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Atmospheric
Chemistry
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Discussions

Interactive comment on "Airborne observations of a subvisible midlevel Arctic ice cloud: microphysical and radiative characterization" *by* A. Lampert et al.

A. Lampert et al.

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1 Introduction

We would like to thank the referee for the useful comments. They gave us another idea how to calculate the lidar ratio and show the agreement of the different measurements, and helped to find unclear points in the description of the in situ retrieval. We propose another title for the article. The detailed replies to the reviewer's comments are given below.

2 Comment 1

P. 605, line 16. Could the authors list the different the microphysical models tested?

Are the authors sure that the proposed combination is unique? Considering all the ice crystal models available with different size distribution, it is pretty sure that other combinations could work. Why not a three - component representation?

We created an own subsection in the discussion about the retrieval of microphysical properties. It was completed with more detailed information about the retrieval methods. The text of the new subsection is shown as the last point. Look up tables containing the angular scattering coefficients of spherical ice crystals, droxtals, columns with three aspect ratios (2,5,10), plates with 4 aspect ratios (0.1, 0.5, 0.2, 1), hollow columns, 6 branch bullet rosettes, aggregates were calculated. Three roughness parameters were also considered (smooth, moderately rough, and deeply rough). We have tested all the possible combinations of these habits. The best model was found for a mixture of spherical ice crystal and rough hexagonal columns with an aspect ratio equal to 2. This model gives the smallest root mean square deviation compared with the measured ASC. Of course since the inverse problem is ill posed for one specific combination of ice crystal geometry different size distribution can be retrieved. This is accounted for in the estimation of the lidar ratio (27 with 25% error) and the bulk microphysical parameters. We agree with the reviewer comment but we think that the goal here is to propose a simplified equivalent microphysical model able to reproduce a representative optical behaviour in accordance with the direct measurements. Of course, the microphysical model could be complexified using a three component representation but the number of free parameters to be retrieved will be too numerous compared to the information content of the measured angular scattering coefficients. So we believe that a two 20 bins PSD scheme is enough considering the information contained in ASC documented between 6.7° and 155°.

3 Comment 2

Line 18: Could the authors quantify the term "deeply";

The description of this term is included in the new Subsection (see last point of this text). The best fit of the measured phase function is achieved using a microphysical model corresponding to a combination of spherical particles and deeply rough hexagonal columns. The roughness of the surface can be defined as a small scale property similar to surface texture. In the simulation, the rough surface is assumed as composed of a number of small facets which are locally planar and randomly tilted from their positions corresponding to the case of a perfectly plane surface. The tilt distribution is supposed to be azimuthally homogeneous. It is specified by a two parametric probability distribution function including a scale parameter sigma and the shape parameter eta (which determines the kurtosis). The model of surface roughness used in this paper is based on the Weibull statistics (Dodson, 1994) and was already proposed by Shcherbakov et al. (2006). This approach incorporates the Cox and Munk model used by Yang and Liou (1998). Surface roughness can substantially affect the scattering properties of a particle if the geometric scale of the roughness is not much smaller than the incident wavelength. In the case for light scattering by large ice crystals (i.e. for size parameters within the geometric optics regime), surface roughness can reduce or smooth out the scattering peaks in the phase function that correspond to halos. For the deeply rough case the computed phase function is essentially featureless. The 22° and 46° halos are smoothed out and the backscattering is substantially reduced because of the spreading of the collimated light beams. We have chosen a roughness scale parameter sigma=0.25 which is according to the Improved Geometric Optic Model (IGOM) considered as deeply rough. We propose to add the reference of Shcherbakov et al. 2006 and Yang and Liou 1998 in the paper concerning this specific point.

Cox, C., and Munk, W.: Measurement of the roughness of the sea surface from photographs of the sun's glitter, J. Opt. Soc. Amer., 44, 838-850, 1954.

Dodson, B.: Weibull Analysis, Milwaukee, Wisconsin: ASQC, 256 pp., 1994

Yang, P., and Liou, K.N.: Single scattering properties of complex ice crystals in terrestrial atmosphere, Contr. Atmos. Phys, 71, 223-248, 1998.

Shcherbakov, V.N, Gayet J.F, Baker B., and Lawson P.: Light Scattering by Single Natural Ice crystals, Journal of the Atmospheric Sciences, 63, 1513-1525, 2006.

4 Comment 3

P. 607, line 12-14: Could the authors explain quickly the methodology? The authors should not expect the readers to seek out an earlier paper to find basic informations about the method.

The methodology is explained in the paper (see new Subsection as the last point of this text). An iterative inversion method developed by Oshschepkov et al. (2000) and upgraded by Jourdan et al. (2003), using physical modeling of the scattered light, is applied to the average angular scattering coefficients (ASC) measured by the Polar Nephelometer (PN) in the subvisible Arctic ice cloud. The method is based on a bi-component representation of cloud composition and uses the non-linear least square fitting of the ASC using smoothness constraints on the desired particle size distributions (PSD). Measurement errors at each angle and PSD's values for each size, in a sense of probability density function, are assumed to be described by the lognormal law, which is the most natural way to take a priori information about the non-negativity of these quantities (Tarantola, 1994). Note that no analytical expression for the particle size distribution is assumed for the converging solution in this method. The only constraint in this connection is smoothness, needed to avoid an unrealistic jagged structure of the desired size distribution, because the inverse problem is ill posed without constraints. The inversion method is designed for the retrieval of two volume particle size distributions simultaneously, in our case one for hexagonal ice columns and another for spherical ice crystals. We need, however, to specify a lookup table containing ASC of individual ice crystals. In this paper, we have considered different hexagonal ice crystals with different aspect ratios and shape and randomly oriented in 3D space. The scattering phase function of spherical ice crystals follows from classic Lorenz-Mie theory and the scattering patterns of hexagonal crystals are computed by an improved geometric-optics model (Yang and Liou, 1996). The best retrievals (best fit to the measured ASC) were obtained for rough hexagonal ice columns with an aspect ratio equal to 2 and ice spheres. Accordingly, two particle size distributions are retrieved. On this basis, we calculate extrapolated ASC in the forward and backward directions at the lidar wavelength (532nm) as well as the extinction coefficient. This step is performed using direct modeling of light scattering corresponding to the retrieved PSD. Therefore, we have access to both terms needed for the lidar ratio computation, namely the scattering coefficient at 180° and the extinction coefficient at 532nm.

Jourdan, O., Oshchepkov, S.L., Gayet, J.-F., Shcherbakov, V.N., and Isaka, H.: Statistical analysis of cloud light scattering and microphysical properties obtained from airborne measurements, J. Geophys. Res., 108 (D5), 4155, doi: 10.1029/2002JD0027232003, 2003a.

Jourdan, O., Oshchepkov, S.L., Shcherbakov, V.N., Gayet, J.-F., and Isaka, H.: Assessment of cloud optical parameters in the solar region: Retrievals from airborne measurements of scattering phase functions, J. Geophys. Res., 108 (D18), 4572, doi: 10.1029/2003JD003493, 2003b.

Oshchepkov, S.L., Isaka, H., Gayet, J.-F., Sinyuk, A., Auriol, F., and Havemann, S.: Microphysical properties of mixed-phase & ice clouds retrieved from in situ airborne "Polar Nephelometer" measurements, Geophys. Res. Lett., 27, 209-213, 2000.

Tarantola, A., Inverse problem theory : Methods for data fitting and model parameter estimation, 2nd imp., 601 pp., Elsevier Sci., Amsterdam, 1987.

Yang, P., and Liou, K.N.: Geometric-optics-integral-equation method for light scattering by nonspherical ice crystals, Appl. Opt., 35, 6568-6584, 1996.

5 Comment 4

P. 610, line 24: By studying the difference of downwelling radiance under clear and cloudy sky, it is theoretically possible to determine the optical thickness of cirrus cloud, and it would be interesting to compare it with lidar determination. The authors must perform such a study.

We performed the suggested calculation, and retrieved the cloud optical thickness from the albedometer measurements. As the cloud optical thickness determined with the lidar measurements contains an estimated value for the lidar ratio, we did not compare the cloud optical thickness retrieved from the two data sets. Instead, we used the cloud optical thickness determined by radiation measurements to calculate the lidar ratio. In Sect. 4.3 the method is presented and the results analyzed:

From SMART-Albedometer measurements, a time series of the cloud optical depth was retrieved for the lidar wavelength of 532 nm. For this purpose, the method described in Sect. 4.2 was applied systematically. Lookup tables were calculated for the downwelling radiance I_downwelling_532nm assuming cloud optical thickness in the range of 0-0.5. For each measurement of the SMART-Albedometer, an appropriate value of tau was derived by interpolating the lookup tables' values to the measured I_downwelling_532nm. Fig. 11 shows a time series of tau retrieved from I_downwelling_532nm. In addition, the cloud optical thicknesses derived from AMALi assuming three different LR (PN measurements LR = 27 sr, mean value LR = 21 sr, transmittance method LR = 15 sr) are given. In general, the derived tau agree within the uncertainty range of tau retrieved from the SMART-Albedometer until 11:59 UTC. After 12:00 UTC the cirrus cloud was above the aircraft increasing the measured radiance. Therefore, tau retrieved from the SMART-Albedometer overestimates the optical thickness of the subvisible cloud. Assuming that single scattering (at a scattering angle of 70°) is dominating the radiative transfer through the subvisible cloud, tau is obtained independent of the ice crystal scattering phase function (and LR). The retrieved tau are used in combination with the AMALi measurements to derive an independent estimate of the LR. By dividing tau by the corresponding integral of the particle backscatter coefficient, the LR is calculated (see Eq. 3). For the time when the cloud was detected without cirrus above, and omitting the cloud free section around 11:57 UTC, this method resulted in an effective LR of 20 (+/- 10) sr.

5 Minor corrections

- This paper concerns a case study, it describes optical and microphysical properties of an Arctic cirrus. The reviewer suggests to add the term "case study" in the title.

We propose to change the title into "Microphysical and Radiative Characterization of a Subvisible Midlevel Arctic Ice Cloud by Airborne Observations - A Case Study"

- In situ is a latin locution. Please write it without the indent.

This is changed in the revised article.

- In the particle backscatter coefficient beta_Aer and the particle extinction coefficient alpha_Aer, the exponent Aer suggests aerosol particles. In the current case, this appellation is not suitable, it would be better to find another exponent, for example "Crys" for crystals.

This is indeed a confusing abbreviation. We suggest using the exponent "part" for particle backscatter and extinction.

- Concerning pyrgeometer measurements, between 3 and 50 micrometers (for example p 614, line 6), the term thermal infrared radiation is inadequate, the reviewer suggests the term "longwave radiation". The thermal infrared region is rather in the interval between 8 and 13 micrometers.

With the term "thermal infrared radiation", we follow the terminology:

Solar spectral range: 0.2 ... 5 micrometers

Terrestrial spectral range: 5 ... 100 micrometers

Thermal infrared (IR) spectral range: 5 ... 50 micrometers

This is, of course, just one possible definition, but it is quite widespread, and we think that the term "thermal infrared radiation" is more precise than the expression "longwave radiation".

6 New subsection 4.1 (microphysical properties)

The inversion method for the PN data is based on a bi-component representation of cloud composition and constitutes a non-linear least square fitting of the scattering phase function using smoothness constraints on the desired particle size distributions (PSD). Measurement errors at each angle and PSD's values for each size, in a sense of probability density function, are assumed to be described by the lognormal law, which is the most natural way to take a priori information about the non-negativity of these quantities (Tarantola, 1994). Note that no analytical expression for the particle size distribution is assumed for the converging solution in this method. The only constraint in this connection is smoothness, needed to avoid an unrealistic jagged structure of the desired size distribution, because the inverse problem is ill posed without constraints. The inversion method is designed for the retrieval of two volume particle size distributions simultaneously, in our case one for hexagonal ice columns and another for spherical ice crystals. The technique needs, however, to specify a lookup table containing the scattering phase functions of individual ice crystals. Lookup tables containing the angular scattering coefficients of spherical ice crystals, droxtals, columns with three aspect ratios (2,5,10), plates with 4 aspect ratios (0.1, 0.5, 0.2, 1), hollow columns, 6 branch bullet rosettes, and aggregates were calculated.

Three roughness parameters were also considered (smooth, moderately rough, and deeply rough). The roughness of the surface can be defined as a small scale property similar to surface texture. In the simulation, the rough surface is assumed as composed of a number of small facets which are locally planar and randomly tilted from their positions corresponding to the case of a perfectly plane surface. The tilt distribution is supposed to be azimuthally homogeneous. It is specified by a two parametric probability distribution function including a scale parameter sigma and the shape parameter eta (which determines the kurtosis). The model of surface roughness used in this paper is based on the Weibull statistics (Dodson, 1994) and was already proposed by Shcherbakov et al. (2006). This approach incorporates the Cox and Munk model used by Yang and Liou (1998). Surface roughness can substantially affect the scattering properties of a particle if the geometric scale of the roughness is not much smaller than the incident wavelength. In the case of radiation scattered by large ice crystals (i.e. for size parameters within the geometric optics regime), surface roughness can reduce or smooth out the scattering peaks in the phase function that correspond to halos. For the deeply rough case the computed phase function is essentially featureless. The 22° and 46° halos are smoothed out and the backscattering is substantially reduced because of the spreading of the collimated beams. We chose a roughness scale parameter sigma=0.25 which is according to the Improved Geometric Optic Model (IGOM) considered as deeply rough.

In this case study, we tested all the possible combinations of the habits listed above. The best fit of the measurement was achieved using a combination of spherical droplets with diameters ranging from 1 μm to 100 μm and deeply rough hexagonal columns (with an aspect ratio of 2) with maximum dimension ranging from 20 μm to 900 μm. This model gives the smallest root mean square deviation compared with the measured ASC. Accordingly, two particle size distributions were retrieved. Since the inverse problem is ill posed for one specific combination of ice crystal geometry, different size distributions can be retrieved. This is accounted for in the estimation of the lidar ratio and the bulk microphysical parameters. The scattering phase function of spherical ice crystals was simulated from Lorentz-Mie theory, and the scattering patterns of rough hexagonal column crystals randomly oriented in 3D space were computed by an improved geometric-optics model (Yang and Liou, 1996). The bulk microphysical (number concentration, IWC, effective diameter) and optical parameters (volume extinction, extrapolated scattering phase function at 532 nm and lidar ratio) were assessed following the method presented by Jourdan et al. (2003b). On the basis of the two particle size distributions, we calculated the extrapolated ASC in the forward and backward directions at the lidar wavelength (532nm) as well as the extinction coefficient. This step was performed using direct modeling of light scattering corresponding to the retrieved PSD. Therefore, we have access to both terms needed for the lidar ratio computation, namely the scattering coefficient at 180° and the extinction coefficient at 532 nm. From this method a LR of 27 sr with 25% error was estimated.

The retrieved ASC from the inversion scheme along with direct PN measurement are displayed in Fig. 9. The measured ASC are flat at the side scattering angles, which is in accordance with most of the observations (Francis et al., 1999; Shcherbakov et al., 2005; Gayet et al., 2006; Jourdan et al., 2003b) or directions in ice cloud remote sensing application (see among others Labonnote et al., 2001, Baran and Labonnote, 2006, 2008, Baran and Francis, 2004). Scattering phase functions of non-spherical ice crystals mostly exhibit enhanced sideward scattering compared to spherical water droplets.

Fig. 9 highlights that the retrieved ASC are in good agreement with PN direct measurements. The minimum root mean square deviation (15 %) between the measured and the retrieved ASC was achieved for a microphysical model representing a combination of ice spheres and deeply rough hexagonal columns of aspect ratio equal to 2 (with maximum dimension of the crystals ranging from 1 to 100 μm and 20 to 900 μm, respectively). The scattering contribution of each microphysical component (dashed lines in Fig. 9) points out that the hexagonal ice crystal component reproduces the general flat behaviour of the measured ASC at side scattering angles. Roughness of the ice crystal mantle removed specific optical features (22° and 46° halos, bows) linked to the hexagonal geometry of ice crystal. However, a small ice sphere component is needed to model the relatively higher scattering in the angular range [15°-60°] and [130°-155°] in comparison with hexagonal shape assumption.

The comparison of the model with direct microphysical measurements is limited in this case study, as only 4 single ice crystal were recorded by the CPI and no statistically significant measurements were performed by the FSSP-100. However, the CPI images (Fig. 6) suggest the presence of rounded edge column ice crystals with an average length of 100-200 μm. This observation supports the choice of a rough column component in the microphysical model. Additionally, as shown in Table 1, the retrieved

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effective diameter and number concentration of the hexagonal ice crystal component are acceptable compared to the measurements (effective diameter of 106 μm and very low concentration of 0.002 cm-3). As mentioned above, a small spherical ice component is needed in order to fit the measured ASC. The only information derived from direct measurements that could confirm the presence of small ice crystals is linked to the minimum detection threshold of the CPI and FSSP-100 instruments. The CPI is not able to detect particle with sizes lower than 10 μm (Lawson et al., 2001) and the FSSP-100 minimum measurable concentration is around 0.2 cm-3. The microphysical retrievals are in agreement with the instruments shortcomings, as the estimated total number concentration of the ice cloud is 0.2 cm-3 and the effective diameter of the small ice crystals is 4.5 μm.

In conclusion, a microphysical model composed of small spherical ice particles and larger deeply rough hexagonal column crystals leads to optical and, to a certain extent, microphysical properties (asymmetry parameter, extinction and ASC), which allows to reproduce the measurements. The low asymmetry parameter (˜ 0.78) of the PN measurements is consistent with the enhanced depolarization measurements of up to 40 % and the CPI images indicating non-spherical ice crystals. It is not possible to distinguish the particle shape from the values of lidar depolarization measurements, not even for clouds composed entirely of one kind of ice particle habits, as was evidenced by Monte Carlo simulations of You et al. (2006). Most of the asymmetry parameter values fall within the range that is typical of cirrus clouds shown by Gayet et al. (2006), i.e., a cloud containing ice particles was sampled. For spherical water droplets the asymmetry parameter is about 0.85, significantly larger than the values reported here. The extinction coefficients retrieved from the PN range between the lidar values (Sect. 3.1) but could not exhibit the maximum of 0.1 km-1 measured by the lidar. This indicates that the aircraft was not within the densest part of the cloud during the in situ measurements, or the cloud generally was in the process of dissolving. The values of RHI around saturation and the round edges of the ice crystals confirm that dissolving processes were taking place in the cloud. The extinction coefficients are much below the typical values of midlatitude cirrus clouds as presented in Gayet et al. (2006). This clearly indicates that a subvisible midlevel ice cloud was probed.

Interactive comment on Atmos. Chem. Phys. Discuss., 9, 595, 2009.

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