Review of “Influence of surface albedo heterogeneity on passive remote sensing of cirrus properties”

General comments:

This manuscript investigates the impact of heterogeneous surface conditions - predominantly vegetated, with some water and urban surface - on the retrieval of ice cloud optical thickness and crystal effective radius for, predominantly, optically thin ice clouds ($\tau<4$). These effects are investigated for two case studies of cirrus clouds, one homogeneous cloud scene and the second a heterogeneous cloud scene, where both cloud cases are located over the same/similar ground conditions. The retrieval of the cloud properties is performed in what is called the ‘standard’ approach, where cloud optical thickness and effective radius are derived from measurements of reflected cloud radiation at different spectral regions where the amount of scattered (giving predominantly optical thickness information) and absorbed radiation (providing droplet size information) from the cloud layer contribute differently dependent upon the wavelength dependence of the cloud optical properties. A statistical algorithm is developed to quantify the impacts of surface albedo on the cloud retrievals. In the statistical algorithm, multiple look-up tables of simulated reflected cloud radiation for unique surface albedo inputs using the ‘standard’ retrieval approach are used to derive a range of possible cloud optical thickness and droplet effective radii, where the results are frequency weighted by the distribution of the heterogeneous surface albedo. This frequency weighting forms the statistical algorithm.

The impact of surface albedo on cloud retrievals (whether ice or water) is of strong interest, particularly for optically thin clouds. It is known that these uncertainties can be large. By applying a weighted average/standard deviation of the surface impacts on the cloud retrievals, the full range of uncertainty due to surface conditions is masked or constrained. What the presented method provides is a metric for providing a “best-case scenario” of these uncertainties based on using the frequency distribution of the surface albedo conditions as a constraint for the retrieval errors. By design, this approach is dependent upon cloud type (cloud optical thickness and effective radius), cloud spatial scale (homogeneous, or heterogeneous distributions), surface type(s), and the distribution of the surface type(s) below the cloud. Therefore, as currently presented, this approach is valid only for case studies and cannot be generally applied, or results inferred, across a broad range of cloud and surface types.

Additionally, the paper investigates the impact of different ice crystal habits on reflected radiation for optically thin clouds and the impact of anistropic surface reflectance on the retrieved cloud properties.

I believe that this study is of interest, but the manuscript needs to be improved and strengthened. This could be achieved by strengthening the motivation for the work, by expanding on the physical basis of the concepts referred to in the work and thereby clarifying the interpretation of the results, correcting inconsistencies, errors, and spelling in the text, and improving the clarity of a number of figures. I recommend accepting the manuscript with however attention to the major comments and suggestions listed below.

References used in this review:

Twomey, S.; Cocks, T. Remote sensing of cloud parameters from spectral reflectance in the near-infrared. *Beitr. Phys. Atmos.* **1989**, 62, 172–179.

Nakajima, T.; King, M.D. Determination of the optical thickness and effective, particle radius of clouds from reflected solar radiation measurements: I. Theory. J. Atmos. Sci. 1990, 47, 1878–1893.

Liang, S.; Shuey, C.J.; Russ, A.L.; Fang, H.; Chen, M.; Walthall, C.L.; Daughtry, C.; Hunt, R., Jr. Narrowband to broadband conversions of land surface albedo: II. Validation. Remote Sens. Environ. 2002, 84, 25–41.

Schaaf, C.B.; Gao, F.; Strahler, A.H.; Lucht, W.; Li, X.; Tsang, T.; Strugnell, N.C.; Zhang, X.; Jin, Y.; Muller, J.-P.; et al. First operational BRDF, albedo nadir reflectance products from MODIS. Remote Sens. Environ. 2002, 83, 135–148.

Eichler, H., Ehrlich, A., Wendisch, M., Mioche, G., Gayet, J.-F., Wirth, M., Emde, C., and Minikin, A.: Influence of ice crystal shape on retrieval of cirrus optical thickness and effective radius: A case study, J. Geophys. Res., 114, D19203, doi:10.1029/2009JD012215, 2009. 3784, 3788.

Rolland, P., and K. N. Liou, Surface variability effects on the remote sensing of thin cirrus optical and microphysical properties, J. Geophys. Res., 106, D19, 2001, 22,965-22,977.

Major Comments:

1. This study offers two case-studies of the surface albedo heterogeneity on passive remote sensing of cirrus by application of a 'standard' retrieval method, interpreted according to a statistical approach. The statistical approach, in essence, roughly quantifies the degree of homogeneity in a heterogeneous surface scene. By this, I mean the standard deviation of the cloud properties used to quantify the impacts of the surface conditions on the cloud properties decrease from their maximum values (based on non-weighted values), for a specific case, dependent upon the distribution of the surface types in the case/scene. Only in the limiting case where the distribution of the surface type(s) below the cloud has equal emphasis/distribution amongst the surface types, will the weighted average/standard deviation be equal to the "true" (non-weighted) average/standard deviation that reflects the full range of impacts of surface albedo heterogeneity on the cloud properties. For all other cases of surface albedo distribution, the uncertainty will reduce based on the weighted averaging in the statistical approach. While some of these details are mentioned in the paper, it should be made more evident, and discussed earlier on in the presentation of the approach. Without such a distinction, a less informed reader may come away with the impression that the statistical method is a *new* retrieval, less subject to uncertainty from surface conditions. There is nothing new about the retrieval, just the manner in which it is applied across various look-up tables. I would argue that instances of 'statistical retrieval' be replaced by 'statistical algorithm' or 'statistical approach', etc. However, once these distinctions are more evident, the suggested approach is a valid method for

quantifying the impacts of surface on cloud retrievals in a limited, case-by-case approach dependent upon the caveats listed above.

2. There is no mention in your introduction of ice crystal habit(s), how/why different crystal habits would result in a different reflected radiance from cirrus, or the motivation for the pursuit of study in this area.
3. Conclusion section and interpretations throughout paper need to be adjusted with respect to #1. For example, "…for the retrieval of cirrus optical thickness the surface albedo heterogeneity is negligible", is not consistent with other published work [Eichler, Rolland]. Please revise/re-present the given the uncertainty in effective radius in this same regard.

Title: The title should better reflect the focus of the work presented. See #1. It also does not reflect your work with crystal habit.

Abstract:

line 7: The number of retrieval wavelengths ('bispectral') is not what makes the retrieval approach standard. What standard is referring to is the methodology for retrieving cloud properties from reflected cloud radiation. [*Twomey and Cocks*, 1989, for example]

Line 9: "For each albedo respectively lookup table," fix awkward phrasing.

Introduction:

Even retrievals of water cloud properties are complicated by spatial heterogeneity of clouds and surface albedo. The cirrus properties have the additional complexity of non-spherical crystal shape (and orientation of the ice particles which is not acknowledged in this work), therefore leading to the problem of how best to parameterize and model the scattering/extinction of non-spherical ice crystal.

Page 3785, line 2: Suggest rephrasing sentence, "Further, it is hard…" to lead with 'optically thin cirrus'. For example, "Further, for optically thin cirrus it is hard to distinguish between…" or something similar.

Page 3785, line 7: An accurate estimation of the surface albedo *and atmosphere* must both be included in retrieval algorithm. The importance of correct atmospheric correction is missing from the manuscript and should be included, not necessarily in introduction, but wherever it would best fit. It should also be described in expanded detail the approach implemented to do this correction.

Page 3785, line 8: Surface albedo not available in most cases? I would suggest reworking this sentence as you present a paper where you rely on a global satellite measurement database of surface albedo.

Page 3785, Line 10: Incorrect statement. For optically *thin* cirrus there is increased uncertainty due to surface type and distribution.

Page 3785, Line 13: the portion reflected by surface *and atmosphere* may dominate signal measured by satellite for thin cirrus conditions.

Page 3785, Line 22 – What microphysical properties were derived from your measurements of spectral radiance?

Page 3785, Line 29: Awkward sentence with topics better dealt with separately: a) difference in passive and active remote sensing, b) – vertically resolved measurements of backscatter ratio measurement not vertically resolved measurements of active measurements.

In general:

1. Better summarize the part played by MODIS albedo (derived from the MODIS BRDF product) in the statistical approach.

2. Emphasize your work is in the solar spectral range (define wavelength range).

<u>Measurements and surface albedo</u>:

Page 3786, line 17: What contributes to the measurement uncertainty? Radiometric variability? Systematic offset? What calibrations is the result based on?

Page 3786, line 22: What wavelength is HSRL lidar backscatter ratio at? Did you remove possibility of water cloud or mixed phase cloud based on the HSRL data? Please explicitly state this.

Page 3786, line 26: Regarding flight pattern, you chose case studies where a number (8) of flight legs cover nearly the same ground region. Do you have other cases where a wider spread in ground was covered? This would be interesting for expanding your results to broader, more general interpretations.

Page 3787 line 3: Awkward sentence and interpretation: How can cloudy and cloudless situations alternate with partly two separate cloud layers?

Page 3787, line 7 and Figure 4: It would be very helpful to see a full spectrum of reflected cloud radiation (for a cirrus cloud case you present). This would be in addition to the time series at two wavelengths (not at a single wavelength as you state in line 7). Please identify cloudy and cloud-free regions on plot. It seems that you have extracted data from a cloud scene with little variability in the cloud properties, or perhaps you have chosen a cloud scenes over a homogeneous water (dark) surface with little surface variability. Either way, I believe this time series does little to inform the reader of a more representative range in reflected radiance from cloud, nor to inform the reader of impacts of different surface albedo. Do you agree? Perhaps you could instead extract time series from a transition of water-to-land. Then, also indicate the surface type on the plot. Also, please explicitly state here that 650 and 1646 nm are the retrieval wavelengths you consider in your analysis.

Please provide more details of the HSRL measurements and the method by which an approximation of extinction based on back scatter ratio is obtained. It would be important to include the uncertainties in cloud optical thickness from the lidar methods (the Klett method can have uncertainties exceeding 20% for thin clouds (tau<2), which is a range in which you present results). This is importance as you base your conclusions on a best match to lidar, which may be faulty in itself. It's also important to note that the differences you report in retrieved cloud tau properties for the different habits vary by much less than the error in lidar-retrieved optical thickness (shown later in 1:1 plots).

Statistics of surface albedo from MODIS

The MODIS albedo is derived from the MODIS BRDF product for solar zenith angle and aerosol optical thickness conditions. What procedure was followed for obtaining the MODIS albedo for the atmospheric and sun angle conditions specific to the flight case(s)?

It would be very helpful to have a plot of spectral surface albedos for the surface types (agricultural, urban, forest, and water). This plot could come from the MODIS data used in your study. In this false-color imagery picture, I don't see urban surface conditions. What do you mean by spectral differences are caused by this (forest?) surface type also? Are you suggesting that the variation is surface albedo within forested surfaces exceeds the variation between water-ocean-vegetation? I may have misunderstood the implication of this sentence.

Please expand on how you assembled the frequency distribution of MODIS surface albedo. For example, are the 8 flight legs over nearly the same ground conditions included in the frequency distribution, or is the frequency distribution extracted from one of the eight flight legs.

Retrieval of cirrus properties from HALO-SR:

Page 3788, line 14: The sentence about statistics being derived with regard to surface albedo variability has been mentioned several times before.

Page 3788, line 14: The physical basis for the retrieval description is lacking in content, and therefore causes confusion as to how cloud properties can be derived from spectral reflected radiation. You are meaning non-absorbing and absorbing wavelengths of ice/water. Look up tables are created in combinations of optical properties (tau/reff). These are not microphysical properties, or perhaps I do not understand what combinations of microphysical properties you simulated.

Equations 1) and 2): Suggest defining optical thickness and effective radii before presenting the retrieval approach. It would be worth how the effective radius of a non-spherical ice crystal is defined depending upon approximated values such as the effective volume and effective projected area of a non-spherical ice particle. In addition, the volume and mean projected areas are values integrated over the particle size distributions, which is not identified in equation 2. What distribution was assumed?

Page 3789, line 6-14: Important details are missing from this brief description. These include the bulk optical properties from the ice cloud particles; how were these parameterized [Baum et al., 2007] and what measurements of index of refraction of ice were the parameterizations based on? It would be very helpful to see a plot of the parameterized spectral optical properties, such as asymmetry parameter (for the different crystal habits), single scattering albedo. Regarding the DISORT II solver, please include the number of terms in the scattering phase function that were used in the cloud scattering simulations (also include citation). Finally, as mentioned previously, atmospheric correction is a very important pre-step in this analysis with little discussion. What were the atmospheric aerosol properties (measured and assumed)? Were clear sky radiances modeled or based on near-by and cloud-free measurements?

Homogeneous surface albedo sensitivity

Reword title of section: Sensitivity of cloud properties to homogeneous surface conditions, or something similar. I also don't understand what is meant by a homogeneous surface albedo sensitivity, implying that the statistical approach would give different results for a heterogeneous surface where, in fact, the statistical approach is based on numerous look-up tables of assumptions of homogeneous surface conditions. Do you agree? I wonder if, instead, what you mean by homogeneous in this case is 'wavelength-independent'.

Page 3789, line 16: Corresponding result –> corresponding retrieval.

Page 3789, line 17: The reflected radiance results from scattering *and absorption* near cloud top.

Page 3789, line 22: The received radiance above cirrus –> The upwelling radiance measured above cirrus

Page 3789, line 25: "for the wavelength (646 nm) considered here"

Page 3790, line 2: Why a range in surface albedo of 0.025 to 0.1 only? This range does not encompass natural variability for the surface types encountered in this case study (water, vegetation, urban).

Cirrus properties from statistical retrieval:

Per #1, I would change occurrences of statistical 'retrieval' to statistical 'approach.' This would be a good place to expand on the justification for the statistical approach, including limiting conditions in order to better understand the results presented. Please take care in section to more accurately present comparisons and interpretations of the statistical approach (using standard retrieval) to those based on a non-statistical approach (also using standard retrieval).

Page 3792, line 5: The use of 2-D here in regards to the surface albedo frequency distribution can cause confusion, as the dimensions could be interpreted as spatial (a more typical interpretation of 2-D), and not spectral.

Please add description to second paragraph to help reader comprehension. From what I understand, you essentially have created a separate lut (specify resolution in tau, reff) for each combination of B1/B6 surface albedo. Then, you interpolate measured radiances with respect to each lut, to obtain tau,reff corresponding to each lut. The cloud retrievals were weighted with frequency of "corresponding albedo" -> here, are you meaning that the reff is weighted with B6 MODIS albedo frequency distribution and tau is weighted with the B1 frequency distribution?

In addition to points in #1, there is an implied physical distance scale to interpreting the weighted mean results. For example, one could analyze 5 km of flight track with 5 different surface types and get a large standard deviation in cloud properties. However, in a pseudo case with the "same cloud" but over much extended horizontal extent, say 100 km, but 95 km of that surface are equal to one of the initial surface types, the standard deviation in cloud properties due to albedo variations is much smaller due to the weighting. Therefore, the standard deviations do not measure the uncertainty of the retrieval with regard to surface albedo heterogeneity, but also to distance impacts. I think a non-weighted average gives the uncertainty of the retrieval. The statistical approach (not retrieval) gives the weighted average of the retrieval uncertainty, hence will differ according to surface type distribution, not just surface type as well as cloud type. This means that, for the *same* cloud over the *same* surface types, there would be different uncertainty values dependent upon the distribution of the surface.

Systematic and microphysical uncertainties:

Shape Effects:

Please provide the motivation and justification for investigating the differences in crystal shape/habit on reflected/scattered solar radiation. Provide the range of optical thickness where it's possible to measure these shape effects (i.e. at some optical thickness, the multiple scattering washes out any of this dependency).

Page 3793, line 13: Please include uncertainty bars for the HSRL-lidar derived optical thickness measurements (I only see those for radiance retrieved cloud properties, but text alludes that the differences plotted are outside the range of uncertainty bars for both instruments). Is it possible to ascertain an effect of crystal shape on retrieved cloud properties within the measurement uncertainty of the lidar and HALO-SR radiance measurements?

Page 3793, line 20: For clarity: The ice crystal parameterization does not represent a mixture of different crystal shapes, but the bulk scattering properties for different collections of crystal shapes.

Page 3793, line 26: Is it that you mean the crystal shape is affecting the results for tau greater or equal than 0.5 *but less than some critical value* (tau = 10, certainly)? Otherwise, due to multiple scattering for optically thick clouds, this statement is not correct.

Grid Density:

Please expand on the known and physically based reason for the 'systematic feature' of cloud properties retrieved from reflected radiation. What you are calling a systematic feature is really a results of the non-separability in cloud optical thickness and effective radius that results from the fact that clouds scatter at all wavelengths, not just visible wavelengths. The orthogonal relationship between tau and reff does not occur until thicker cloud optical thickness values (tau > 40). This fact is *not* just a feature of the statistical retrieval approach, it is a reality for all cloud retrievals based on the 'standard' method [Nakajima and King, and others].

Page 3794, line 17: When you use the expression of number of grids = albedo values, are you using the same binning in albedo you applied earlier? What is the resolution (in albedo space) that defines one albedo value as unique from any other albedo value? This information is necessary in interpreting Figure 13b, which provides grid numbers exceeding 200 for possible lower boundary solutions. More helpful would be a variable that relates to surface types instead of albedo 'values' in interpreting these results.

Page 3794, line 14: Terminology: 'Changing the radiance grid', you mean using a different look-up table defined by its surface albedo value (at a mid-visible wavelength?, both wavelengths?)

Bidirectional Reflectance distribution function:

Page 3795, line 4: "the spectral MODIS BRDF product…has been implemented in the retrieval." How? Please elucidate on the approach.

It's not clear in the manuscript if the surface albedo used in previous sections was corrected for the solar zenith angle and aerosol optical thickness (represents percentage of diffuse skylight required to interpolate between the black sky and white sky MODIS albedo products) during time of the flights. I must ask, how much of the difference between results using surface albedo versus full BRDF parameters is due to simplifying assumptions in the albedo product?

Conclusions

Please modify concluding statements to take in point #1 above: the weighted standard deviation/mean will be < than the uncertainties (based on non-weighted values) for all cases where the frequency of surface albedo types is not divided equally amongst the types. Therefore, the smaller uncertainties found in these studies are due to surface scene and not that the 'standard' retrieval method is new or changed, resulting in a better retrieval (i.e. a retrieval less impacted by surface conditions).

Page 3796, line 19: Incorrect statement. "The *larger* the cirrus optical thickness the larger the uncertainty of the effective radius…"

Line 20: Incomplete statement? "Uncertainties caused by the ice crystal shape are observed for optical thicknesses larger than 0.5 *and less than 4(?)* and can be neglected for lower values."

Line 23: This limit… What limit?

Line 24: "The influence of the bidirectional reflectance distribution (BRDF) is minimal as it shows no significant differences to the use of isotropic reflecting surface albedo. " I believe this statement is also supported by findings that verify the assumption of Lambertian surfaces in satellite retrievals of surface albedo [see, Liang et al., [2002] for example].

Please provide more discussion around the concluding statements for ice crystal shape.

Figures:

In general, several figures (1, 2, 6, 7, 13) are too small.

Please be consistent with x-axis units (time of day(s) or UTC) for the figures depicting a subset of data from the time frame shown in Figure 2).

Figure 2b) caption. "…showing a *constant but heterogeneous*…" is awkward/contradictory phrase.

Figure 4: Per above discussion, please provide surface type and regions of cloud and cloud-free on plot.

Figure 6: Is the legend incorrect on one of the plots (dashed line equals albedo of 0.025 in plot a and equals 0.075 in plot b).

Figure 7: Based on Figure 5, are you using the median or mode of the surface albedo to perform the statistical approach? The maximum likelihood and mean of the frequency distribution will only be the same for Gaussian distributions.

Figure 8 caption: Comparison between τ *and* σ_τ (likewise for *reff and* σ_{reff}).

Figure 11: "For the simulations a mixture of ice crystal shapes is used." Please expand on what mixture. Aggregates?

Figure 12: Figure caption does not match legends in plots (for example, plot a is solid-columns, but identified as droxtals in caption).

Figure 13: Reflectance decreases with increasing particle size (not the opposite as indicated on the plot). Could you use colors to help identify between the 3 look-up tables? Either the text describing this plot is incorrect or incomplete, or the plot is from a different set of look-up tables then discussed in text. For example, as tau -> 0, the reflectance will approach the surface albedo. This plot suggests the surface albedo at the visible wavelength (please specify λ in plot) is 0.1 for all look-up tables. The surface albedo at the near-ir wavelength (please specify λ in plot) varies between 3 different values. Also, in most of paper, you use radiance units. Please define reflectance.

Figure 14: In this plot, (and based on 13), what wavelength (or both) correspond to the changing surface albedo values? Would you agree that the plot shows a systematic retrieval feature for τ below 1, not 0.5?

<u>Grammatical and spelling errors</u>:

Please define HALO-SR prior to first use of acronym.

Abstract, line 9: dependend-dependent

Albstract, line 17: Therefor - Therefore

Abstract, line 20: However, it *will* be shown…

Introduction, line 16: "…reflected *from* cirrus *by* the new…

Introduction, line 30: "…vertically resolved active measurements *of …* which *are not impacted by* the surface albedo.

Section 2.2, line 22; "the investigated measurement data are spectrally *smoothed convolved* with…" (redundant – are both terms necessary?)

Section 3.3, line 21: Awkward phrase (highlighted text) which is difficult to understand: "However, the standard deviations are slightly larger in some cases for the BRDF case *which can be explained by the differences in the total amount of surface albedo values affecting the retrieval*."

Conclusions, line 18: "For the effective radius retrieval*, the sensitivity to surface albedo* depends…"