal estimation (OE) shows promising potential to quantify even low concentrations of LAPs on a global scale from spaceborne imaging spectroscopy observations (Bohn et al., 2021, 2022}. However, the approach utilizes the surface reflectance as an intermediate non-physical retrieval quantity assuming Lambertian behavior. It is obtained from statistical

modeling using constrained priors, impeding a proper consideration of surface topography and anisotropy. This could lead to significant biases in downstream estimates of LAP concentration, and propagate to erroneous calculations of LAP radiative forcing as these physical effects influence both magnitude and shape of measured spectral radiance as a function of local view and solar geometry (Carmon et al., 2022, 2023). Specifically, Picard et al. (2020) demonstrated the sensitivity of snow albedo measurements to surface slope based on spectral data taken in the field, and proposed a correction approach to retrieve the intrinsic albedo. Using a digital elevation model (DEM), this local geometry, including surface slope and aspect, can be calculated and incorporated in atmospheric modeling schemes in order to correct for spectral distortions in the retrieved surface reflectance (Richter and Schläpfer, 2017}. However, given the complex terrain of mountainous regions, and the current unavailability of coincident radar/lidar and imaging spectroscopy data in orbit, reliance on fixed DEMs may introduce additional retrieval errors, not only due to variability in local snow depth, but also because of uncertainties in the DEM product itself (Dozier et al., 2022). For instance, Donahue et al. (2023) showed that topographic correction with coarse and non-coincident DEMs introduces significant errors in estimated snow albedo from air- or spaceborne imaging spectroscopy of up to 20 %. Overall, a mature and comprehensive modeling of topography for spaceborne imaging spectroscopy data over mountain snow has not yet been demonstrated, and only a few studies have applied a limited post-hoc correction at the airborne scale (Painter et al., 2013a, Seidel et al., 2016).

To improve the downstream estimation of biogeophysical quantities, we need to align the surface and atmospheric forward modeling assumptions. In particular, the retrieval of properties on highly anisotropic surfaces such as snow and ice will benefit from capturing local topographic conditions through physical modeling as directional effects are minimized. We present an updated version of the algorithm that was originally introduced by Thompson et al. (2018) and modified by Bohn et al. (2021). We developed a surface-atmosphere radiative transfer model that couples the MODTRAN code with a combination of Mie scattering calculations and the multistream DISORT program. The model provides a full physics-based characterization of atmosphere and surface by yielding simulations of directional reflectance as a function of biogeophysical properties as well as view and illumination geometry. This facilitates the consideration of local surface anisotropy and topography in the forward model and removes dependency from external DEMs (Carmon et al., 2023). Aim is to utilize this best in class physical and atmospheric modeling simultaneously to present estimations of snow surface properties directly from measured radiance. Initial results for a single EMIT scene from Patagonia in South America are shown in Bohn et al. (2023) and indicate that retrieval errors of mineral dust concentration and LAP radiative forcing increase when a physics-based modeling of the surface is omitted. In this contribution, we substantiate previous findings by adding a comprehensive sensitivity analysis of both our forward model and individual snow surface parameters, and provide more robust numbers by utilizing another EMIT image from a different region in Patagonia. Finally, we include a detailed investigation of the artificial hook prominent in the blue wavelengths in remotely sensed snow reflectance when retrieved over challenging mountainous terrain."

We also changed the title of Sect. 4.2 to:

"Sensitivity of snow physics"

and slightly revised multiple phrases throughout Sect. 4.2 and the discussion section, mostly to move the focus from solely topography to physics in the forward model in general. Finally, we substantially updated the conclusion to address the changes in the general narrative of the manuscript:

"We introduce a new retrieval algorithm that estimates snow surface properties directly from at-sensor radiance measured by the spaceborne EMIT imaging spectrometer. We utilize a coupled full physics snow and atmosphere model and apply Optimal Estimation to solve for the most probable surface state. On one hand, this allows to reduce the number of retrieved state vector elements to only a handful of snow surface and atmosphere properties, including AOD, water vapor, snow grain size, liquid water content, LAP concentration, and local solar zenith angle. On the other, it facilitates a more thorough consideration of physical surface characteristics such as anisotropy and topography. We utilize two representative EMIT images acquired over the Argentine plain and the Chilean ice field in Patagonia, South America, to conduct a sensitivity analysis of our proposed forward model. We demonstrate that the retrieval of snow liquid water fraction and snow algae concentration is insensitive to topographic and directional effects. In contrast, estimations of snow grain size and mineral dust mass mixing ratio can be biased under these scenarios, which directly propagates into incorrect calculations of LAP radiative forcing. A validation with field measurements is still missing for the presented approach, but comparisons to Landsat 8 and Sentinel-2 reflectance values as well as to estimates of radiative forcing of previous studies indicate that surface reflectance as an intermediate quantity can be omitted in the retrieval framework in favor of inferring surface properties directly from radiance. Finally, we evidence that erroneous assumptions about surface topography are one of the -though not the only- major causes for the formation of the ``blue hook" in remotely sensed retrievals of snow reflectance. Future work must include a thorough validation effort, and needs to address mixed pixels and the modeling of both ice and LAP OPs to account for local geographical characteristics. Nevertheless, our findings are critical for updating melt runoff and climate model input, but also for the conception of retrieval algorithms for future orbital imaging spectroscopy missions, such as NASA's SBG. These missions provide the framework to develop and enhance processing schemes and retrieval algorithms on a global scale."

Below, we address the additional line-by-line comments by providing respective responses and by indicating the changes to the manuscript.

Some detail comments:

- p3: l88: it is stated that the terrain may be rapidly shifting; this is indeed a problem for high spatial resolution imager - but at the resolution of EMIT such shifts are quite seldom and should not be a problem when using standard DSM products.

Thanks for this comment. That's certainly true. The topography is not rapidly shifting on a 60 m pixel resolution. We may have not fully correctly transferred the conclusion from Dozier et al. (2022). We rather wanted to express that reliance on auxiliary data products introduces an additional uncertainty component. We modified our statement to clarify our intention:

"However, given the complex terrain of mountainous regions, and the current unavailability of coincident radar/lidar and imaging spectroscopy data in orbit, reliance on fixed DEMs may introduce additional retrieval errors, not only due to variability in local snow depth, but also because of uncertainties in the DEM product itself (Dozier et al., 2022)."

- p4, l97: it is claimed that a fully physics based model is employed when analyzing the data. On the other hand the optimal estimation is not based on physical parameter retrieval but rather on mathematical optimization what bears the risk of resulting in non-physical outputs at false minima. This limitation should be explained from the beginning.

We agree that optimal estimation poses the risk of reporting local minima as the solution state. We now mention this limitation in more detail at the end of Sect. 3.2:

"Our selected optimization scheme implies the risk of ending up in a local minimum, reporting a non-physical output. However, we use a traditional sequential atmospheric correction approach to initialize our inversion, which provides a first guess close to the probabilistic solution from OE. This promotes stability and fast convergence (Thompson et al., 2018)."

- p 4, l114: the term HDRF is used ambigously in this paper (and also in Literature). While Nicodemus defines HDRF as a physically well defined surface property with fully diffuse illumination and directional measurement, Schaepman-Strub 'redefined' the term as the real world hemispherical-directional situation with a anisotropic illumination field. That quantity would better be described as bottom-of-atmosphere directional reflectance rather than talking about 'HDRF". Please clarify in the paper how 'HDRF' is defined and uesd clearly. The same confusion is also geivn in line 120; integrating the 'Schaepman-Strup'-HDRF will not result in spectral albedo as long as the illumination field is not isotropic while integrating the Nicodemus-HDRF leads to a correct result.

We agree that the use of the different reflectance terms is ambiguous and not consistent. Likewise, we understand that we compounded different terms and meanings ourselves. We actually follow the definition of HDRF as given by Schaepman-Strub et al. (2006), which is based on the nomenclature of Nicodemus et al. (1977) but incorporates the adaptations to the remote sensing case from Martonchik et al. (2000). We assume an anisotropic illumination field (direct + diffuse irradiance), including the dependency of the HDRF on atmospheric conditions and on the reflectance of the neighboring terrain. We revised the respective paragraph in Sect. 2.1 to clarify our usage of the term HDRF:

"The HDRF is defined as the ratio of reflected spectral radiance L_r at a particular solar and view geometry to the radiant flux L_{id} that would be reflected from an ideal Lambertian surface, illuminated and observed under the same conditions (Schaepman-Strub et al., 2006):
…
The HDRF scenario is composed of hemispheric illumination, i.e., both direct and diffuse irradiance, but only direct reflection."

- p6, l141: again: the HDRF only depends on atmospheric conditions if the in-field bottom of atmosphere reflectance is confused with the real HDRF. A BRDF correction of the topographic effects would therefore be of high importance to analyze snow parameters in terrain.

We hope that our answer to the previous comment clarified the usage of the term HDRF in our manuscript and that it follows the definition of Schaepman-Strub et al. (2006), including the dependency on atmospheric conditions and on the reflectance of the neighboring terrain. We also concur with the referee's comment that a BRDF correction would be the optimal way to get to accurate snow surface parameters. However, a BRDF correction is usually complex and less straightforward, and we believe that we address the consideration of topographic effects to a large extent by using DISORT as our snow surface model and optimizing for the local solar zenith angle during the inversion.

- p8 eq (2): this equation does not include adjacency effects and terrain illumination on a pixel. In a snowy environment this assumption is a very rough approximation of the radiative interaction on a ground pixel.

Yes, that is correct. Our forward model does not include adjacency effects. While we agree that this factor is important, we also believe that it is less critical than modeling the ratio of direct to diffuse illumination correctly. We therefore decided to only include the latter in our study, as it is rather a proof of concept. However, subsequent work certainly needs to include additional physical effects of the terrain in the forward model. We added the following sentence to justify our choice:

"We currently exclude the effects of adjacent pixels and slopes both to limit the complexity of our forward model and because their impact on modeled radiance is less critical than the separation of downward direct and diffuse transmittance (Guanter et al., 2009; Picard et al., 2020)."

- p9 l204: the transferability of signatures between Greenland and Patagonia is a very rough assumptions. This should be corroborated by appropriate references or reasoning. The same applies to the transferability of dust signatures from Colorado to Patagonia.

That is a good point and certainly requires a thorough foundation. We implemented a detailed discussion about our choice of algae optical properties, and extended the justification for our selection of dust optical properties in Sect. 5.2:

"To model biological LAPs, we utilize a set of algae OPs for the species Ancylonema (glacier algae) as well as Sanguina nivaloides and Chloromonas nivalis (snow algae), derived from samples collected on the Greenland Ice Sheet (Chevrollier et al., 2022). Despite being characterized at a different geographic location far away from our study site, we assume that these OPs adequately represent algae cells found on ice sheets, glaciers, and snow worldwide. This is corroborated by previous studies that identified those three species as being responsible for the darkening of snow and ice surfaces in various regions, including the Greenland Ice Sheet, Svalbard, the European Alps, and the Sierra Nevada in California (Yallop et al., 2012; Remias et al., 2012; Di Mauro et al., 2020a; Painter et al., 2001). Moreover, Takeuchi & Kohshima (2004) and Kohshima et al. (2007) identified Ancylonema and Chloromonas algae as among the most frequently encountered species on the Patagonian Ice Sheet.

The use of dust OPs poses a different challenge, as they strongly depend on mineralogy and source area (Di Biagio et al., 2019). Several sets of dust OPs from different geographic regions, derived using diverse techniques and data, are publicly available. They have been obtained from any combination of field samples, spectral measurements, and linear mixing modeling, with Sahara, Colorado, Greenland, and Mars being the most prominent regional types (Polashenski et al., 2015; Skiles et al., 2017b; Balkanski et al., 2007, Singh et al., 2016). However, only a few studies have considered specific dust minerals when assessing their impact on snow melt (Lawrence et al., 2010; Kaspari et al., 2014; Reynolds et al., 2014). For our study, we selected only one type of dust OPs representing rather large particles, measured from samples that were collected in the San Juan Mountains of southwestern Colorado (Skiles et al., 2017b). In the lack of dust OP characterization in South America, we believe that the

Colorado type is closest to the dust type found in Patagonia. This is especially supported by the finding that very large dust particles are often present in patchy snow of arid environments (Skiles et al., 2017b). Moreover, studies of the geochemical composition and mineralogy suggest that both the San Juan and the Patagonian dust are significantly dominated by quartz with 30-50 % of the total mineral mass (Lawrence et al., 2010; Demasy et al., 2024). Such analyses will be facilitated on even larger geographical scales by the EMIT mission objective, which is providing an improved understanding of the mineralogy of dust particle source regions, and enabling an enhanced identification and classification of dust OPs and their distribution around the Earth's snow-covered areas."

We also added a sentence earlier in the manuscript that points the reader to the references and reasoning in the discussion section:

"A thorough discussion about our choice of LAP OPs can be found in Sect. 5.2."

- p10, fig5: just wondering: why are algae only influencing the visible part of the spectrum; what was the measurement database or could it be that the SWIR dat was simply not available?

Algae absorb solar radiation only in the visible part of the spectrum where the energy of the irradiance is highest, to maximize their photosynthesis (Chevrollier et al., 2022). Cell compounds such as carotenoid and chlorophyll lead to the characteristic absorption features (Painter et al., 2001). Moreover, absorption by the surrounding ice and snow is overly strong in the near- and shortwave-infrared wavelengths, so that almost no solar energy would remain for algae pigments. We added this clarification:

"Note that algae absorb solar radiation only in the visible part of the spectrum where the energy of the irradiance is highest, to maximize their photosynthesis (Chevrollier et al., 2022). Moreover, absorption by the surrounding ice and snow is overly strong in the near- and shortwave-infrared wavelengths, so that almost no solar energy would remain for algae pigments."

As mentioned in lines 202-204, we use the dataset from Chevrollier et al. (2022), which also includes the infrared part of the spectrum, to represent algal absorption in our DISORT simulations.

- p11 l226: it is stated that 'flat priors' are used in OE, however at the same time it is claimed that the method is fully physics based. How are physical boundary conditions enforced in the OE process then to avoid unphysical results?

We enforce the physical boundary conditions by utilizing a full-physics model to simulate snow reflectance during the inversion. Hence, the optimized snow and ice surface parameters are constrained by the physical shape of the reflectance as a function of grain size, liquid water content, and LAP concentration. Furthermore, and as mentioned in line 227, our problem is well-posed since we retrieve eight state vector parameters from 285 elements in the measurement vector. Under such conditions, the use of constrained priors in the OE setup can be obviated (Rodgers 2000). We added the following statement to Sect. 3.2:

"We enforce physical boundary conditions by utilizing DISORT to simulate surface reflectance during the inversion. Hence, the optimized snow and ice parameters are constrained by the

physical shape of the reflectance as a function of grain size, liquid water content, and LAP concentration."

- p11 eq. 4: how is the anisotropy factor c retrieved, a LUT is mentioned, what's in this LUT?

As mentioned in line 242, the LUT contains spectral anisotropy factors c for different geometries and grain sizes, where c is the ratio of spectral albedo to directional reflectance. We follow the approach of Painter et al. (2013b) and pre-calculated various c coefficients by utilizing modeled spectral albedo for different grain sizes as well as HDRF for different view and illumination geometries and varying grain sizes obtained from DISORT simulations (as stated in line 241). However, we revised to provide some clarification:

"... where c is a function of observation and illumination geometry as well as snow grain size, and is calculated as the ratio of spectral albedo to HDRF. We follow the approach of Painter et al. (2013b) and use a LUT of pre-calculated c coefficients based on modeled spectral albedo for different grain sizes as well as HDRF for different view and illumination geometries and varying grain sizes obtained from DISORT simulations."

- p16 l316: it does not seem obvious to me why liquid water and algae outputs should not be depending on terrain- please give some arguments.

Thanks for this comment. We realize that our phrasing in line 316 is misleading. We do not want to express that liquid water content and algae are independent of terrain. We rather wanted to make the point, that the difference in the retrieved values for those two quantities is uncorrelated with the difference in assumed local solar zenith angle. In other words, if the forward model does not consider topography and anisotropy, liquid water and algae estimates are not significantly biased. We revised our statement accordingly:

"It is obvious that the difference in retrieved values of liquid water and algae is uncorrelated with the difference in assumed local solar zenith angle. Both scatter plots feature an r^2 *of around 0.0 and almost no slope of the regression line. It seems that omitting topography and anisotropy in the forward model has no significant influence on the retrieval of those properties that have subtle absorption features and only marginally form the reflectance magnitude."*

- Figure 9: this is very small.. but the differences between L2A and OE is quite large; why?

Yes, we agree that the figure is quite small. We increased its size as much as possible. To clarify, both the L2A and the multi-transmittance spectra were retrieved using the same OE approach. The technical differences are 1. in the forward model, that considers topography in the multi-transmittance case; and 2. in the state vector, that comprises all 285 EMIT reflectance values in the L2A case, but only a handful of snow parameters in the multi-transmittance case. Since we show EMIT L2A spectra already in Sect. 4.2.1, we added the following phrases there:

"We also show corresponding spectra from the EMIT L2A product. They were retrieved by applying the same OE technique, but without considering topography in the forward model, and by obtaining HDRF from statistical modeling using constrained priors instead of utilizing a snow surface radiative transfer model."

The potential reasons for the difference between the EMIT L2A spectra and the results from the multi-transmittance approach are given in Sect. 4.2.1. Please see lines 288-307 in the initial version of the manuscript.

- P18 l356: 'a good agreement' of incidence angles is reported, how 'good' is it indeed, how large where the samples, and how about the statics on a per-pixel basis?

We agree that ‘good agreement’ is a very ambitious statement here. To substantiate our claim, we added a few statistics about the per-pixel comparison:

“We observe a good agreement in our six examples between θ_{iest} *and* θ_{ical} *with only marginal deviations of up to 4°. This is confirmed by looking at the regression analysis of all 995,372 snow covered pixels in the image, which shows an* R^2 *of 0.64 and an RMSE of 3.58° between* θ_{iest} *and* θ_{ical}*.”*

- Table3: differences in RF are quite large and one does not know the real value. So, how could you absolutely validate the results and why are you sure that the Multi-transmittance output is more reliable?

That is correct, we do not know the true value and cannot do a comprehensive validation. However, since LAP radiative forcing is obtained from the spectra shown in Fig. 9, we assume that the multi-transmittance output provides more reliable input to the RF calculation, simply because we see more reasonable reflectance shapes and magnitudes given the topographic characteristics of each of the six examples. We modified our wording to highlight that we only make assumptions here:

“The result for S3 highlights that LAP radiative forcing is more than 400 W m^{-2} *higher on sun-facing slopes if snow surface physics are neglected in the forward model. Not accounting for* $\theta_i < \theta_0$ *causes a steeper slope in the estimated blue reflectance, which resembles LAP absorption. On pixels with* $\theta_i > \theta_0$*, e.g., locations S4 and I2, radiative forcing estimated from EMIT L2A spectra is generally smaller. The assumed underestimation ranges between 140 and 207 W* m^{-2} *in our examples.”*

We also added a new section to the discussion dealing with the missing field validation. In particular, we focus on the evaluation of estimated RF from the multi-transmittance approach:

“*“One essential part of remote sensing retrievals is still missing for the presented multi-transmittance approach, which is the validation with field measurements. This can be explained by the remoteness of our study sites in South America, but also by the fact that this work has rather been designed as a theoretical proof of concept. A good indication for the accuracy of our proposed inversion method is already given by the comparison to Landsat 8 and Sentinel-2 data in Sect. 4.2.3. However, to further compensate for the lack of validation and to put our results into the right context, we provide a comparison to findings from previous studies.*

We look at the estimated error in radiative forcing when topography and anisotropy are not considered in the forward model. Previous work in the Chilean and Argentinian Andes reports daily or annual averages of LAP radiative forcing, or even the mean over a period of multiple years (Rowe et al., 2019; Cordero et al., 2022; Figueroa-Villanueva et al., 2023). Their values range between 0 and 10 W m^{-2}*, mainly investigating the influence of black carbon, which was* *not the focus of our study. In contrast, our method provides the instantaneous radiative forcing due to LAP, which allows a reasonable comparison to similar work conducted in the Sierra Nevada, CA, or the Rocky Mountains, CO (Painter et al., 2013a; Seidel et al., 2016). Even though estimated in a different geographical location, their values of up to 400 W m*$^{-2}$ *agree well with the range of LAP radiative forcing retrieved from the multi-transmittance approach (see Table 3).”*

- p22: Conclusion: it is again stated that a 'full physics' approach was used, maybe I misunderstand the paper but as far as I can see this is not an inversion of full physics model but rather a statistical optimization with flat priors.

We agree that our wording might be misleading here. We invert a coupled full physics snow and atmosphere model that provides snow HDRF and atmospheric absorption and scattering properties by utilizing Optimal Estimation as inversion technique. So yes, the entire approach is not ‘fully physics-based’, but the inverted model is. We try to clarify this by revising:

“We introduce a new retrieval algorithm that estimates snow surface properties directly from at-sensor radiance measured by the spaceborne EMIT imaging spectrometer. We utilize a coupled full physics snow and atmosphere model and apply Optimal Estimation to solve for the most probable surface state. On one hand, this allows to reduce the number of retrieved state vector elements to only a handful of snow surface and atmosphere properties, including AOD, water vapor, snow grain size, liquid water content, LAP concentration, and local solar zenith angle. On the other, it facilitates a more thorough consideration of physical surface characteristics such as anisotropy and topography.”

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