STUDY OF ICE CRYSTALS ORIENTATION IN ICE CLOUDS BASED ON POLARIZED OBSERVATIONS FROM THE FARS SCANNING LIDAR

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ABSTRACT

In specific atmospheric conditions, ice crystals in cirrus clouds can follow a preferential orientation, an effect which has important consequences for the cloud radiative impact. Recent satellite observations have detected this phenomenon in more than 30% of the observed cirrus clouds. Documenting the parameters that drive this phenomenon, and understanding its geographic distribution are requirements for the correct parameterization of cirrus clouds in General Circulation Models.

An analysis of preferential orientation of crystals in cirrus clouds based on scanning lidar observations is presented. The angular evolution of linear depolarization ratio δ is shown to follow an analytical model. The three parameters governing this model are retrieved by fitting observations to the model. Two different orientation modes are found depending on altitude and temperature, with smaller deviations from the horizontal for colder clouds.

1. INTRODUCTION

Ice clouds cover permanently more than 40% of the Earth, and as such are important actors of the global radiative balance. Due to their high altitude, they are composed of ice crystals, which come in a infinite variety of sizes and shapes. These microphysical properties drive the cloud radiative behavior, but unfortunately are difficult to study at these altitudes. Moreover, properties derived from in situ observations cannot be extended to the entire population of cirrus clouds. Due to this limited knowledge of cirrus microphysical properties, cirrus clouds are still poorly implemented in General Circulation Models and remain one of the main source of uncertainties in climate prediction.

Traditionally, most radiative models of cirrus clouds suppose a random orientation of particles, an assumption shared by most studies of ice clouds. However, under certains hydrodynamic conditions, ice crystals can orient themselves horizontally to maximize their resistance to the falling motion [1]. Computer models have shown the crystal alignment with the horizontal plane depends on the crystal shape [2], and that this phenomenon has an important effect of the cloud radiative impact, increasing the cloud hemispherical albedo by as much as 20% [3]. Recent studies even suggest it influences the particle creation process [4].

Crystal orientation in cirrus cloud is impossible to observe in-situ, so remote sensing is the only option. The first studies of oriented crystals used photographic observations [5] and radar [6]. More recently, a specific signature of oriented crystals was found in POLDER satellite observations, in the form of a narrow peak of reflected polarized radiance [7]. This signature was used to quantify the alignment of crystals in the studied clouds [8], and highlights the strong potential of multi-angle observations for the study of oriented crystals. The same conclusion was also reached by concurrent studies of lidar observations, which showed that measurements of linear depolarization ratio δ were rapidly changing as the lidar incidence angle on the cloud was slightly tilted away from the zenith direction [9]. A comparison of multi-angle, scanning lidar observations with a ray-tracing simulation model showed that the crystal maximum deviation from the horizontal plane could be inferred by observing the inflexion point on the angular evolution of depolarization ratio [10].

The present paper uses this knowledge to retrieve the deviation of crystals in several cases of cirrus clouds, using observations of depolarization ratio from a scanning lidar. A single case is detailed in Sect. 2, and is used to present the technique to retrieve the crystal deviation. Results from several cases are presented in Sect. 3, and are discussed in Sect. 4.

2. A CIRRUS CASE STUDY : Jan, 11th 1999

2.1. Observations

Ice clouds were observed using the Polarization Diversity Lidar [11]. This dual-wavelength instrument (532 and 1064 nm) operates since 1994 at the Facility for Atmospheric Remote Sensing, leading to an important database of atmospheric soundings.

At first, a single scan of linear depolarization ratio δ for the January, 11th case is presented in Fig. 1, the lidar incidence angle from zenith θ going from -10 to +10º. A cirrus cloud is detected between 6.9 and 8.6 km. Outside the zenith region (horizontal range above 0.1 km), ranges between 0.2 and 0.35. However, for an horizontal range below 0.1 km, δ decreases sharply, down to below 0.05 for the exact zenith direction. This behavior is a typical signature of oriented crystals and is apparent between 7.0 and 7.9 km.

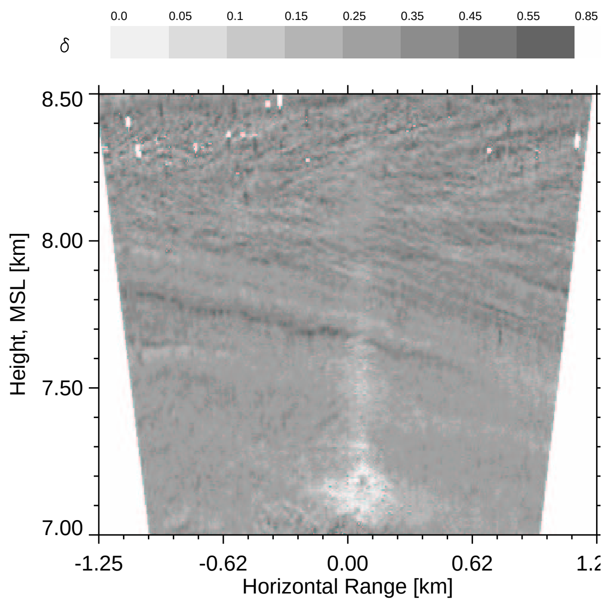

Fig. 1 : Scanning lidar observations of depolarization ratio in a cirrus cloud for Jan. 11th 1999 case

2.2. An analytical model for angular evolution of depolarization ratio

Depolarization ratio δ extracted between 7.1 and 7.2 km is shown in Fig. 2 as a function of the lidar incidence angle from zenith θ (with θ=0º denoting the zenith direction). The decrease in the zenith region seems to follow a gaussian distribution, which can be written as :

$$\delta(\theta)=\delta_{\text{out}}-\exp\left(\frac{\theta}{2\sigma^2}\right)\cdot(\delta_{\text{out}}-\delta_{\text{in}}) \qquad (1)$$

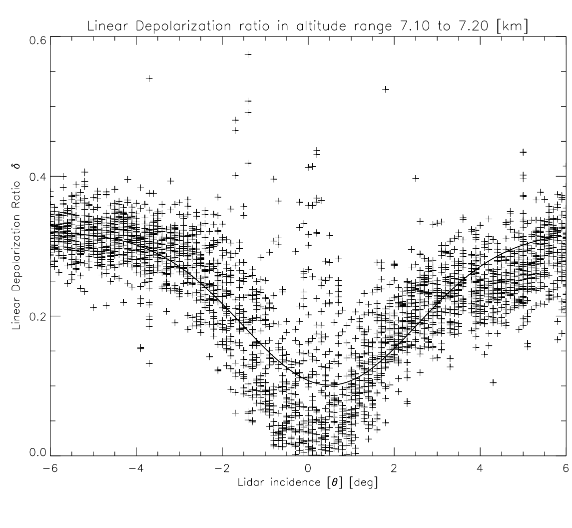

Fig. 2 : Depolarization ratio between 7.1 and 7.2 km as a function of lidar incidence angle

with δ_{out} the depolarization ratio value outside the zenith region, δ_{in} the value in the zenith direction, and σ, the standard deviation of the gaussian function. In this model, σ gives an information on the particle maximum deviation from the horizontal plan (Sect. 1).

The three parameters δ_{out} , δ_{in} and σ are retrieved by studying the angular dependence of δ in a given altitude range (e.g. Fig. 2). First estimates for δ_{out} and δ_{in} are found by averaging δ inside and outside the zenith region, and are used as starting points for a Levenberg-Marquart least-square minimization fitting technique. An angle variation domain between 0 and 10º is allowed for σ. Retrieved parameters are recorded with the corresponding altitude range and temperature.

2.3. Conditions for oriented crystals

To ensure the presence of oriented crystals in the studied altitude range, retrieved parameters must fulfill three conditions.

- High values of depolarization ratio outside the zenith region (typically, $\delta_{\text{out}}>0.05$). This condition makes sure there is a cloud in the studied altitude range.
- A significant decrease in depolarization ratio in the zenith direction (typically a 10% decrease was found to be enough).
- A good correlation with the gaussian model is required to avoid cases when a high δ_{out} and a low δ_{in} would be created by small-scale cloud inhomogeneities.

As an example, fitting the observations in Fig. 2 to the analytical model leads to parameters : $\delta_{\text{in}}=0.09$ $\delta_{\text{out}}=0.32$ and σ=2.19º. The resulting function (bold line in Fig. 2) follows the observations very closely .

2.4. Retrieved angles as a function of altitude

The same technique was applied to all altitude levels of consecutive scans for Jan. 11th, 1999. Retrieved parameter σ fulfilled the required conditions (Sect. 3.3) in 50.9% of cases, and are shown in Fig. 3 as a function of altitude.

The highest deviation angle is found at cloud bottom (near 7.0 km, σ~1.4º), decreases as low as σ~0.4º at mid-cloud (7.5 km) and increases again up to 1º at high altitudes. Angles retrieved above 8.1 km show high uncertainties and were discarded. These profile follows closely the vertical evolution of depolarization ratio near the zenith direction in Fig. 1.

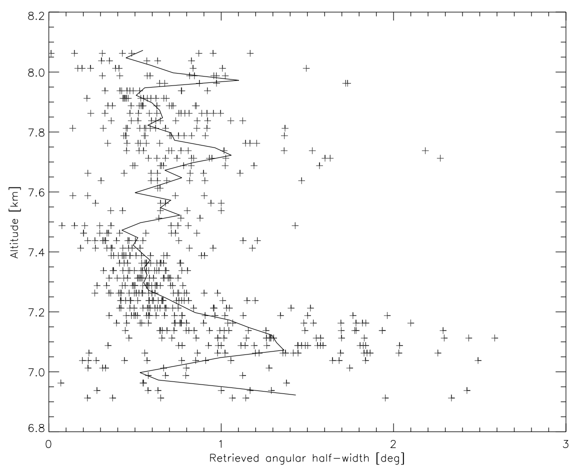

Fig. 3 : Vertical profile of retrieved deviation angles for Jan. 11th 1999 case

3. RETRIEVALS ON MULTIPLE CASES

3.1 Case description

The same technique was applied to 6 cases of ice clouds. Their properties are summarized in Table 1.

Case	*Alt. range, km*	*T. range, ºC*	*Oriented crystals*
1	6.9-8.6	-32.6,-26.8	50.90%
2	6.3-8.3	-32.0,-26.8	35.70%
3	4.8-6.4	-22.6,-17.8	20.70%
4	4.2-6.5	-16.7,-13.4	25.00%
5	4.0-5.0	-7.9, -6.8	22.00%
6	7.4-10.0	-36.3,-30.3	25.80%

Table 1 : Properties of studied layers of oriented crystals

Most of these cases do not share the same altitude. To allow the study of the vertical variability of retrieved parameters, results will be shown as a function of the penetration depth into the layer (0% meaning bottom and 100% top).

The orientation behavior depends on the particle shape [2], and in absence of oriented crystals the linear depolarization ratio is highly sensitive to particle shape. The off-zenith linear depolarization ratio δ_{out} can thus highlight variation of particle shapes amongst the studied cases. It was found that cases could be divided into two distinct groups, one centered around $\delta_{out} \simeq 0.25$ (cases 3, 4 and 5) and the other centered around $\delta_{out} \simeq 0.35$ (cases 1, 2 and 6). By reporting these cases into Table 1, it appears the first group gathers "warm" clouds (T>-20ºC) while the second gathers "cold" clouds (T<-20ºC). This seems reasonable as temperature directly affects the crystals growth process and thus their final shape.

3.2 Angle frequencies

Oriented crystals were retrieved in 22.5% of warm clouds. Retrieved angles for these clouds (Fig. 4) follow a smooth distribution, with maximum frequencies for 1.75º< σ <2.25º. Frequencies quickly decreases as the angle departs from this range. Still, 28% of angles are above 3º.

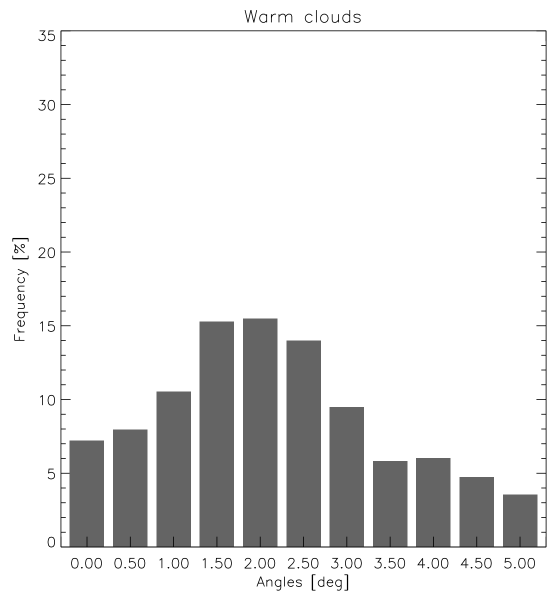

Fig. 4 : Frequencies of retrieved deviation angles for warm clouds

For cold clouds, the frequency of oriented crystals reached 35.8%. Their distribution is much more narrow, and is centered on the lower range 0.75º< σ <1.25º. Only 7% of angles are above 3º. Small deviations are clearly dominant.

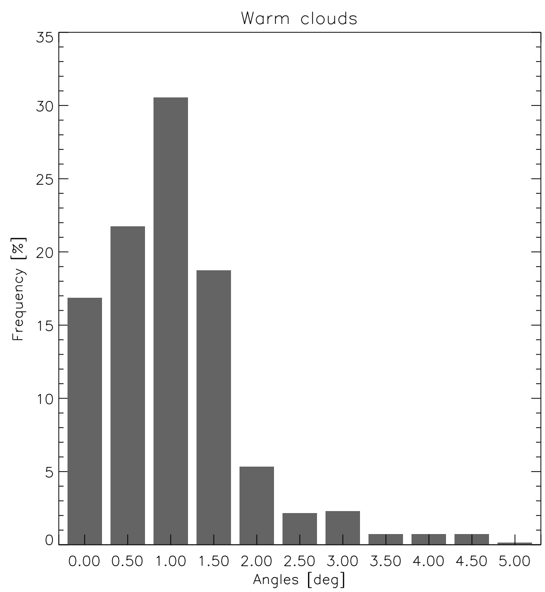

Fig. 5 : Frequencies of retrieved deviation angles for cold clouds

4. DISCUSSION AND CONCLUSION

A technique for retrieving the deviation angle of horizontally-oriented crystals in ice clouds was presented (Sect. 2.2) and applied to several observations from a scanning lidar (Sect. 2.4). Crystals in warm clouds were found to bear a higher deviation from the horizontal plane (Fig. 4), centered on an average 2º and distributed smoothly between 0 and 5º. On the other hand, crystals in high clouds are more closely aligned with the horizontal plane, with more than half of the retrieved angles below 1º (Fig. 5). These two orientation modes might be explained by differences in particle shapes, as suggested by the difference in off-zenith depolarization ratio.

The low $\delta_{out} \simeq 0.25$ observed for warm cloud is typically in the depolarization range of oriented plates. However, most theoretical studies tend to suggest a perfect horizontal orientation for this particular shape. Hollow plates, or late evolutions of planar crystals in their lifecycle are a possibility. The higher $\delta_{out} \simeq 0.35$ observed in cold clouds is more difficult to interpret, as it lies into the depolarization range of several particle shapes. However, only particle susceptible to horizontal orientation should be considered, in which case dendrites or thick plates are a possible hypothesis.

Among the studied cases, oriented ice crystals were more frequent in cold clouds (~35%), and there showed the closest alignment with the horizontal plane. This has important radiative consequences : horizontally-oriented crystals increase the cloud hemispherical albedo, with noticeably higher increases for perfectly horizontal particles. As the albedo of high clouds directly impacts the quantity of sun radiation entering the atmosphere in the visible wavelength, this phenomenon could have a noticeable impact on the global radiative balance. More studies of crystal orientation are required to evaluate the geographic distribution of this phenomenon and the variability of the deviation angle. This will require the use of multi-angle satellite observations [7], such as polarized radiances from the upcoming Parasol experiment.

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