# Angular Scattering of the Sahara Dust Aerosol

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**Abstract.** Soil erosion aerosols can be transported considerable distances, the Sahara is one of the major sources on the world. In June 2016 the volume scattering function of the atmospheric aerosol has been determined in the Sierra Nevada, Spain, at an altitude of 2500 m. Measurements were performed with a polar nephelometer permitting measurements
10  between scattering angles of 5° to 175°. The values at the missing angles could be estimated to a high accuracy, using the shape of the scattering function adjacent to the missing angles, thus a complete volume scattering function was available. During the measuring period intrusions of long range transported Sahara aerosol happened several times. The classification of the aerosol was done by back trajectories and by the Angström exponent of the wavelength dependent scattering coefficient, which was determined by a three wavelength Integrating Nephelometer. The phase function of the Sahara
15  aerosol had a stronger forward scattering, more side scattering and less backscattering compared to the usual aerosol, which is in agreement with other findings for irregular particles. The asymmetry parameter of the phase function is the best characteristic to distinguish Sahara Aerosol from non-Sahara aerosol. In this study the asymmetry parameter for the Sahara aerosol was larger than 0.65, whereas the non-Sahara aerosol had an asymmetry parameter below 0.6. A comparison with measurements performed with long range transported Gobi Desert aerosols observed in Kyoto, Japan, showed very similar
20  results.

## 1. Introduction

Deserts are a major source of aerosol particles. On a global scale the desert aerosol contributes 60–1800Tg/y of the total
25  yearly aerosol production of 2900–4000 Tg (Jaenicke, 1988). Junge (1979) estimates the global source strength of deserts as 260 to 400 Tg/y, with the Sahara contributing 60 to 200 Tg/y. In contrary to most of the other particles present in the atmosphere, desert aerosol particles are produced from minerals by mechanical processes, which obviously lead to irregular shaped particles. This is documented by innumerous electron micrograph studies (see e.g. Falkovich et al. 2001, Iwasaka et al., 2003, ). Among many other effects, the desert aerosol is expected to have an influence on the radiative balance, see e.g.
30  Obregón (2014), Valencuela et al. (2012), Antòn et al. (2014).

The mechanical production of particles results in particle sizes usually larger than 1 µm. Mean sizes range up to 10µm (Kontratyev et al. (2006), Alfaro et al. (2003), Cheng et al. (2005), Xin et al. (2005),  Alfaro & Gomez, (2001), Falkovich et al., (2001)), and during atmospheric transport the size distribution is modified, mainly due to settling of larger particles.

5    Since the dust particles have an irregular shape, their scattering properties are difficult to model. Below we report measurements of the volume scattering function of the Sahara aerosol transported to the Iberian Peninsula, which were performed during several dust outbreaks.

## 2 Definitions, units, and nomenclature

The volume scattering function $\gamma(\theta)$ of the aerosol is defined as follows, see figure 1: Let a volume dV of aerosol be
10    illuminated by radiation having a flux density S. The light flux $d\Phi$ scattered into a solid angle $d\omega$ at the scattering angle $\theta$ is obtained as

$d\Phi = E \cdot \gamma(\theta) \cdot d\omega \cdot dV.$    The unit is $[\gamma] = m^{-1}.sr^{-1}$.

The total scattering coefficient $\sigma_s$ is obtained by integrating the volume scattering function $\gamma(\theta)$ over whole solid angle:

$\sigma_s = {_0}\int^{4\pi} \gamma(\theta)\, d\omega,$

15    or for scattering with rotational  symmetry with respect to the incident beam

$\sigma_s = 2\pi._0\int^{\pi} \gamma(\theta)\, \sin(\theta)\, d\theta.$

The scattering coefficient can be understood as the fraction of the light flux scattered per unit length out of a parallel beam of light, its unit is $[\sigma_s] = m^{-1}$. Both the volume scattering function and the scattering coefficient are extensive properties.

20    The phase function is an intensive property and describes the relative angular dependence of the scattered light of a volume element of particles. For the phase function $P(\theta)$ we have used the following definition:  $P(\theta) = 4.\pi.\gamma(\theta)/\sigma_s$ .

The angular distribution of the scattered light frequently is characterized by two parameters:

The asymmetry parameter g is obtained by folding the phase function with cos ($\theta$), therefore

$g = \frac{1}{2} {_0}\int^{\pi} P(\theta)\, \sin(\theta)\, \cos(\theta)\, d\theta.$

25    The asymmetry parameter is zero for symmetric scattering such as Rayleigh scatter of the air molecules and g=1 for only forward scatter. Another characteristic is the fraction b of the back scattered radiation. It is obtained by integrating $\frac{1}{2} P(\theta) \sin(\theta)$  between  $\frac{1}{2}\pi$ and $\pi$. Both parameters g and b are intensive.

The measurement of the scattering coefficient at  three wavelengths (e.g. with an integrating nephelometer, Charlson et al., 1967) permitted the determination of the wavelength dependence of the scattering coefficient. In many cases it can be
30    represented by a power law relation $\sigma(\lambda) = \sigma(\lambda_0)\cdot(\lambda/\lambda_0)^{\alpha}$ with $\alpha$ the Ångström exponent  (Ångström 1929, 1930). The value of $\alpha$ is independent of the absolute magnitude of the scattering coefficient, i.e. the concentration of the particles. But it is different for different types of aerosols and mainly influenced by the size distribution of the particles. For a power law

number size distribution given by $dn/dr = n_0.(r/r_0)^{-\nu}$, the exponent α can be obtained by $\alpha = 3 - \nu$. (Junge 1963). For an aerosol with a size distribution having $\nu > 3$, the smaller particles dominate and $\alpha < -1$, i.e. the scattering coefficient decreases with increasing wavelength. This is the normal case. If the particles are larger than a few micrometers, then $\nu < 3$ and the Ångström exponent is zero or even positive. A strong wavelength dependence of the scattering coefficient ($\alpha < -1$) is an

5    indication for the usual aerosol, whereas little or almost no dependence on wavelength is a sign for desert aerosol particles.

## 3. Instrument and methods

10   The volume scattering function of the aerosol has been determined by a custom made polar nephelometer, its design is similar to the one of Waldram (1945), see figure 2: Light from a 532 nm solid state laser of 10 mW power shines into a light trap and illuminates the particles within the beam. A photomultiplier with a collimation optic is mounted on a goniometer and can measure scattered light between 5 and 175°. The scattering volume is approximately 70 mm³ at 90° scattering angle, increasing to 800 mm³ at 5° and 175° respectively. Measurements are taken at intervals of 5°, in the near forward direction at

15   1 to 2°. For one volume scattering function a scan from 175° to 5° and back is made and the average is used. One full scan takes 35 minutes, which can pose a problem with rapidly changing aerosols. Therefore a check for differences between the forward and the back scan is made and if the difference was larger than a factor of 1.5 the data were not used. The instrument is enclosed in an airtight housing; by sucking air out of the enclosure, air from outside can be brought into the instrument. Calibration is done by filling the instrument with carbon dioxide, whose volume scattering function is well known. For all

20   data reported below, the scattering of the air molecules has been subtracted, i.e. all scattering functions, phase functions, asymmetry parameters or back scattered fractions are for aerosol particles only.

Experimentally it is impossible to measure the volume scattering function between 0 to 5°, and 175° to 180°; but the contribution of this range cannot be neglected, especially the forward region. The measured volume scattering function and

25   its shape between 10° and 5° and 170° and 175° can be used to extrapolate the missing regions. This can be done with an accuracy of better than 5% (Horvath, 2015), thus the complete scattering function is available.

The flow rate through the instrument was $3.3 \times 10^{-4}$ m³ s⁻¹. The connection to the sampling inlet of the field laboratory was by a slightly downwards inclined hose of a diameter of 10 mm and a length of 2.5 m.   Using data given by given by Hinds

30   (1999, Chapter 10), the loss of particles due to sedimentation in 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%. Thus it can be concluded, that for the most important particles sizes below 5 µm the sampling losses are negligible.

Sampling took place in the Albergue Universitario of the University of Granada, located in the Sierra Nevada at an elevation of 2505 m a.s.l. Its coordinates are  37° 5' 43.72"N,  3° 23' 12.57"W. The surrounding mountains had elevations of approx. 3000 m, extending at distances of 20 km from the sampling location. The instruments were located in a room below the flat roof of the building. A pipe with a diameter of 10 cm extended 2.1 m above the roof and into the laboratory. A blower

5     maintained a flow of 0.00167 $m^3s^{-1}$, all instruments sampled from this pipe. The residence time of the air in the pipe was 0.6 s . Losses in the pipe can be considered negligible.

Measurements were made in the framework of the SLOPE campaign between June 6 and 30, 2016, but not continuously, due to instruments failures and absence of the operator; in total 120 phase functions were determined. During this time several

10     intrusions of Sahara dust occurred, usually the dust was layered and could be recognized with the unaided eye. For distinguishing dust aerosols from others, two methods have been applied: (1) The size of the dust particles is larger than 1µm, thus the Angström exponent normally is larger than -1, whereas the usual aerosol has Angström exponents below -1. (2) Using 72 hour back trajectories (from the NOAA HYSPLIT web site, Draxler & Rolph, 2003), the likely origin of the particles can be estimated. The origin of the air mass was classified in a total of six groups. Figure 3 shows the typical

15     situations: Sahara, Sahara high,  Atlantic, Atlantic North, Atlantic/Sahara, North Africa/Mediterranean. From the source region in the Sahara to the receptor region in the Sierra Nevada the particles traveled around 1500 km. Table 1 characterizes the 6 types, which occurred during this campaign.

A plot of the Angström exponent as a function of time measured with the three wavelength integrating nephelometer is

20     shown in Figure 4. The classification using the back trajectories is given above. It is evident, that for aerosols influenced by the Sahara, the Angström exponent is larger than -1, thus the two methods of determining Sahara aerosols agree in most of the cases.

## 4. Results

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An overview of the scattering coefficient obtained by integration of the measured volume scattering function and the value measured with the Integrating Nephelometer is shown in figure 5, only the scattering of the particles is plotted, i.e. the Rayleigh scattering of the air was subtracted. The data obtained with the Integrating Nephelometer are values, taken at intervals of minutes, and depict also the variability of the layered aerosol. The scattering coefficient obtained by integration

30     of the polar nephelometer data are averages of about 35 minutes. Agreement between the two datasets is evident.  Three periods of measurements can be seen. During Period 1 mostly a distinct intrusion of Sahara Aerosol was observed, except for the beginning, in Period 2 mainly aerosol from the Atlantic reached the site, whereas during Period 3 again Sahara particles

dominated the aerosol. The air masses passing over the Atlantic had a much lower scattering coefficient, being about twice the one of pure air.

A plot of all Sahara and non-Sahara Phase functions is depicted in figure 6. There is some scatter in the data due to the

5    layered aerosol, but it is evident, that the phase functions of the Sahara and non-Sahara aerosol are different. The averages of all phase functions of definite Sahara origin and of definite non-Sahara origin are shown in figure 7.

## 5. Discussion

10   The comparison between the two types of average phase functions of figure 7 shows definite differences. The non-Sahara (mainly Atlantic) phase function has less forward scatter (on the average 31 sr$^{-1}$ at 0°) than the Sahara phase function (62 sr$^{-1}$). This is readily explained by the larger size of the desert particles. Whereas spherical particles are a good approximation for the near forward scattering, the smaller backscattering of the Sahara phase function compared to the non-Sahara particles only can be explained by the irregular shape of the particles; For spherical large particles interferences and resonances are

15   most pronounced, which leads to a considerable increase in backscattering and a low side scattering, which both have not been observed. For irregular shaped particles which furthermore are randomly oriented by Brownian rotation, the backscattering is by far less up to a factor of 10 compared to spherical particles, see e.g. Von Hoyningen-Huene and Posse (1997) or  Mishchenko et al. (1997), Mishchenko (2000), Nousiainen and  Kandler (2015). Another effect of the irregular shape of the Saharan particles is their higher side scattering around 80 to 140°, as has been observed also in this study.

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The complete volume scattering function or phase function can be used to determine derived properties. The scattering coefficient is obtained by integrating the volume scattering function over the full solid angle. A comparison with the calculated and the measured scattering coefficient was shown in figure 5, the agreement is evident.

25   For modelling of e.g. radiative transfer, the asymmetry parameter of an aerosol is an important parameter. It is obtained by folding the phase function with the cosine of the scattering angle.  For the average phase functions shown in figure 7 the asymmetry parameter for the Sahara aerosol particles is 0.706 with a standard deviation of 0.031, for the non-Sahara particles it is 0.562±0.047. The difference is significant, therefore the asymmetry parameter is a good indicator for the desert aerosol. In figure 5 the measured asymmetry parameter is added to the graph of the Angström exponent and the origin of the

30   aerosol. Whenever the origin of the aerosol indicates desert particles the asymmetry parameter is high. At the same time the Angström exponent also is high.  Figure 8 is a plot of all the data points and shows the relationship between Angström exponent and the asymmetry parameter for all measured phase function for which Integrating Nephelometer data were available. Evidently a larger asymmetry parameter is associated with a larger Angström exponent, but the relationship is not very pronounced.

The scattering function of the desert aerosol has a low back scattering, which is typical for non-spherical particles. Therefore it is to be expected, that a characterization of desert aerosol particles could be achieved by considering the fraction of backscattered light. It is defined as the ratio of integral of the volume scattering function between 90 and 180° divided by the integral over the full angle and is readily available once the volume scattering function is known. A time series of the

5 backscattered fraction obtained in this way is shown in Figure 9, black squares; The back scattered fraction obtained from polar nephelometer measurements is lower for the aerosol dominated by desert particles, as expected; but less distinct than the asymmetry parameter. Furthermore the back scattered fraction obtained with the Integrating Nephelometer (red line) is systematically larger, which has the following reason: The backscattered fraction for the Integrating Nephelometer is obtained by dividing the signals BbsG by BsG. Both signals are proportional to the light flux scattered by the aerosol, but

10 they are truncated, since it is experimentally impossible integrate the scattered light flux from 90° to 180° and 0° to 180° respectively. But the measured volume scattering functions permits the simulation of the truncation effect; and for a range of the scattering angles between 8° and 170° the expected signal is also shown (blue circles), which is in much better agreement with the Integrating Nephelometer data.

15 For the Sahara-particle dominated aerosol the asymmetry parameter is larger and the back scattered fraction is smaller than for the usual aerosol. So it is obvious to use both parameters to characterize the Sahara aerosol. A plot of all data points in the (b,g) plane is shown in figure 10. The points representing the Sahara aerosol and the non-Sahara aerosol are well separated. The curve gives the relationship between the backscattered fraction and the asymmetry parameter calculated for monomodal spherical particles. For other refractive indices or ellipsoidal particles an almost identical curve is obtained, the

20 point of inflection is at a slightly different location. For bimodal size distributions the data points are located to the right of the curve (Horvath et al., 2016), as it is the case for the data of this study. A clear distinction between the points representing Sahara and non-Sahara particles is possible. Additionally, points are plotted, which were obtained in Kyoto, Japan, during an event of long range transport dust intrusion from the Gobi Desert. These data perfectly fit together with the Sahara data.

25 **6. Conclusion**

The volume scattering function of the atmospheric aerosol was measured in the Sierra Nevada, where intrusions of Sahara aerosol are frequent. The origin of the aerosol particles was determined by back trajectories and/or by the Angström exponent of the wavelength dependence of the scattering coefficient of the aerosol.

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The phase function of the Sahara aerosol has more forward scatter, less back scatter and more side scatter; it is more asymmetric than the non-Sahara aerosol, which in this study was mainly marine, with little continental influence. A few parameters of the aerosol are listed in table 2.

The best distinction between Sahara and non-Sahara aerosol is possible when using the asymmetry parameter, as is evident also in figures 5 and 11. This study suggests that particles causing an asymmetry parameter of the phase function above a value of 0.65 could be considered of Sahara desert origin. The asymmetric scattering of the Gobi desert aerosol is very similar to the one of the Sahara Aerosol.

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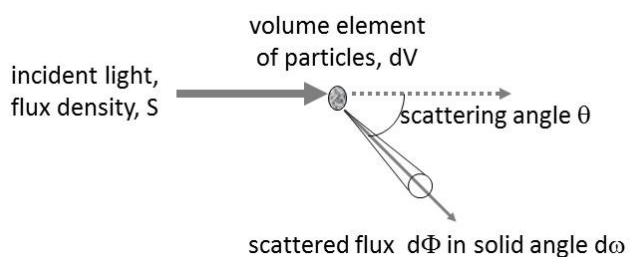
**Figure 1: Definition of volume scattering function**
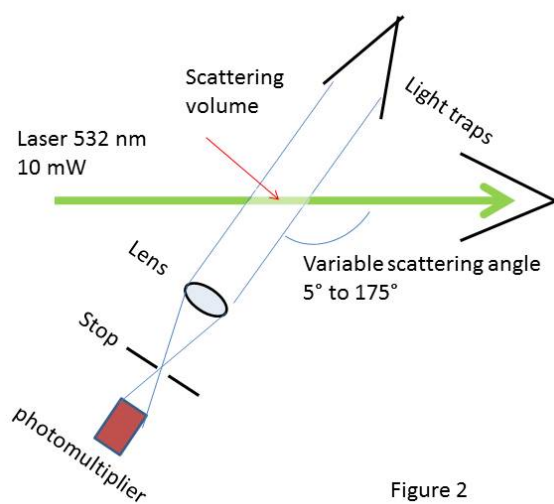
Figure 2

**Figure 2: Principle of the polar nephelometer**
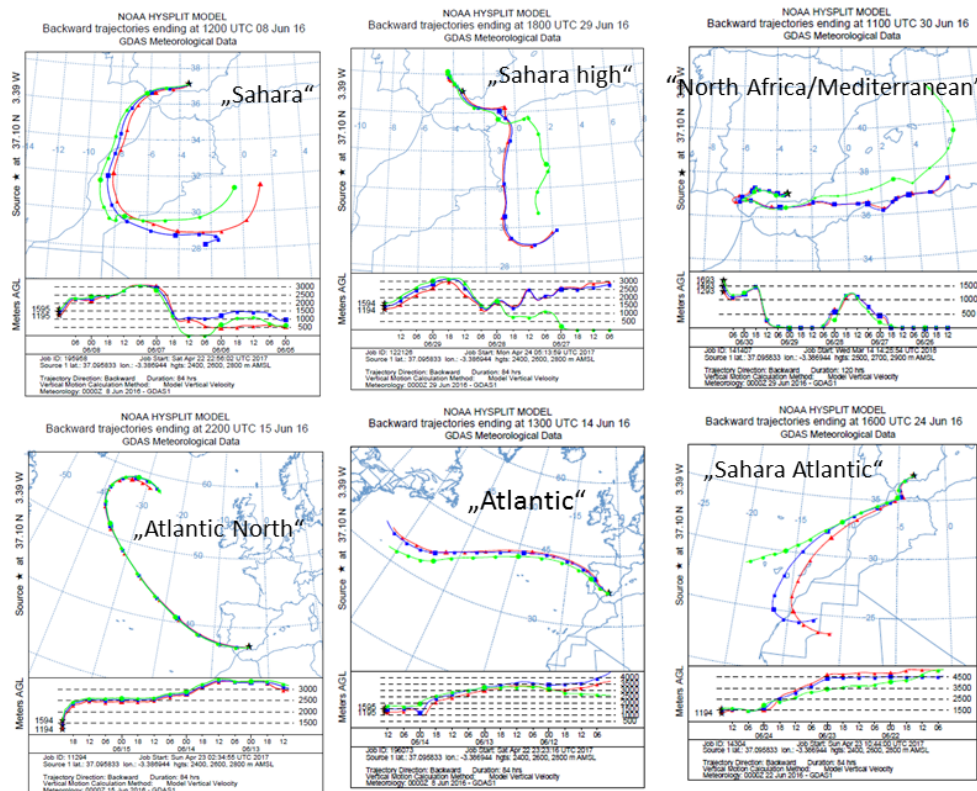
Figure 3

**Figure 3: Back trajectories used for classification of aerosol types**
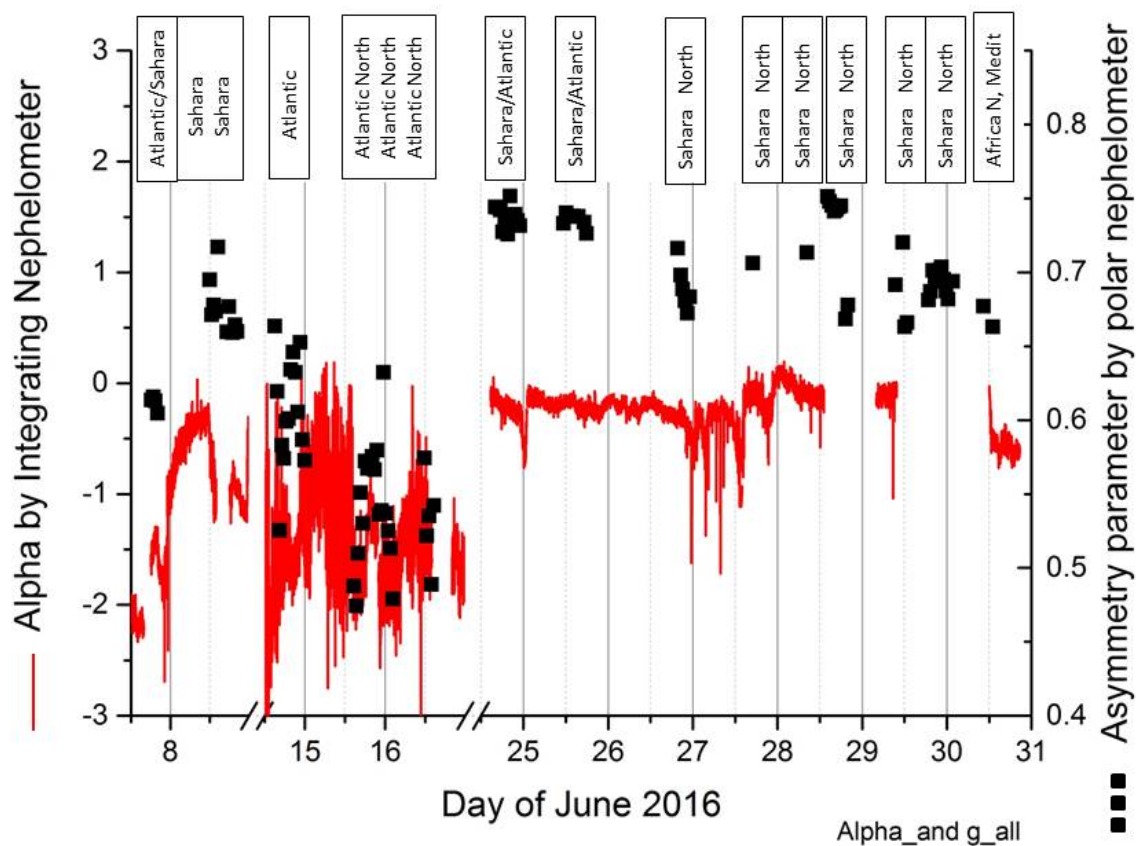
**Figure 4: Angström exponent of the spectral scattering coefficient of the aerosol measured and classification by back trajectories. For the desert aerosol the Angström Exponent is larger than -1. In addition the asymmetry parameter is plotted too, for desert aerosol it is larger than 0.65.**
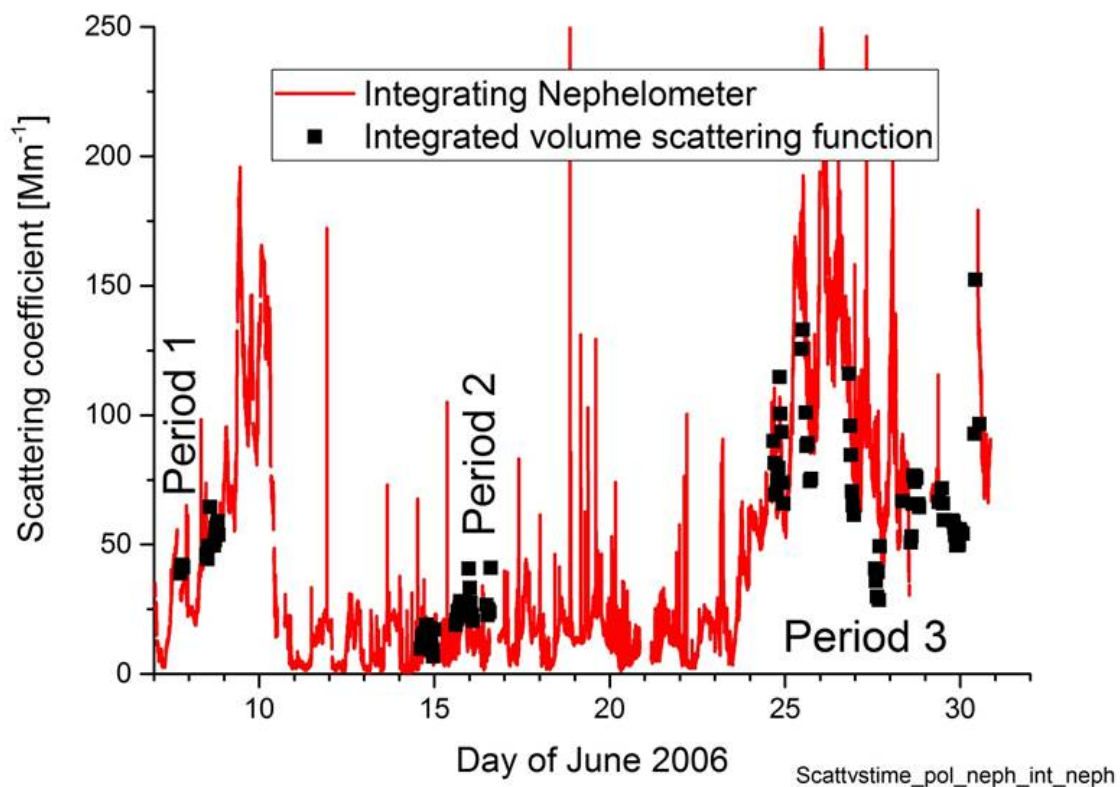
**Figure 5: Measured scattering coefficient of the aerosol during the three periods of observation. The solid red line is the signal of the Integrating Nephelometer, the points are scattering coefficients obtained by integrating the measured volume scattering function.**
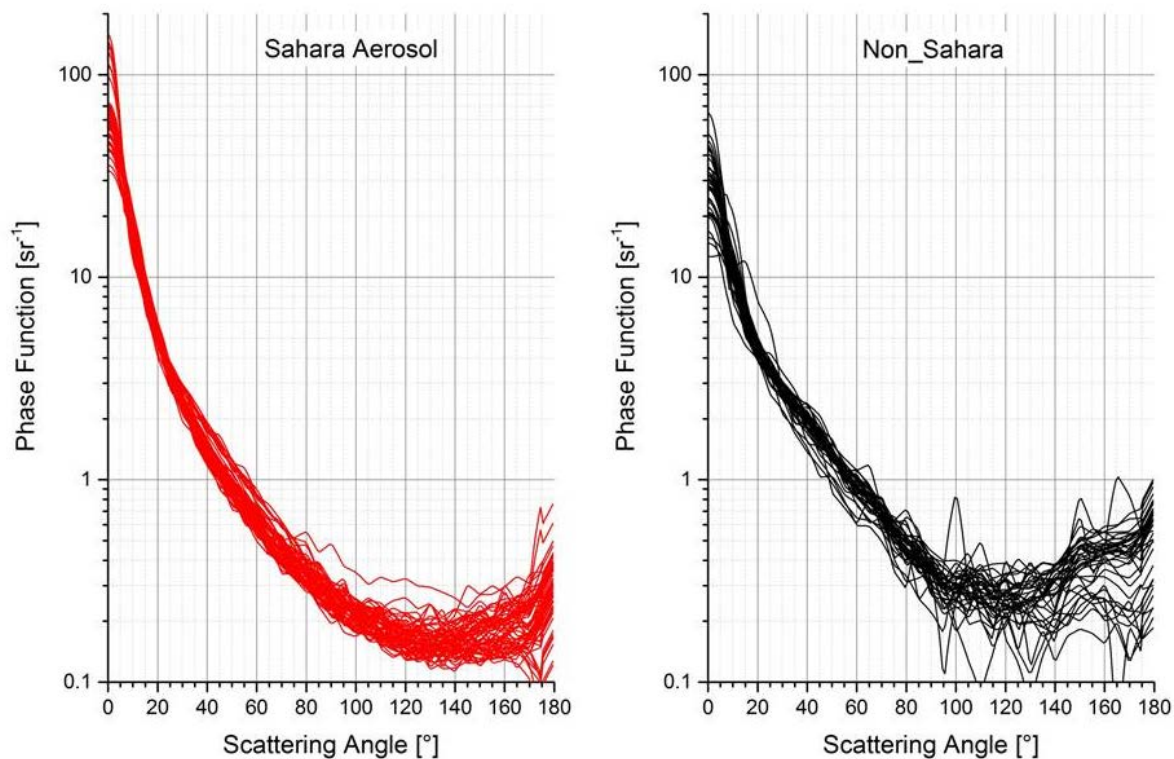
**Figure 6. Comparison of phase function attributed to Sahara and non-Sahara aerosols.**
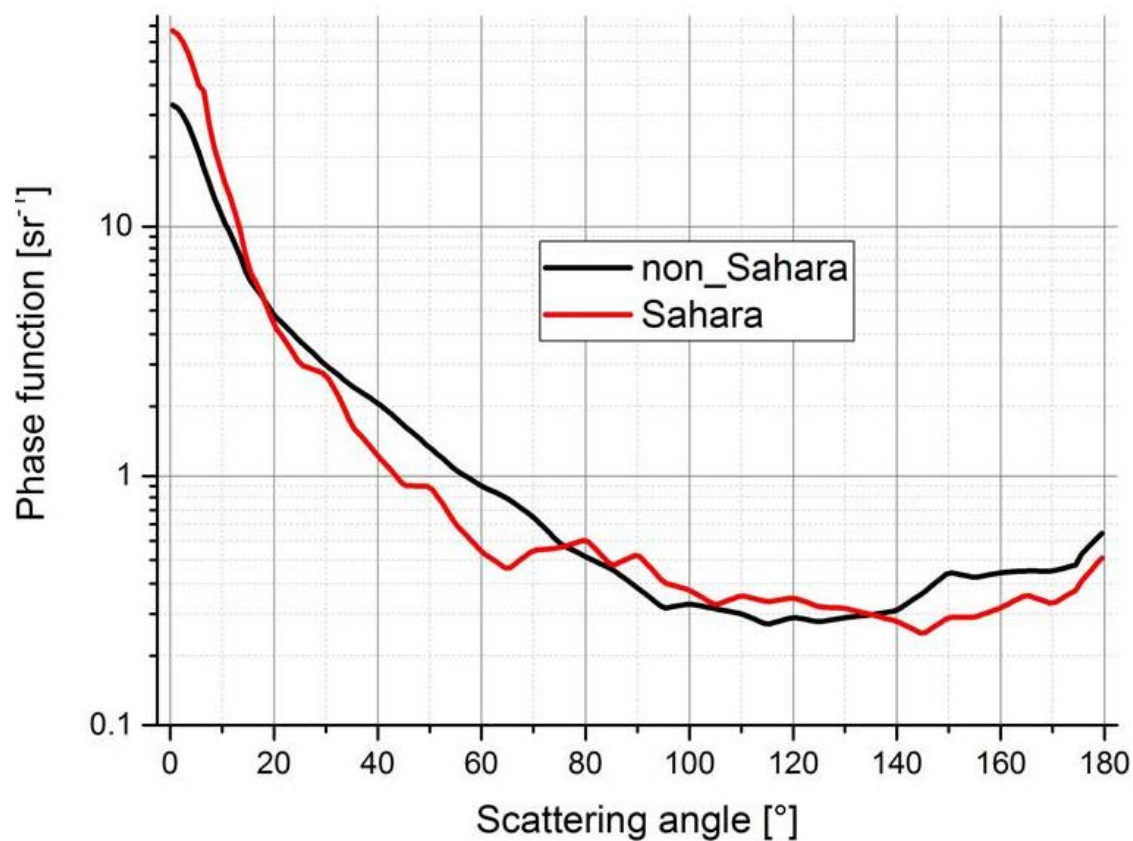
**Figure 7. Average of the Sahara and non-Sahara aerosol phase functions.**
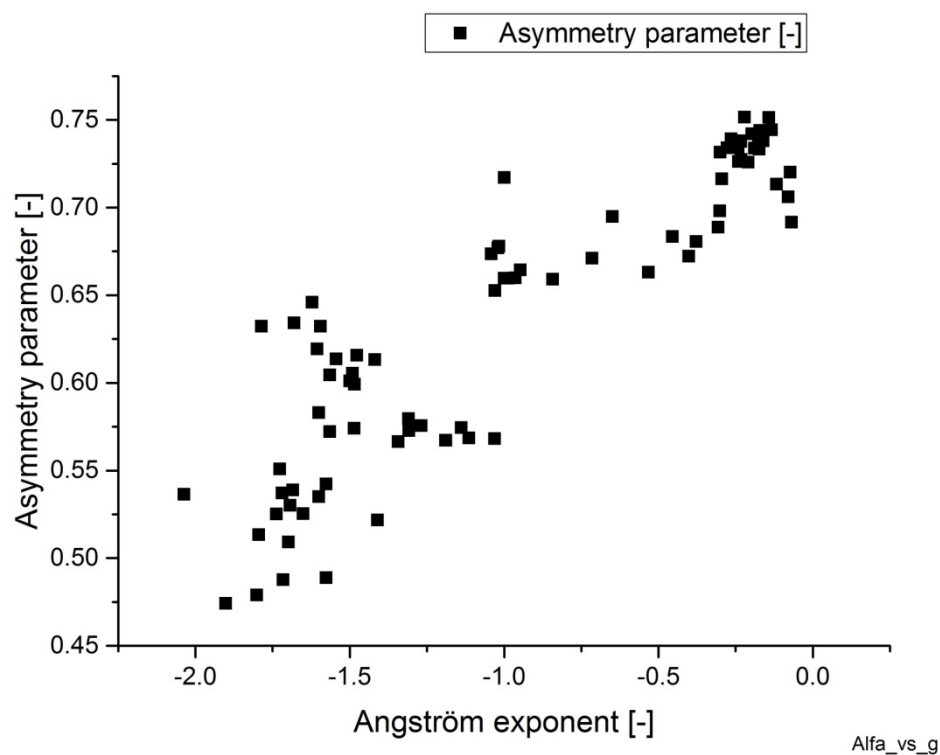
**Figure 8. Relationship between the measured Angström exponent and the asymmetry parameter using the measured phase function.**

Back_period3
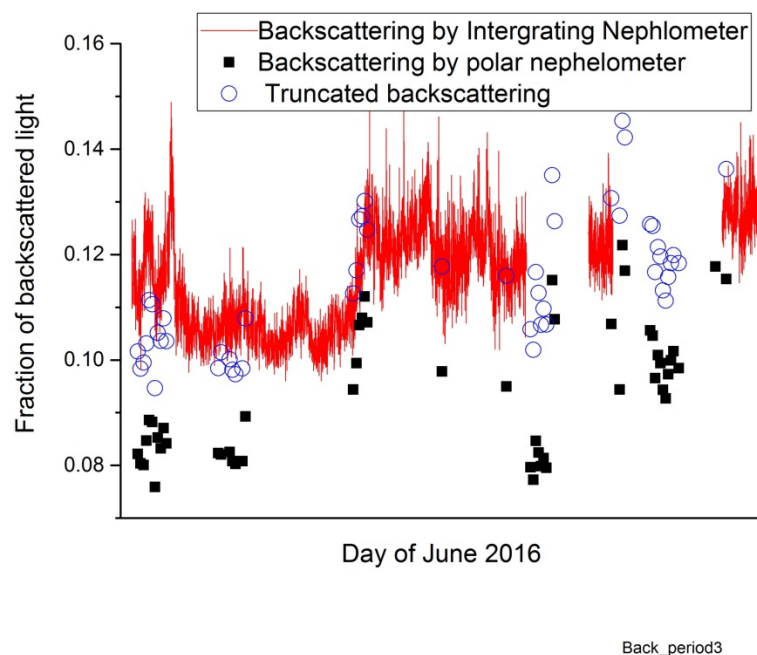
**Figure 9. Back scattered fraction measured with the Integrating Nephelometer (red curve) and values obtained by the measured Volume scatteing function. Simulation of the truncation is shown by the hollow points.**

AsybackAerosolTyps_with_Gobi
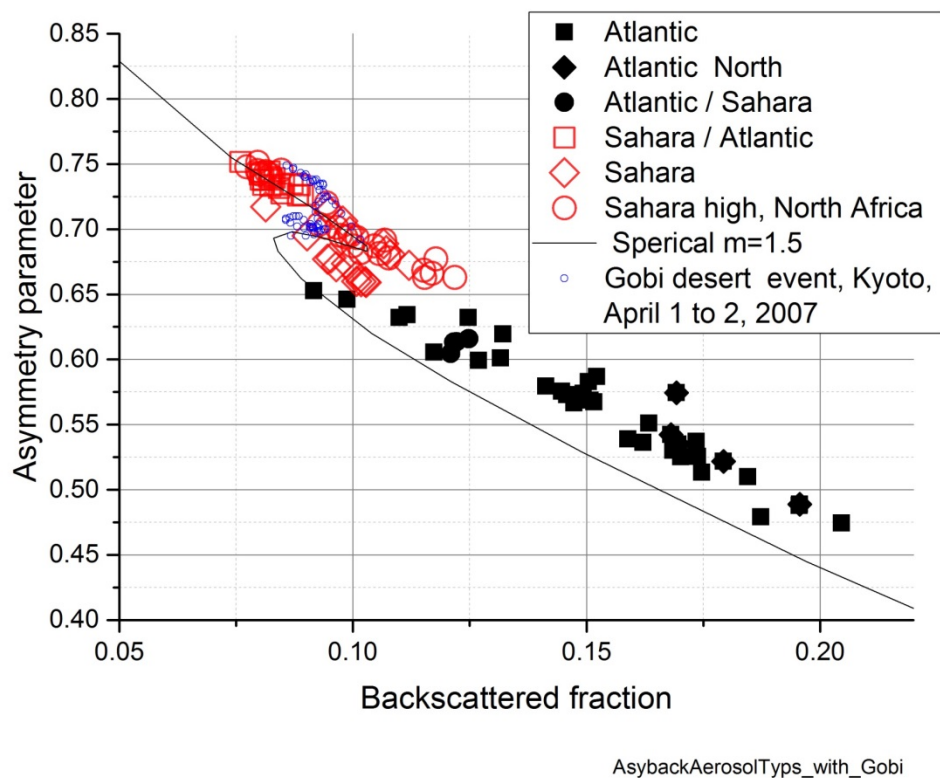
**Figure 10: Asymmetry parameter and backscattered fraction calculated for the aerosols measured during this study. A clear separation between Sahara and non-Sahara aerosols is evident. The data points are in excellent agreement with data for the Gobi**

5 **Desert aerosol.**

| Table 1. Classification of back trajectories | | |
|---|---|---|
| Name | Air passes over | Remark |
| „Atlantic" | 60°W<longitude<0°, 35°N<latitude<40°N | |
| "Atlantic North" | 40°W<longitude<0°, 60°N<latitude<40°N | |
| "Sahara" | 10°W<longitude<5°E,37°N<latitude<26°N | |
| "Sahara high" | 5°W<longitude<5°E, 37°N<latitude<26°N | |
| "Sahara/Atlantic", "Atlantic/Sahara" resp. | Up to 500 km West of the coast of Africa | Distinction between the two by Angström exponent |
| "North Africa/Mediterranean" | 6°W<longitude<8°E, 35°N<latitude<37° | |

| Table 2. Characteristics of the two types of aerosols | | | | |
|---|---|---|---|---|
| | Sahara aerosol | | Non-Sahara Aerosol | |
| | Value | Stddev. | Value | Stddev. |
| Asymmetry parameter  [-] | 0.706 | 0.032 | 0.562 | 0.047 |
| Backscattered fraction  [-] | 0.094 | 0.014 | 0.153 | 0.027 |
| Average scattering coefficient [Mm$^{-1}$] | 71 | 22 | 22.3 | 7.3 |
| Phase function at 0°  [sr$^{-1}$] | 67 | 27 | 31 | 10 |
| Phase function at 90°  [sr$^{-1}$] | 0.26 | 0.04 | 0.35 | 0.04 |
| Phase function at 180°  [sr$^{-1}$] | 0.31 | 0.11 | 0.59 | 0.21 |