ANONIMOUS REFEREE #1

Dear reviewer,

We thank you for your comment (reported here in italic font), which we address immediately below.

Sincerely,
M. Ottaviani, B. van Diedenhoven, B. Cairns

In the paper "Photopolarimetric retrieval of snow properties" by M. Ottavani et al. airborne RSP measurements over snow and ice surfaces were analysed. Retrieving RSP measurements, optimal crystal parameters of the developed polarized reflectance model for snow and ice surfaces were estimated.
In the conclusions authors write: "The spectral dependence of the polarized reflectance is larger than for soil or vegetated surfaces, but nonetheless small". Figure 1 (second row) demonstrates strong spectral dependence of the surface polarized reflectance: polarized reflectance at 440nm can be more than 2 times larger than polarized reflectance at 864nm. Authors should make more clear statement about the spectral dependence of polarized reflectance for snow and ice surfaces.

The point we were trying to make here is that the spectral spread of the surface polarized reflectance is only slightly larger than that of other land surfaces. Given its small absolute value, to a very good approximation the retrieved polarized surface reflectance at 2264 nm (essentially all of the polarized signal measured by RSP at altitude) can be subtracted from the polarized signal at any shorter RSP wavelength, where the atmosphere constitute the major contributor, when attempting aerosol retrievals. In view of this argument, we propose to modify the sentence in question (Page 3065, line 18) as follows:
"The spectral dependence of the polarized reflectance is slightly larger than for soil or vegetated surfaces, but nonetheless small relative to typical aerosol contributions (cfr. Fig. 6 in O12)."
The referenced figure is part of the conclusions of our published preliminary study.

Dear Reviewer,

We thank you for your thorough reading of the manuscript. Our replies to your comments are included point-by point in the following.

Sincerely,
M. Ottaviani, B. van Diedenhoven, B. Cairns

Analyses of the polarimetric measurement of snow by the Research Scanning Polarimeter (RSP) instrument aboard NASA ER-2 aircraft are reported. Substantial revisions are necessary before the manuscript in its present form is accepted for publication. Below are some specific comments for the authors' consideration.

1) The quality of figures needs to be improved. In particular, the font size for the figure legend of Figure 1 is too small and essentially illegible.

Figure 1 was assembled with the intention of having it of full-page size in the final form of the paper. While we could not control the size in the Discussions phase due to the "slide" format of the draft, we'll work with the editorial office to make sure it will get printed in the right size.

2) For remote sensing applications, the asymmetry factor is not very useful. To simulate polarized radiative transfer in the earth-atmosphere coupled system involving snow surface, the complete scattering phase matrix is needed. For the revisions, the phase matrix associated with the retrieved asymmetry factor should be presented.

This is a very good suggestion. We have added the following figure showing the phase functions elements obtained by averaging, scene by scene, all retrieved minima:

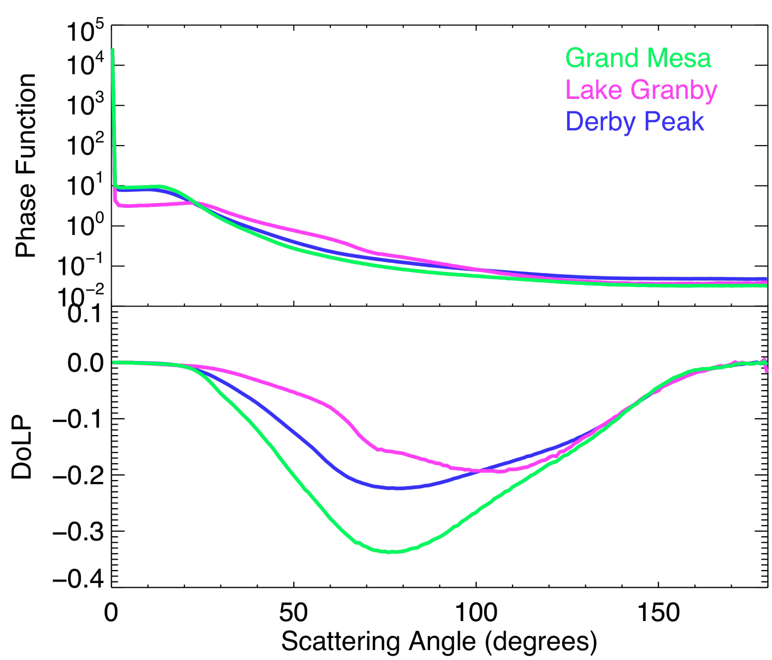

Figure 3. Phase function (*upper panel*) and degree of linear polarization (*lower panel*) resulting from the average over the optimal habits retrieved for each scene,. The color-coding is the same as in Fig. 2.

Also, we have added the following to the text:
"Figure 3 shows the phase function and the degree of linear polarization for each scene, obtained by averaging over all the phase matrices associated with the retrieved minima. The lack of halo peaks in the 20°-40° range of the phase function characteristic of pristine crystals, and the general smooth behavior (except from the strong forward peak) is consistent with the moderate-to-high roughness parameters determined in the analysis."

3) In terms of ice crystal habit model, the manuscript largely cites the work by a coauthor, Dr. van Diedenhoven, assuming hexagonal ice crystals. Over the years, Dr. Bryan Baum and colleagues have extensively considered the effects of various ice crystal habits. However, those studies are completely ignored in this manuscript. Overall, the selection of the references in this manuscript is largely biased.

The database by Yang et al., which is used by Dr. Bryan Baum, contains several different ice habits. However, it has been shown previously that complex habits that are made of hexagonal components (i.e. all habits in Yang's database excluding the droxtal) have phase matrices that closely resemble the phase matrices of the individual components (Iaquinta et al., 1995; Um and McFarquhar 2007; 2009; Fu 2007). For example an aggregate of plates has a phase matrix that is very similar to an individual plate that has the same aspect ratio as the plates in the aggregate. By far the most important properties of these complex crystals determining their scattering phase matrix are the aspect ratio of the components and the level of surface roughness.
In the database of Yang et al., the aspect ratios of (components of) crystals are based on very limited in situ measurements or educated guesses. It is clear from cloud particles observed in situ that particular habits feature a substantial variety of realizations (e.g., Um et al. 2015). The database of Yang et al. does not capture this variation and in our view is therefore too limited for useful implementation in a retrieval algorithm. As noted by Cole et al. (2014), the variation in POLDER measurements could not be captured by the simulations based on the database of Yang et al. The dependency of the assumed aspect ratios of crystal components with crystal size complicates matters further as results depend on the assumed crystal size, as found by Cole et al. (2013, 2014).
Räisänen et al. (TC, 2015) recently attempted to use the Yang et al. database to fit to a limited set of measured phase functions of blowing snow. They constructed a rather arbitrary mixture of habits to fit the data, but, encountering similar issues as described above, they concluded that this mixture "…most probably does not represent properly the actual distribution of snow grain shapes in blowing snow (or snow on ground)."
This rationale is the basis of our approach in which we use single columns and plates as radiative proxies of complex crystals consisting of hexagonal components. This simplification allows us to use a database that contains a virtually continuous

range of aspect ratios and distortion/roughness values. This approach is subsequently rigorously tested. In van Diedenhoven et al. (2012), we calculated simulated measurements based on the database of Yang et al. and applied our retrieval approach to assess the results. All habits in the database (to that date) were included, i.e., droxtals, columns, plates, bullet rosettes, aggregates of columns, hollow columns, hollow bullet rosettes and aggregates of plates, all with three different roughness levels applied to them. A total of 270 combinations of habit, roughness and size distributions are included in the sample. Furthermore the mixtures of these habits created by Baum et al. were used to calculate additional simulated measurements. Asymmetry parameters were found to be retrieved to within 0.04 with a mean bias of 0.004 and standard deviation of 0.018.

In the manuscript, the relative paragraphs and the references have been thoroughly revisited and now are presented as:

"It should be noted that for the specific task of remote sensing of aerosols over snow, a model capable of accurately reproducing the contribution of the surface to the total signal should be considered successful regardless of its capability to mimic the true shape of the crystals. Räisänen et al. (2015) recently attempted to fit measured phase functions of blowing snow by using phase functions of several complex habits provided by Yang et al. (2013) in addition to phase functions of other habits. However, the selection of habits in their study remained limited and to fit the data a rather arbitrary mixture of droxtals, aggregates of plates and Koch fractals was needed, leading them to conclude that this mixture "most probably does not represent properly the actual distribution of snow grain shapes in blowing snow (or snow on ground)". Our approach is based on the recognition that hexagonal plates and columns can be effectively used as radiative proxies for more complex crystal habits (Fu, 2007; Um and McFarquhar, 2007, 2009; Baran, 2009; van Diedenhoven et al., 2012; Ottaviani et al., 2012a). As demonstrated by van Diedenhoven et al. (2012), matching measured polarized reflectances with a look-up table of values simulated by adjusting the aspect ratios and roughness parameters of simple hexagonal particles yields an estimate of the asymmetry parameter of more complex ice crystals within the top of the snowpack. Our database, initially created to be of use for the retrieval of ice clouds properties, contains 765 different combinations of aspect ratios and roughness parameters and was computationally assembled by running Monte Carlo simulations based on geometric optics (Macke et al., 1996), the performance of which was evaluated by van Diedenhoven et al. (2012). The retrieved aspect ratios are interpreted as the mean of the aspect ratios of the components of the complex crystals.''

4) Section 3 "Methodology" needs to be improved. To be more specific, the description of the technical approach used in this study is not clear although the Ottaviani et al. (2012) is cited. A brief summary of the method developed in the previous study will help the reader to better understand this paper.

We agree with the reviewer that the concerning paragraphs can be made less terse. For this reason, we have rewritten them as:
"The method employed for the atmospheric correction procedure is explained in detail in O12, to which the reader can refer if interested in the rigorous mathematical formalism. To provide a brief summary, the signal measured by the instrument is a non-linear function of the surface reflectance due to the interaction of the radiation reflected by the surface with the atmosphere above. For this reason, a linear regression cannot be applied to infer the model parameters. Nevertheless, a cost function with the departure of the model from the measurements can still be computed and minimized, provided the availability of the derivatives (Jacobians) of the radiative transfer model with respect to the descriptive parameters. The Jacobians, generated without extra-computational cost from the linearization of the Doubling-Adding radiative transfer code in use at GISS [deHaan, 1987], are used in an iterative scheme based on an inversion and optimization procedure of the Gaussian-Newton kind [Rodgers, 2000] to search for a minimum of the cost function. The result is the decoupling of the surface and the atmospheric contributions of the total signal measured at instrument altitude, i.e., an automated atmospheric correction. Within this scheme, […]"

5) In the conclusions, the term " a novel analysis" is used. Is the novel method significantly different from the method developed by Roger (2000)? At several places, the word "novel" is used, which should be justified.

The novel character of this study was explained at line 5, page 3063:
"With the exception of O12, the visible and SWIR behavior of the polarized reflectance of snow has not been previously published".
We assume the reviewer refers to the classic textbook by Rodgers (2000) on inverse methods for remote sensing applications. However, no specific (real) data are used in this book, and snow surfaces are not addressed.

6) Please define the "roughness parameter" used in Figure 2 in a quantitative manner (e.g., by using an equation). Because the ray-tracing code developed by Macke et al. (1996) is used, the effect of surface roughness is approximately simulated by randomly titling a particle facet for every incident ray impinging on the facet. This is a statistical approach. The "roughness parameter" for uniformly tilting the facet and that for tilting the facet based on Gaussian distribution are different. Thus, without a clear definition of the "roughness parameter", this quantity has little practical value for downstream applications. Furthermore, when the facet is substantially tilted, the shadowing effect and the effect associated with rays' re-entries into the particle are not considered. Thus, a large "roughness parameter" is unphysical and meaningless.

We agree and regret that the definition of the roughness parameter was left out the first version of the paper. Also, the reviewer is correct that roughness values of up to 1 are unphysical. For this reason the roughness parameter was limited to 0.7 as

described by van Diedenhoven et al. 2012. The following was added to the revised version of the manuscript:
"The microscale surface roughness is statistically accounted for by tilting, for each interaction with a ray, the normal to the crystal surface by an angle randomly selected in the $\delta \cdot [0^\circ, 90^\circ]$ interval, where δ is referred to as the roughness parameter. In our case, δ is limited to 0.7 (i.e., a maximum tilt angle for the facet of 63°) because for higher values the probability of unphysical scattering events strongly increases, resulting in progressively larger loss of accuracy of the GO calculations of a given number of rays. Neshyba et al. (2013) have shown that various other definitions and parameterizations of crystal surface roughness lead to similar results. Yang et al. (2008) found that such approaches are efficient, yet accurate treatments of microscale roughness. Furthermore, the effects of microscale surface roughness and macroscale crystal distortion were shown to be largely equivalent by Liu et al. (2014)."

7) Page 3060, "Fresnel kernel…for vegetated surfaces…": But the indices of air and ice are used (the line below Eq. 3). Furthermore, Fresnel formula is for the reflection and refraction at the interface of two continuous media. However, snow is a densely packed medium. Here (Eq. 3), the application of Fresnel formula needs to be justified. Wonder how much error will be produced if the effective medium theory (e.g., the Maxwell-Garnett mixing rule) is used. Furthermore, polarization state is not considered in Eq. (3). It is confusing how to apply Eq. (3) to the polarized radiative transfer code (De Haan et al. 1987) that fully considers the polarization state of radiation field.

This approach is a standard for polarization instruments like POLDER or RSP (note that gravel-like soils or vegetation canopies are not continuous media either). We have inserted a reference to Waquet et al. ,2009, that specifically addresses the formalism for RSP aerosol retrievals over land.
Regarding Eq. 3, the expression does consider properly the polarization field since Fp is the fractional polarized reflectance, i.e., the fraction of the total incident intensity that gets polarized upon reflection. Exhaustive explanations of the use of this equation can be found in Ottaviani et al. 2012 and references therein:
"Specular reflection is also the basic mechanism governing the reflection properties of most land surfaces, a fact that has been attributed to the smooth wax coating the leaves and to the mineral facets of bare soils [28]. In a reflection event, the Fresnel formulae predict that the component of light perpendicular to the plane of reflection always exhibits higher reflectivity than does the parallel component, in a variable amount that depends on the angle of incidence. For this reason, a specular reflector always polarizes light in a direction perpendicular to the plane of reflection, with the extreme case of 100% of polarization introduced at Brewster angle."
We also modified the line after Eq. 3 with:
"where <u>in our case</u> n1 and n2 are the indices of refraction of pure air and ice".

REFERENCES:

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Yang, P., L. Bi, B. A. Baum, K.-N. Liou, G. W. Kattawar, M. I. Mishchenko, and B. Cole, 2013: Spectrally Consistent Scattering, Absorption, and Polarization Properties of Atmospheric Ice Crystals at Wavelengths from 0.2 to 100 µm. J. Atmos. Sci. , 70 (1), 330–347.

Dear Editor,

We thank you and the reviewers for your keen eye that allows us to improve this manuscript. The comments received by the two anonymous referees have been addressed and posted as individual replies. Moreover, we would like to include other minor corrections inspired by our desire of making the manuscript more readable. These latter adjustments DO NOT insert sentences, paragraphs or modify concepts, but only concern occasional choices of a better word or shifted the position of a paragraph to give a better flow. In a couple of instances, we removed a redundant sentence. All proposed changes are highlighted in red in the attached pdf. Line and page numbers below refer to the manuscript published on the Discussions.

Faithfully,
M. Ottaviani, B. van Diedenhoven, B. Cairns

Proposed changes:

Page 3059, line 2:
“from” substituted with “as reported by”

Page 3059, line 8:
“reports” substituted with “recorded”

Page 3060, line 12:
“Shifting the attention to” substituted with “For”

Page 3060, line 14:
Sentence ” In these retrievals, the fit is sought to the RSP measurements by using a database of ice crystal properties to implement the radiative transfer within the snow layer.” deleted because redundant.

Page 3061, line 5:
Corrected “with simulated values” with “a look-up table of values simulated”

Page 3061, line 7:
Eliminated because incorrect “within the top of the snowpack”

Page 3061, line 8:

Paragraph “Our database, initially created to be of use for the retrieval of ice clouds properties, contains 765 different combinations of aspect ratios and roughness parameters and was computationally assembled by running Monte Carlo simulations based on geometric optics [Macke96a].”
was moved to Page 3060, line 22. (Immediately after, we added the content specified in the reply to reviewer #2, point 6)).

Page 3061, line 13:
Eliminated “instead”

Page 3061, line 16:
Substitute “The single scattering albedo at a given wavelength” with “,which”

Page 3061, line 25:
Substituted “their volume over the crystal surface area” with “the crystal volume over its surface area,”

Page 3061, line 26:
Modified paragraph: “Here, we estimate the effective diameter of snow for a given scene by matching the measured reflectance with a simulated value assuming an ice crystal model with an asymmetry parameter consistent with the asymmetry parameter retrieved for that scene using the method described above.”
With paragraph:
“The effective diameter of snow for a given scene is estimated by matching the measured reflectance with an ice crystal model whose asymmetry parameter is consistent with that retrieved for that scene using the method described above.”

Page 3062, line 17:
This paragraph moved close to the end of the Introduction after line 18 at Page 3057:
“There certainly is debate on the applicability of the radiative transfer theory to a densely packed medium as snow. In any case, the formalism is recognized to model the total reflectance with sufficient accuracy for reasons likely associated with the large number of scattering events taking place within the snowpack. Based on this assumption, the method is expected to perform even better for the polarization component because the polarimetric signatures of a medium are known to originate from its top layer [vanDiedenhoven13]: deeper into the medium (i.e., past the first units of optical depth) multiple scattering randomizes polarization.”

Page 3062, line 2:
Eliminated “doubling adding”

Page 3062, line 6:
Substituted sentence: “In the analysis, it should be remembered” with “Another important aspect to consider is”

Page 3062, line 12:
Substituted “scenes” with “regions”

Page 3062, line 27:
Substituted commas with parentheses around sentence “corresponding to a spatial resolution of about 225 m”

Page 3062, line 26:
Paragaph:
“The analysis for each scene (different columns in the figure) was performed over a single RSP pixel, corresponding to a spatial resolution of about 225 m, since averaging over a few adjacent aggregated scans did not show appreciable scan-to-scan variability, revealing more or less uniform snow conditions within the instrument instantaneous field of view. The upper panels […]”
Adjusted to:
“For each of the three scenes (different columns in the figure) the analysis was performed over a single RSP pixel, corresponding to a spatial resolution of about 225 m. Indeed, averaging over a few adjacent aggregated scans did not show appreciable scan-to-scan variability, revealing more or less uniform snow conditions on a scale larger than the instrument instantaneous field of view. Real-time imagery from the high-resolution camera onboard the ER-2, overlaid to Google Earth, is included for context. The second and third rows of panels […]”

Page 3063, line 14:
Modified paragraph:
“Nevertheless, it should be remembered that a layer of a few millimeters is sufficient to fulfill the semi-infinite approximation at the long wavelengths used for the retrieval of grain size. Conversely, the SWIR channels at 1594 and 2264 nm are very dark as expected by the strong absorption of ice at these wavelengths.”
With:
“Nevertheless, a layer of a few millimeters is sufficient to fulfill the semi-infinite approximation at the longer wavelengths used for the retrieval of grain size: the RSP SWIR channels at 1594 and 2264 nm are very dark because of the strong absorption of ice at these wavelengths.”

Page 3064, line 24:
Eliminated: “conveniently”

Page 3065, line 9:
Substituted “selected” with “different”

Page 3066, line 4:
Inserted reference: “[Macke et al., 1996]”

Manuscript prepared for The Cryosphere Discuss.
with version 2014/09/16 7.15 Copernicus papers of the LaTeX class copernicus.cls.
Date: 3 September 2015

Photopolarimetric retrievals of snow properties

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Abstract

Polarimetric observations of snow surfaces, obtained in the 410–2264 nm range with the Research Scanning Polarimeter onboard the NASA ER-2 high-altitude aircraft, are analyzed and presented. These novel measurements are of interest to the remote sensing community because the overwhelming brightness of snow plagues aerosol and cloud retrievals based on air- and space-borne total reflection measurements. The spectral signatures of the polarized reflectance of snow are therefore worthwhile investigating in order to provide guidance for the adaptation of algorithms currently employed for the retrieval of aerosol properties over soil and vegetated surfaces. At the same time, the increased information content of polarimetric measurements allows for a meaningful characterization of the snow medium. In our case, the grains are modeled as hexagonal prisms of variable aspect ratios and microscale roughness, yielding retrievals of the grains' scattering asymmetry parameter, shape and size. The results agree with our previous findings based on a more limited dataset, with the majority of retrievals leading to moderately rough crystals of extreme aspect ratios, for each scene corresponding to a single value of the asymmetry parameter.

1 Introduction

The development of accurate techniques for the retrieval of climatologically relevant parameters in snow-covered regions is of obvious importance for the success of climate models predictions (Comiso, 2006; Zwally and Giovinetto, 2011; Zatko et al., 2013). For instance, the retrieval of grain size and surface temperature leads to information that can be used to map the snow melting state, valuable to understand the mass balance of the ice sheets (Stamnes et al., 2007; Lyapustin et al., 2009). Passive optical sensors are employed in this regard to evince the optical and microphysical properties of snow grains from measurements of snow reflectance, and advanced algorithms have been applied to data collected by the MODerate resolution Imaging Spectroradiometer (MODIS) and sensors with similar capabilities (Hori et al., 2007; Aoki et al., 2007; Jin et al., 2008; Stamnes et al., 2011). However, the limited information content of such measurements translates into uniqueness problems during the retrieval process, with the result that operational snow products are still limited to snow covered area and albedo (with the exception of the recent addition to MODIS of the dust radiative forcing product as described in Painter et al., 2012). Polarimetric remote sensing (Diner et al., 2007; Cairns et al., 2009; Dubovik et al., 2011; Hasekamp et al., 2011; Chowdhary et al., 2012; Ottaviani et al., 2012a; Knobelspiesse et al., 2012) adds to the information contained in MODIS-type observations because it can provide information on the ice grain shape (van Diedenhoven et al., 2012; Ottaviani et al., 2012b) and an accurate characterization of the optical and microphysical properties of aerosols present in the scene including possible impurities embedded in the snowpack. The benefits of passive polarimetric observations originate from both their extreme sensitivity to particle microphysics and the specifics of surface polarized reflectance. For conventional land types (soil, vegetation), the latter can be effectively parameterized as a scaled Fresnel reflection function with negligible spectral dependence. As a consequence, the separation of the signal into its surface and atmospheric contributions (i.e., the atmospheric correction procedure) is achieved with improved accuracy.

There certainly is debate on the applicability of the radiative transfer theory to a densely packed medium as snow. In any case, the formalism is recognized to model the total reflectance with sufficient accuracy for reasons likely associated with the large number of scattering events taking place within the snowpack. Based on this assumption, the method is expected to perform even better for the polarization component because the polarimetric signatures of a medium are known to originate from its top layer (van Diedenhoven et al., 2013): deeper into the medium (i.e., past the first units of optical depth) multiple scattering randomizes polarization.

The NASA GISS Research Scanning Polarimeter (RSP, Cairns et al., 1999), born as an aerosol research instrument, collects a target's total and polarized reflectance with high accuracy in 9 bands between 410 and 2264 nm and at 152 viewing angles per scene. A recent deployment led to the first published study of the polarimetric signatures of snow reflectance from airborne observations (Ottaviani et al. (2012b), hereafter referred to as O12). In that case, the measurements were acquired over a topologically complex terrain in the Yosemite National Park region and processed with an automated, iterative atmospheric correction scheme purposely created to analyze the spectral dependence of the polarized reflectance. A preliminary retrieval of crystal microphysical and optical properties was also tested. The purpose of this new work is to apply the same atmospheric correction procedure and to extend the surface properties retrieval scheme to a more recent dataset of improved quality, in terms of the flatness of the surveyed terrain.

In the next section we describe the data collection, and in Sect. 3 the processing scheme. In Sect. 4 we discuss the results obtained from the analysis. The conclusions are found in Sect. 5.

2 Data collection

The data analyzed here were collected onboard the high-altitude ER-2 aircraft during the POlarimeter Definition EXperiment (PODEX) mission, a NASA effort to ultimately test and compare the performance of different polarimeters, as part of the Decadal Survey activities and in preparation of the Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys (SEAC4RS) campaign. Compared to more traditional aircraft such as the King Air B200 used in O12, the ER-2 offers the advantages of a perspective more similar to that of a satellite. For example, interference caused by cirrus clouds is readily assessed using the RSP 1880 nm channel, which is usually very dark because of the strong absorption by tropospheric water vapor that masks the surface, and is therefore very sensitive to high-altitude clouds. There is in fact interest in exploiting this wavelength as a cirrus screener in a broader context, since cold places tend to have dry atmospheres and the reflectance of snow at 1880 nm is much less than at, say, 1380 nm (the effective strength of absorption by ice at 1880 nm is twice that exhibited at 1380 nm). Also, RSP operations on the ER-2 benefit from the stable attitude intrinsic to stratospheric flights, which enhances data quality since the RSP scans along the flight track (approximately 50° on either side of nadir) to assemble the multiangle view of a target's reflectance from subsequent scans.

About a dozen snow-covered targets were selected for the 6.8 h flight over Colorado and the Sierra Nevada range in California on 15 March 2012. Well-formed snowpacks with little to no interference from vegetation and flatness of terrain were the main priorities. Three scenes were chosen for this analysis. The Grand Mesa plateau (39°08′ N, 108°12′ W, ∼ 3000 m a.s.l.) in Western Colorado exhibits remarkable flatness and a consistent snowpack with a depth of greater than one meter as reported by nearly simultaneous in-situ surveys (Mesa Lakes SNOTEL site managed by the Natural Resources and Conservation Service of the US Department of Agriculture, and M. Skiles, personal communication, 2013). Lake Granby (40°10′ N, 105°53′ W, ∼ 2500 m a.s.l.), the third largest body of water in Colorado and second largest reservoir, was frozen at the time of the overpass and covered with a thin layer of aged, likely metamorphosed snow (the SNOTEL site at Stillwater Creek recorded a snow depth of ∼ 0.5 m). The scene denoted by Derby Peak (39°59′ N, 107°10′ W, ∼ 3500 m a.s.l.) is another high-altitude rather flat region (in fact belonging to the Flat Tops Wilderness Area). The closest SNOTEL site at Trapper Lake, 2950 m a.s.l., reports a snow depth of 0.7 m.

3 Methodology

The method employed for the atmospheric correction procedure is explained in detail in O12, to which the reader can refer if interested in the rigorous mathematical formalism. To provide a brief summary, the signal measured by the instrument is a non-linear function of the surface reflectance due to the interaction of the radiation reflected by the surface with the atmosphere above. For this reason, a linear regression cannot be applied to infer the model parameters. Nevertheless, a cost function with the departure of the model from the measurements can still be computed and minimized, provided the availability of the derivatives (Jacobians) of the radiative transfer model with respect to the descriptive parameters. The Jacobians, generated without extra-computational cost from the linearization of the Doubling-Adding radiative transfer code in use at GISS (De Haan et al., 1987), are used in an iterative scheme based on an inversion and optimization procedure of the Gaussian-Newton kind (Rodgers, 2000) to search for a minimum of the cost function. The result is the decoupling of the surface and the atmospheric contributions of the total signal measured at instrument altitude, i.e., an automated atmospheric correction. Within this scheme, the surface total reflectance is expressed as the weighted sum of three kernels as in the RossThick – LiSparse form (Wanner et al., 1995; Lucht et al., 2000):

$$R(\Theta) = f_{\mathrm{iso}} + f_{\mathrm{vol}} K_{\mathrm{vol}}(\Theta) + f_{\mathrm{geo}} K_{\mathrm{geo}}(\Theta) \tag{1}$$

where Θ is the scattering angle. The three terms on the right-hand side describe different scattering mechanisms: a Lambertian component for isotropic reflection, a volumetric term K_{vol} for scattering from small structures and a geometric term K_{geo} for a macroscopic shadowing from large objects. Although this model was created for reflection from surfaces other than snow, its mathematical form adapts without problems to snowpacks, with the isotropic kernel systematically assuming the largest weight because of the dominance of multiple scattering in the reflection of light from snow.

As far as the polarized reflectance is concerned, we instead employ a scaled Fresnel kernel elsewhere used for vegetated surfaces (Nadal and Bréon, 1999; Waquet et al., 2009):

$$R_{\mathrm{p}} = \frac{F_{\mathrm{p}}(\theta_{\mathrm{i}})}{4[\cos(\theta_s) + \cos(\theta_v)]} \tag{2}$$

with the fractional polarized reflectance $F_{\mathrm{p}}(\theta_{\mathrm{i}})$ given by (Born and Wolf, 1999):

$$F_{\mathrm{p}}(\theta_{\mathrm{i}}) = \frac{1}{2}\left[\left(\frac{n_1 \cos\theta_{\mathrm{i}} - n_2 \cos\theta_t}{n_1 \cos\theta_{\mathrm{i}} + n_2 \cos\theta_t}\right)^2 - \left(\frac{n_2 \cos\theta_{\mathrm{i}} - n_1 \cos\theta_t}{n_2 \cos\theta_{\mathrm{i}} + n_1 \cos\theta_t}\right)^2\right] \tag{3}$$

where in our case n_1 and n_2 are the indices of refraction of pure air and ice, and the angle of refraction θ_t is connected to the angle of incidence θ_{i} by Snell's law.

For the retrieval of crystal habit, the polarized reflectance at 864 nm is used because of the very weak ice absorption at this wavelength and the relatively weak Rayleigh scattering contribution. ~~In these retrievals, the fit is sought to the RSP measurements by using a database of ice crystal properties to implement the radiative transfer within the snow layer.~~ Limited by the lack of constraints on the correct optical properties, very few studies have departed from the common practice of assuming spherical shapes for the snow grains, an approximation which can negatively impact the quality of the albedo products (Tedesco and Kokhanovsky, 2007; Aoki et al., 2000). In our case, the description of the snowpack is refined by treating it as a compact, optically semi-infinite medium composed of ice crystals modeled as hexagonal prisms with variable aspect ratios and microscale facet roughness.

It should be noted that for the specific task of remote sensing of aerosols over snow, a model capable of accurately reproducing the contribution of the surface to the total signal should be considered successful regardless of its capability to mimic the true shape of the crystals. Räisänen et al. (2015) recently attempted to fit measured phase functions of blowing snow by using phase functions of several complex habits provided by Yang et al. (2013) in addition to phase functions of other habits. However, the selection of habits in their study remained limited and to fit the data a rather arbitrary mixture of droxtals, aggregates of plates and Koch fractals was needed, leading them to conclude that this mixture "most probably does not represent properly the actual distribution of snow grain shapes in blowing snow (or snow on ground)". Our approach is based on the recognition that hexagonal plates and columns can be effectively used as radiative proxies for more complex crystal habits (Fu, 2007; Um and McFarquhar, 2007, 2009; Baran, 2009; van Diedenhoven et al., 2012; Ottaviani et al., 2012a). As demonstrated by van Diedenhoven et al. (2012), matching measured polarized reflectances with a look-up table of values simulated by adjusting the aspect ratios and roughness parameters of simple hexagonal particles yields an estimate of the asymmetry parameter of more complex ice crystals ~~within the top of the snowpack~~. Our database, initially created to be of use for the retrieval of ice clouds properties, contains 765 different combinations of aspect ratios and roughness parameters and was computationally assembled by running Monte Carlo simulations based on geometric optics (Macke et al., 1996), the performance of which was evaluated by van Diedenhoven et al. (2012). The retrieved aspect ratios are interpreted as the mean of the aspect ratios of the components of the complex crystals.

The microscale surface roughness is statistically accounted for by tilting, for each interaction with a ray, the normal to the crystal surface by an angle randomly selected in the $\delta \cdot [0°, 90°]$ interval, where δ is referred to as the roughness parameter. In our case, δ is limited to 0.7 (i.e., a maximum tilt angle for the facet of $63°$) because for higher values the probability of unphysical scattering events strongly increases, resulting in progressively larger loss of accuracy of the GO calculations of a given number of rays. Neshyba et al. (2013) have shown that various other definitions and parameterizations of crystal surface roughness lead to similar results. Yang et al. (2008) found that such approaches are efficient, yet accurate treatments of microscale roughness. Furthermore, the effects of microscale surface roughness and macroscale crystal distortion were shown to be largely equivalent by Liu et al. (2014).

The retrieval of grain size is instead based on the total reflectance at selected ShortWave InfraRed (SWIR) bands where ice absorption is high. The total reflectance of an optically semi-infinite snow layer at 2264 and 1594 nm is effectively determined by the asymmetry parameter and the single scattering albedo at the respective wavelength, which in turn is mainly determined by the effective diameter of the ice crystals. The grain diameter is not unequivocally defined in the literature, which is understandable since the definition of snow grain itself is often ambiguous. There is a consensus for expressing grain effective diameter as proportional to the ratio of crystal volume to projected area, but the value of the multiplier can vary according to the specific choice of the author (Kokhanovsky et al., 2011; Kokhanovsky and Zege, 2004; Aoki et al., 2000). In line with several recent publications (see for example Zege et al., 2011; Jin et al., 2008), we define it as $3/2$ times the ratio of the crystal volume over its surface area, as outlined in the Appendix, which includes the details of the relationship to geometric size. The effective diameter of snow for a given scene is estimated by matching the measured reflectance with an ice crystal model whose asymmetry parameter is consistent with that retrieved for that scene using the method described above. To this end, various modified gamma size distributions were applied to yield varying effective diameters and the ~~doubling-adding~~ radiative transfer code was used to simulate the corresponding 1594 and 2264 nm reflectances (van Diedenhoven et al., 2014). For conditions equivalent to those found in snowpacks, Bi et al. (2014) showed that the errors in retrieved effective radius attributable to the use of the conventional geometric optics approach are below 5 %. Another important aspect to consider is that the 1594 and 2264 nm channels experience different penetration depths, with the former weighted more towards the top layer while the latter probes deeper into the medium: as a consequence, the retrieved sizes contain information on the vertical structure of the snowpack (Wang et al., 2009; Li et al., 2001; Warren, 1982).

As far as the atmospheric component is concerned, the high elevation of these alpine regions allowed us to assume negligible contributions from aerosols, so that in the radiative transfer code a standard Rayleigh atmosphere was used with a surface pressure extrapolated at the indicated altitude. Cirrus-free conditions were guaranteed from the screening procedure described earlier. The SWIR channels were corrected for the minimal interference caused by absorption from a standard amount of trace gases.

4 Results and discussion

The core of our findings is condensed in Fig. 1. For each of the three scenes (different columns in the figure) the analysis was performed over a single RSP pixel, corresponding to a spatial resolution of about 225 m. Indeed, averaging over a few adjacent aggregated scans did not show appreciable scan-to-scan variability, revealing more or less uniform snow conditions on a scale larger than the instrument instantaneous field of view. Real-time imagery from the high-resolution camera onboard the ER-2, overlaid to Google Earth, is included for context. The second and third rows of panels show the results of the iterative correction scheme applied to the relevant RSP channels. With the exception of O12, the visible and SWIR behavior of the polarized reflectance of snow has not been previously published.

The total reflectance exhibits the familiar high spectral albedo in the visible, although with some expected scene-to-scene variability. Lake Granby in particular shows lower total reflectance than the other two scenes; in situ simultaneous surveys from the personnel at the US Forest Service in Arapaho National Forest reported a snow depth on the order of 5–8 cm. These values are close to the limit of thickness required to visually mask the underlying surface, leaving the possibility that the lake ice underneath the snow cover is darkening the reflectance. Nevertheless, a layer of a few millimeters is sufficient to fulfill the semi-infinite approximation at the longer wavelengths used for the retrieval of grain size: the RSP SWIR channels at 1594 and 2264 nm are very dark because of the strong absorption of ice at these wavelengths.

The polarized reflectance as a function of the scattering angle is very similar among the three scenes. Note that in the case of Derby Peak the flight track was oriented at about 45° with respect to the principal plane (i.e. the plane defined by the solar azimuth and the normal to the surface), leading to a smaller range of scattering angles collected by the RSP. It has already been observed in O12 as the land model used for the polarized reflectance converges to zero toward backscatter (scattering angle $> 160°$), and in this region agreement with the data is not to be expected. It is useful to quantify the spectral spread of the channels by examining the differences from the reference 2264 nm channel. The signal in this band is in fact a proxy for the surface contribution, since the Rayleigh (and fine-mode aerosol) contribution becomes more and more negligible as the observation windows shifts to the SWIR. If the spectral differences are small, that same signal can then be subtracted from the shorter RSP wavelengths when aerosols retrievals are attempted. The residuals with respect to the 2264 nm polarized reflectance are found to be within 0.005, which as in O12 is larger than conventional land surfaces but still very small. The polarized reflectance is small too in absolute value.

Shifting the attention to the search of a snow model, the plots at the bottom contour the Root Mean Square Error (RMSE) of the data fit to each combination of aspect ratio and roughness parameter in the database. Multiple combinations led to a satisfactory fit to each of the three polarized reflectance observations, so we considered as optimal all habits with an RMSE falling below a small threshold value (4.5×10^{-7}). These minima, marked with red circles, therefore correspond to those crystal habits that when used to model the snowpack at the bottom of the simulated atmosphere yield the best fits to the data. The analysis shows that the polarized reflectances are consistent with particles that have components that are like thin plates or like thin columns, a fact already observed in O12. Interestingly, the butterfly-like topology of the RMSE was recognized to closely resemble that obtained for the asymmetry parameter g plotted vs. the same coordinates (Fig. 2). In each scene, the optimal crystal habits are associated with very similar values of the asymmetry parameter (0.84 for Lake Granby, 0.876 for Derby Peak and 0.90 for Grand Mesa). This result is understood by considering that the asymmetry parameter is the main descriptor for the scattering properties. As demonstrated by van Diedenhoven et al. (2012) using a large variety of complex ice crystal shapes, all the combinations of aspect ratio and roughness parameter fitting a polarized reflectance measurement are ultimately characterized by similar values of g. Consequently, they will also yield similar particles size retrievals.

Figure 3 shows the phase function and the degree of linear polarization for each scene, obtained by averaging over all the phase matrices associated with the retrieved minima. The lack of halo peaks in the $20^\circ - 40^\circ$ range of the phase function characteristic of pristine crystals, and the general smooth behavior (except from the strong forward peak) is consistent with the moderate-to-high roughness parameters determined in the analysis.

All retrieved parameters are ~~conveniently~~ reported for comparison in Table 1, together with the results of the size retrievals. Using the simple approach outlined in the previous section, we obtained effective diameters equal to 152, 182 and 144 µm for the Grand Mesa, Lake Granby and Derby Peak scene, respectively, when using the RSP band at 2264 nm. Using instead the 1594 nm channel, diameters typically 30 µm smaller are obtained for each scene, which can be explained by the different penetration depths of the two channels, indicating crystal size increasing with depth as expected (Hori et al., 2007; Li et al., 2001; Aoki et al., 2000; Warren, 1982). These values, at the lower end of common retrieval ranges, are normally associated with fresh snow conditions as found in studies based on other remote sensors in alpine regions (Negi and Kokhanovsky, 2011; Painter et al., 2009; Dozier and Painter, 2004; Nolin and Dozier, 2000) and polar plateaus (Lyapustin et al., 2009; Hori et al., 2007). However, a direct comparison is challenged by differences in the definition of grain size, assumptions on grain sphericity and different penetration depths achieved by the use of different instrument channels. The larger grain sizes obtained for the Lake Granby scene were attributed to the shallow aged snow over the lake, since metamorphized snow is recognized to be composed of larger grains (Aoki et al., 2000; Warren, 1982).

5 Conclusions

We have presented the extension of a novel analysis described by Ottaviani et al. (2012b) to a dataset acquired with the high-accuracy RSP airborne instrument overflying high-altitude snow fields. The data were processed within an automated retrieval scheme capable of isolating the surface contribution. The spectral dependence of the retrieved polarized surface reflectance is slightly larger than for soil or vegetated surfaces, but nonetheless small relative to typical aerosol contributions (cfr. Fig. 6 in O12). This fact has important implications for the construction of advanced algorithms which aim at the retrieval of the microphysical properties of aerosols layers located over ice and snow fields.

Furthermore, we applied a retrieval procedure which is demonstrated to yield snow microphysical parameters of primary climatological interest. We retrieve snowpacks behaving as a collection of grains of extreme geometries (thin plates and/or long columns) and moderate to high microscale roughness. These results reinforce those of our previous study based on a limited dataset acquired over very rugged terrain. For each scene, the best fits are obtained for a set of crystal habits characterized by very similar values of the asymmetry parameter. Size retrievals were also tested, leading grain effective diameters in the 140–180 µm range.

Appendix: Size descriptors for hexagonal prisms

The results of Macke's Geometric Optics code (Macke et al., 1996) were tabulated with the choice of the radius of the sphere with equal surface area, r_{sph}, as a size descriptor. This parameter is linked to the geometric size of hexagonal prisms and to the grain effective diameter by the following relations:

$$A_{\mathrm{hex}} = 4\,\pi\,r_{\mathrm{sph}}^2 \quad \text{(Surface area of sphere and hexagonal prism)} \tag{A1}$$

$$A_{\mathrm{p}} = A_{\mathrm{hex}}/4 = \pi\,r_{\mathrm{sph}}^2 \quad \text{(Projected surface area of hexagonal prism)} \tag{A2}$$

$$r_{\mathrm{hex}} = \sqrt{\frac{4\,A_{\mathrm{p}}}{3\,\sqrt{3} + 12\,\alpha}} \quad \text{(Radius or side length of hexagonal prism)} \tag{A3}$$

$$V = 3\,\sqrt{3}\,\alpha\,r_{\mathrm{hex}}^3 \quad \text{(Volume of hexagonal prism)} \tag{A4}$$

$$d_{\mathrm{eff}} = \frac{3}{2}\frac{V}{A_{\mathrm{p}}} = \frac{6\sqrt{3}\alpha}{\sqrt{3}+4\alpha} r_{\mathrm{hex}} \quad \text{(Effective diameter)} \tag{A5}$$

where α is the aspect ratio, defined as the ratio of the cross section width of the prism to its length. The last expression is valid for a single particle of any solid shape. In case of a polydisperse collection of particles, the effective diameter is obtained through integration over a size distribution:

$$D_{\mathrm{eff}} = \frac{3}{2}\frac{\int_0^\infty V(D)\,N(D)\,\mathrm{d}D}{\int_0^\infty A_{\mathrm{p}}(D)\,N(D)\,\mathrm{d}D} \tag{A6}$$

with N denoting the number density of crystals with maximum dimension D, which can be defined as $2\,r_{\mathrm{hex}}$ for plates and $2\,\alpha\,r_{\mathrm{hex}}$ for columns.

Acknowledgements. This work was possible through the dedication of the ER-2 pilots Tom Ryan, Dean Neeley and Stu Broce. Their exceptional skills and proactive attitude towards the goals of the mission were critical to success. The assistance of personnel on the ground was invaluable, especially that of Hans Moosmüller from the Desert Research Institute, Davide Sartoni from Mistras-Ropeworks, Rick Brinkam from Water Services at the City of Grand Junction, Sam Williams and Aldin

Strautins from NOAA, McKenzie Skiles from NASA JPL, Holly King from the Trappers Lake Lodge, and Dan Matthews and John Saye from the US Forest Service in Arapah1o National Forest. We also thank Rose Dominguez and Dennis Gearhart from NASA GSFC for providing access to the ER-2 DCS camera imagery, and the reviewers for improving the overall quality of the manuscript. The RSP data used for this analysis are publicly available on the GISS server (http://data.giss.nasa.gov/pub/rsp/). The graphs were produced with IDL© supplemented by David Fanning's Coyote Graphics free library of routines. Partial support from the Radiation Sciences Program managed by Hal Maring is gratefully acknowledged.

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Table 1. List of ice crystals' parameters retrieved for the three analyzed scenes. The value in parentheses indicates the RSP band used in the retrieval. The effective diameter can be obtained using either the 2264 or the 1594 nm channel (see text), and a crystal habit characterized by the asymmetry parameter retrieved for the corresponding scene.

Retrieved Parameter	Grand Mesa	Lake Granby	Derby Peak
Asymmetry parameter (864 nm)	0.90	0.84	0.876
Aspect ratio (864 nm)	< 0.08	< 0.05	< 0.2, >10
Roughness parameter (864 nm)	0.3–0.5	0.6–0.7	0.2–0.6
Effective diameter (2264 nm)	152 µm	182 µm	144 µm
Effective diameter (1594 nm)	122 µm	152 µm	114 µm

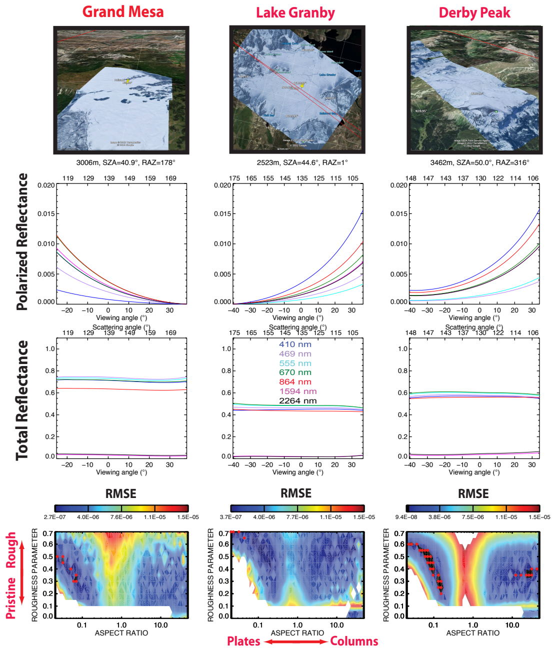

Figure 1. Atmospherically corrected polarized (*second row*) and total (*third row*) reflectance for three snow fields (*columns*) overflown in Colorado, USA. The first row shows real-time imagery from the high-resolution camera onboard the ER-2. The last row pertains to the search of the optimal ice grain model ~~for each scene~~: the contour plots map the RMSE of the fit to the polarized reflectance at 864 nm when simulating the snowpack with each crystal habit (i.e., each combination of aspect ratio and roughness parameter) in the database. The red circles locate the values of the RMSE falling under a predetermined threshold, and are taken to represent the retrieved (optimal) habits.

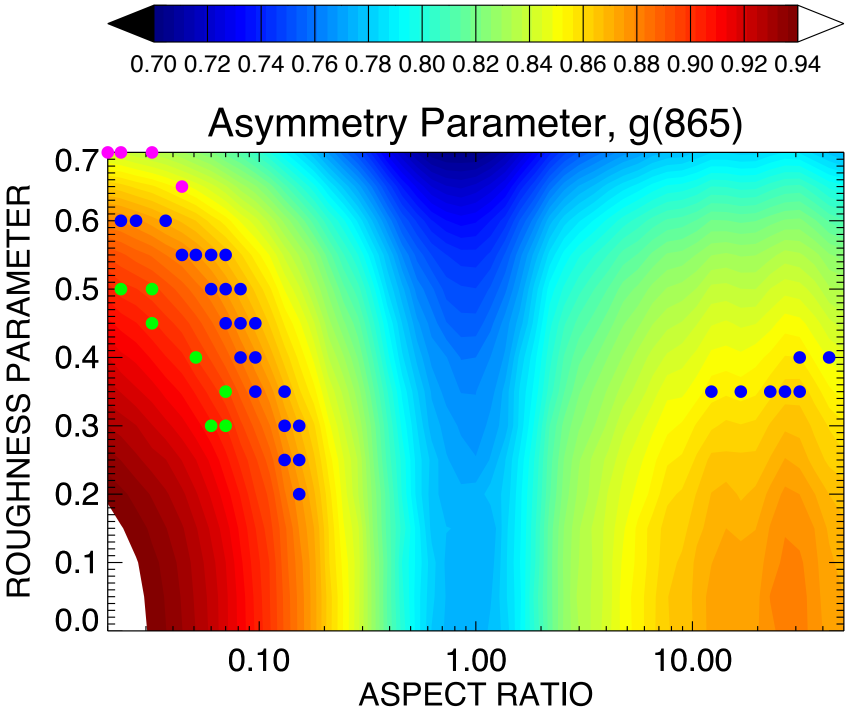

Figure 2. [WHITE DOTS MODIFIED TO GREEN] The "butterfly" pattern of the contour plot for the asymmetry parameter g as a function of aspect ratio and roughness parameter resembles that obtained for the RMSE plots in Fig. 1. The red circles in Fig. 1 (here in green for Grand Mesa, magenta for Lake Granby and blue for Derby Peak) that identify the retrieved optimal crystal habits are found for each scene clustered around a single value of g.

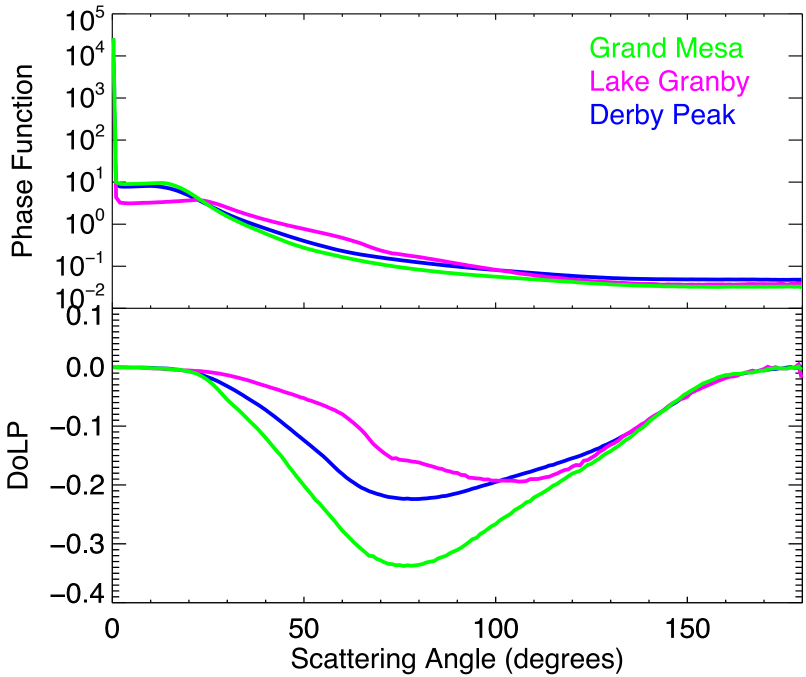

Figure 3. [NEW FIGURE] Phase functions (*upper panel*) and degree of linear polarization (*lower panel*, resulting from the average over the optimal habits retrieved for each scene. The color-coding is the same as in Fig. 2.