Microphysical properties of mixed-phase & ice clouds retrieved from in situ airborne ”Polar Nephelometer” measurements

Sergey Oshchepkov, Harumi Isaka, Jean-François Gayet, Alexander Sinyuk, Frédérique Auriol, Stephan Havemann

GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 2, PAGES 209-212, JANUARY 15, 2000

Microphysical properties of mixed-phase & ice clouds retrieved from *in situ* airborne "Polar Nephelometer" measurements

Sergey Oshchepkov [1]

Environmental Systems Business Division, FUJITSU FIP Corporation, Tokyo, Japan

Harumi Isaka, Jean-Francois Gayet

Laboratoire de Météorologie Physique, UPRES A 6016/CNRS, Université Blaise Pascal, Aubiere Cedex, France

Alexander Sinyuk

Stepanov Institute of Physics, National Academy of Sciences, Minsk, Belarus

Frederique Auriol

Laboratoire de Météorologie Physique, UPRES A 6016/CNRS, Université Blaise Pascal, Aubiere Cedex, France

Stephan Havemann

German Aerospace Center, German Remote Sensing Data Center, Neustrelitz, Germany

Abstract. In this paper we present microphysical properties of natural clouds retrieved from an airborne "Polar Nephelometer" measurements. The retrieval was done by means of an iterative inversion method, which is based on the bi-component (water droplets and ice crystals) representation of ice and mixed phase cloud composition. The present study shows that experimental scattering phase functions of ice crystals are characterized by high information content with respect to the aspect ratio of ice crystals which can be estimated in addition to their effective size distributions.

Introduction

We recently described a new airborne "Polar Nephelometer" and presented some scattering phase functions of cloud particles in natural clouds obtained during European AEROCONTRAIL experiment [*Gayet et al.,* 1998]. Size distributions of droplets in water clouds or quasi-spherical ice particles in young contrail were retrieved from these data by means of an inversion method [*Oshchepkov et al.,* 1997]. The preliminary tests showed rather good agreement between size distributions obtained with PMS probes and those retrieved from the "Polar Nephelometer" data [*Gayet et al.,* 1998].

The measurement of scattering phase functions of natural ice crystals is known to be also one of the important issues in the study of cloud optical characteristics. These experimental phase functions permit one to investigate how scattering properties of natural ice crystals differ from computed ones. However, we can also question how these phase functions should be interpreted in term of the shape and size of ice crystals. We need to make a clear distinction between direct and inverse light scattering problems of ice, because it is evident that we cannot include complex irregular ice crystal shapes in the inverse problem. Accordingly, we need to examine the information content of measured scattering phase functions with respect to ice crystal shape and size. We also have to examine whether liquid water droplets and ice crystals can be separated from scattering phase functions obtained in mixed-phase clouds.

Oshchepkov and Isaka [1997] presented an iterative inversion method to analyze experimental scattering phase functions of ice clouds as a combination of ice crystals with a simple geometrical shape and spherical particles. However, their method does not provide any information about the shape of ice crystals, because the aspect ratio is maintained as constant. A possible extension of this retrieval method is the inclusion of aspect ratio as parameter to retrieve. In this paper, we present microphysical parameters of ice and mixed phase clouds retrieved with the improved retrieval method from "Polar Nephelometer" data acquired in natural condition.

Principles of the inversion method

The iterative inversion method used in this study was already described in detail elsewhere [e.g., *Dubovik et al.,* 1995, *Oshchepkov et al.,* 1997]. Physically, the method is based on the bi-component (water droplets and ice crystals) representation of ice and mixed phase cloud composition. It is defined by considering both measured and desired parameters in logarithmic space and by using the combination of search solution with the inversion of the Fisher matrix for each step of the iteration procedure. The logarithmic transformation is consistent with the assumption that the probability density function of both measured quantities and retrieved parameters obeys the log-normal law. This transformation enables one to take *a priori* information about non-negativity of these quantities into account in a natural way. Additionally, slight smoothness constrains on both desired size distributions are used in solving the inverse problem.

To retrieve ice and mixed cloud parameters from polar nephelometer data, we have not only to reproduce correctly measured light scattering properties, but also to imagine clear pertinent relationships between the measured data and a set of

[1] Also at National Institute for Environmental Studies, Tsukuba Japan. On leave from Stepanov Institute of Physics, NASB

Paper number 1999GL010784.
0094-8276/00/1999GL010784$05.00

retrievable cloud parameters. As in our previous studies [*Oshchepkov et al.,* 1997], an one-dimensional function is also used to describe size composition of ice crystals for a hexagon assumption. This assumes implicitly that the aspect ratio of ice crystals should depend on the sizes of ice crystal only. One of the possible dependencies used in this study was a constant value of the aspect ratio for all sizes of ice crystals.

The size distribution is represented, to a first-order approximation, through the equivalent ice crystal size which is the radius R_{eq} of an area-equivalent circle whose area is equal to the ice crystal cross section averaged over all possible 3D random orientation. Since the mean projected area of any convex particle is equal to one-fourth its total surface area, we can uniquely define the geometry of hexagon at a given equivalent size R_{eq} and aspect ratio β (these two parameters define the size and shape constrains when solving the inverse particle size distribution problem). As usually, we define β as the ratio of crystal length to crystal diameter base.

The inverse model is designed for the retrieval of two volume particle equivalent size distributions simultaneously: one for ice and another water components. These components are distinguished by refractive index and particle shape on the one hand, and by the aspect ratio of ice crystals for a hexagonal crystal assumption, on the other hand. We first retrieve cloud particle size and component composition according to the inversion method at a given aspect ratio of ice crystals and then, the root-mean-square deviation (RSD) between the measured and calculated phase function for retrieved size distributions is investigated as a function of the aspect ratio.

To apply the retrieval scheme described above; we need the phase functions of individual water droplets and ice crystals to evaluate the corresponding corners of the integral transformation in solving the inverse problem [*Oshchepkov et al.,* 1997]. The phase function of spherical particles can be computed easily with the Lorenz-Mie scattering code. The scattering pattern of ice crystals with large size factor can be computed by using a ray tracing technique [*Macke,* 1993]. In this approach, the size effect is included only in the diffraction part of the phase function. To include the size effect more correctly, *Oshchepkov and Isaka* [1997] used the phase function based on the modified Kirchhoff approximation [*Muinonen,* 1989]. However, such a phase function cannot really integrate the size effect for small size factor. Consequently, in this study, we computed phase functions of small ice crystals (less than 4μm in equivalent radius) with a Discretized Mie Formalism [*Rother,* 1999] (DMF). The DMF is applicable for column-like ice crystal with aspect ratio more than 2-3 which has been partially validated by the comparison with an exact solution for circular cylinders.

By using these two computer codes, we set up a lookup table containing scattering phase functions of individual ice crystals shaped as hexagons with different aspect ratios and randomly oriented in 3D space. The last is not a simplification of real cloud conditions in which ice crystals are frequently of a size which is sufficient to induce a preferred orientation but approximately reflects the behavior of ice crystals under highly turbulent conditions in the "Polar nephelometer" sampling volume only [*Oshchepkov et al.,* 1997].

Airborne measurements used in the study

The measurements used in the study were obtained from three different airborne experiments: AEROCONTRAIL, NEPHELOMETER'97 and CIRRUS'98. The experiment which was held near Munich in October 1996 employed the Falcon aircraft of the German DLR. The French F27 ARAT aircraft was used for the NEPHELOMETER'97 experiment which was conducted during November 1997 in the Clermont-Fd area. The CIRRUS'98 field campaign was carried out in the SouthWest of France (from the Tarbes airport) in February 1998 using the French Socata TBM700 aircraft.

These three aircraft were equipped with the "Polar Nephelometer" for the scattering phase function measurement, a PMS 2D-C probe for measurements of particle images sized from 25 to 800 μm diameter and, except for the CIRRUS'98 experiment a PMS FSSP probe for droplet size spectra measurements (3 to 45 μm in diameter).

Retrieved cloud parameters

a). Water cloud

First of all, we present the typical inversion results for liquid water conditions obtained in Altocumulus at 6100 m altitude (15 October 1996) (top graph of Fig.1). The comparison of the measured scattering phase function depicted by bar symbols with those calculated according to the retrieved results is presented at the bottom graph of Fiq.1. The value of the phase function RSD is indicated in percent in Fig.1. The RSD is calculated in logarithmic space [*Oshchepkov et al.,* 1997], which is why its low values correspond to mean relative deviation between these scattering phase functions.

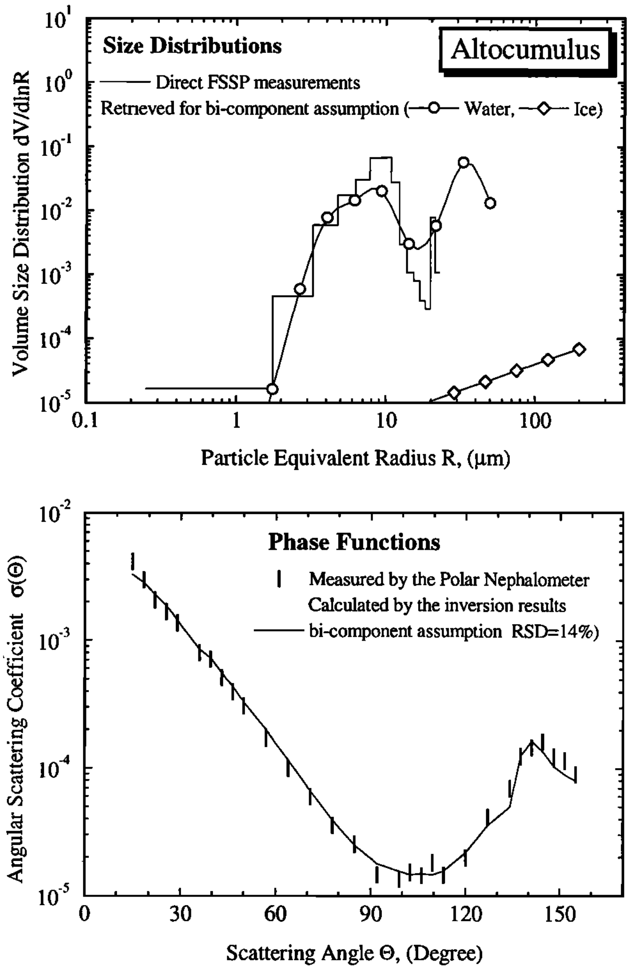

Figure 1. Typical example of scattering phase function measurements and results of solving the inverse problem for water cloud obtained during AEROCONTRAIL airborne measurements.

The agreement of the inversion results with direct measurements (histogram) for water droplets (open circles) is acceptable. It should be noted that the deviation between the retrieved distribution and the histogram for large water droplets ($R > 10\mu m$) obtained by the MPS FSSP could be explained by the different physical principles used in the data acquisition. Namely, the direct measurements obtained by a single particle counter enable us to measure particle number size distribution directly and we have to convert it to volume size distribution for a comparison with the retrieval results. By this reason, even small errors of the direct measurements due to poor statistics of the relatively small number of large particles maybe amplified significantly with respect to volume size distribution.

The inversion results presented for water cloud also show that the bi-component assumption which we used enables us to identify water phase only in spite of the fact that the solution admits a sufficient number of degree of freedom to allow for a second ice component. Indeed, as one can see from Fig.1, the values of the retrieved ice size distribution (curve with diamond symbols) are negligibly small in comparison with those for water droplets (curve with opened circles). This capacity to discriminate components reflects the high information content of phase function measurements with respect to cloud composition and can be explained by the persistent differences in scattering pattern for water droplets and ice crystals.

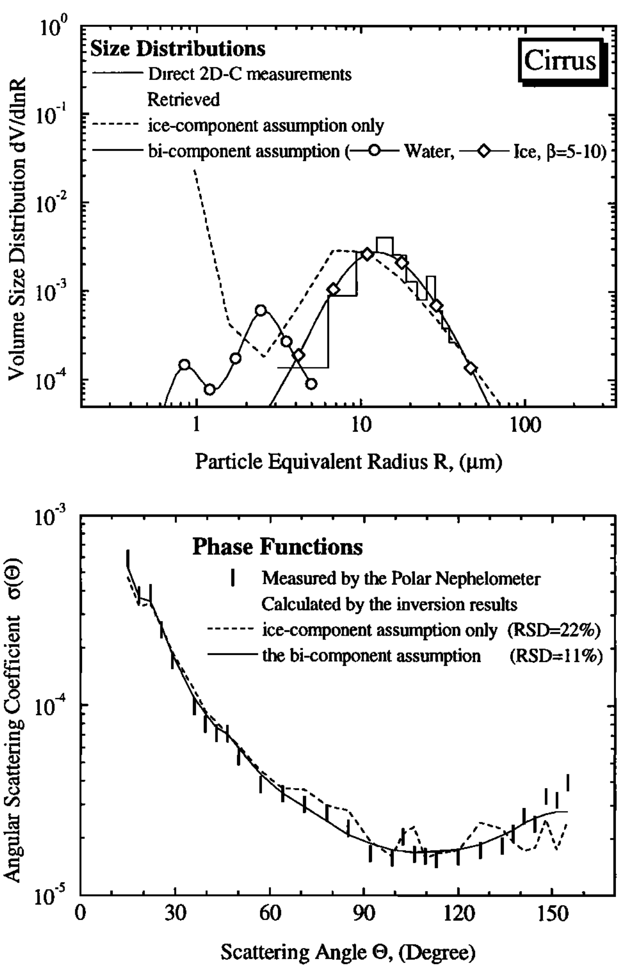

Figure 2. The same as in Fig.1 but for ice cloud obtained during CIRRUS'98 airborne measurements.

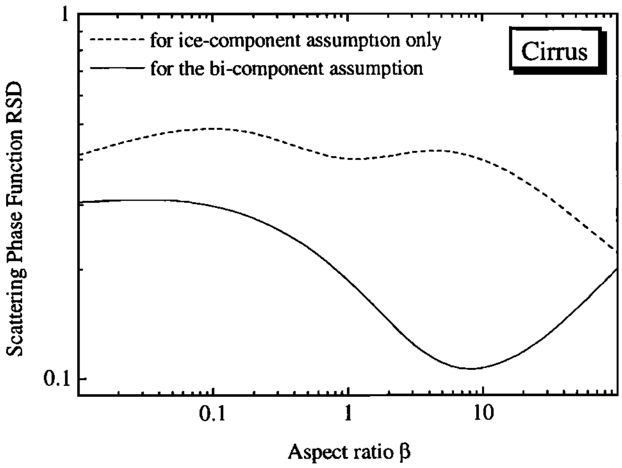

Figure 3. Scattering phase function RSD versus the aspect ratio of ice crystals fed in solving the inverse problem with respect to retrieval of equivalent crystal size distribution for cirrus (ice crystal assumption only).

b). Ice crystal cloud

By way of illustration of the inversion method for an ice cloud we first present the scattering phase function measurements obtained in natural cloud conditions near 7700 m / -35^{0}C (February 19, 1998) with detectable 22^0 and 46^0 halo features (Cirrus). The corresponding measured phase function is depicted by bar symbols at the bottom of Fig.2. The inversion results along with direct 2D-C probe measurements are presented at the top of this Figure.

Notice that the direct comparison of MPS 2D-C data measurements with the retrieval results requires that the 2D-C size spectrum be presented in terms of mean cross section size since these data are defined through the so called geometrical mean diameter [*Gayet et al.,* 1996]. We take this into account by considering the geometry of 2D-C measurements, by the definitions of both mean sizes and by angular averaging of crystals orientations. In doing so, the presentation of 2D-C data in terms of mean cross section size leads to a shift of the corresponding size spectrum along the size axis as a function of the aspect ratio. The 2D-C data measurements in Fig.2 were accordingly transmitted with a resulting shift of the 2D-C spectrum towards small particle sizes.

Given this correction, the retrieved equivalent size distribution of crystals is in rather agreement with that obtained by the 2D-C probe (discretized curve and curve with diamond symbols in the top graph of Fig.2). For the assumption of only an ice component, however, it takes place for equivalent ice crystal sizes greater than 10μm. That is one of the reasons why using the bi-component assumption enabled us to improve agreement between the retrieved ice component spectrum (line with diamond symbols) and that for direct measurement significantly. The appearance of a second water droplet component herewith (curve with open circles) could represent supercooled small droplets, as was observed in [*Oshchepkov et al.,* 1997] for laboratory measurements. The rapid increase of retrieved size distribution with decreasing particle size in the region of $R_{eqv} \le 1\mu m$ could be explained by the presence of small aerosol particles or other scatters in the cloud and calls for further examination.

The above inversion results for cirrus were obtained for values of the aspect ratio around 5-10 under the bi-component assumption which is approximately in consistent with ice crystal replica. This range corresponds to local minimum of scattering

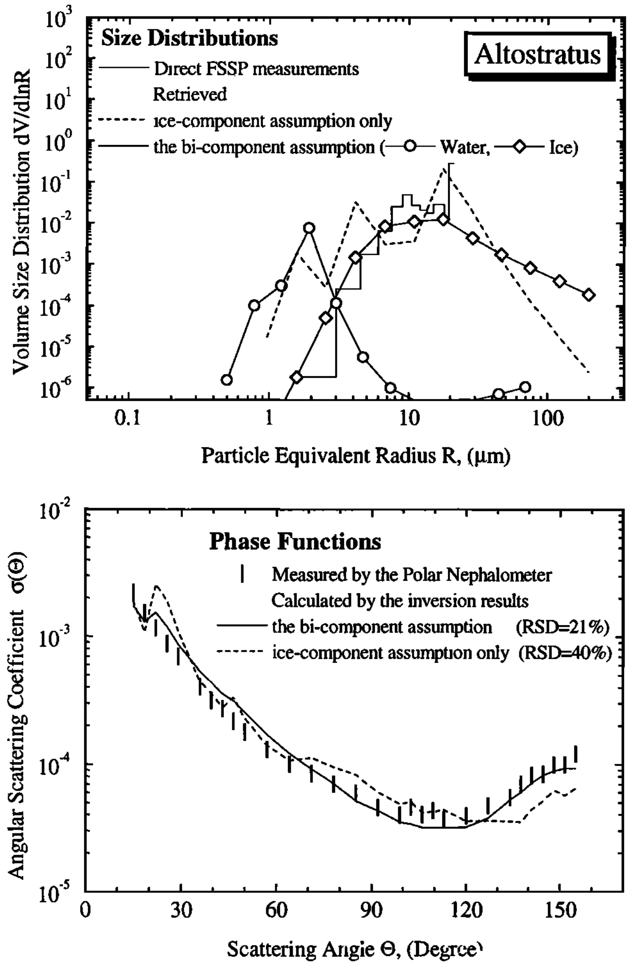

Figure 4. The same as in Fig.1 but for mixed-phase cloud obtained during NEPHELOMETER'97 airborne measurements.

phase function RSD as a function of the aspect ratio (solid line in Fig.3). As can also be seen from the comparison of solid and dashed lines in Fig.3, the minimal values of RSD are halved in contrast to those obtained under ice crystal assumption. This test along with additional numerical simulation clearly shows the potential for retrieving the aspect ratio and size composition of ice crystals simultaneously from scattering phase function measurements obtained by the "Polar Nephelometer". The assertion is also supported through additional simulated retrievals with synthetic data presented in [*Oshchepkov et al.*, 1999].

c). Mixed-Phase cloud

Typical measured scattering phase function and direct measurements along with corresponding inversion results for mixed-phase cloud (Altostratus) at 4000 m / -9^{0}C (November 26, 1997) are presented in Fig.4.

As may be seen the assumption of a single ice component only can not provide low values of the RSD (40%) and the behavior of the calculated scattering pattern differs significantly from that of the measured data. In particular, we can show false 22^0 and 46^0 halos features which are not observed in the measured phase function. The phase function RSD is reduced significantly (20%) for the bi-component assumption when one accounts for water droplet phase. In such a case, the retrieved equivalent size distribution for ice cloud is in rather good agreement with that obtained by the direct measurements (solid line with diamond symbols and histogram at the top of Fig.4).

The data presented in Fig.4 were obtained for a crystal component aspect ratio of β =5 that approximately corresponds to minimum phase function RSD as a function β.

Conclusions

The main results in treating scattering phase function measurements obtained by new airborne "Polar Nephelometer" in natural mixed-phase and iced cloud conditions were presented. A simple ice component model in which ice crystals are shaped as hexagonal plates or columns, permitted the retrieval of equivalent size distribution, component composition and the aspect ratio of ice crystals. Preliminary tests in solving the inverse light scattering problem for mixed-phase and ice clouds show that the retrieval results for particle size distribution are in rather good agreement with those obtained by the direct measurements (for which account has been taken the different physical principles governing the data acquisition). We recognize that both the direct and inverse model of ice crystal light scattering properties used in this study is still far from the ideal simulation of the natural environment. Among other factors which could be taken into account are a mixture of crystals with different shapes in the sampling volume, roughness surface of the particles, non-convex crystals, etc. The present study is however one of the first attempts to retrieve the shape of ice crystals with size and component composition of the particles simultaneously. We have to be careful not to overextend the inverse model by introducing a lot of sophisticated microphysical parameter information which could exceeds the real information content in scattering phase function measurements. It holds even the corresponding direct light scattering model would be available to reproduce light scattering properties of individual ice crystals. By this reason, one possible effective way to take complicated shape of ice crystals into account is appropriate definition of optical equivalent size in ice crystal sizing.

Acknowledgments. This research was supported in part by NASDA (under contract No.G-0033) through the facilities of the Laboratory of Meteorological Physics at Plaise Pascal University. It was also supported by grants from DRET n° 9634104, grants from ONERA n° 23.140/DA.B1/DC and was part of the AEROCONTRAIL project supported by European Economic Community.

References

Dubovik O.V., Lapyonok T.V., and Oshchepkov S.L. Improved technique for data inversion: optical sizing of multicomponent aerosols, *Appl. Opt.*, *34*, 8422-8435, 1995.

Gayet J.-F., Febre G., and Larsen H., The reliability of the MPS FSSP probe in the presence of small ice crystals. *J. Atmos. Ocean. Tech.*, *13*, 1300-1310. 1996.

Gayet J.-F., Auriol F., Oshchepkov S.L., Schröder F., Duroure C., Febvre G., Fournol J.-F., Crépel O., Personne P., and Daugereon D., In situ optical and microphysical measurements with a new airborne Polar nephelometer. *Geophys. Res. Lett.*, *25* , 971-974, 1997.

Macke A., Scattering of light by polyhedral ice crystals, *Appl. Opt.*, *32*, 2780-2788, 1993.

Muinonen K., Scattering of light by crystals: a modified Kirchhoff approximation, *Appl. Optics*, *28*, 3044-3050, 1989.

Oshchepkov, S.L., and Isaka H.,: Inverse scattering problem for mixed-phase and ice clouds. Part1: Numerical simulation of particle sizing from phase function measurements, *Appl. Optics*, *36*, 8765-8774, 1997.

Oshchepkov, S.L., Isaka H., Sinyuk A.F., and Havemann S. 1999: Inversion method for retrieval of shape and size composition of ice crystals from scattering phase function measurements: application to mixed-phase and ice clouds, in *Electromagnetic and Light Scattering by Nonspherical Particles. Theory and Applications*, edited by F. Obelleiro et al., pp. 175-182, Vigo, 1999.

Rother T., Havemann S., and Schmidt K.: Scattering of plane waves on finite cylinders with non-circular cross-sections, in *Progress in Electromagnetic Research* (PIER) 23, edited by J.A.Kong, pp. 79-105, EMV Publishing, Cambridge, Massachusetts, USA, 1999.

(Received April 21, 1999: revised August 23, 1999; accepted: November 11, 1999)