Influence of surface albedo inhomogeneities on remote sensing of optical thin cirrus cloud mikrophysics.

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Summary

Cirrus clouds play an important role in atmospheric chemistry and climate, but they are complicated to handle mostly due to the complex non-spherical shape of the particles and their spatial inhomogeneity which causes major problems in remote sensing of cirrus from satellite platforms. Therefore spectral measurements of solar radiation are applied on the new research aircraft for atmospheric research and earth observation of the german science community HALO (High Altitude and LOng range research aircraft). With its maximum flight altitude of 14 km combined with times of flight up to 10 hours it provides the opportunity to study fields of radiation all over the world. Aboard of the first HALO flight with operational scientific instruments (Techno-Mission in October/November 2010) a spectrometer system to measure the upward radiance was operated by the University of Leipzig together with an instrument for measurements of the actinic flux density in co-operation with the Forschungszentrum Jülich called HALO-SR (HALO-SolarRadiation). The data is generally used in combination with 1-dimensional radiative transfer calculations (1D) to derive informations on the shape and spatial distribution of cirrus cloud ice crystals based on the retrieval of Nakajima & King (King et al.,1990), supported by lidar data gathered by the DLR (Deutsche Luft und Raumfahrt) instrument WALES (WAter vapour Lidar Experiment in Space) during the Mission. Due to the low optical thickness of the observed cirrus clouds ($0.2 \leq \tau \leq 2$) the effect of the surface albedo has to be considered. In this regard, the topic of this report will be the influence of the heterogeneity of the surface albedo on the cloud retrieval. Based on the albedo map derived from MODIS satellite-data (MODerate resolution Imaging Spectroradiometer), the retrieval is performed in a statistic approach to determine the effect of the albedo variation on the retrieved cloud properties. Mean values and standard deviations of optical thickness and effective particle diameter are derived depending on frequency distributions of the surface albedo. For the cloud optical thickness the results are additionally compared with lidar data derived from the DLR instrument WALES. Methodology and results are presented.

Zusammenfassung

Zirruswolken sind hinsichtlich ihres Einflusses auf das Klima von besonderer Bedeutung, gleichzeitig aber aufgrund der komplexen nichtsphärigen Form ihrer Partikel schwer zu beschreiben. Desweiteren verursachen räumliche Inhomogenitäten der Zirruswolken Probleme bei satellitenbasierten Fernerkundungsmessungen. In dem Zusammenhang finden Strahlungsmessungen auf dem neuen deutschen Forschungsflugzeug HALO mittels eines

neuen Spektrometersystemes statt. Die maximale Flughöhe von 14 km kombiniert mit einer Flugdauer von bis zu 10 Stunden bietet die Möglichkeit weltweit grossräumige Strahlungsfelder zu erfassen. Während der ersten HALO Kampagne mit wissenschaftlicher Instrumentierung an Bord (Techno Mission Oktober/November 2010) kam das Spektrometersystem HALO-SR (HALO-SolarRadiation) erstmalig zum Einsatz. Dabei wurden Messungen der aufwärtsgerichteten Strahldichte, betrieben von der Universität Leipzig, zusammen mit Messungen der aktinischen Flussdichte des Forschunszentrums Jülich durchgeführt. Die Strahldichtemessungen werden anschliessend mithilfe von eindimensionalen (1D) Strahlungstransferrechnungen genutzt, um Informationen über die Ausbreitung sowie die Form der der Partikel der Zirruswolken auf Basis des Nakajima&King Verfahrens zu gewinnen. Aufgrund der zu untersuchenden optisch dünnen Zirren ($0.2 \leq \tau \leq 2$) muss hierbei zusätzlich der Einfluss der reflektierten Strahlung der Bodenoberfläche berücksichtigt werden. Dieser ist jedoch nicht eindeutig zuweisbar. Somit wird hier der Einfluss der Heterogenität der Bodenalbedo auf die Fernerkundung der Wolkeneigenschaften untersucht. Mittels von Satelliten (MODIS) gewonnenen Daten der Bodenalbedo wird die Fernerkundung in einem statistischem Ansatz durchgeführt. Gewichtete Mittelwerte und Standardabweichungen der optischen Dicke sowie der Effektivradien werden in Abhängigkeit der Verteilung der Bodenalbedo ermittelt. Zusätzlich werden die Ergebnisse der optischen Dicke mit den Messwerten des DLR (Deutsche Luft und Raumfahrt)-Lidars WALES (WAter vapour Lidar Experiment in Space) verglichen. Methodik und Ergebnisse werden dabei präsentiert.

Airborne measurements and cirrus cloud mikrophysics

Remote sensing techniques, either satellite or plane based, are a well established method for retrieving cloud microphysical parameters (Stephens et. al, 2007, Eichler, 2009). Multispectral measurements are used for this purpose. The information is gathered by measuring the upward directed radiation and using the spectral proportionalities relating to the radiation going into the atmosphere for a retrieval of cloud mikrophysic properties. For remote sensing purposes the appropriate measured paramater is the radiance.

$$I(\hat{s}) = \frac{\mathrm{d}F}{\mathrm{d}\Omega} = \frac{\mathrm{d}\Phi}{\mathrm{d}A_{\perp}\mathrm{d}\Omega} \qquad (1)$$

It describes the radiant flux $\mathrm{d}\Phi$ entering a receiving plane $\mathrm{d}A_{\perp}$ perpendicular to the direction of the incident radiation $\hat{s}$, depending on the solid angle $\mathrm{d}\Omega$ and is given in units of $\mathrm{W\,m^{-2}\,nm^{-1}\,sr^{-1}}$. During October, 27th and November, 4th the radiance was measured during the first scientific HALO-campaign using a multispectral spectrometer from Zeiss operated by the University of Leipzig monitoring a spectral range between 350 nm and 2 μm. With the measured radiance and the knowledge of the incident solar radiation input at the top of the atmosphere the reflectance R is calculated. Cloud microphysical and optical properties are retrieved using the method developed by Nakajima & King

(Nakajima & King, 1990). It bases on the main principle of using a non-absorbing wavelength in the visible spectral range (650 nm) in addition with an absorbing wavelength in the near infrared spectral region (1646 nm). One retrieved quantity is the cloud optical thickness τ.

$$\tau = \int_{z2}^{z1} b_{ext}(z)\,\mathrm{d}z \tag{2}$$

It describes the integrated extinction b_{ext} within a given vertical column z. Thus it is a quantity to describe the fraction of radiation that is extinct by travelling through the cloud given by the integration limits. The second parameter is the the effective radius of cloud particles r_{eff},

$$D_{eff} = 2\,r_{eff} = \frac{\int \mathrm{d}N/\mathrm{d}D \cdot D'^3 \mathrm{d}D'}{\int \mathrm{d}N/\mathrm{d}D \cdot D'^2 \mathrm{d}D'} \tag{3}$$

which is described by the relation of the volume to the area cross section of the respective particle using a infinitesimal number of particles $\mathrm{d}N$. However, this equation is only valid for spherical ice/water particles. For non-spherical ice crystal shape situations different approaches of parametrizations exist.

Influence of heterogeneous surface albedo

Optical thick clouds lead to high extinctions, thus the reflected radiance mainly results from scattering within in the cloud. The surface albedo has only a minor impact. The situation for optical thin clouds is more complex. The reduced extinction of optical thin clouds leads to an increased part of incident radiation that is passing the cloud either by transmission or scattering in forward directions. This fraction of radiation interacts with the surface. Depending on the albedo of the surface an increasing part of radiation reflected by the ground is transmitting and scattered in upward direction. Due to the fact of measuring the total amount of upward directed radiation during remote sensing measurements in nadir direction, the received signal consists of parts reflected by the cloud and parts reflected by the surface as well. To apply a N.-King retrieval the surface albedo has to be known exactly. The investigated measurements were performed in a flight altitude of 14 km covering cirrus cloud situations. These situations offer the following problem. The variability in the measured radiance results either from variations in the surface albedo or from the variation of cloud optical thickness. Both cloud optical thickness and surface albedo are highly inhomogeneous for the observed scene. Unfortunately, the variation of surface albedo is not known exactly. Using a fixed surface albedo may cause high errors in the retrieved cloud properties. These aspects lead to the question:

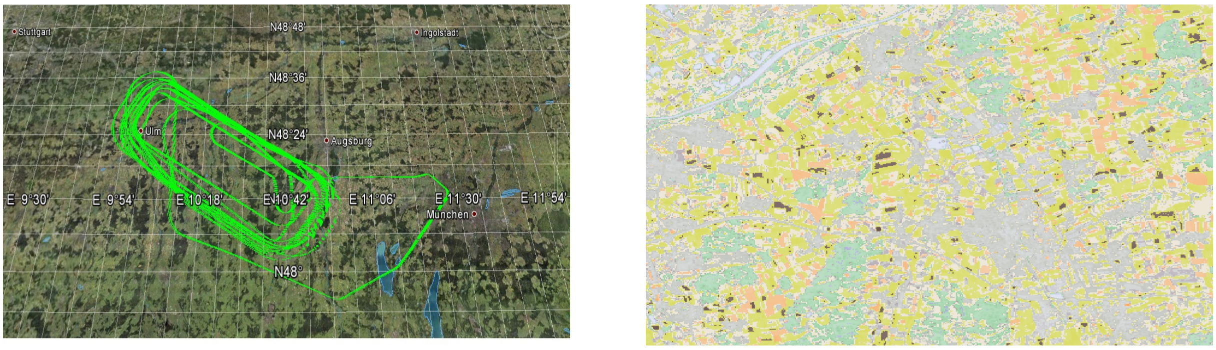

Figure 1: ***left panel:*** *Example flight track showing the measurement area in the Allgäu region using GPS (illustrated using Google Earth).* ***right panel:*** *Classified surface albedo types of the area below the flighttrack within a windows of approximately* 35 x 26,5 *km. Classification includes several field types (yellow), different forest (green), urban (dark grey) and water areas (light grey). Image is based on LANDSAT data.*

What is the exact influence of the surface albedo on the retrieval of cloud mikrophysics and is a cloud retrieval still possible without knowing the accurate albedo values?
Figure 1 shows the general situation during the flights. The investigated data was collected above a flight area (Allgäu, southern Germany) with a small scale heterogeneos surface albedo as shown in the right panel of *Figure 1*. It shows a classification of several surface types based on LANDSAT image data that were present in the flight area. The surface types are agricultural, urban, forest and water areas on a small scale.
To investigate the influence of the surface albedo on the cloud retrieval the following strategy has been applied. As no direct measurements exist, processed MODIS satellite data, based on GPS based flighttrackrecording, is used for the campaign time. These are time averaged athmosperic corrected albedo values representing the estimated surface reflectance as if there were no atmosperic scattering or absorption present (Wanner et. al, 1997). Because the Nakajima & King retrieval is based on the use of two wavelengths, the MODIS surface albedo is obtained for two available wavelength bands, a visible band covering $620-670$ nm (VIS) and a near infrared band covering the $1628-1652$ nm (NIR) range. The MODIS data is smoothed on the footprint size of the HALO-SR radiance measurements. The footprint results by combining the opening angle of the optical inlet ($2\,°$) and the flight path over which is integrated during the exposure time of up to five seconds. A measurement altitude of 14 km and flight velocities of 200 m/s were considered. Since no explicit allocation of the albedo value distributions of both wavelength bands to the radiance measurements is possible, the retrieval of τ and r_{eff} has to be performed in a statistic approach. In this regard 1D radiative transfer calculations are performed for each possible albedo combination of the whole distribution derived from MODIS. For the simulations the radiative transfer calculation package libRadtran (Mayer et. al, 2005) was used. For each albedo a possible combination of τ and r_{eff} is derived. The generated pool of possible solutions has to be weighted afterwards with the frequency distribution of the surface albedo. Thus a 2-dimensional frequency distribution of the combined VIS+NIR albedo value is generated (*Figure 2*). The combined albedo distribution presents a pro-

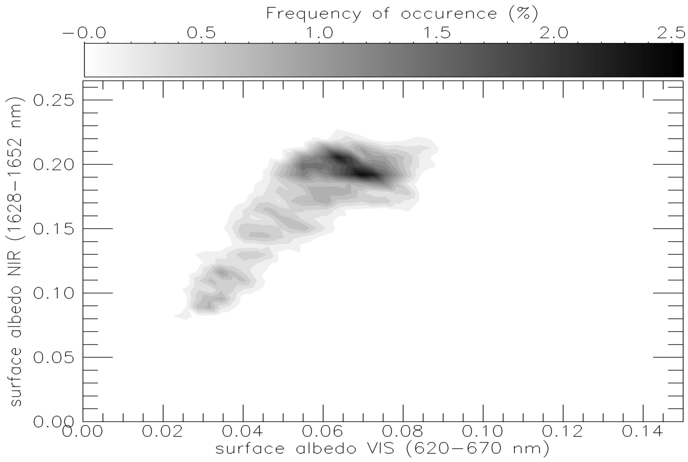

Figure 2: *2-dim. frequency distribution of the combined VIS+NIR surface albedo for the area of interest. Each value stands for a surface albedo pair with bin size of 0.005.*

portional characteristic between both wavelenghts. It offers possible value pairs for the VIS between 0.025-0.09 and 0.08-0.23 for the NIR wavelength band with a maximum of VIS/NIR probability around 0.07/0.2. This distribution is now used to calculate weighted mean values ($\bar{x}^*$) and weighted standard deviations (σ^*) of τ and r_{eff} for each timestamp of measurement (4). Here, w_i is the weight for the ith albedo value of all combinations, N marks the amount of used combinations of albedo values and M the total amount of albedo values N.

$$\sigma^* = \sqrt{\frac{\sum_{i=1}^{N} w_i(x_i - \bar{x^*})^2}{1 - \frac{1}{M}\sum_{i=1}^{N} w_i}} \qquad \bar{x^*} = \sum_{i=1}^{N} w_i x_i \tag{4}$$

Figure 3 displays the results for two example measurements. A distribution of possible solutions is calculated of which the weighted statistic is generated afterwards. Both examples show similar results for τ ranging between 0.5 and 1 for the first and 0.7 and 1.3 for the second case. The narrow frequency distribution lead to small uncertainties with a standard deviation below 0.1. For r_{eff} both examples show differences in the valuation of the solution spaces of the frequency distributions leading to different uncertainties described by the standard deviation. The retrieval method has been applied for two parts of campaign flights from November, 3rd and November, 4th by calculating $\bar{x}^*$ and σ^* for each measurement of a time series. Data with roll and/or pitch angles larger 3 ° were excluded from the retrieval. *Figure 4* shows the retrieved results for the flight of November, 4th between 11:00 and 11:30 UTC. During the time of measurements HALO was at an altitude of 14 km. A cirrus cloud field between 9 and 13 km derived by the DLR lidar WALES was situated below the plane.
The retrieval results for τ were compared to the optical thickness calculated by integration of the extinction backscatter coefficient measured by the DLR Lidar Wales during the

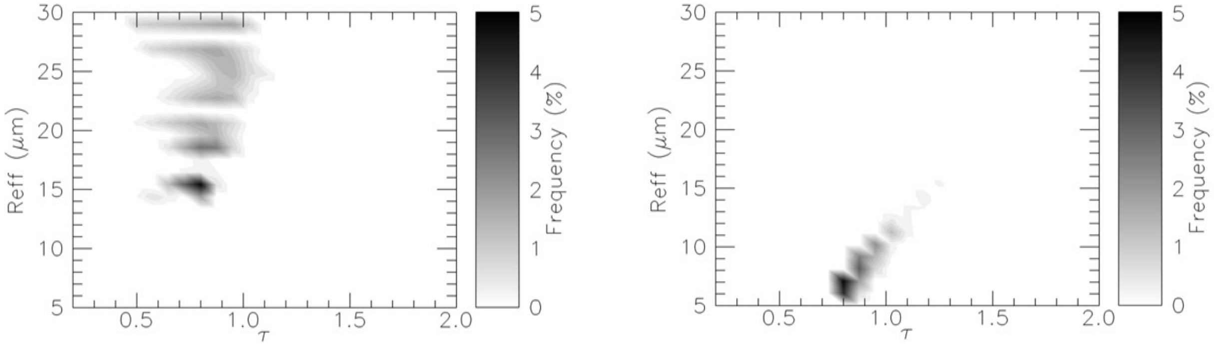

Figure 3: *Solution space of two measurement examples. While the possible τ is situated in a small band of solutions in both cases (between 0.5-1 in the left and 0.7-1.2 in the right case), r_{eff} offers a larger uncertainty in general as well as different uncertaincies between the measurements ($dr_{eff} = 15\,\mu$m in the left and $dr_{eff} = 10\,\mu$m in the right case).*

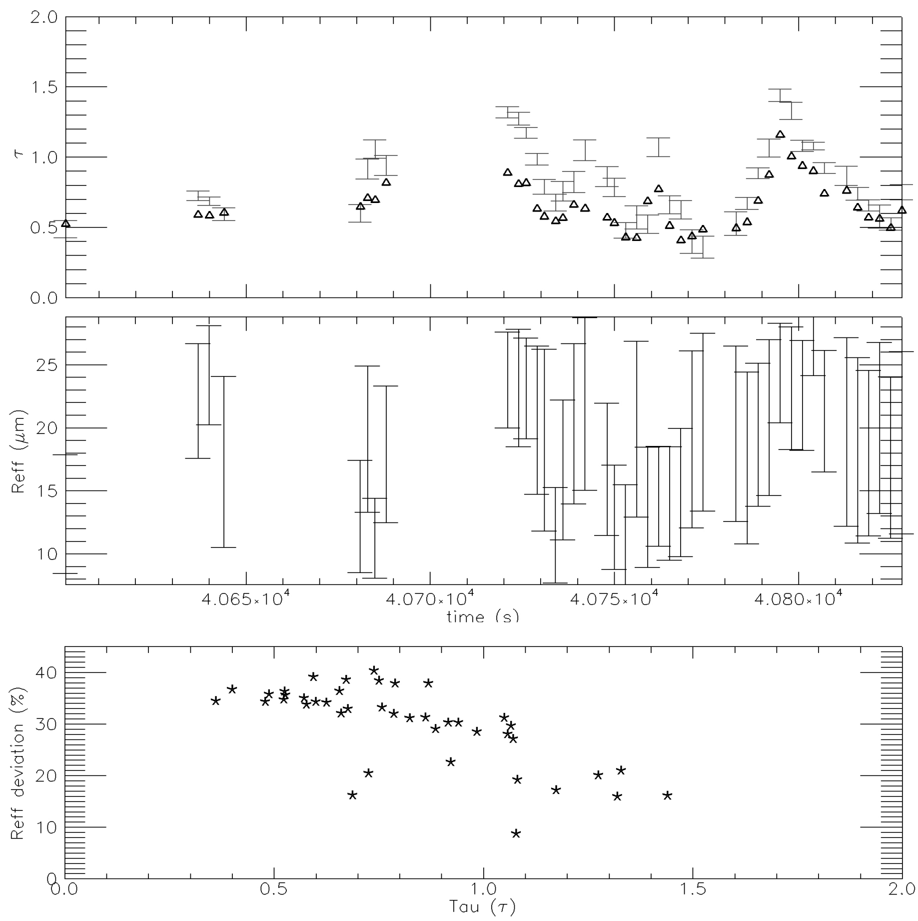

Figure 4: ***upper panel:*** *τ comparison between statistic retrieval (bars) and values derived of the DLR Lidar WALES (triangle) from the November, 4th flight between 11:00 and 11:30 UTC. Gaps are caused by roll movements of the plane, where nadir measurements could not be obtained.* ***middle panel:*** *σ^* for r_{eff} of the corresponding timeframe.* ***lower panel:*** *τ dependance of r_{eff} deviation.*

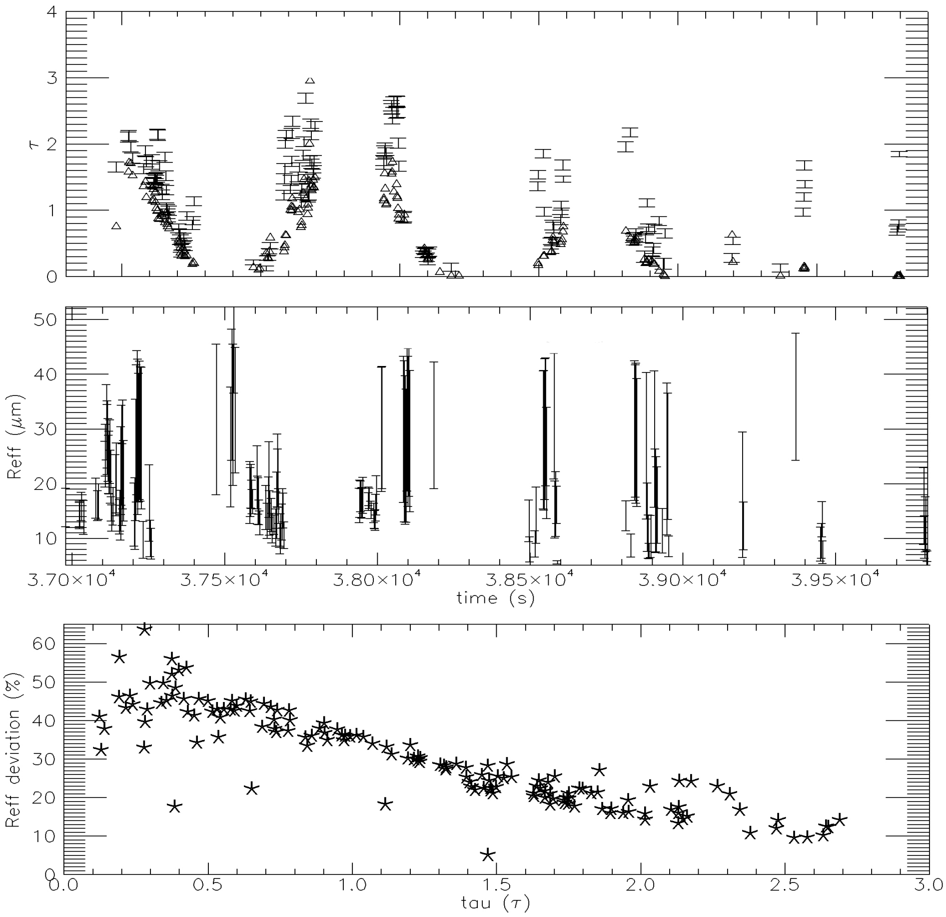

Figure 5: ***upper panel:*** *τ comparison between statistic retrieval (bars) and values derived of the DLR Lidar WALES (triangle) from the November, 3th flight between* 11 : 00 *and* 11 : 30 *UTC. Gaps are caused by roll movements of the plane, where nadir measurements could not be obtained.* ***middle panel:*** *σ^* for r_{eff} of the corresponding timeframe.* ***lower panel:*** *τ dependance of r_{eff} deviation.*

flight between 9 and 13 km. As displayed in the upper panel of *Figure 4*, the retrieved values for the optical thickness show similar characteristics between the statistic approach and the LIDAR values throughout the whole time frame. Although differences in the individual timestamps of measurements occur, the changing ascending and descending optical thickness during the time series can be seen in both results. The investigated cloud situation had optical thicknesses between 0.3 and 1.5 with deviations for the retrieved τ lower than 0.1. For r_{eff} the retrieved mean values vary between 5 μm and 24 μm with uncertainties between $\pm 3\,\mu$m and $\pm 7.5\,\mu$m as shown in the middle panel of *Figure 4*. Obviously there is a relationship between the uncertainty of r_{eff} and the retrieved values of τ. With increasing τ the deviation of r_{eff} decreases (*Figure 4*, lower panel). While the deviation is approximately 40 % for $\tau = 0.5$ it decreases to deviations of 20 % for $\tau = 1.5$. To verify this result, a time series of the flight from November, 3rd is shown in *Figure 5*.

Contrary to the flight of November, 4th the cloud field was not continuous during the

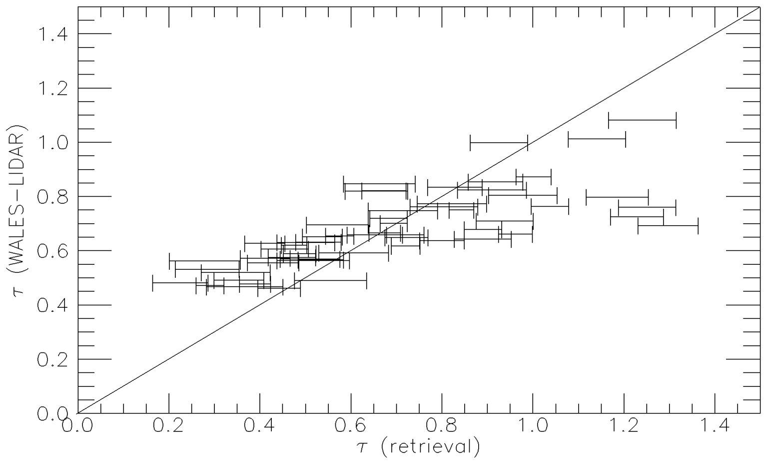

Figure 6: *Comparison of statistic retrieval approach and LIDAR measurements to determine τ from a 30 min time series of the flight from November, 4th. Displayed are the weighted standard deviations as degree of uncertainty compared to the LIDAR values.*

measurements. Cloudy and cloudless situations were alternating with two seperate cloud layers below the plane. In areas with cirrus clouds a second cloud layer was situated around 5 km altitude below to the cirrus between 8.5 and 13 km. While the τ retrieved from the Lidar is based on the extinction between 7 and 13 km only, the statistic approach is based on the signal during the measurements including reflected radiation of the cloud in 5 km altitude. Thus, as seen in *Figure 5* the statistic retrieval approach delivers higher values for τ. Nevertheless the time dependent characteristics are comparable again. The statistic approch leads to values of τ between 0.2 and 2.8 with deviations of the statistic retrieval below 0.1. $\bar{x}^*$ for r_{eff} vary between 9 μm and 40 μm with a higher variation of deviation compared to the flight of November, 4th. As for the time frame from November 4th the deviation for the time series reaches values between 40 % and 50 % for $\tau = 0.5$. Correlating to the decreasing character of the deviation with increasing τ the deviation reduces to 10 % for $\tau = 2.5$. The reason for the decreasing deviation is the decreasing influence of the surface albedo with increasing τ as less radiation is transmitted through the cloud for higher cloud optical thickness. Unlike the consistently small deviation for the retrieved τ, the results for r_{eff} offer a high sensitivity to the values for τ.

The optical thickness derived from the lidar measurements are compared to the HALO-SR retrieval in *Figure 6*. Both results do not agree within the uncertainties for most of the measurements.

For low optical thicknesses ($\tau \leq 0.5$) the statistic approach results in an underestimation. With increasing ($\tau \geq 0.5$) it switches to an overestimation. One possible reason is the influence of the ice crystal shape. Different to water clouds the non-spherical particles are not consistently defined leading to several parametrization approaches. The calculations presented here are performed using an ice crystal parametrization by Baum (Baum et. al, 2007) simulating a mixture of different crystal shapes within a cloud. Differences of the observed clouds from the assumed ice crystal mixture would cause a deviation.

Another possible reason is the surface albedo product provided by MODIS combined with 1D radiative transfer calculations. Surface reflectances are dependent on the viewing angle, as each surface type has a charactaristic reflectance behavior that is described with the bidirectional reflectance distribution function (BRDF). At this point the radiative transfer calculations are performed in a 1D approach leaving out possible 3D radiative effects. Both reasons will be adressed in further investigations.

Conclusion

The influence of surface albedo inhomogeneities on the retrieval of cloud microphysics has been investigated. Because the affecting surface albedo necessary for the retrieval is unknown, the influence is investigated using a statistic approach. The optical thickness and the effective radius are retrieved by deriving statistic weighted mean values and standard deviations as dimensions for uncertainty. For the optical thickness the standard deviations ranges below 0.1 (including measurement error, which got considered by repeating the retrieval with limiting values given by the measurement error) which shows that the presented method is suitable for retrieving cloud optical thicknesses over heterogeneous surface situations when the exact influence cannot be addressed. It has to be pointed out that these results do hold only for the cloud analyzed here. The result is depending on the data pool the statistic is beeing performed with. The influencing surface albedo types should be reduced to a valuation which includes the affecting surface albedo types only. For the effective radius the suitability depends on the cloud optical thickness. The larger the part of the measured signal affected by the surface albedo the larger is the deviation of the effective radius gets. In consequence the statistic based retrieval of the effective radius offers only limited use as the influence for optical thin clouds leads to high deviations. Possible 3D as well as ice crystal particle shape effects are investigated in the following.

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