ATSR-2 derived cirrus crystal size and optical thickness for different hexagonal crystal shapes

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ABSTRACT: In this paper the effect of changing the crystal shape of hexagonal ice crystals on ATSR-2 retrievals of cirrus crystal size (r_{eff}) and optical thickness (τ) is investigated. The 0.87 µm and 1.6 µm channels of ATSR-2 are used to simultaneously retrieve r_{eff} and τ. The shape of the crystals is adjusted by changing (1) the degree of crystal imperfectness, and (2) the crystal aspect ratio (the ratio of the two principal crystal axes). It is found that, by varying the degree of crystal imperfectness, consistent nadir/forward retrieval of *both* r_{eff} and τ is problematic. Consistent retrievals of r_{eff} prove to be possible for a broad range of crystal aspect ratios. By considering existing relationships between aspect ratio and crystal size, it appears that most of the retrieved combinations of crystal size and aspect ratio are inconsistent with these measurements.

Introduction

Several studies suggest that the accuracy of crystal size and optical thickness retrievals from satellite measurements is dependent on the assumed particle shape in single-scattering models. Mishchenko et al. (1996), for example, pointed out the importance of using the correct particle shape model for cirrus clouds, i.e. crystal instead of water droplet. Since ice clouds may consist of a variety of non-spherical particles, such as hexagonal columns or plates, dendritic crystals, needles, and all sorts of complex-shaped crystals (Auer and Veal, 1970), the question of which crystal shape(s) should be used is a matter of debate. In this paper we investigate the effects of changing the degree of crystal imperfectness and the magnitude of the aspect ratio (the ratio of the two principal crystal axes) on satellite retrievals of crystal size and optical thickness. The investigation is limited to the hexagonal crystal shape. The analysis is performed on the basis of ATSR-2 reflectivity measurements made over a tropical cirrus anvil in the area of the southern Pacific Ocean (14°N, 134°E) on September 6, 1996. The potential of retrieving microphysical parameters of (cirrus) clouds from ATSR-2 data has been demonstrated before by e.g. Watts (1995) and Baran et al. (1998).

ATSR-2 measurements

The reflectivity measurements are obtained by the Along-Track Scanning Radiometer (ATSR-2) on board the ESA/ERS-2 satellite. This imaging instrument produces images of the Earth at three visible/near-infrared wavelengths (0.55, 0.67 and 0.87 µm) and four infrared wavelengths (1.6, 3.7, 11 and 12 µm). The instrument has been designed to observe the same scene in nadir view (zenith angle between 0° and 25°) and in forward view (zenith angle between 52° and 55°). The spatial resolution at nadir is about 1×1 km^2. For the analysis presented here we utilized measurements made at wavelengths of 0.87 and 1.6 µm, and in nadir and forward viewing directions. These directions correspond to scattering angles of 161° and 121°, respectively. The solar zenith angle at the time of the ATSR-2 overpass is 23°.

The case used for our analysis has formerly been described by Knap et al. (1999). For the sake of clarity, some of the results shown by these authors will be repeated here. As an example, Figure 1 shows the cirrus reflectivity measurements at 0.87 and 1.6 µm for the nadir viewing direction. Going from the lower left to the upper right corner of the figure, the observed cloud system gradually thickens from the single scattering regime to the asymptotic limit of optically thick cirrus. The flattening of the curve is typical for measurements made at two wavelengths for which the absorption of ice is highly different: the imaginary part of the refractive index of ice at 1.6 μm is three orders of magnitude larger than at 0.87 μm (Warren, 1984).

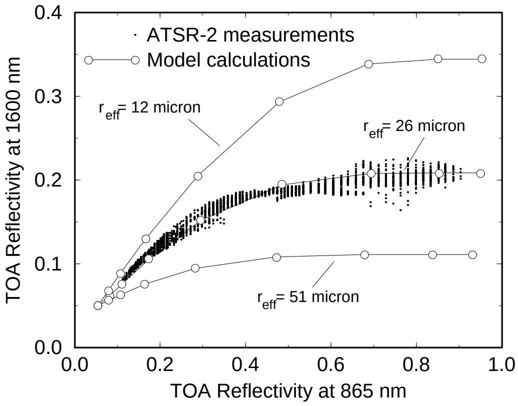

Figure 1: ATSR-2 nadir measurements of reflectivity at 0.87 and 1.6 μm made over a tropical cirrus anvil (small dots), compared to model calculations for a cloud consisting of single-sized imperfect hexagonal ice crystals (open circles).

Retrieval method

For simultaneous retrieval of effective crystal size (r_{eff}, to be defined below) and optical thickness (τ) from the ATSR-2 reflectivities we performed single scattering calculations with a model based on the principles of geometrical optics and ray-tracing (described by Hess et al., 1998), and multiple scattering calculations with a model based on the doubling-adding method (described by Stammes, 1994).

The basic ice particle that we used for single scattering calculations is the regular hexagonal crystal. The shape of the crystal is defined by two parameters: A and α. The first parameter, the aspect ratio of the crystal, is the ratio of the crystal c-axis (c) and the a-axis ($2a$). The second parameter relates to a certain degree of crystal imperfectness, i.e. a deviation from the ideal hexagonal shape. Following Macke et al. (1996), crystal imperfectness is modelled by randomly tilting the crystal surface every time a photon interacts with and air/ice interface. The maximum tilt (zenith) angle is indicated by the parameter α mentioned above. The value α = 0° corresponds to the ideal hexagon. The larger α, the more the crystal shape deviates from the ideal shape. Hess et al. (1998) state that α = 30° is a suitable value for irregular hexagonal ice crystals.

Here, we define the effective crystal size r_{eff} as the volume-equivalent sphere radius for the hexagon:

$$r_{eff} = \left(\frac{9\sqrt{3}}{8\pi} a^2 c \right)^{1/3}$$

In order to retrieve τ and r_{eff}, we followed a look-up table approach (details are described by Knap et al., 1999). The retrieval of τ is mainly determined by the 0.87 μm reflectivity, whereas there is a strong size effect on the 1.6 μm reflectivity (at 1.6 μm the single scattering albedo depends to a high degree on the particle size).

Results

Figure 1 shows, besides ATSR-2 measurements, model calculations for three clouds consisting of imperfect hexagonal ice crystals of different size (all columns with α = 30°). The crystal dimensions are taken from the COP data library (Hess and Wiegner, 1994) and correspond to effective radii of 12 μm (type C1), 26 μm (C2) and 51 μm (C3). Apparently, the ATSR-2 measurements are adequately explained by calculations for a cloud consisting of imperfect crystals of type C2. This suggests that the variability in crystal size over the cirrus cloud system is relatively small, which makes the selected ATSR-2 image a good case for studying the effect of assumed crystal shape on retrievals of crystal size.

Figure 2 shows retrievals of τ and r_{eff} for a cloud consisting of imperfect hexagonal columns (α = 30° and A = 1.4; COP type C2). Nadir- and forward-derived values of r_{eff} agree well: on average we find r_{eff} = 28 ± 2 μm (nadir) and r_{eff} = 27 ± 1 μm (forward). In order to avoid large retrieval errors, these averages were calculated using only pixles for which τ > 10. In this regime the retrieval error in r_{eff} due to errors in the ATSR-2 reflectivities is estimated to be 1-2 μm. Retrieval errors in τ are generally small, ranging from 2 for optically thick clouds to 0.2 for optically thin clouds. All errors are estimated on the basis of an absolute error of 0.01 in the ATSR-2 reflectivities.

The retrievals of τ reveal a trend for nadir-derived τ and forward-derived τ to diverge as τ increases. In the following two subsections we will investigate the effect of changes in α

and A on the retrievals of τ and r_{eff}. Emphasis will be laid on the degree of consistency of nadir- and forward-derived τ and r_{eff}.

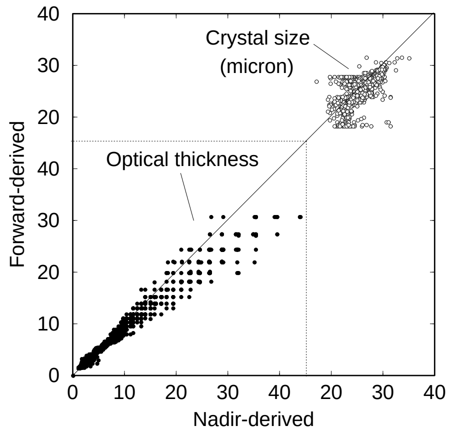

Figure 2: Nadir- and forward-derived τ and r_{eff} for α = 30° and A= 1.4 (COP type C2). Note that the axes are divided into two parts: one for τ (0-40) and one for r_{eff} (20-40 µm).

Changing the maximum tilt angle

Figure 3 summarizes the effect of changing the maximum tilt angle α (i.e. changing the degree of crystal imperfectness) on the retrievals of τ and r_{eff}. Shown are the ratio of nadir- to forward-derived r_{eff} and the slope of a linear fit through the data pairs of nadir- and forward-derived τ. The largest difference between r_{eff}(nadir) and r_{eff}(forward) is found for α = 0°, where the former is about 4 µm larger than the latter. Apparently, best agreement between the two quantities is reached for $\alpha \sim 35°$.
The decrease of the ratio r_{eff}(nadir) / r_{eff}(forward) with increasing α is mainly on account of an increase in r_{eff}(forward). This quantity increases uniformly from ~ 23 µm (α = 0°) to ~ 28 µm (α = 40°).

Whereas r_{eff}(nadir) and r_{eff}(forward) agree better as α increases, best agreement for τ is obtained for α close to 0. For larger α, τ(nadir) overestimates τ(forward), in particular for optically thick clouds. In conclusion we may state that we cannot reconcile nadir with forward retrievals of both τ and r_{eff} by varying α.

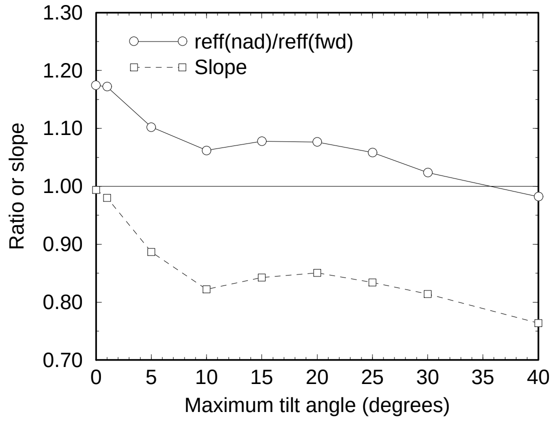

Figure 3: Retrievals of τ and r_{eff} as a function α. The aspect ratio A = 1.4 (COP type C2). The circles refer to the ratio r_{eff}(nadir) / r_{eff}(forward). The squares give the slope of a linear fit through the data pairs (τ(nadir), τ(forward)). If nadir and forward retrievals are consistent, the ratio and the slope both equal unity for the same α.

Changing the aspect ratio

Starting point of the computations presented in this section is the variation of the aspect ratio of hexagonal ice crystals with size, according to Hess and Wiegner (1994) (Figure 4). The shape-size relationship presented by these authors is based on measurements made in natural clouds and compiled by Auer and Veal (1970).

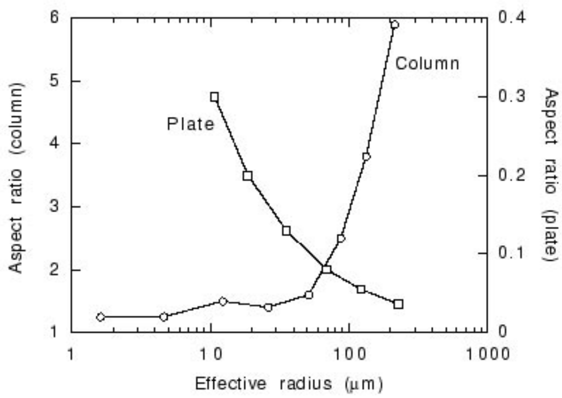

Figure 4: Aspect ratio [A] as a function of effective crystal radius (r_{eff}), according to the COP data library of optical properties of hexagonal ice crystals (Hess and Wiegner, 1994).

We chose eight different aspect ratios, varying from 0.05 (flat hexagonal plate) to 5.9 (long hexagonal column). This range more or less covers the shapes found in the COP data library. To focus on the effect of changes in the aspect ratio only, the maximum tilt angle was fixed to its value for rough crystals (α = 30°). Table 1 summarizes the results.

Table 1: Results of the aspect-ratio experiment. The average maximum crystal size is indicated by *D*. The range in the fifth column refers to the range of maximum crystal sizes corresponding to a certain aspect ratio, according to Hess and Wiegner (1994). The bold numbers indicate ATSR-2 retrievals that are consistent with these ranges.

A	r_{eff} (μm)		D	Range (D)	Slope
	nadir	forw.	(μm)	(μm)	(τ)
0.05	16 ± 1	17 ± 1	42	> 900	0.79
0.1	19 ± 1	20 ± 1	40	> 200	0.88
0.25	23 ± 1	24 ± 1	**34**	**< 40**	0.79
0.5	28 ± 1	27 ± 1	32	< 20	0.81
1.25	28 ± 2	27 ± 1	60	< 20	0.82
1.4	28 ± 2	27 ± 1	**63**	**40 – 90**	0.81
2.5	25 ± 1	26 ± 1	86	200 – 400	0.74
5.9	24 ± 1	25 ± 1	149	900 - 2000	0.76

Concentrating on the effective radius, two regimes can be distinguished: one where r_{eff} is insensitive to variation in the aspect ratio ($0.5 \leq A \leq 1.4$) and one where r_{eff} decreases with decreasing or increasing aspect ratio ($A < 0.5$ or $A > 2.5$). In the first regime, where the crystals are neither very long nor very flat, the single scattering characteristics (for the scattering angles considered) are determined by the volume of the crystals, and not by their shape: for fixed effective radius, or volume, the phase function appears to be insensitive to variation in the crystal shape (result not shown). In the second regime the model cirrus cloud consists of either flat plates ($A < 0.5$) or long columns ($A > 1.4$). Opposite to the situation in the former regime, the phase function is sensitive to variation in the crystal shape: flattening or elongating of the hexagons leads to a strong reduction in the phase function for the two scattering angles considered (not shown). Referring to the retrieval of r_{eff}, the reduction in the phase function is compensated by a decrease in the degree of absorption. This explains the observed reduction in the retrieved effective radius, or volume, of the ice crystals.

The results described above suggest that there is no preference for a certain value of the aspect ratio: retrievals of r_{eff} and τ are possible for the entire range 0.05 – 5.9. However, Figure 4 suggests that there is a typical relationship between aspect ratio and crystal size. Hess and Wiegner (1994) give ranges of maximum crystal dimension (*D*) for different aspect ratios. If we compare these with maximum crystal sizes derived from the ATSR-2 data (Table 1), we can conclude that the range of solutions is narrowed significantly, and that only two crystal shapes produce maximum crystal sizes that are consistent with the measurements (bold in Table 1).

As for optical thickness (see last column of Table 1), the slope deviates always significantly from unity. So, in contrast to varying α, changing the aspect ratio of the crystals does not lead to consistent retrievals of τ for nadir and forward viewing angles.

Concluding remarks

In this paper we investigated the effect of the assumed shape of imperfect hexagonal ice crystals on ATSR-2 retrievals of effective crystal-size (r_{eff}) and optical thickness (τ) of a tropical cirrus anvil. Two shape experiments were performed: changing the degree of crystal imperfectness (from $\alpha = 0°$ to $\alpha = 40°$) and the aspect ratio (from $A = 0.05$ to $A = 5.9$).

The effect of changing α on mean retrievals of r_{eff} can be up to five times larger than the standard error in the mean of the ATSR-2 retrievals (5 μm compared to 1 μm on an average of 28 μm for irregular crystals). The effects of α on r_{eff} and τ are highly correlated (Figure 3) which, in this particular case, resulted in the fact that, by varying α, we could not obtain consistent retrievals of *both* r_{eff} and τ for the nadir and forward viewing direction of ATSR-2. In this respect it should be noted that the set of experiments that we carried out is not exhaustive. For example, we have not varied A for $\alpha = 0°$ (ideal hexagon). Besides, we have not investigated any inadequacy with respect to the multiple scattering model. It is conceivable that complex factors, such as vertical cloud structure, contribute to nadir/forward inconsistencies.

The aspect-ratio experiment learned that retrievals of r_{eff} and τ are possible for the entire range of A considered (0.05 - 5.9). For A between 0.5 and 1.4 the retrieval of r_{eff} appears to be insensitive to variation in A. Outside this range, r_{eff} decreases significantly (largest decrease: from 28 to 16 μm as A

decreases from 0.5 to 0.05). Through consideration of *in situ* measurements of crystal size and aspect ratio (not related to the present study), it appeared that most of retrieved combinations of crystal size and aspect ratio are inconsistent with these measurements (Table 1). It is therefore important to note that relationships between crystal size and aspect ratio derived from *in situ* measurements are indispensible as constraint in retrieval methods.

Acknowledgements

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