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Abstract. An Inhhomogeneous Hexagonal Monocrystal (IHM) model is used to simulate light scattering by randomly oriented hexagonal ice crystals containing air bubbles. This model based on a combination of ray-tracing, Mie theory and Monte-Carlo techniques, allows to retrieve the scattering phase function. In-situ measurements of the light scattering diagram in natural cirrus clouds with an airborne nephelometer have been performed. The results given by the IHM model have been favorably adjusted with these measurements. This agreement provides an opportunity to use this model in order to analyze ADEOS-POLDER reflectance measurements over cirrus clouds. POLDER uses an original concept to measure, for a given scene, total and polarized reflectances under several viewing directions. A first analysis of cirrus cloud spherical albedoes for the 10th November 1996 shows a rather good agreement between measurements and calculations.

1. Introduction

Cirrus clouds are generally known to have a very significant impact on the climate [*Liou*, 1986], but are identified as a major unsolved problem in climate research [*Stephens et al.*, 1990]. Natural cirrus clouds are composed of ice crystals with a very large variability in shape and size [*Miloshevich and Heymsfield* 1997]. Various well-documented observations of cirrus clouds are necessary to improve our understanding of processes relating radiative properties and microphysical characteristics. Recently, campaigns using an airborne nephelometer were held in the south of France to study the optical properties and microphysical characteristics of cirrus ice crystals [*Durand et al.* 1998]. These measurements of the differential scattering cross section of cloud particles permit to test the results of scattering phase functions obtained by theoretical models of light scattering by prismatic ice crystals. This paper investigates the potentialities of scattering phase functions deduced from hexagonal monocrystals with air bubble inclusions that we will call Inhomogeneous Hexagonal Monocrystals (IHM).

Otherwise, reflectances of cirrus clouds have been measured by the POLDER (Polarization and Directionality of Earth's Reflectances) [*Deschamps et al.* 1994] radiometer on the ADEOS platform. The IHM model adjusted from nephelometer measurements is then used to interpret these global coverage of cirrus cloud reflectance.

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2. Modeling

In the approximation of geometric optics, the calculation of the scattering matrix for simple ideal shapes of ice crystals, i.e. Pure Hexagonal Monocrystals randomly oriented in space (PHM), is commonly obtained by ray-tracing calculations enhanced with Fraunhofer diffraction [e.g. *Wendling et al.* 1979; *Macke et al.* 1996a]. These crystals are defined by their lenght L and radius R. We have considered a more realistic model following some in-situ observations. Measurements performed from ice replicator and microphotographic observations [*Strauss et al.* 1997] have shown that (i) hexagonal structure for ice particle is rather common due to natural crystalline structure of ice water at thermodynamical conditions of cirrus clouds, and (ii) air bubble inclusions appear very often inside cirrus ice particles due to a rapid growing of crystals. We have modeled ice crystals by keeping the hexagonal structure of randomly oriented ice monocrystals, but by adding trapped air bubbles as in *Macke et al.* [1996b]. Radii of bubbles follow a gamma standard law characterized by the effective radius r_{eff} and the effective variance v_{eff}. The bubbles are arbitrarily located in the crystal with a mean free path length $\langle \ell \rangle$. The ray-tracing considers the reflection and refraction events at the boundary of the ice crystal. The Monte-Carlo technique allows to simulate the internal scaterrings. When a light ray hits an air bubble, its direction is changed following the bubble scattering phase function. This internal phase function is calculated by using Mie theory.

On Fig. 1, we present the effect of inclusions on the scattering phase function $P(\Theta)$ of randomly oriented hexagonal ice crystals. The crystals have an aspect ratio $L/2R$=220μm/44μm. The PHM model is compared to the IHM model,

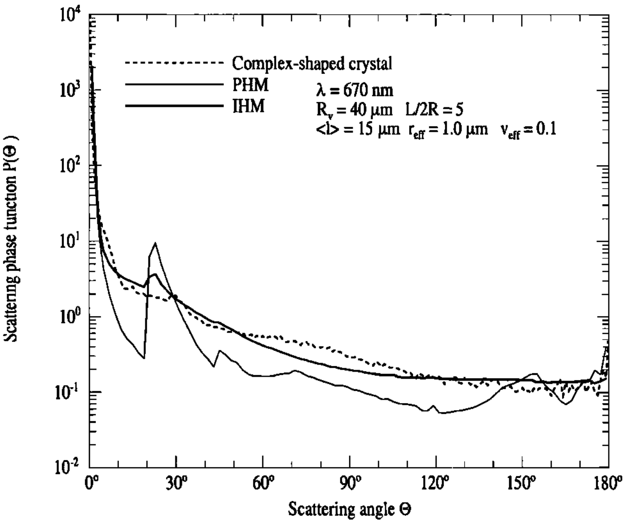

Figure 1. Comparison between different scattering phase functions.

characterized by a mean free path length $\langle \ell \rangle$ of 10 μm, an effective radius of inclusions r_{eff}=1.0 μm with an effective variance v_{eff}=0.1. The scattering phase function obtained with the IHM model has a very smooth behavior with scattering angle. Such a smoothing effect produced by a large number of internal inclusions has already been demonstrated for various host crystals [*Macke et al.* 1996b; *Mishchenko and Macke*, 1997]. It is rather comparable to those obtained with complex-shaped models as fractal polycrystals [*Macke et al.,* 1996a].

3. Airborne polar nephelometer

The polar nephelometer has already been described in details [*Gayet et al.* 1997]. It consists in measuring the differential scattering cross section $\sigma^d_{sca}(\Theta)$ of cloud particles at $\lambda = 804nm$. Due to the optical design, the scattering angles are sampled from 3.5° to 169° by a circular array of 54 photodiodes.

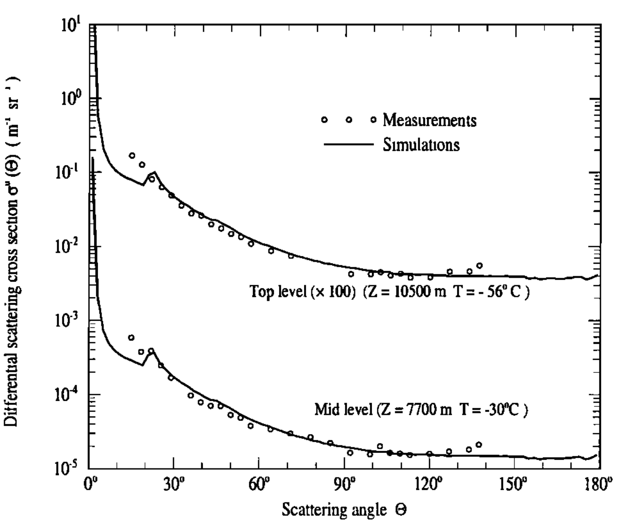

Figure 2. Comparison between in-situ measurements and IHM scattering phase function.

CIRRUS'98 was an aircraft experiment performed in Southeastern of France, during the period from 15 January to 20 February 1998 [*Durand et al.* 1998]. The polar nephelometer was installed on board the aircraft TBM 700 able to fly at a ceiling altitude of about 11000 m. Figure 2 shows examples of measurement of the differential scattering cross section $\sigma^d_{sca}(\Theta)$ as a function of scattering angle Θ. These functions are obtained for two different cirrus clouds observed on 16 February at the altitude of 7700 m (mid level in the cloud), and on 19 February at the altitude of 10500 m (upper level in the cloud). These different scattering properties are due to different microphysical characteristics of cirrus cloud, which are evidenced by the PMS OAP-2D2-C probe measurements. The mid-level distribution sampling gives an effective size S_{eff} of the crystal distribution of about 80 μm with a total crystal concentration N of about 60 particles per liter; for the other sampling we have $S_{eff} \simeq$ 50 μm and $N \simeq 200\ \ell^{-1}$. Measurements of differential scattering cross section are relatively smooth. They show sometimes weak peaks corresponding to 22° and 46° haloes, which demonstrates the presence of ice crystals with hexagonal structure.

We have adjusted our IHM model to nephelometer measurements following the relationship:

$$\sigma^d_{sca}(\Theta) = \frac{NC_{sca}}{4\pi} P(\Theta) \tag{1}$$

where N is the total particle concentration, C_{sca} is the mean scattering cross section for the randomly oriented particle, and $P(\Theta)$ the normalized scattering phase function. This adjustment reported in Fig. 2, accounts for: (i) the size and the concentration of the IHM particles, which are directly related to the value of NC_{sca}, and which is strongly linked to the magnitude of the measurements. (ii) the aspect ratio $L/2R$, which governs the relative magnitude of the secondary scattering peaks at Θ = 22°, and 46°. (iii) the mean free path lenght $\langle \ell \rangle$, which depends on the bubble concentration and size distribution and is sensitive to the magnitude of the side scattering. The main characteristics of the modeled crystal at λ=804 nm, allowing to retrieve polar nephelometer measurements for the two cases presented above, are summarized in Table 1. That corresponds to $\sim$ 4000 air bubbles per crystal, i.e. a relative volume concentration of $\sim$ 6%. The resulting asymmetry factor $\langle \cos\theta \rangle$ is 0.7809 and the single-scattering albedo is close to unity (ϖ_o=0.9999).

4. POLDER

The POLDER radiometer uses an original concept to observe a given scene under up to 14 viewing directions.

Table 1. Physical characteristics of the model.

N	82 l^{-1} (Mid level) 225 l^{-1} (Top level)
$L/2R$	220 μm/44 μm
$\langle \ell \rangle$	15 μm
$r_{eff} - v_{eff}$	1.0 μm − 0.1
C_{sca}	15450 μm^2

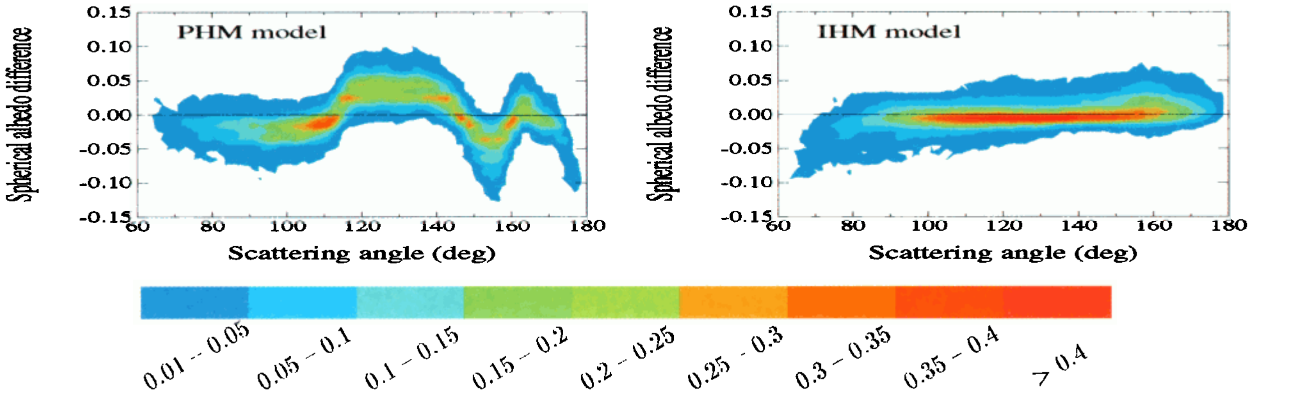

Figure 3. Difference between the directional and the directionality-averaged cirrus cloud spherical albedo, for PHM and IHM models.

POLDER onboard ADEOS has worked during 8 months from November 1996 to June 1997.

Measurements of angular reflectances obtained from the POLDER instrument are used to retrieve, for each scene, the cloud visible optical thickness (or equivalently the cloud spherical albedo) [*Buriez et al.* 1997]. The current POLDER algorithm retrieves the cloud spherical albedo without distinction between liquid and ice particles, although this distinction is possible from polarization measurements [*Parol et al.* 1999]. We selected a subset of pixels by applying following criterias: 100% ice cloud cover, absence of snow, a minimum of 7 available directions, and a minimum difference between maximum and minimum scattering angles of 50°. Due to these criteria, most of these pixels are located in midlatitude areas. We reprocessed the POLDER data of 10th November 1996 using the Discrete Ordinate Method [*Stamnes et al.*, 1988] for two models: (i) the IHM model whose parameters are in agreement with nephelometer measurements (see Table 1), and (ii) the PHM model whose external dimensions corresponds to those of the IHM model.

Figure 3 shows the difference between the "directional" and the directionally-averaged cloud spherical albedo as a function of the scattering angle. It clearly appears that the IHM model is well appropriated for ice clouds. The standard deviation of the residual directional albedoes is 0.018 for IHM while it is 0.033 for PHM.

5. Conclusion

The analysis presented in this paper shows the potentialities of the IHM model. This model is able to fit with a good agreement the measurements of differential scattering cross section performed in cirrus clouds with the airborne polar nephelometer. Moreover, the shape and the size of the IHM model is realistic and coherent with microphysical in situ measurements. Compared to PHM, the scattering phase function given by IHM gives very good results for the total reflectance measured by ADEOS-POLDER. It also gives better results than the complex-shaped ice crystals such as fractal polycrystals [*Doutriaux-Boucher et al.* 1999]. However at this stage, we cannot exclude other possibilities of microphysical model since a smooth phase function can also be obtained from inclusions in crystals with a different shape and/or irregularities at the crystal surface. As polarization is very sensitive to the shape of cirrus scatters, the measurements of polarized reflectance by POLDER is expected to be a constraint for the model. This point is under study.

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