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Abstract

A set of 6500 angular scattering function data have been obtained at various locations of the world: Vienna (Austria), Kyoto (Japan), Granada (Spain) and Palencia (Spain). The aerosols in these locations were considerably different, ranging from continental, urban, maritime, to desert dust. The volume scattering function has been measured between 5° and 175°, the values for 0° to 5° and 175° to 180° have been obtained by extrapolation of the shape of the curve, thus the whole range of scattering angles was available for calculating the backscattered fraction and the asymmetry parameter of the aerosol. The majority of the data points suggest an unanimous relation between backscattering and asymmetry parameter. The location where sampling took place and the type of aerosol seems to be of minor importance. These data have been compared with results of calculations for spherical or ellipsoidal particles having a lognormal monomodal size distribution of various sizes as well as several approximations for the relationship asymmetry vs backscattering available from the literature. With one exception it appears that an unanimous relation, fairly independent of location and type of aerosol, has been found between asymmetry parameters and backscattering ratio. The assumption of spherical particles seems to be a good assumption. Only for aerosols dominated by coarse mode particles the data points fall outside of the general trend, but again Mie calculations for spherical particles explain the behaviour.

Introduction

The fraction of backscattered light is defined as the ratio of the integral of the volume scattering function over the backward half solid angle divided by the integral of the volume scattering function over the full solid angle. It can be measured with an integrating nephelometer since it only is needed to exclude the forward scattered light by a shutter (small angular truncation occurs). On the other hand the asymmetry parameter is the integral over the full solid angle of the volume scattering function weighted with the cosine of the scattering angle divided by the integral of the volume scattering function. To determine the asymmetry parameter the measurement of the angular dependence of the volume scattering function is needed, which can be obtained e.g. with a polar nephelometer.

The asymmetry parameter is an important input parameter for radiative transfer calculations in order to obtain information of effects of the atmospheric aerosol (climate, screening, visibility, and others).

Unfortunately measurements of the asymmetry parameter of the atmospheric aerosol are scarce. It is obvious, that a relation between the asymmetry parameter and the backscattered fraction should exist: the smaller the backscattered fraction, the more asymmetric the scattering, thus the larger the asymmetry parameter.

Defintions

A volume element dV be illuminated by parallel light with flux density S, see figure 1. The light flux $d^2\Phi$ scattered by the particles of this volume element into a cone of angular extent $d\omega$ in the direction characterized by the scattering angle θ (which is the angle between the considered direction of the scattered light and the direction of the transmitted light) is $d^2\Phi = S \cdot \gamma(\theta) \cdot dV \cdot \mathrm{d}\omega$ with $\gamma(\theta) = \frac{d^2\Phi}{S \cdot dV \cdot d\omega}$ the volume scattering function. Rotational symmetry around the direction of the incident light beam is assumed. This is the case for spherical particles or particles undergoing Brownian rotation.

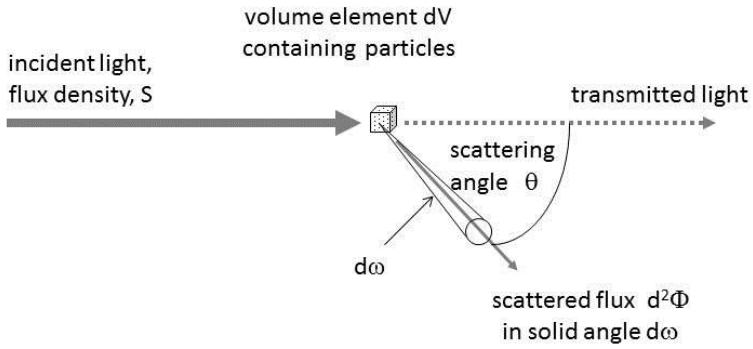


Figure 1. Definition of the scattering function.

Integrating the volume scattering function over the full solid angle yields the scattering coefficient $\sigma_s = \int_{\omega} \gamma(\theta) d\omega = 2\pi \int_0^{\pi} \gamma(\theta) \sin\theta . d\theta$, which characterizes the totally scattered light by the volume element. The fraction of light scattered in the backward direction (also called hemispheric backscattering)

is obtained as $b = 2\pi \int_{\pi/2}^{\pi} \gamma(\theta) \sin\theta . d\theta \Big/ 2\pi \int_{0}^{\pi} \gamma(\theta) \sin\theta . d\theta = 2\pi \int_{\pi/2}^{\pi} \gamma(\theta) \sin\theta . d\theta \Big/ \sigma_s$. The asymmetry parameter g is obtained by weighing the volume scattering function with the cosine of the scattering angle: $g = 2\pi \int_{0}^{\pi} \gamma(\theta) \sin\theta . \cos\theta . d\theta \Big/ \sigma_s$. For isotropic scattering or symmetric scattering such as Rayleigh scattering the asymmetry parameter is g=0 and $b = \frac{1}{2}$; for scattering in the forward direction ($\theta = 0$) only, we obtain g=1 and b=0, for backscattering only ($\theta = \pi$) the asymmetry parameter is g=-1 and b=1.

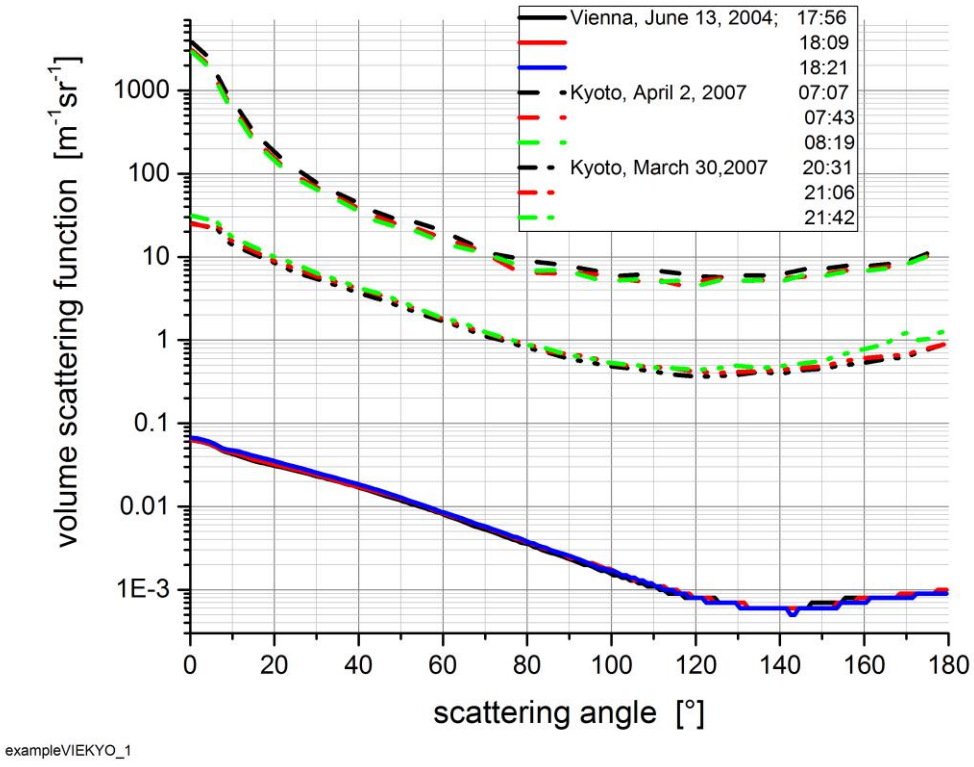
If the phase function $P(\theta) = 4\pi \frac{\gamma(\theta)}{\sigma_s}$ is used, the relations are as follows: $g = \frac{1}{2} \int_{0}^{\pi} P(\theta) \sin\theta . \cos\theta . d\theta$ and $b = \frac{1}{2} \int_{0}^{\pi} P(\theta) \sin\theta . d\theta$. Both the asymmetry parameter, the backscattered fraction, and the phase function are intensive parameters of the aerosol. The scattering coefficient and the volume scattering coefficient can be made intensive by dividing by the density of the aerosol (i.e. mass of particles per volume of air), yielding the specific scattering coefficient, or more systematically the specific cross section and the specific volume scattering coefficient. The usual units are $m^2 g^{-1}$ and $m^2 g^{-1} sr^{-1}$.

For an aerosol the scattering coefficient can be measured e.g. with a nephelometer, or calculated when knowing the size distribution, shape, and refractive index of the particles. The scattering coefficient is an extensive property, depending on the size of the system (e.g. the mass of particles per unit volume). Dividing the scattering coefficient σ_s by the mass m of the particles per volume of suspended medium, the specific scattering cross section $\left(\frac{d\sigma_s}{dm} \right)$ is obtained. The scattering coefficient of an aerosol of mass *m* per volume and specific scattering cross section $\left(\frac{d\sigma_s}{dm} \right)$ is obtained as $\sigma_s = m \cdot \left(\frac{d\sigma_s}{dm} \right)$.

Instruments and methods.

The volume scattering function is obtained with a polar nephelometer. Its design is similar to Waldram (1945). In principle it uses the definition of the volume scattering function (see figure 1). The scattering volume is illuminated by a green laser and the flux of scattered light is measured by a photodetector, which rotates from 5.5° to 172.5°. A scan starts at 5.5° going to 172.5° and back in intervals of 5°, but uses smaller intervals in the near forward and backward region. The volume scattering function is obtained by averaging the forward and the back scan, rejecting measurements with discrepancies between the scans in the two directions. Calibration of the nephelometer is done by a Rayleigh scattering gas, in particular CO_2. The instrument thus can measure the volume scattering coefficient for scattering angles between 5.5 and 172.5°. For the determination of the backscattered fraction and the asymmetry parameter the volume scattering function has to be extrapolated to 0° and 180°, a common problem (Middleton 1968). Only a small angular range of the scattering function cannot be determined by the polar nephelometer used in this study , therefore the extrapolation is possible with a high degree of accuracy; the shape of the measured curve can be used as an indicator for the continuation (Horvath, 2015, companion paper). All volume scattering functions given below are for particles only, i.e. without the Rayleigh scattering of the

air. All data for the scattering function, backscattered fraction and asymmetry parameter are for a wavelength of 532 nm.



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Fgure 2: Examples for volume scattering functions. The backscatterd fraction and the asymmetry parameter for the volume scattering function, given as pairs [g,b] are: Vienna: [0.082,.628], [0.0825,0.628], [0.0771,0.637]; Kyoto, April 2: [0.088,0.743], [0.091,0.738], [0.094,0.732]; Kyoto March 30: [0.134,0.577], [0.137,0.576], [0.138,0.577].

The measurements of the volume scattering function have been performed at various locations (Vienna, Austria; Granada, Spain; Palencia, Spain; and Kyoto, Japan), a total of 6500 volume size distributions have been determined. At all locations the instrument was situated in an unheated room with temperatures close to the outside air. Sampling was done through a tube with 12 mm inner diameter and a length of 1.5 to 2.5 m, depending on the location, at a flow rate of 20 liters per minute. The sampling inlet was 10 to 20 m above ground at a location shielded by wind. The particles are taken out of the mostly still air by a horizontal tube. This process can be size selective, since in the tube the particles can be lost due to sedimentation and diffusion. Using the graphs for sampling in still air given by Hinds (1999) the intake with the given diameter and flow rates had negligible losses for particles up to a diameter of 10 µm. Loss of particles due to sedimentation in the horizontal part of the tube amounted to 10, 2, and 0.3 % for particles with diameters of 10, 5, and 2 µm. Losses due to diffusion were below 0.02%. In the rare case of air movement above 3m.s^{-1} the sampling would be anisokinetic. For a wind speed of 10 m.s^{-1} and the sampling at 90° (worst case), the inlet losses would be 25, 3, and 0 % for particles with diameters of 10, 5, and 2 µm. Thus it can be concluded, that for the most important particles sizes, which are below 5 µm, the sampling losses are negligible.

Results

Three examples for scattering functions determined in this study can be seen in figure 2.

The aerosol measured in Vienna is the usual continental aerosol, with a minimum of the phase function around a scattering angle of 140° a slight increase in the backwards region and strong forward scattering. The usual aerosol measured in Kyoto (March 30, 2007) has a similar shape, except for its higher absolute value on these two days. As contrast the phase function of a completely different aerosol sometimes observed in Kyoto is shown (April 2, 2007). The majority of the particles in this aerosol is aeolian dust originating from the deserts in Mongolia, Northern China and Kasachstan and transported to Kyoto. For this aerosol the majority of the particle mass is in the super micrometer size range, and consequently, the forward scattering is greatly enhanced as well as some increase in backscattering can be seen. For all the measured volume scattering functions the asymmetry parameter and the backscattered fraction were calculated and all the data points are shown in figure 3.

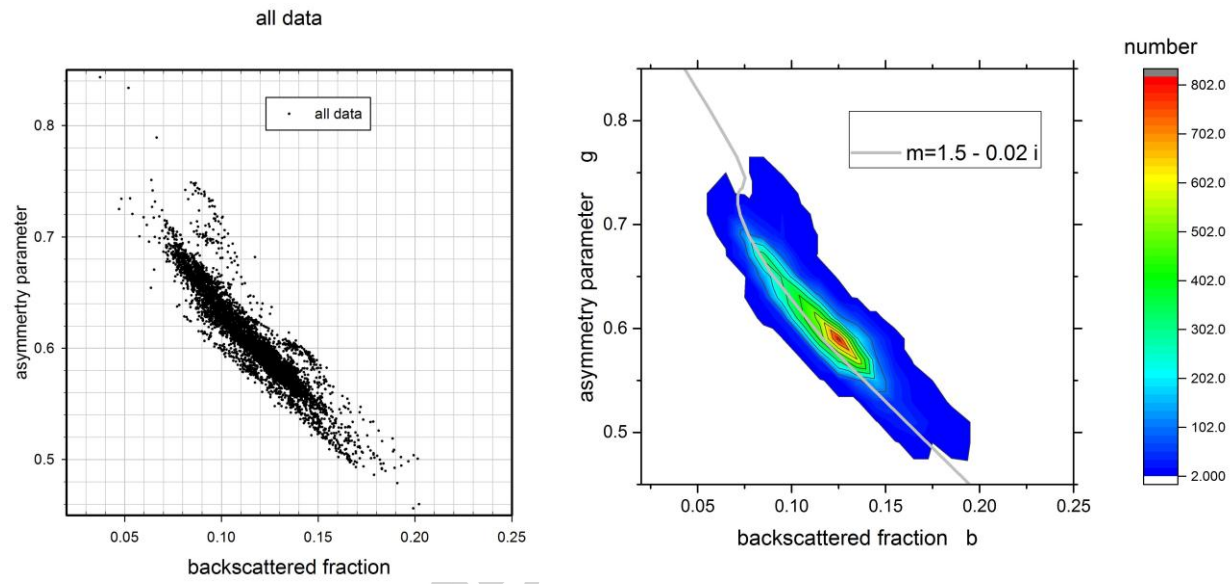

Figure 3. Relation of backscattered fraction to the asymmetry parameter. Left: all data points, right: contour plot for all data points. The solid line represents the relation between b and g for spherical particles having a lognormal size distribution with a geometric standard deviation of 1.7. and variable median size.

The data for the different locations are shown in figure 4. There is no essential difference between the sites.

Discussion

For model aerosols with a monomodal lognormal distribution of spherical particles and varying mass median diameter, the scattering function has been calculated and used to determine the relationship between asymmetry parameter and backscattering fraction, which is shown as grey line in figures 3 and 4. The experimental data points are very close to this line. Using other refractive indices gives an almost identical curve, except for pure carbon (see below).

The volume scattering function of an aerosol depends on the particles size and refractive index. Examples are shown for particles below and above 1 µm in figures 5. The asymmetry parameter and the backscattered fraction are listed in table 1. Particles with a median diameter of 30 nm have an almost symmetric scattering, consequently the backscattered fraction is close to 0.5 and the asymmetry parameter is close to zero. For particles of 50 nm (slightly larger) an increase in the forward scattering is clearly visible, thus the scattering is asymmetric. This leads to an increase in the asymmetry parameter and a decrease in backscattering. With increasing particle size the forward scattering becomes more pronounced, causing a larger asymmetry parameter and a smaller backscattering fraction. For particles sizes larger than 1µm the backscattering considerably increases with some indications of resonances. This is not the case for irregularly shaped particles, here the increase of the backscattering is restrained but on the other hand the side scattering is increased, compared to the spherical counterpart (Mishchenko, 2009). Zubko et al (2015) found a similarity of the phase function for various morphologies, but a strong influence of the refractive index.

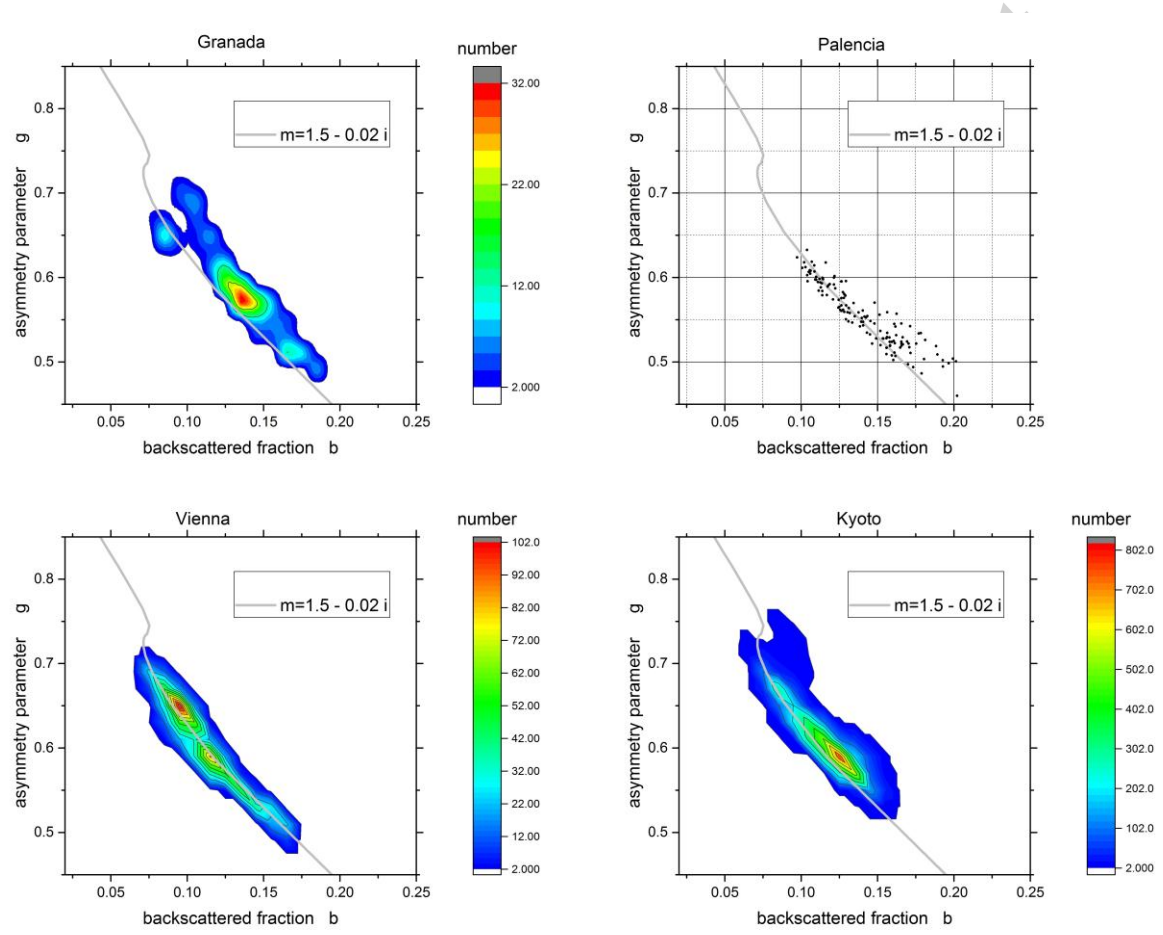

Figure 4: Relationship between backscattered fraction and asymmetry parameter for the different locations. Only slight differences between the locations do exist. At each location the data points are very close to the line for the model aerosol.

For comparison the specific volume scattering function for black carbon is shown in figure 6. Two features are immediately evident: For the 30 nm particles specific scattering function is a considerably larger for the light absorbing particles, whereas for larger particles the specific scattering function is less and especially the back scattering is without any structure and no increase when approaching 180°. But it should also be noted, that spherical black carbon particles above 100 nm are very unlikely in the atmosphere.

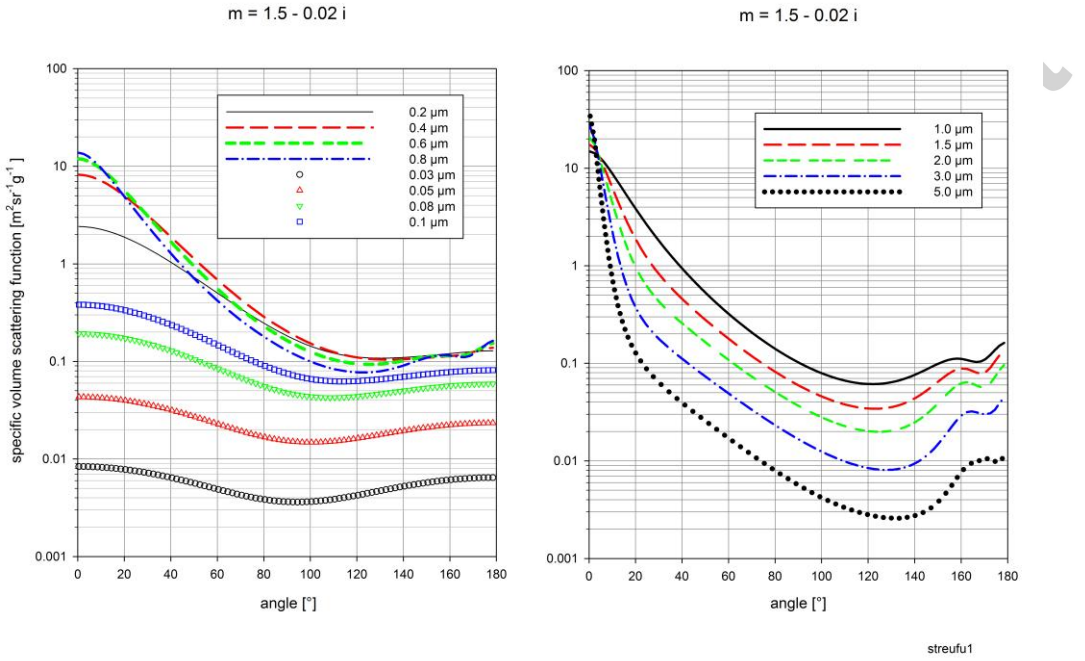

Figure 5. Specific volume scattering functions for aerosols with variable median diameter.

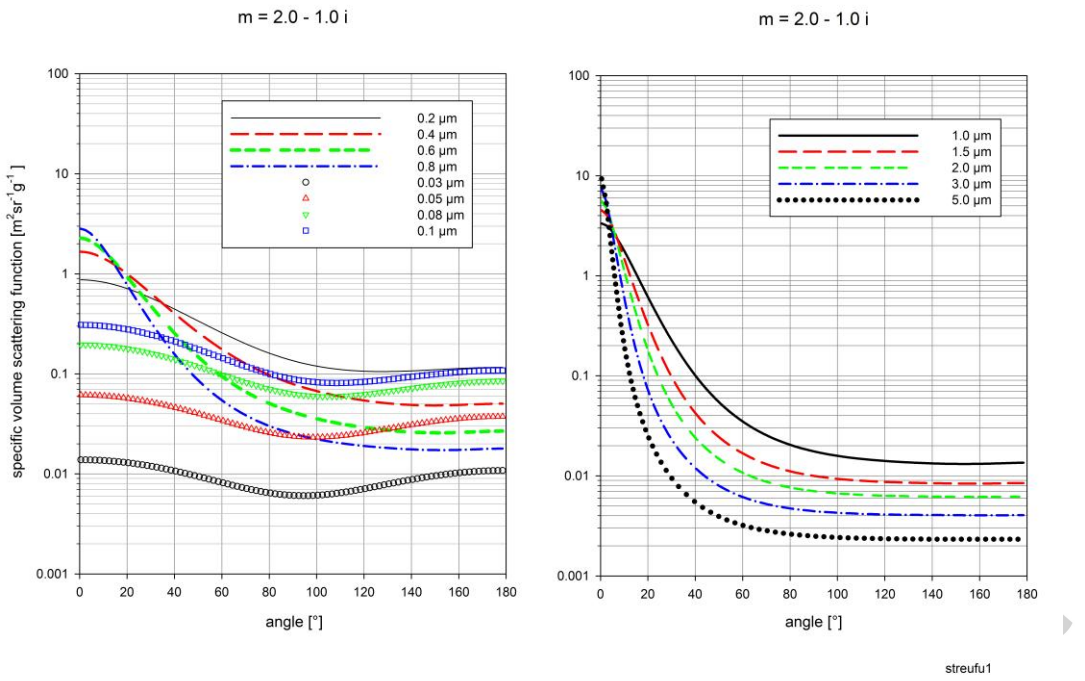

Figure 6. Specific volume scattering functions for black carbon aerosols with variable median diameter.

Table 1

median diameter [µm]	back scattered fraction	asymmetry parameter	median diameter [µm]	back scattered fraction	asymmetry parameter	median diameter [µm]	back scattered fraction	asymmetry parameter
refractive index 1.5 - 0.0 i			refractive index 1.5 - 0.02 i			refractive index 2.0 - 1.0 i		
0.03	0.461	0.055	0.03	0.461	0.055	0.03	0.462	0.053
0.05	0.408	0.129	0.05	0.409	0.128	0.05	0.425	0.105
0.08	0.327	0.246	0.08	0.328	0.244	0.08	0.379	0.171
0.1	0.28	0.315	0.1	0.282	0.313	0.1	0.353	0.209
0.2	0.129	0.549	0.2	0.148	0.53	0.2	0.256	0.362
0.4	0.089	0.662	0.4	0.082	0.674	0.4	0.154	0.554
0.6	0.083	0.693	0.6	0.072	0.715	0.6	0.112	0.658
0.8	0.087	0.698	0.8	0.072	0.729	0.8	0.094	0.715
1	0.093	0.694	1	0.073	0.735	1	0.086	0.749
1.5	0.01	0.683	1.5	0.075	0.745	1.5	0.079	0.789
2	0.01	0.687	2	0.071	0.765	2	0.077	0.806
3	0.092	0.715	3	0.054	0.816	3	0.076	0.82
5	0.074	0.755	5	0.034	0.879	5	0.076	0.829

The relation between backscattered fraction and asymmetry parameter has been calculated for spherical particles having a monomodal lognormal size distribution with various median diameters and refractive indices. Results are shown in figure 7. The relationship between backscattering and asymmetry is influenced by the diameter; smaller diameters are represented in the right bottom part of the curve, larger diameters in the left upper part. For sizes up to 0.6µm (<0.25µm for black carbon) the relationship is independent of the refractive index. For sizes between 0.6 and 5 µm the curves representing the relationship between backscattering and asymmetry have an inflection point, this is especially pronounced for the refractive index of 1.5 – 0.0 i. For sizes less than 0.6 µm an increase in particle size causes a decrease in backscattering and an increase in asymmetry. For particle sizes between 0.6 and 2 µm the opposite is true, the backscattering increases and simultaneously the asymmetry decreases;

It maybe questionable whether spherical particles are representative for the atmospheric aerosol, therefore results of calculations for prolate and oblate spheroids are shown in the right part of figure 7. There is no difference to the relationship for spherical particles, also the inflection points can be recognized as well, with some influence of the shape of the particles.

For the monomodal size distributions the curve representing the relation between backscattering and asymmetry is slightly concave (between median sizes of 50 nm and 0.6 µm).

The atmospheric aerosol usually consists of a mixture of particles, and in many cases the size distribution can be described as a sum of several lognormal size distributions, representing the different modes. One simple model is the trimodal size distribution with a nucleation mode (mass median diameter below 0.1 µm), an accumulation mode (0.3 – 0.6µm) and a coarse mode (>3µm), first introduced by Whitby (1978). Other models and nomenclatures exist, but this is of no importance for the following.

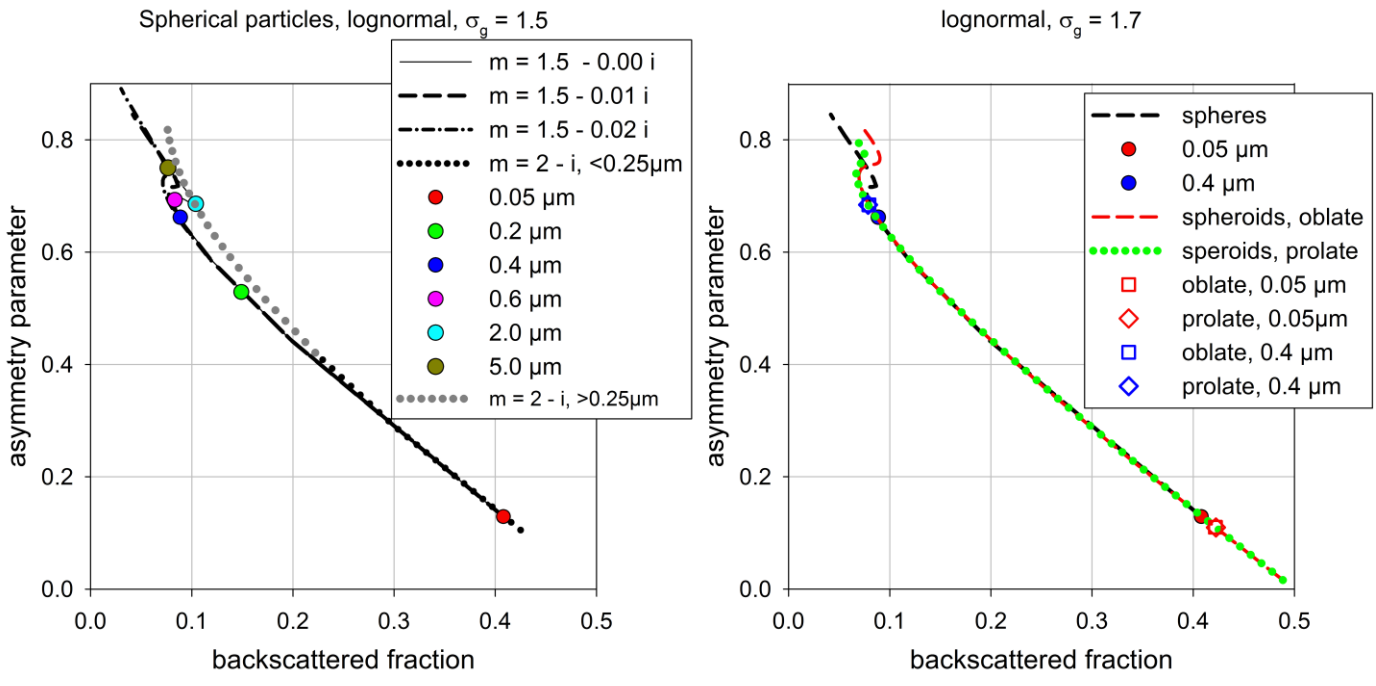

Figure 7. Relation between backscattered fraction and asymmetry parameter for spherical particles and prolate and oblate spheroids.

Let us assume a mixture of two aerosols with mass concentrations m_1 and m_2, specific scattering coefficients $\left(\frac{d\sigma_s}{dm}\right)$ and $\left(\frac{d\sigma_s}{dm}\right)$, asymmetry parameters g1 and g2 and backscattered fractions b1 and b2.

Since the integrals for calculating the asymmetry parameter and the backscattering fraction are linear, the asymmetry parameter and the backscattered fraction of the mixed aerosol is a linear combination of of the corresponding values of the two aerosols:

$$g = f_1 \cdot g_1 + f_2 \cdot g_2 \text{ and } b = f_1 \cdot b_1 + f_2 \cdot b_2 \text{ with } f_i = \frac{m_i\left(\frac{d\sigma_s}{dm}\right)_i}{m_1\left(\frac{d\sigma_s}{dm}\right)_1 + m_2\left(\frac{d\sigma_s}{dm}\right)_2} \quad , \quad i = 1,2$$

The contribution of the individual aerosols to the asymmetry parameter (back scattered fraction) is influenced both by mass concentration and the specific scattering cross section. The specific scattering cross section play an important role since it is strongly dependent on the size, which can be seen in figure 8 It is immediately evident, that the most important size range is between 0.2 and 1 µm, i.e. the accumulation mode or, using another nomenclature, the fine particles. Therefore this size range will be dominant for the value of the asymmetry parameter and the backsattered fraction Although of minor importance, the light absorbing particles of 30 nm size are a factor of 4 more important than the non-absorbing counterpart. For illustration a few relevant data are listed in table 2. In the last column the factor relative to the accumulation has been calculated. This is the factor the mass of the selected mode has to be larger to have the same scattering coefficient as the accumulation mode. The Aitken/nucleation mode can be neglected, since for transparent particles a mass 400 times and for soot particles 100 times the mass of the accumulation mode will not occur. Also for the coarse mode it would need 7 times the mass of the accumulation mode to have the same scattering coefficient. Usually the mass of the coarse mode is between half and twice of mass of the accumulation mode, although exceptions exist, see below. Therefore the micrometer sized particles will have some influence on the backscattered fraction and the asymmetry.

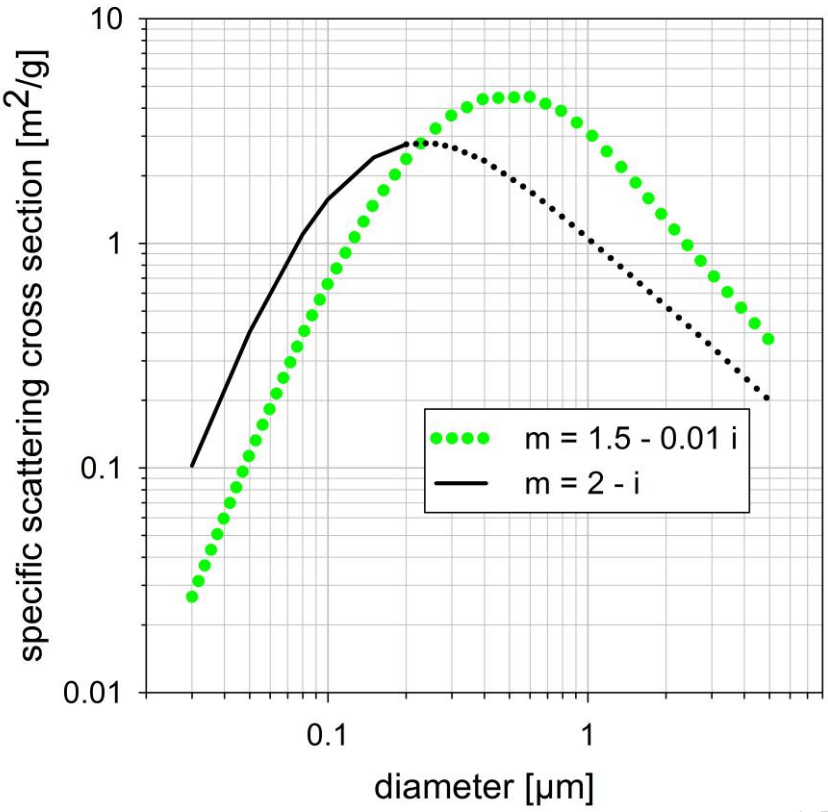

Figure 8. Specific scattering cross section for spherical particles

Table 2. Specific scattering cross sections of various aerosols

mass modal diameter	name	refractive index	specific cross section	factor relative to accumulation mode
µm			m^2/g	
0.05	nucleation/Aitken mode	1.5	0.011	400
0.05	nucleation/Aitken mode	2 - i	0.04	100
0.4	accumulation mode	1.5 - 0.01 i	4.42	1
3	coarse mode	1.5 - 0.01 i	0.73	6

To illustrate this, we have considered an aerosol being a mixture of non-absorbing, absorbing nucleation mode particles (0.05µm), accumulation mod particles (0.4 µm) and coarse mode particles (3 µm). The mass of the respective modes, in μgm^{-3}, is given by the numbers between semi-colons in the legend of figure 9. The points in the (b.g) plane representing monomodal aerosols with modal diameters of 0.05, 0.3, 0.4, and 3.0 µm exactly lie on the line calculated for a refractive index of 1.5 – 0.02 I, as expected. Adding a small amount of coarse mode particles (0;0;20;20) gives a negligible shift upwards. The same is true when adding small amounts of nucleation mode particles both absorbing and non-absorbing. For the case of having equal mass in the accumulation mode and the black carbon nucleation mode (5:20;20;20) the point in the (b,g) plane is shifted to the right. All these points lie above the solid line representing the monomodal aerosol. This is completely evident, when using the using the analogue of the center of mass, which always has to be within the polygon spanned by the masses. Since the solid curve is slightly bent upwards, the points have to be above the line, thus explains in a simple way, that the cloud of data points is above the line representing monomodal aerosols (see figures 3 and 4). The curve for monomodal particles has an inflection point for particles sizes around 3 µm, with a dependence on refractive index. This area in the (b.g) plane can only be reached, if the coarse mode aerosol dominates, as shown by the combination of 2, 5, 20, 200 μgm^{-3} of transparent nucleation mode, soot mode, accumulation mode and coarse mode in figure 9.

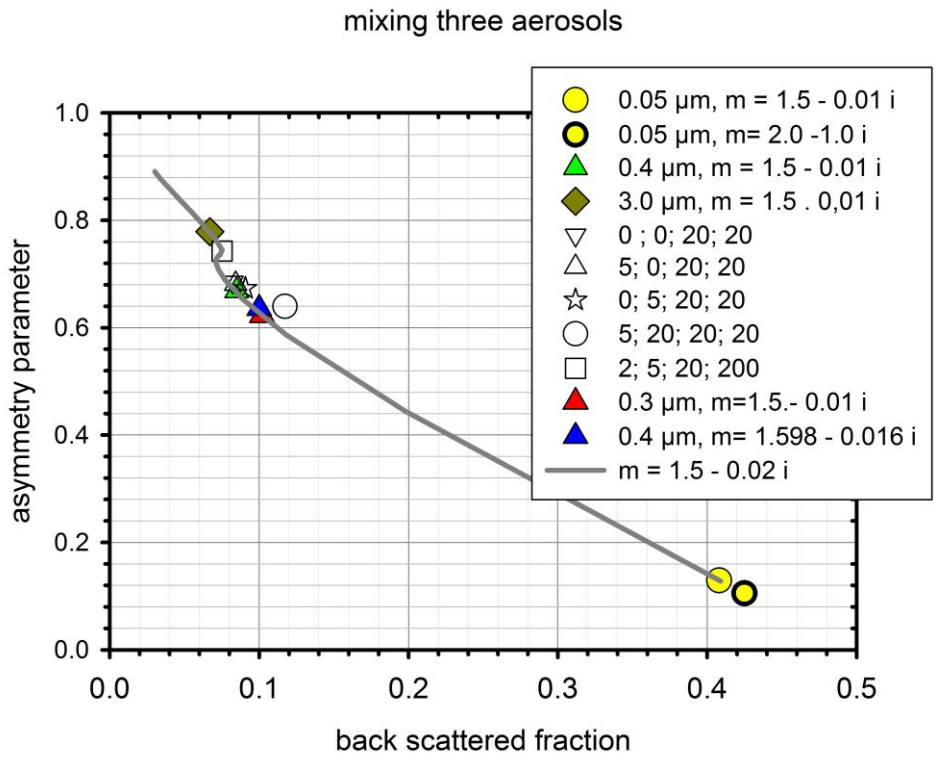

Figure 9: Backscattered fraction and asymmetry parameter of mixed aerosols. The aerosol is assumed to consist of four kinds of particles having a lognormal size distributions with modal diameters of 0.05µm (transparent particles), 0.05µm (soot particles), 0.4 µm (accumulation mode, transparent), and 3 µm (coarse mode, transparent). The mass of the different modes is indicated by the numbers separated by semi-colons.

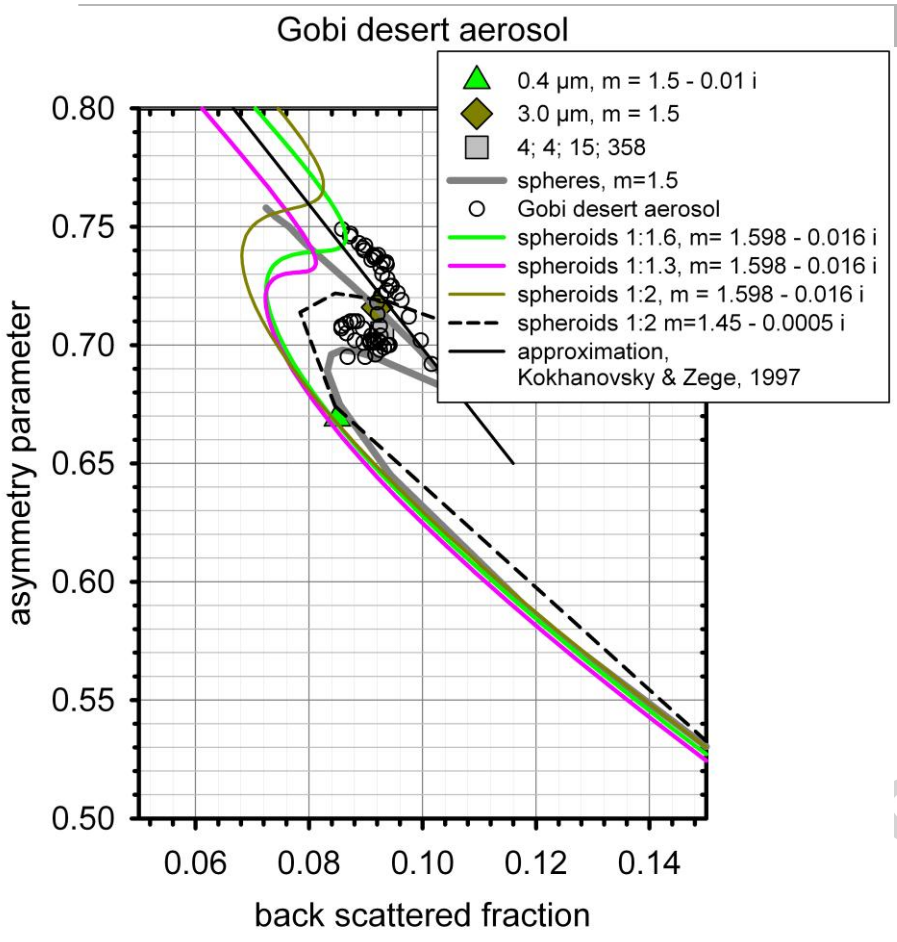

Figure 10. Backscattered fraction and asymmetry parameter for long range transported aerosols. The circles are data points for aerosol originating in the Chinese loess Plateau, the curves are various models.

Occasionally an aerosol, dominated by coarse mode particles can be observed, and this is associated with long range transport of desert dust aerosols. In Kyoto this is known as a yellow sand or Kosa event. In that case aeolian dust originating from the Chinese Loess Plateau travels a distance of >2000 km. This takes several days and the larger particles of the coarse mode are lost by sedimentation. The mass size distribution peaks at an aerodynamic diameter of 4.5µm (Ishizaka et al., 2009); the geometric diameter, being important for the optics, can be obtained by dividing this value by the square root of the density of the particles (main constituent quartz) and is 2.67µm. Obviously the Loess particles are not spherical; furthermore the particles pick up pollution by and condensation, when passing over China, thus these particles have a complex surface. The mass of the dust particles was 358µg/m^3 compared to the usual accumulation mode value of 15µg/m3, thus the coarse mode aerosol obviously dominates the optical properties.

Occurrence of Gobi desert aerosols was identified by back trajectories (see Horvath et al., 2006); Data points of all measurements of long range transport desert aerosols are shown in figure 10. Since practically all particles are in the above 1 µm size, the points, as expected, are situated around the inflection point of the curve for spherical particles. For illustration the backscattered fraction and the asymmetry parameter has been calculated for an aerosol consisting of some nucleation and accumulation mode particles and a huge coarse mode and this point (denoted by 4;4;15;358) is situated well in the cloud of Gobi desert data points, although spherical particles have been assumed for all modes. As already mentioned these particles are irregular as most particles generated by abrasion, but furthermore carry other substances and/or particles on the surfaces. Thus modelling without knowledge of the fine structure will be impossible. Figure 10 shows the (b,g) relationship for spheroids of various aspect ratios and refractive indices. They are similar to the curve for spherical particles, but the inflection points are displaced. Obviously also a spheroid is not a perfect simulation of the complex dust particles, but all curves show, that the behavior can be explained

at least semi quantitatively. Also an empirical relation $b \approx \frac{1-g}{3}$ for ocean and cloud phase functions can also be seen, which fits the data well (Kokhanovsky et al., 2006), despite its simplicity.

The relation between backscattering and asymmetry depends on particles' size distribution, shape and refractive index, and thus cannot be given explicitly. This has been notes by several authors (e.g. Marshall et al. 1995 or Andrews et al, 2006). For model phase functions which are given analytically, a theoretical relation can be found. E. g. for the Henyey-Greenstein Phase function (Henyey and Greenstein, 1941), $P(\theta) = \frac{1-g^2}{(1+g^2-2g\cos\theta)^{1.5}}$, the integration over the full and half solid angle is possible, yielding

$b = \frac{1-g^2}{2g}\left[\frac{1}{1+g} - \frac{1}{\sqrt{1+g^2}}\right]$ since this is not an explicit function of b, a parameterization has been given by Wiscombe and Grams (1976, see also Andrews et al. 2006), representing g as a function of b. An empirical relation for super micrometer sized particles has been indicated by (Kokhanovsky et al., 2006) $b \approx \frac{1-g}{3}$; Sviridenkow (2010) has analyzed a large set of sun and sky radiation measurements and found the following relations: denoting $C = \frac{1}{b} - 1$ and $A = \frac{1}{1-g}$, then

$C \approx 1.1A^{1.85}$ or $b = \left[1.1\left(\frac{1}{1-g}\right)^{1.85} + 1\right]^{-1}$.

These three approximations together with the data of this work are shown in figure 11, as well as averages including the standard deviation. The numbers can also be seen in table 3.

Table 3. Average of measurements

Number of points	backsattered fraction	standard deviation	Asymmetry parameter	standard deviation
6	0.0752	0.0113	0.7545	0.0173
50	0.0784	0.0145	0.7292	0.0118
325	0.0809	0.009	0.6953	0.0151
1012	0.0862	0.0072	0.6705	0.014
1736	0.0955	0.0085	0.6448	0.0167
2740	0.1103	0.0102	0.6141	0.0152
3523	0.1233	0.0099	0.5906	0.014
2182	0.1332	0.0087	0.5728	0.0124
536	0.1479	0.0095	0.5442	0.0148
174	0.1642	0.0113	0.515	0.0116
43	0.1784	0.0118	0.4967	0.0103

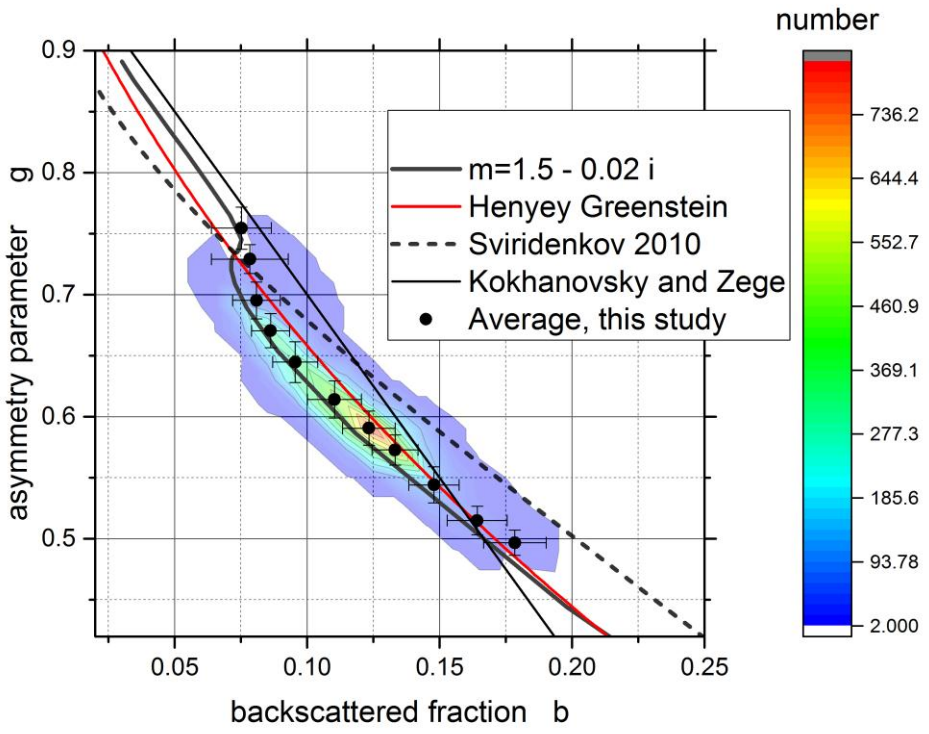

Figure 11. Comparison of data with empirical/theoretical relations between backscattering and asymmetry.

The scatter is influenced obviously by the number of data points, but in the top part of the figure additionally the ambiguity of the curve due to the inflection point (see figure 10) causes an additional increase in the standard deviation . It is evident, that the assumption of monomodal spherical particles (greý line) is a quite good approximation. The refractive index is of minor importance, as already noted by Marshall et al (1995) and demonstrated in figure 7. The data are slightly shifted upwards and to the right, caused by the contribution of the nucleation and/or coarse mode. The Henyey-Greenstein approximation can be considered as a good first guess. Since the Henyey Greenstein formula for the phase function cannot model the increase in backscattering at all, as well as a strong increase in the forward scattering deviations for back scattering fractions 0.05 and 0.1 occur. The approximation by Kokhanovsky and Zege (1997) has been derived for ocean and cloud phase functions and obviously fits excellent in this range (b<0.08), see also figure 10. The Sviridenkov (2010) approximation can also be considered a good first approximation.

Conclusion

Analyzing a large data set on the relation of backscattered fraction and asymmetry parameter, for most of the data the relation can well be described by an approximation by spherical particles. This is independent of the location where the data were gathered, and gives the same relationship for continental, maritime or urban aerosols. The presence of the coarse mode and/or the nucleation mode shifts the data points slightly

to the right, which is in agreement with the data. Since the specific scattering coefficient of the coarse and nucleation mode is much smaller than the one for the accumulation mode, their influence is limited.

Only coarse mode particles at least 20 times in mass of the accumulation mode, have a marked influence. This has been observed for desert dust aerosols and the data points agree with theoretical values.

Empirical formulae or the Henyey-Greenstein phase function for the (b,g) relation can be considered a good first approximation, the best approximation is the assumption of spherical particles consisting of a slightly absorbing material which agrees well with the average of the data.

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Highlights

Using a large data set of volume scattering function the relation between backscattering and asymmetry has been investigated.

The relationship can be simply approximated by spherical particles, slightly absorbing

Agreement with empirical relation and simple phase functions