We say thanks to both reviewers for their detailed and constructive comments, which most of them have been used to improve the paper.

One basic idea of Referee #1 was to make a clear distinction between “desert dust” and “mineral particles”. So we decided even to modify the title of our manuscript. The new title is:
“Technical Note: Optical properties of desert aerosol with non-spherical mineral particles: data incorporated to OPAC”

In the following we discuss each point of the remarks in detail, with the reviewer comment partly repeated (in italics).

Referee#1
I.17 I ... would use rather Mineral dust or Desert dust, not both...
We mentioned “mineral desert dust particles” since also particles besides the mineral components may be part of desert aerosol. However, in the new OPAC only the shape assumptions for the mineral particles have been changed. But we improved the manuscript with respect to this aspect, and even the title as mentioned at the beginning.
I.20 It is quite unusual to use references in the abstract
We agree. But in our case the paper is directly an improvement of the old OPAC paper, which therefor must be mentioned already in the abstract with detailed information.
I.23 It is an (of course quite reasonable) assumption that the T-matrix approach improves the phase function. Nevertheless…I would rather suggest... to be a bit more conservative here…
We changed the wording.
I.25 ff It would be good to provide the corresponding changes in asymmetry parameter here also….
We added the information on the asymmetry parameter, since its small change is of special interest in comparison the large phase function deviations.
I.*40 For full reliable optical properties you also need an absorption theory …….*
Mie theory takes absorption into account, as well as T-matrix theory does. But we skipped the words scattering theory.
II.42ff ... another reason is that particles have no preferential direction…
Even under the assumption that the particles have no preferential direction the particle shape will have influence on the scattering function. Thus we agree with the referee that it is a good idea to advance beyond Mie theory for dust optical properties.
I.51 Is the largest fraction meant with biggest part?
Yes, we agree and changed the diction.
II 54 I do not agree with this statement…..
We eliminated the statement.
II 67ff That is too much simplification…. Passive remote sensing also includes infrared methods, which not so much rely on the scattering phase function
We changed the text
II 70ff You should clarify somewhere above that your major concern is on solar wavelengths and define your spectral region of interest……
OPAC covers the broad spectral region from 0.25 to 40 µm, and thus the improved assumptions on the shape of mineral particles are taken into account also in the thermal infrared. That the effect of non-spherical particles is largest in the solar spectral range is one point of the results, mentioned in the text and shown in the figures, but nevertheless it is also considered up to 40 µm.
I 88 ….show that T-Matrix really improves….
The improvement of the scattering properties of non-spherical particles using T-matrix instead of Mie-theory in the solar spectral range has been shown by references mentioned in the paper.
I 92 …physical reasoning for that?
The variation of the aspect ratio distributions with particle size is fact, found be electron microscope measurements. Physical reason may be the particle formation.

l 106 ….campaigns showed abundance of much larger particles….effective radius around 5 µm *or larger is not covered by OPAC...*
OPAC takes the variability of mineral dust size distributions into account by providing the possibility to mix 3 different mineral components as required (e.g. using Eq. 2 – 4). When comparing with the SAMUM measurements we refer to the pre-defined mixture "OPAC desert". The flexibility of OPAC with respect to large particles is limited by the coarse mode mineral component (MICM). This component has an effective radius of 8.1 µm and a maximum particle size of 60 µm (see Tab. 1), which means that OPAC covers mineral dust radii up to these values.
l 187 …"mineral component" sounds like you are …taking into account variable dust composition..
The three mineral components used in OPAC have the same refractive indices, as mentioned in the manuscript. The possibility of their individual mixture makes it possible to take into account variable dust compositions with respect to the size distribution.
l 197 …physical reasoning for assuming prolate particles, i.e. from microscopic imagery?....
With electron microscopy generally the projection of the particle is analyzed. Thus it is not possible to detect whether the individual particle is oblate or prolate. As a consequence, the selection of the form with the better fit is a reasonable decision.
l 274 …… be more specific on spectral regions here…
and
l 275 … dust also has significant longwave radiative forcing…
The referee is right that both the SW and the LW spectral range are essential for radiation budget and for remote sensing of desert dust. But, as mentioned, our improvement for the scattering properties of mineral particles holds for both spectral regions. Nevertheless we have corrected this paragraph.
l 306 It is not true that solar wavelength generally is use for aerosol remote sensing…
We have corrected the sentence.
l 313 …very large particles also in transported dust… results of SALTRACE campaign ..
We agree with the referee that the size dependent loss of particles during transport is an assumption that no longer may be valid for desert dust. Since our institute took part and thus we are informed about the results of the SALTRACE campaign, we will consider this aspect carefully in future aerosol modelling. However, in the actual manuscript the assumption is used only to test the effect of non-sphericity for mixtures of particles with different size distribution. (As mentioned, OPAC has the advantage that any user can decide for an individual composition of the given components and thus for the size distribution of the mixture.) However, we added an explanation.
l 376 … comment a bit that only one specific set of refractive index is used…
The referee is right that the refractive index is important for the optical properties of particles. But this manuscript, as a technical note, strictly focusses on the particle shape of mineral aerosol and thus leaves the other properties of OPAC unchanged. However we add a sentence belonging to the question of the uncertainty of the refractive indices in the conclusion.
l 429 … spectral resolution in the different wavelength ranges…
The data in OPAC are available for the wavelengths that can be chosen from the data base. The spectral resolution is not given specifically since it is assumed that the spectral properties of aerosol particles vary rather weak, in contrast to gaseous absorption. Nevertheless, for some specific applications the spectral resolution may be too low. Here improvements will be discussed in future versions of OPAC.

Referee #2
3997 10 … more representative publications…
Thank you for the suggested references.
4000 1 ….additional modern accounts of the T-matrix method...
We wanted to give credit to Waterman and his original paper. The used updated accounts of the TMM are mentioned in the text. Nevertheless we added the Mishchenko reference, but not Doicu, because we did not use his advanced method.
4000 4 und 13 ..distinction between the aspect ratio and the axial ratio ..

We agree that the definition of the aspect ratio in our text was incorrect and emended it in the revised manuscript.

General comment …..the effects of non-sphericity are well known to depend on the imaginary part of the refractive index….. include a table showing the refractive indices used…. different types of dust with different origin...

The dependence of the effects of the particle shape on the refractive index, and especially on its imaginary part, is known and partly considered in the answer to referee #1 and mentioned in the improved conclusion of the manuscript. We prefer not to add a table or figure with the refractive index of the mineral components because it is referenced and the data can be looked up in the ASCII files of the OPAC package. The refractive index used in OPAC for the mineral particles is an average value, for an “average” mineralogical composition. We agree that mineral aerosol originating from different deserts may have different chemical composition and thus different refractive index. But considering a large variation of individual aerosol components is far beyond the idea of OPAC, which will be easy, to be used without too detailed information on the actual aerosol properties. Nevertheless, for a future version of OPA C, we plan to add an additional component with stronger absorbing mineral particles.

Technical note:

Optical properties of desert ~~dust~~aerosol with non-spherical mineral particles: Data incorporated to OPAC

P. Koepke[1], J. Gasteiger[1], M. Hess[2,3]

[1] L-M-University Munich, Meteorological Institute, Theresienstr. 37, 80333 Muenchen, Germany
[2] DLR - German Aerospace Center, Remote Sensing Technology Institute, Oberpfaffenhofen,
82234 Weßling, Germany
[3] RASCIN, Thalkirchner Str. 284, 81371 Muenchen, Germany

Correspondence to P. Koepke (peter.koepke@lmu.de)

Abstract

Mineral ~~desert dust~~ particles in general are no spheres and assuming spherical particles, instead of more realistic shapes, has significant effects on modeled optical ~~dust~~ properties and so on the belonging remote sensing procedures for desert ~~dust~~aerosol and the derived radiative forcing. Thus in a new version of the data base OPAC (Optical Properties of Aerosols and Clouds; Hess et al., 1998), the optical properties of the mineral particles are modeled describing the particles as spheroids with size dependent aspect ratio distributions, but with the size distributions and the spectral refractive indices not changed against the previous version of OPAC. The spheroid assumption ~~strongly improves~~is known to substantially improve the scattering functions, but pays regard to the limited knowledge on particle shapes in an actual case. The relative deviations of the ~~phase functions~~optical properties of non-spherical mineral particles from those of spherical particles are for the phase function in in the solar spectral range up to +60% at scattering angles of about 130° and up to –60% in the backscatter region, but ~~the~~less than 2% for the asymmetry parameter. The deviations are generally small in the thermal infrared and for optical properties that are independent of the scattering angle. The improved version of OPAC (4.0) is freely available under ~~www.rascin.net.~~www.rascin.net.

1. Introduction

The optical properties of aerosol particles are the basis for modeling their direct radiative forcing (Lacis a. Mishchenko, 1995; Haywood a. Boucher, 2000; Yi et al., 2011) and ~~thus~~correspondingly for their effect on climate (McCormick a. Ludwig, 1967; Myhre et al., 2013). Moreover, the optical properties are necessary for all inversion techniques used for aerosol remote sensing (Koepke a. Quenzel, 1979; Kaufmann, 1993; Kalashnikova a. Sokolik, 2002; Nousiainen, 2009). Thus, for an easy availability of spectral optical properties of aerosol particles, the software package OPAC, Optical Properties of Aerosols and Clouds, had been created (Hess et al., 1998).
The optical properties of aerosol particles in general are modeled ~~with a scattering theory~~ using the size distribution and the spectral refractive indices of the particles. In the past, commonly the assumption has been made that the particles are spheres, using Mie-theory (Mie, 1908). This has ~~three~~different reasons: on the one hand, the assumption of spherical particles is reasonable in many cases, especially for water soluble aerosol types under typical meteorological conditions with relative humidity higher than 50%. On the other hand, the shape of individual particles is known only for a limited number of examples, because it needs electron microscopy measurements. Thus, for actual conditions, for practical use, the shape of particles, particularly as function of size, is not available. But even if the particle shape would be available, the problem remains that modeling of non-

Formatvorlagendefinition: Standard: Zeichenausrichtung: Automatisch
Formatvorlagendefinition: Überschrift: Zeichenausrichtung: Automatisch
Formatvorlagendefinition: Textkörper: Zeichenausrichtung: Automatisch
Formatvorlagendefinition: Text body: Zeichenausrichtung: Automatisch
Formatvorlagendefinition: Liste: Zeichenausrichtung: Automatisch
Formatvorlagendefinition: Beschriftung: Zeilennummern nicht unterdrücken, Zeichenausrichtung: Automatisch
Formatvorlagendefinition: Verzeichnis: Zeilennummern nicht unterdrücken, Zeichenausrichtung: Automatisch
Formatvorlagendefinition: Heading: Zeichenausrichtung: Automatisch
Formatvorlagendefinition: Index: Zeilennummern nicht unterdrücken, Zeichenausrichtung: Automatisch
Formatvorlagendefinition: Sprechblasentext: Zeichenausrichtung: Automatisch
Formatvorlagendefinition: Listenabsatz: Zeichenausrichtung: Automatisch
Formatvorlagendefinition: Kopfzeile: Zeichenausrichtung: Automatisch
Formatvorlagendefinition: Fußzeile: Zeichenausrichtung: Automatisch
Formatvorlagendefinition: Kommentartext: Zeichenausrichtung: Automatisch
Formatvorlagendefinition: Kommentarthema
Formatiert
Formatiert
Formatiert
Formatiert
Formatiert: Schriftartfarbe: Automatisch
Formatiert: Schriftartfarbe: Automatisch
Formatiert: Schriftartfarbe: Automatisch
Formatiert: Schriftartfarbe: Automatisch
Formatiert ...
Feldfunktion geändert

spherical particles is complex and time consuming (Mishchenko ~~a. Travis, 1998).~~et al., 2000; Kahnert, 2003). Thus the use of Mie-theory often is a good or the only possible assumption and it has also been used in OPAC.

Desert ~~dust~~aerosol, besides sea salt, forms the ~~biggest part~~largest fraction of the atmospheric particles (D 'Almeida et al., 1991; Kinne et al., 2006). Thus desert ~~dust~~aerosol is very important for the radiation budget and consequently for the climate, especially because it is distributed, often with high optical depth, over large areas. Since its amount shows very strong spatial and temporal variations (Sokolik et al., 2001~~) it generally is investigated with~~), remote sensing methods~~, which~~ are important for desert aerosol research. However, remote sensing is always based on the assumed particle characteristics.

Especially for ~~desert dust~~ mineral particles the optical properties modeled under the assumption of spherical ~~particles~~shape are ~~insufficient~~questionable, since ~~the mineral~~these particles are generated by mechanical processes which give rise to highly irregular particle shapes, as to be seen by electron micrographs (Falkovich et al, 2001; Kandler et al., 2011).

In comparison to spherical particles the phase function of irregular particles generally shows increased sideward, but reduced backward scattering, if the particles are relatively large in comparison to the wavelength (Zerull et al., 1980; Koepke a. Hess, 1988; Nousiainen, 2009; and see Fig.1). Thus, if ~~measured~~ radiation data measured at short wavelengths are used to derive aerosol properties, the assumption of spheres may lead to wrong results.~~ Errors in~~ This holds also for particle properties derived from backscatter-lidar measurements (Gobbi et al., 2002; Wiegner et al., 2009; Sakai et al., 2014~~) may result from~~), since, amongst others, they are influenced by the lidar ratio~~ that has to be taken into account~~, which combines backward scattering with the extinction coefficient. For passive remote sensing from satellite, ~~the retrieval error is dominated by the~~ an assumed wrong phase function of the particles ~~(Mishchenko et al., 1997)~~can introduce significant retrieval errors and ~~in~~ for considerations of the radiation budget ~~considerations~~of mineral particles in the solar spectral range the assumption of spheres is a major source of error (Nousiainen, 2009). The amount of solar radiation scattered back to a radiometer at a satellite depends on the scattering angle, i.e. the angles of Sun and satellite, on the aerosol optical thickness, and on the reflectance at the ground. Thus the error in the case of assuming spherical particles is highly variable, and it is essential to use the appropriate scattering function (Horvath et al., 2006). The particle shape effect can cause up to 30% difference in dust forcing at the top of the atmosphere (Yi et al., 2011).

These aspects are the reason to account for the non-sphericity of mineral particles in OPAC (Hess et al., 1998) and so to improve this algorithm. The user-friendly data base and software package "Optical Properties of Aerosol and Clouds" presents the single-scattering properties of 10 aerosol components that are given with size distribution and spectral refractive indices for a spectral range from ultraviolet to far-infrared. These components easily can be combined by the user to individual mixtures, i.e. to variable aerosol types, for which phase functions and other optical and microphysical parameters are modeled after user request.

If a particle no longer is assumed to be spherical, the possible variability of the particle shape is increased dramatically, from spheres, over spheroids and cubes to really irregular particles (Cheng, 1980). Thus, if the shape of particles will be taken into account for general modeling of the optical parameters, it is necessary to decide for simplifications. Moreover, a model is necessary that allows one to consider reasonable forms of non-spherical particles. In this paper the non-spherical mineral particles are approximated as spheroids, since this substantially improves the ~~results (~~agreement between modelled and measured optical properties (Mishchenko et al., 1997; Kahnert et al., 2005) and an appropriate~~ scattering~~ theory exists, the T-matrix method (Waterman, 1971).

In the new version of OPAC the optical properties of the mineral components are modeled as spheroids with the T-matrix method (Mishchenko a. Travis, 1998), with the aspect ratio distributions of the used spheroids varied with the particle size~~.~~, as found by electron microscope investigations. The other microphysical properties of the components, the size distribution and the spectral refractive indices, have not been changed against the old OPAC. During the Saharan Mineral Dust Experiment

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Feldfunktion geändert

field campaign (SAMUM-1), which was located close to the Sahara and its mineral sources and used a lot of different aerosol measurement systems (Heintzenberg, 2009), desert ~~dust~~aerosol size distributions have been measured both in situ at an air plane (Weinzierl et al., 2009) and inferred by the AERONET network inversion algorithm from ground-based photometer measurements. The results differ considerably (Müller et al., 2010), but the OPAC size distributions are in-between. Moreover, photometer measurements in the solar aureole (where the non-sphericity has no influence) and values modeled with OPAC type “desert” agree very well (Gasteiger, 2011). Also optical properties of Saharan dust measured by aircraft data in 1999 compare very favorably with OPAC results (Haywood et al., 2001) for radiative properties that are independent of the scattering angle, like asymmetry parameter, single scattering albedo and specific extinction coefficient, for which the non-sphericity has negligible influence. Thus the OPAC size distributions for ~~mineral~~ desert aerosol are assumed to be adequate for a combination with the information on particle shape from SAMUM.
Also not changed against the old OPAC is the possibility of the flexible mixing of the components and of the outcome of OPAC, like optical properties depending on relative humidity and available for a large wavelength range. In the new version of OPAC (4.0), which is freely available for non-commercial use, now the optical properties modeled for non-spherical mineral particles are taken into account, directly for practical ~~use~~application.

2. Methods

2.1. Non-spherical particle scattering

The most suitable method to model the optical properties of mineral aerosol particles on a systematic basis (Wiegner et al., 2009) is the T-matrix method, TMM. It provides a solution of Maxwell´s equations for the interaction of radiation with arbitrarily-shaped particles (Waterman, 1971) and is most efficient for rotationally symmetric particles. In our model the ~~desert dust~~mineral particles are given as spheroids, originating from rotation of ellipses about one of their axis. Thus, an additional microphysical parameter that has to be taken into account is the aspect ratio ε, which is the ratio between the ~~rotational axis~~longest and the shortest axis ~~perpendicular to it~~ (Dubovik et al., 2006). Moreover, the particles can be prolate (cigar like) and oblate (disk like) spheroids.
For the results in this paper and the new version of OPAC, the state-of-the-art TMM code from Mishchenko ~~and~~a. Travis (1998) for randomly oriented particles has been used for the mineral components. The T-matrix calculations are supplemented by geometric optics calculations with the code of Yang et al. (2007) for large particles not covered by the TMM code. Wiegner et al. (2009) show the size coverage of the TMM code, which can model dust spheroids up to size parameters, x=2πr/λ, around 110 – 120 for aspect ratio 1.6 and smaller. For aspect ratio 3.0 the maximum size parameter of TMM is around 25. These codes have been used to create a data set of single particle scattering properties of spheroids covering a wide range of particle sizes, aspect ratios, and refractive indices. The grid of particle parameters in this data set is given in Gasteiger et al., 2011. The optical properties of the OPAC mineral components were calculated from this data set according to their microphysical properties described below. For the selection of the adequate aspect ratio distributions depending on particle size, measurements of the Saharan Mineral Dust Experiments (SAMUM I and SAMUM II) have been used (Kandler et al., 2009; Kandler et al~~,~~., 2011).

2.2. Particle properties

This paper presents an improvement of OPAC, by modifying the shape of mineral ~~dust~~ particles. The other microphysical parameters used in OPAC, as the particle size distribution and the spectral refractive indices, have been left unchanged.

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Einzug: Links: 0,63 cm, Hängend: 0,63 cm, Mit Gliederung + Ebene: 1 + Nummerierungsformatvorlage: 1, 2, 3, … + Beginnen bei: 1 + Ausrichtung: Links + Ausgerichtet an: 0,63 cm + Einzug bei: 0,63 cm

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Einzug: Links: 0,63 cm, Hängend: 0,63 cm, Mit Gliederung + Ebene: 2 + Nummerierungsformatvorlage: 1, 2, 3, … + Beginnen bei: 1 + Ausrichtung: Links + Ausgerichtet an: 0,63 cm + Einzug bei: 0,63 cm

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Einzug: Links: 0,63 cm, Hängend: 0,63 cm, Mit Gliederung + Ebene: 2 + Nummerierungsformatvorlage: 1, 2, 3, … + Beginnen bei: 1 + Ausrichtung: Links + Ausgerichtet an: 0,63 cm + Einzug bei: 0,63 cm

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Feldfunktion geändert

In OPAC the aerosol particles are given as components (Shettle a. Fenn, 1979; Deepak a. Gerber, 1983) resulting from an internal mixture of particles of a certain origin. The particles of a component *i* have a log-normal size distribution (Eq.1).

$$\frac{dN_i(r)}{dr} = \frac{N_i}{r\sqrt{2\pi}\log\sigma_i \ln 10}\exp\left(-\frac{1}{2}\left(\frac{\log r - \log r_{mod,i}}{\log\sigma_i}\right)^2\right) \qquad (1)$$

N_i is the total number of particles of the component *i* per cubic centimeter, *r* the particle radius, $r_{mod,i}$ the mode radius of component *i* with respect to the particle number, and σ_i measures the width of the distribution. The radius *r* of each spheroid is assumed to be the radius of a sphere with the orientation-averaged geometric cross section of the spheroid. The relative optical properties do not depend on *N*, thus they are given always for N=1. For absolute values of optical properties, for actual or individual conditions, N_i must be chosen adequately for each component that will be taken into account.

The mineral dust is described in OPAC with three components as given in Tab. 1: Mineral Nucleation Mode (MINM), Mineral Accumulation Mode (MIAM), and Mineral Coarse Mode (MICM), with r_{mod} and σ the data of the size distributions, and r_{min} and r_{max} the borders that have been taken into account for modeling the optical properties.

Tab. 1. Microphysical properties of mineral ~~aerosol~~ components

~~Component Mineral... r_{mod} [µm] σ r_{min} [µm] r_{max} [µm]~~
~~Nucleation mode MINM 0.07 1.95 0.005 20~~
~~Accumulation mode MIAM 0.39 2.00 0.005 20~~
~~Coarse mode MICM 1.90 2.15 0.005 60~~

Component Mineral...		r_{mod} [µm]	σ	r_{min} [µm]	r_{max} [µm]
Nucleation mode	MINM	0.07	1.95	0.005	20
Accumulation mode	MIAM	0.39	2.00	0.005	20
Coarse mode	MICM	1.90	2.15	0.005	60

These mineral components can be mixed externally, also together with other components, to form individual aerosol types. In general, both over deserts and for other aerosol conditions with a dominant mass of mineral particles, also water-soluble particles (WASO) are present. These particles can be assumed to be spherical. Their amount usually is small with respect to their mass per volume, but since the particles are small their numbers per volume may be large.
In OPAC the aerosol type "desert" is a mixture of more than 200 µg/m³ mineral particles and only 4 µg/m³ water soluble particles (WASO), however, resulting in 2000 particles per cm³ of WASO, and 300 cm^{-3} of mineral particles belonging to ~~the~~their three components. A small amount of WASO generally is taken into account in the following results, which show optical properties of mixtures of mineral particles.
The refractive indices of the components are wavelength dependent (d Álmeida et al., 1991; Koepke et al., 1997). The particles of the mineral components all have the same refractive indices, since they are assumed to result from the same sources at the surface. The refractive index is given with an imaginary part that is responsible for the absorption properties of the particles.

To describe the shape properties of mineral particles of different size, for each of the three mineral components, the data of the "reference" case of SAMUM-1 have been used (Wiegner et al., 2009). The reference case was a situation with a very homogeneous ~~mineral dust~~desert aerosol layer up to 5 km above sea level which was very stable in time. The aspect ratio distribution of the particles was measured using electron microscopy and is given depending on particle size intervals by Kandler et al. (2009). For modeling the optical properties of mineral ~~aerosols~~particles these wide aspect ratio dis-

Formatiert

Formatiert: Schriftart: Cambria Math, Kursiv

Formatiert: Schriftart: Cambria Math, Kursiv

Formatiert

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Schriftartfarbe: Automatisch

Formatiert

Formatiert

Formatiert: Schriftartfarbe: Automatisch

Feldfunktion geändert

tributions are applied, to account for the large variety of the natural dust particle shapes. The belonging modeling results, compared to measured phase functions, are remarkably better than results when using only a single aspect ratio (Mishchenko et al., 1997; Nousiainen a. Vermeulen, 2003). Moreover, all mineral particles are assumed to be prolate, because this gives better agreement with measured scattering matrix elements of dust particles than ~~those of~~ using oblate or mixtures of prolate and oblate spheroids (Nousiainen a. Vermeulen, 2003).

It is worth mentioning that the aspect ratio distribution of mineral particles did not vary significantly during SAMUM-1 and also not during the SAMUM-2 campaign, which was conducted further away from the dust source Sahara (Kandler et al., 2009; Kandler et al., 2011). Thus the selected aspect ratio distribution might be regarded as representative for Saharan dust.

The aspect ratio distributions depend on the size of the particles. For the reference case the relative frequency of particles with a given aspect ratio is available for 6 ranges of particle size (Kandler et al, 2009; Wiegner et al., 2009). Some of them have similar aspect ratio distributions so that only three radius ranges must be differentiated: For particles with r < 0.25 µm the frequency decreases strongly with increasing aspect ratio. For particles with r > 0.5 µm the shape distributions for all analyzed size intervals are similar with a small maximum for the aspect ratio of about 1.5. Between these two regimes the particles between r = 0.25 and r = 0.5 µm have an aspect ratio distribution that gives a transition between the other two regimes (see Tab. 2).

Tab. 2. Aspect ratio distributions as function of particle radius interval according to Kandler et al. (2009). The first line represents the range from ε = 1.0 to 1.3, the last line is valid for ε > 2.9 and the other values cover ε-intervals of 0.2.

~~ε~~	~~r<0.25 µm~~	~~0.25 µm <r< 0.5 µm~~	~~r>0.5 µm~~
~~1.2~~	~~0.535~~	~~0.220~~	~~0.103~~
~~1.4~~	~~0.289~~	~~0.205~~	~~0.234~~
~~1.6~~	~~0.108~~	~~0.150~~	~~0.218~~
~~1.8~~	~~0.040~~	~~0.105~~	~~0.157~~
~~2.0~~	~~0.015~~	~~0.070~~	~~0.101~~
~~2.2~~	~~0.007~~	~~0.050~~	~~0.065~~
~~2.4~~	~~0.003~~	~~0.040~~	~~0.041~~
~~2.6~~	~~0.001~~	~~0.030~~	~~0.027~~
~~2.8~~	~~0.001~~	~~0.020~~	~~0.018~~
~~3.0~~	~~0.001~~	~~0.080~~	~~0.036~~

ε	r<0.25 µm	0.25 µm <r< 0.5 µm	r>0.5 µm
1.2	0.535	0.225	0.103
1.4	0.289	0.212	0.234
1.6	0.108	0.156	0.218
1.8	0.040	0.110	0.157
2.0	0.015	0.075	0.101
2.2	0.007	0.054	0.065
2.4	0.003	0.039	0.041
2.6	0.001	0.028	0.027
2.8	0.001	0.022	0.018
3.0	0.001	0.079	0.036

Each OPAC mineral component contains particles in all radius ranges given in Tab. 2, with proportions that are varying according to the size distribution of the components (Tab. 1). To check the shape effects, as a first test (Kandler A) each mineral component is divided into the three radius ranges of Tab. 2 and the belonging aspect ratio distribution of each range is applied. This test is the most exact approach based on the available aspect ratio data. As a second test -- with respect of the idea of OPAC to keep things ~~simple~~easy -- for all particles of each of the three OPAC mineral components a

Formatiert: Schriftfarbe: Automatisch

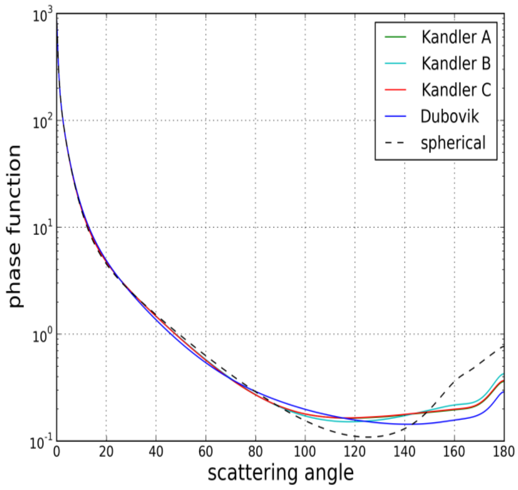
Formatiert: Schriftfarbe: Automatisch

Feldfunktion geändert

fixed aspect ratio distribution has been used: the distribution of r < 0.25 µm for MINM, of 0.25 µm < r < 0.5 µm for MIAM, and of r > 0.5 µm for MICM (Kandler B). This test setup seems appropriate since the mode radii of the three components (Tab.1) fall into these three radius intervals used to separate the aspect ratio distributions (Tab.2). As a third test (Kandler C), the second test is modified by assuming also for all particles of the accumulation mode (MIAM) the aspect ratio distribution that has been measured for particles with r > 0.5 µm. This use of the aspect ratio distribution measured for the larger particles also for MIAM was tested, since the maximum of the surface area distribution of MIAM is close to a radius of 1 µm. Finally a further association of radius and aspect ratio distribution has been tested: Dubovik et al. (2006) has derived aspect ratio distributions by analyzing measured phase functions, with the assumption that they are independent of the particle size. These are investigated as a forth test (Dubovik) for the particle shape effects.

Formatiert: Schriftartfarbe: Automatisch

As example for the different considerations of the aspect ratio distributions, in Fig.1 are shown the phase functions under the assumption of spherical particles and for non-spherical particles after the 4 tested radius dependent aspect ratio distributions. The phase functions are given for a wavelength 0.55 µm (however the results at other wavelengths are similar, see Fig.2), and as size distribution the combination of the three mineral components of the aerosol type “desert” after OPAC, including WASO at 0% relative humidity, has been used.



Feldfunktion geändert

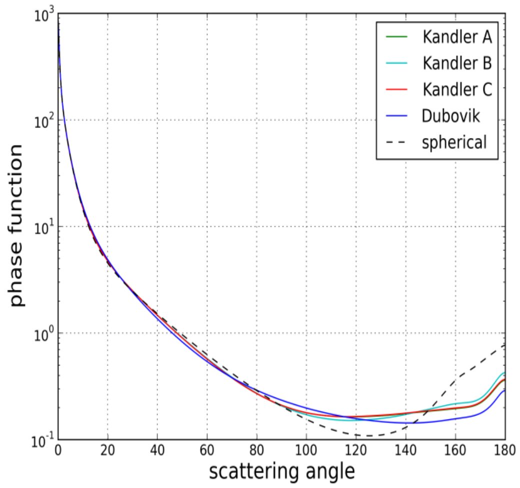


Fig. 1. Phase functions at 0.55 µm for the mixture of the mineral components after the aerosol type “desert”, under the assumption of spherical mineral particles and for mineral particles with various aspect ratio distributions (see text for details).

In Fig. 1 the increased sideward and reduced backward scattering clearly is to be seen which holds for all phase functions resulting from particles with non-spherical shape. The phase function after Dubovik is ~~clearly~~noticeably separated against those after Kandler A to C. But this result is not ~~really~~ astonishing, since the direct electron microscopic investigations show that the aspect ratio distributions are size dependent, in contrast to the size-independent assumption by Dubovik. The phase functions after Kandler A (exact approach) and Kandler C are nearly identical, which means that the simpler assumptions in Kandler C give already correct results. Thus for all optical property modeling of non-spherical mineral particles, both for the results shown in the following and for the new OPAC, the size dependent aspect ratio ~~distributions~~distribution after Kandler C is used.

3. Results

The effects of the particle shape are different for different optical properties, which is shown in this paragraph for a variation of the optical properties available from OPAC. Examples are presented for the deviations between optical properties caused by mineral particles that are assumed as spheres, on the one hand, and those assumed as spheroids with the aspect ratio distributions after Kandler C, on the other hand.

~~As mentioned above, the~~The phase function is very important for remote sensing of desert ~~dust~~aerosol and for its radiative forcing, and moreover, as mentioned above, for this optical quantity the effect due to non-sphericity is large, especially ~~large~~in the solar spectral range. Thus Fig. 2a shows the phase function for the two particle shape assumptions, for the mixture “desert” (Hess et al., 1998) and for different wavelengths. The assumed shape variation (spherical or non-spherical) is modeled only for the mineral particles: MINM 269.5 cm^{-3}; MIAM 30.5 cm^{-3}, MICM 0.142 cm^{-3}. The 2000 cm^{-3} particles of the WASO component always are assumed as spherical.

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Einzug: Links: 0,63 cm, Hängend: 0,63 cm, Mit Gliederung + Ebene: 1 + Nummerierungsformatvorlage: 1, 2, 3, … + Beginnen bei: 1 + Ausrichtung: Links + Ausgerichtet an: 0,63 cm + Einzug bei: 0,63 cm

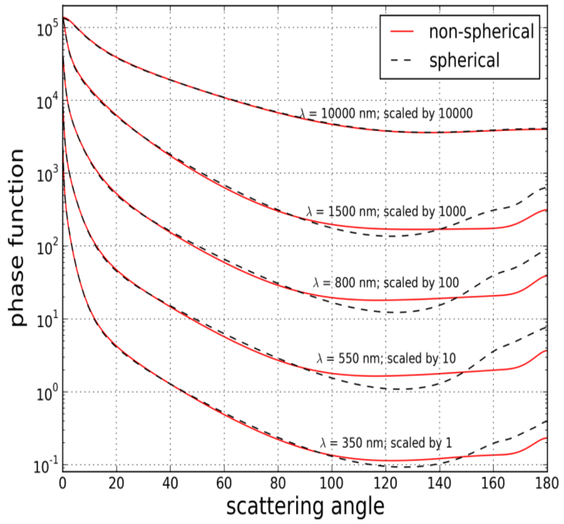
Formatiert

Formatiert

Formatiert

Formatiert

Feldfunktion geändert



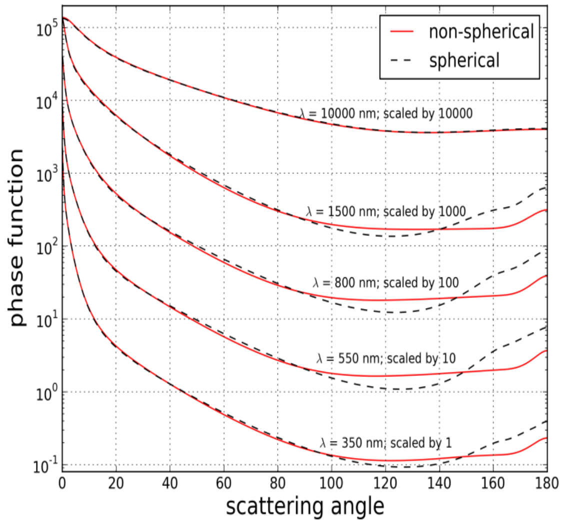
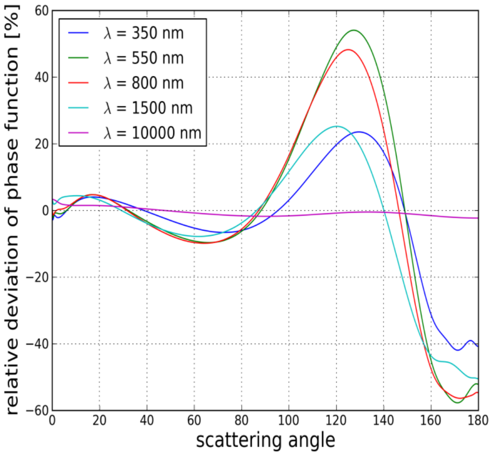


Fig. 2a. Phase functions of ~~“~~desert ~~dust”~~aerosol for different wavelengths, assuming spherical and spheroidal mineral particles with a size dependent aspect ratio distribution after Kandler C. For details see text. The scale of the phase functions for the different wavelengths is shifted by a factor 10 in each case.

The phase functions show the known strong forward peak of aerosol particles, which is not influenced by the particle shape. It is increasing with increasing size parameter, and thus decreasing with wavelength. The particle shape effect is clearly to be seen in Fig. 2a in the backward scattering region, but more pronounced in Fig. 2b, where the belonging percentage deviations between the phase functions for particles with size dependent aspect ratio distributions and for spherical particles are shown.

Formatiert: Schriftartfarbe: Automatisch

Feldfunktion geändert



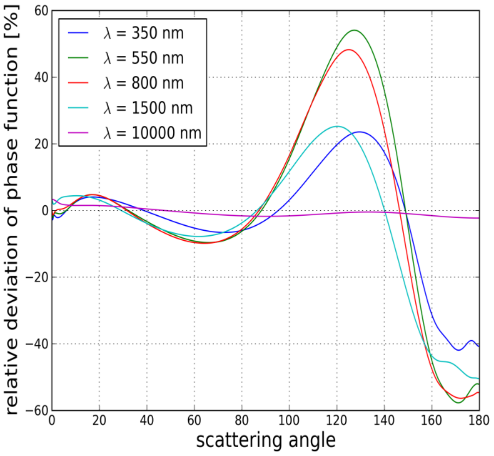


Fig. 2b. Relative deviations (%) of phase functions assuming spheroidal mineral particles from phase functions of spherical particles, for ~~“~~desert ~~dust”~~aerosol and the conditions shown in Fig. 2a.

The effect of the particle shape is up to almost + 60 % at scattering angles around 130° and – 60 % around 170°, in the backscatter region. The effect decreases with increasing wavelength~~, since~~ and is nearly negligible at 10 µm, as also shown. The reason is that the shape properties of the particles become less relevant if the wavelength of the radiation becomes larger relative to the particle size. In contrary, the effect of the particle shape is relatively low at 350 nm, but this ~~result~~results from the strong absorption of the mineral particles at this wavelength, which reduces the scattering effects in general and thus overcompensates the shape effect. As to be seen, the effect of the particle shape is strongest in the solar wavelength range, which is ~~generally~~often used for aerosol remote sensing and which is essential for radiative forcing and thus for climate effects. This documents again the need to take the non-spherical ~~particle ~~shape of ~~desert dust~~mineral particles into account for remote sensing or climate studies.

As mentioned, the aspect ratio distribution depends on the particle size. Thus size distributions with different amount of small and large particles may result in different variations of the phase function compared to that under the assumption of spheres. Since the life time of big particles in the atmos-

Feldfunktion geändert

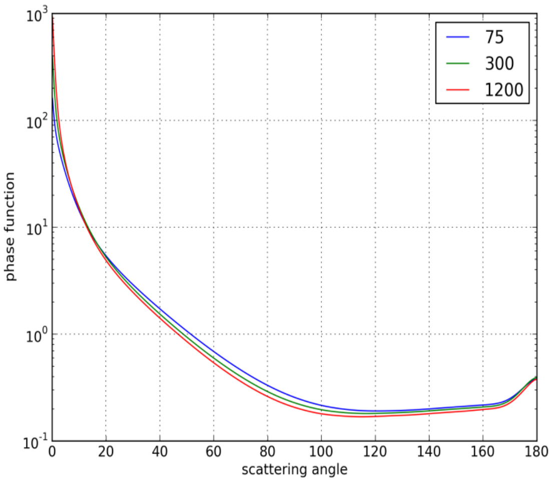
phere is less than that of smaller particles, in a dust storm not only the total amount of mineral particles in the air is high, but also the relative amount of large particles. During the transport, i.e. with the time after the dust generation, the particle amount will be reduced due to sedimentation, but this effect ~~is~~can be stronger for larger particles. Finally, for background conditions, the total amount of mineral particles is low, with ~~strongest reduction for~~the lowest amount of large particles (d`Almeida, 1987; Longtin et al., 1988; Tanré et al., 1988). The relative increasing amount of large particles with increasing turbidity ~~is given~~that we assume to test the effect of non-sphericity with respect to particle size distribution is shown in Eqs. 2 – 4 (d`Almeida, 1987; Koepke et al., 1997). Given are correlations between the total number of ~~desert~~mineral dust particles and the belonging numbers for the three mineral components.

$$\ln N_{MINM} = 0.104 + 0.963 \ln N_{mineral} \quad (2)$$

$$\ln N_{MIAM} = -3.94 + 1.29 \ln N_{mineral} \quad (3)$$

$$\ln N_{MICM} = -13.7 + 2.06 \ln N_{mineral} \quad (4)$$

For desert ~~dust~~aerosol with different turbidity, ~~given~~implemented with different total particle number and belonging different number of particles of the three mineral components, in Fig. 3 the phase functions for non-spherical desert particles are shown. N gives the total number of mineral particles, the value of $N_{mineral}$ in Eqs.2 - 4. N = 75 stands for “background desert” conditions, N=300 for average “desert” and N=1200 for “dust storm”. It can be seen that the general effect of the non-spherical particle shape is always given, but does not differ considerably for the different size distributions, as result of different total particle number. The effect of varying size distribution is more pronounced in the forward peak and the sideward scattering.



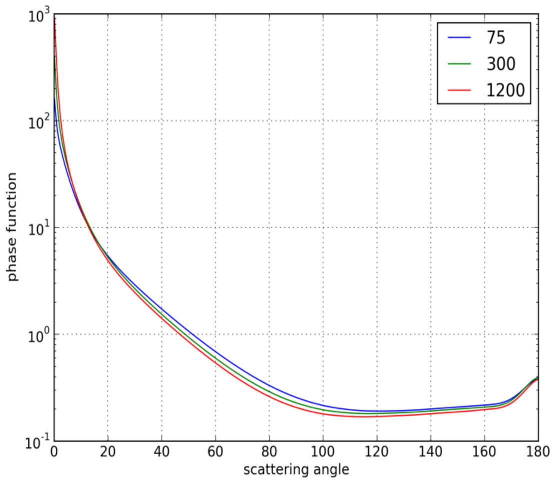
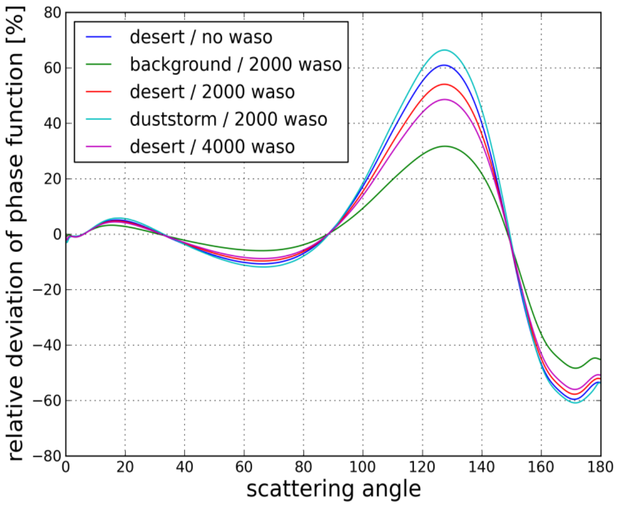


Fig. 3. Phase functions of ~~non-spherical~~ desert aerosol ~~particles~~ at 0.8 µm, with a mixture of the non-spherical mineral components MINM, MIAM and MICM after the Eqs. 2-4, using the total number of mineral particles given in the figure. In each case 2000 WASO particles assuming 0% r. h. are included.

As mentioned, the WASO particles are spheres, with the consequence that the variation of their amount changes the phase function of the mixture. This is shown in Fig. 4 for “desert” with different amount of WASO, on the one hand, and for average amount of 2000 WASO particles, but in combination with mineral particles for “background” and for “dust storm” conditions, on the other hand.

Formatiert



Feldfunktion geändert

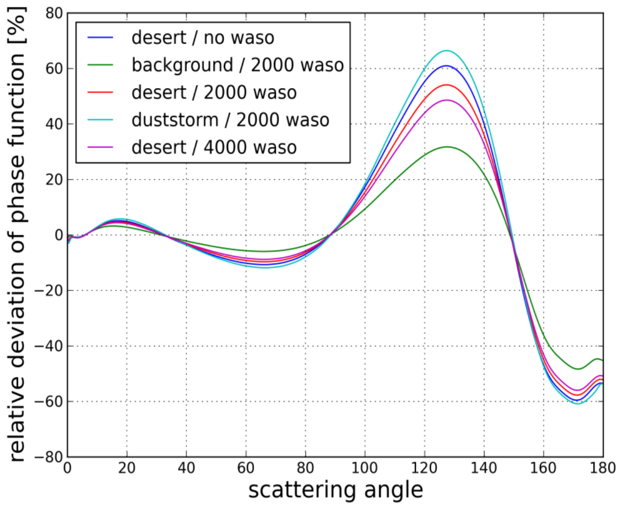


Fig. 4. Relative deviations (%) of phase functions at 0.55 µm, assuming spheroidal mineral particles, from phase functions of spherical particles, for different combinations of the components WASO, MINM, MIAM and MICM (for details see text).

Figure 4 shows that the effects due to the particle shape increase from background over desert to dust storm if the number of WASO is fixed, simply due to the increasing amount of non-spherical mineral particles. In contrary, the effect due to non-spherical shape is reduced, to be seen for the type “desert”, if the amount of spherical WASO particles is increased. But it should be mentioned that the effect due to doubling or omitting WASO for the relative deviations of the phase function is less than the effect due to the variation of the amount of the mineral particles.

For the determination of the height dependent aerosol extinction coefficients, often backscatter lidar systems or ceilometers are used, because they are cheaper than higher sophisticated lidar instruments (Mona et al., 2012; Wiegner et al., 2014). However, for these instruments the measured signal is result of both the ~~scattering~~extiction coefficient and the phase function at 180°. Thus, to get the interesting height dependent extinction coefficient, it is necessary to use a quantity “lidar ratio”, which depends on the phase function and thus on the particle shape.

Fig. 5 shows the lidar ratio for the aerosol type “desert”, both under the assumption of non-spherical and spherical mineral particles. The values are given for a wavelength range up to 40 µm, although no lidar instruments are available for wavelength larger ≈2 µm. Moreover for the large wavelengths, the particles behave more and more like spheres, as already to be seen in Fig. 2b. For the interesting wavelength range around and below 1 µm, however, the consideration of non-sphericity is essential. With respect to independently measured lidar ratios, the agreement with modeled values is much better under the assumption of spheroids than of spheres (Gobbi et al., 2002). The lidar ratios to be seen in Fig. 4 are in good agreement with measured values from SAMUM (Groß et al., 2011). This also generally is valid for all lidar-wavelengths that have been used during SAMUM, but here the agreement between measured and modeled lidar ratios was reduced for 355 nm, probably due to wrong assumptions with respect to the refractive index (Wiegner et al., 2009).

Feldfunktion geändert

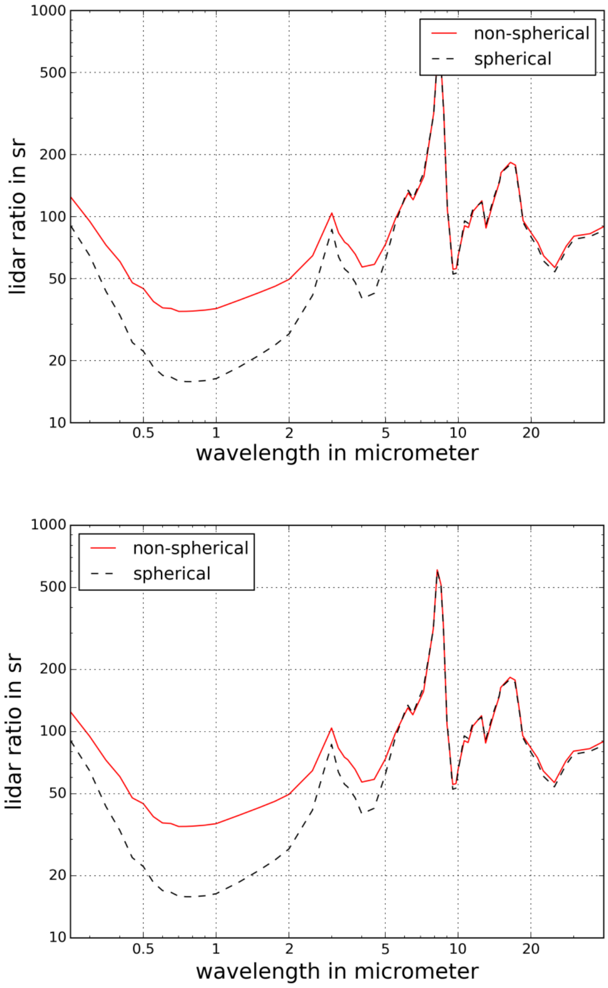
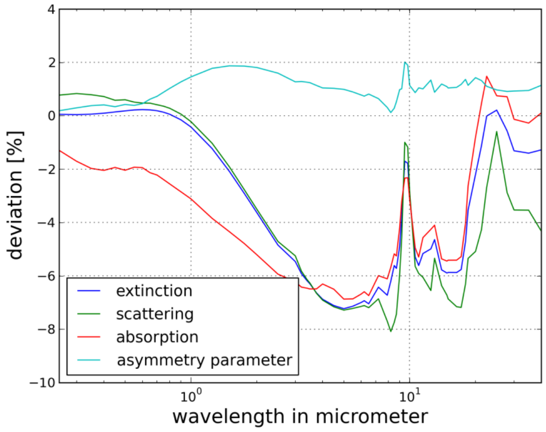


Fig. 5. Modeled values of the lidar ratio for “desert” aerosol under the assumption of spherical and non-spherical particles.

Optical quantities that are independent of the scattering angle or given as ratio between wavelengths are expected to be less sensitive with respect to the particle shape. To investigate this aspect, in Fig. 6 relative differences between spherical and non-spherical desert particles are presented for the spectral scattering -, absorption - and extinction- coefficients and for the asymmetry parameter. For all these quantities the deviations are less than 6 % and even less than 4 % in the part of the solar spectrum that is most relevant for climate effects. The same low dependency on the particle shape also holds for the single scattering albedo and the Ångstrom coefficient, not shown in a figure.

Feldfunktion geändert



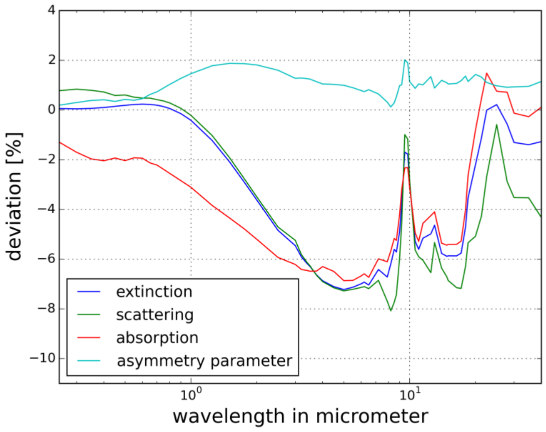


Fig.6. Deviation (%), between spherical and non-spherical “desert” aerosol for different optical quantities

4. New version: OPAC (4.0)

Formatiert: Einzug: Links: 0,63 cm, Hängend: 0,63 cm, Mit Gliederung + Ebene: 1 + Nummerierungsformatvorlage: 1, 2, 3, … + Beginnen bei: 1 + Ausrichtung: Links + Ausgerichtet an: 0,63 cm + Einzug bei: 0,63 cm

The main improvement of the new version of OPAC is the consideration of the non-sphericity of ~~desert dust~~mineral particles. In OPAC always the large wavelength range between 0.25 and 40 µm is considered, with the consequence that the improved particle shape of mineral particles works both in the solar and in the infrared spectral region. Additionally new in OPAC (4.0) is the possibility to model ~~PM10, PM2.5 and PM1~~the particle mass for ~~the individual mixtures of components~~different cut off radii, as used e.g. for PM10. On the other hand, the component “mineral transported”, MITR, no longer is considered. This component had been used to describe desert aerosol under very remote conditions, as part of aerosol in polar regions. However, the amount of ~~desert~~mineral dust particles should be reduced continuously on its way from the source, depending on their life time~~, which~~. This is possible with the remaining mineral components (e.g. using Eqs. 2-4), instead of switching to MITR. Thus the aerosol type “~~antarctic”~~Antarctic” in OPAC has been modified.

Feldfunktion geändert

As discussed in the paper, the shape of the mineral particles has been improved. To avoid mistakes, the new mineral components are named in the new OPAC version with an N at the end, standing for non-spherical.

The change from spheres to spheroids was made on the basis of cross section equivalence, resulting in a small reduction of the particle volume and thus the particle mass, ~~with~~resulting in the reduction factors shown in Tab. 3.

Tab. 3. Reduction factors for particle volume and mass for the non-spherical mineral components, compared to the old components.

~~MINM >> MINN 0.9754~~
~~MIAM >> MIAN 0.9273~~
~~MICM >> MICN 0.9273~~

MINM → MINN	0.9754
MIAM → MIAN	0.9273
MICM → MICN	0.9273

All the other microphysical aerosol properties are unchanged against the previous version of OPAC. Also the new version of OPAC gives the possibility to combine different aerosol components, in each case with individually decided particle number density for each component.

Results of OPAC (4.0) are ~~microphysical properties, like particle mass per volume and PM10, and the~~a large number of optical properties (like phase function, scattering- absorption- and extinction coefficient, asymmetry parameter, single scattering albedo, Ångstrom coefficient, ~~and~~ lidar ratio~~).~~ and visibility)and particle mass per volume. All properties can be modeled for different relative humidity and the optical properties are available as spectral values for the wide wavelength range of 0.25 to 40 µm and spectrally weighted for the solar and terrestrial range. For non-commercial use OPAC (4.0) is freely available: www.rascin.net.

5. Conclusion

Aerosol particles are one of the main gaps in the present knowledge of radiative forcing (Myhre et al., 2013), and mineral ~~particle~~particles are especially essential due to their large amount and temporal and spatial variability. Since mineral particles in general are no spheres, Mie-theory ~~as scattering theory~~ may lead to wrong values~~ of~~, both, if their optical properties~~, if they~~ are modelled based on size distribution and refractive index, and vice versa, if remote sensing data are used to get aerosol properties. Thus~~, as a major improvement~~, the optical properties of mineral particles in the new version of OPAC are derived using T-Matrix method for spheroids. ~~In~~As described in this paper the non-sphericity is ~~described~~given by typical size dependent aspect ratio distributions of spheroids, which have been derived from measurements at observation campaigns. The predefined components in OPAC, now also for non-spherical mineral particles, are ~~an advantage of OPAC~~a big convenience, because users do not need to decide for individual single particle properties, as available from various studies and data bases (Nousiainen, 2009; Meng et al., 2010).

The differences between spherical and non-spherical mineral particles are shown for a wide range of optical properties of desert ~~dust~~aerosols. They are small, nearly negligible, for angular-independent optical quantities, like extinction-, scattering- and absorption- coefficient, asymmetry factor, single scattering albedo and Ångstrom coefficient. However the differences between spherical and non-spherical particles are large, up to 60 %, in the sideward and backward scattering regions of the phase functions~~.~~ in the solar spectral range. As a consequence the deviations also are large in the lidar ratio, a parameter required to get height dependent extinction values from often used backscatter lidar measurements. The effect of the particle shape decreases with wavelength, since for wavelengths

Formatiert: Einzug: Links: 0,63 cm, Hängend: 0,63 cm, Mit Gliederung + Ebene: 1 + Nummerierungsformatvorlage: 1, 2, 3, … + Beginnen bei: 1 + Ausrichtung: Links + Ausgerichtet an: 0,63 cm + Einzug bei: 0,63 cm

Feldfunktion geändert

that are rather large with respect to the particle size, the irregular particle shape is of less relevance. ~~However, in the solar spectral range the shape effects can be large. Since this is the wavelength range that is generally~~

It should be born in mind that the size distribution and the complex refractive index of the aerosol particles are very important for their optical properties. For the radiative properties in the thermal infrared the uncertainty in the refractive index will outperform the shape effect, which moreover depends on the absorption of the particles (Legrand et al., 2014). However, in this article only the aspect of the shape of mineral particle is discussed, and in the new version of OPAC the shape of the mineral particles has been improved, but the assumed size distributions and spectral refractive indices have not been changed. This will be done in the future, where it is planned also to add a stronger absorbing mineral component that allows for a larger variability of mixtures to describe desert aerosol.

Since the solar spectral range is often used for remote sensing of aerosol particles, on the one hand, and relevant for aerosol radiative forcing, on the other hand, the ~~use~~consideration of the phase functions of non-spherical mineral particles ~~will be~~is a real improvement~~. To allow an easy use~~ of ~~the optical properties of desert aerosol with non-spherical particles, the data are made~~OPAC, now available ~~in OPAC (~~as version 4.0~~)~~..

Acknowledgements

This publication was partly funded by LMU Munich's Institutional Strategy LMUexcellent within the framework of the German Excellence Initiative.

References

d 'Almeida, G.A.: On the variability of desert aerosol radiative characteristics, J. Geophys. Res., 92, D3, 3017 – 3026, 1987.

d 'Almeida, G.A., Koepke, P., and Shettle, E.P.: Atmospheric aerosols, A. Deepak Publ. Hampton, Virginia, USA, pp 561, 1991.

Cheng, R.J.: Physical properties of atmospheric particulates , In: Light scattering by irregularly shaped particles [D.W. Schuerman (ed.)], Plenum Press, New York, USA, 69 - 78, 1980.

Deepak, A. and Gerber, H.E.: Report of the experts meeting on aerosols and their climatic effects, WCP-55, World Meteorolog. Org., Geneva, Switzerland, 107 pp, 1983.

Dubovik, O., Sinyuk, A., Lapyonok,T., Holben, B.N., Mishchenko, M.I., Yang, P., Eck, T.F., Volten, H., Munoz, O., Veihelmann, B., van der Zande, W.J., Leon, J.F., Sorokin, M.,and Slutsker, I.: Application of spheroid models to account for aerosol particle non-sphericity in remote sensing of desert dust, J. Geophys. Res.- Atmos., 111, D11208, 1 - 34, 2006

Falkovich, A.H., Gomez, E., Lewin, Z., Formenti, P., and Rudich, Y.: Analysis of individual dust particles, J. Geophys. Res. – Atmos., 106 ,D16, 18029 – 18036, 2001.

Gasteiger, J.K. : Retrieval of microphysical properties of desert dust and volcanic ash aeosols from ground –based remote sensing, Diss. Univ. Muenchen, 124 pp., 2011.

Gasteiger, J., Groß, S., Freudenthaler, V., and Wiegner, M.: Volcanic ash from Iceland over Munich: mass concentration retrieved from ground-based remote sensing measurements, Atmos. Chem. Phys., 11, 2209-2223, 2011.

Gobbi, G.P., Barnaba, F., Blumthaler, M., Labow, G., and Herman, J.R.: Observed effects of particles non-sphericity on the retrieval of marine and desert dust aerosol optical depth by lidar, Atmos. Res., 61, 1 – 14, 2002.

Groß, S., Tesche, M., Freudenthaler, V., Toledano, C., Wiegner, M., Ansmann, A., Althausen, D., and Seefeldner, M.: Characterization of Saharan dust, marine aerosols and mixtures of biomass-burning aerosols and dust by means of multi-wavelength depolarization and Raman lidar measurements during SAMUM 2, Tellus B, 63, 706-724, 2011.

Formatiert: Schriftfarbe: Automatisch

Formatiert: Schriftfarbe: Automatisch

Formatiert: Schriftfarbe: Automatisch

Formatiert: Schriftfarbe: Automatisch

Formatiert: Schriftfarbe: Automatisch

Formatiert: Schriftfarbe: Automatisch

Formatiert: Schriftfarbe: Automatisch

Formatiert: Einzug: Links: 0 cm, Hängend: 1,25 cm

Feldfunktion geändert

Haywood, J.M. and Boucher, O.: Estimates of direct and indirect radiative forcing due to tropospheric aerosol: A review, Rev. Geophys., 38, 513 – 543, 2000.

Haywood, J.M., Francis, P.N., Glew, M.D., and Taylor, J.P.: Optical properties and direct radiative effect of Saharan dust: A case study of two Saharan dust outbreaks using aircraft data, J. Geophys. Res.- Atmos., 106, D16, 18417 – 18430., 2001

Heintzenberg, J. :The SAMUM-1 experiment over Southern Morocco: overview and introduction, Tellus B, 61, 2 – 11, 2009.

Hess, M., Koepke, P., and Schult, I.: Optical properties of aerosols and clouds: The software package OPAC, Bul. Am. Meteorol. Soc., 79, 5, 831 – 844, 1998.

Horvath, H., Kasahara, M., Tohno, S., and Kocifaj, M.: Angular scattering of the Gobi desert aerosol and its influence on radiative forcing, J. Aerosol Sci., 37, 1287 – 1302, 2006.

Kalashnikova, O.V. and Sokolik, I.N.: Importance of shapes and compositions of wind-blown dust particles for remote sensing at solar wavelengths, Geophys. Res. Lett., 29, 10, 38-1 – 38-4~~-~~, 2002~~.~~

Kahnert, F.M.: Numerical methods in electromagnetic scattering theory, J. Quant. Spectrosc. Rad. Transfer, 79, 775 – 824, 2003.

Kahnert, M., Nousiainen, T., and Veihelmann, B.: Spherical and spheroidal model particles as an error source in aerosol climate forcing and radiance computations: A case study for feldspar aerosols, J. Geophys. Res.-Atmos~~.,~~., 110, D18S13, 2005.

Kandler, K., Schütz, L., Deutscher, C., Ebert, M., Hofmann, H., Jäckel, S., Jaenicke, R., Knippertz, P., Lieke, K., Massling, A., Petzold, A., Schladitz, A., Weinzierl, B., Wiedensohler, A., Zorn, S., and Weinbruch, S.: Size distributions, mass concentrations, chemical and mineralogical composition, and derived optical parameters of the boundary layer aerosol at Tinfou, Morocco, during SAMUM 2006, Tellus B, 61, 32 – 50, 2009.

Kandler, K., Lieke, K., Benker, N., Emmel, C., Küpper, M., Müller-Ebert, D., Scheuvens, D., Schladitz, A., Schütz, L., and Weinbruch, S. : Electron microscopy of particles collected at Praia, Cap Verde, during the Saharan mineral dust experiment: particle chemistry, shape, mixing state and complex refractive indices, Tellus B, 63, 457 -496, 2011.

Kaufmann, Y.J.: Measurements of the optical thickness and the path radiance - Implications on aerosol remote sensing and atmospheric corrections, J. Geophys. Res., 98, 2677 – 2692, 1993.

Kinne, S., Schulz, M., Textor, C., Guibert, S., Balkanski, Y., Bauer, S.E., Berntsen, T., Berglen. T.F., Boucher, O., Chin, M., Collins, W., Dentener, F., Diehl, T., Easter, R., Feichter, J., Fillmore, D., Chan, S., Ginoux, P., Gong, S., Grini, A., Hendricks, J., Herzog, M., Horowitz, L., Isaksen, I., Iversen, T., Kirkevag, A., Kloster Koch, D., Kristjansson, J.ER., Krol, M., Lauer,A., Lamarque, J.F., Lesins, G., Liu, X., Lohmann, U., Montanaro, V., Myhre, C., Penner, J., Pitari, G., Reddy, S., Seland, O., Stier, P., Takemura, T., and Tie, X.: An AeroCom initial assessment – optical properties in aerosol component modules of global models, Atmos. Chem. Phys., 6, 1815 – 1834, 2006.

Koepke, P. and Quenzel, H.: Turbidity of the atmosphere determined from satellite, J. Geophys. Res., 84, C12, 7847 – 7856, 1979.

Koepke, P. and Hess, M.: Scattering functions of tropospheric aerosols: the effects of non-spherical particles, Appl. Optics, 27, 12, 2422 – 2430, 1988.

Koepke., P., Hess, I., Schult, and Shettle, E.P.: Global Aerosol Data Set, Report No.243, MPI Hamburg, Germany, 44 pgs, 1997.

Lacis, A.A. and Mishchenko, M.I.: Climate forcing, climate sensitivity, and climate response: a radiative modeling perspective on atmospheric aerosols. In: Aerosol forcing of climate [Charlson, R.J. and Heintzenberg, J. (eds.)] John Wiley & Sons, 11 – 42, 1995.

Legrand, M., Dubovik, O., Lapyonok, T., and Derimian, Y.: Accounting for particle non-sphericity in modeling mineral dust radiative properties in the thermal infrared. J. Quant. Spectroscop. Rad. Transfer, 149, 219 – 240, 2014.

Longtin, D.R., Shettle. E.P., Hummel, J.R., and Pryce, J.D.: A desert aerosol model for radiative transfer studies, In: Aerosols and climate [Hobbs, P.V. and McCormick, M.P. (eds.)]A. Deepak Publ., Hampton Virginia, USA, 261 – 269, 1988.

Formatiert: Einzug: Links: 0 cm, Hängend: 1,25 cm

Formatiert: Schriftartfarbe: Automatisch

Formatiert: Einzug: Links: 0 cm, Hängend: 1,25 cm

Feldfunktion geändert

McCormick, R.A. and Ludwig, J.H.: Climate modification by atmospheric aerosols, Science, 156, 1358 – 1359, 1967.

Meng, Z., Yang, P., Kattawar, G.W., Bi, L., Liou. K.N., and Laszlo. I.: Single-scattering properties of tri-axial ellipsoidal mineral dust aerosols: A database for application to radiative transfer calculations, J. Aerosol Sci., 41, 501 – 512, 2010.

Mie, G.: Beiträge zur Optik trüber Medien, speziell kolloidaler Metallösungen, Ann. Physik, 25, 377 – 445, 1908.

Mishchenko, M.I., Travis, L.D., Kahn, R.A., and West, R.A.: Modeling phase functions for dust-like tropospheric aerosols using a shape mixture of randomly oriented polydisperse spheroids, J. Geophys. Res., 102, 13543 – 13553, 1997.

Mishchenko, M.I. and Travis, L.D.: Capabilities and limitations of a current Fortran implementation of the T-Matrix method for randomly oriented, rotationally symmetric scatterers, J. Quant. Spectrosc. ~~Ra.,~~Rad. Transfer, 60, 309 – 324, 1998.

Mishchenko, M.I., Hovenier, J.W., and Travis, L.D. (Eds): Light scattering by nonspherical particles: Theory, measurements, and applications, Academic Press, San Diego, USA, 2000.

Mona, L., Liu, Z., Müller, D., Omar, A., Papayannis, A., Pappalardo, G., Sugimoto, N., and Vaughan, M~~.~~ ~~:~~.: Lidar measurements for desert dust characterization: An Overview, Adv. Meteorology, 2012, ID356265, 36 pp, 2012.

Müller, D., Weinzierl, B., Petzold, A., Kandler, K., Ansmann, A., Müller, T., Tesche, M., Freudenthaler, V., Esselborn, M., Heese, B., Althausen, D., Schaditz, A., Otto, S., and Knippertzt, P.: Mineral dust observed with AERONET Sun photometer, Raman lidar, and in situ instruments during SAMUM 2006: Shape –independent particle properties, J. Geophys. Res.- Atmos., 115, D07202,2010.

Myhre, G. , Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee. D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and Zhanh, H.: Anthropogenic and natural radiative forcing, In: Climate Change 2013 [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M. (eds.)] Cambridge Univ. Press, Cambrige, UK, and New York, USA, 2013.

Nousiainen, T. and Vermeulen, K.: Comparison of measured single-scattering matrix of feldspar with T-matrix simulations using spheroids, J. Quant. Spec. Rad. Trans., 79, 1031 – 1042, 2003.

Nousiainen, T. : Optical modeling of mineral dust particles: A review, J. Quant. Spectroscop. Ra., 110, 1261 – 1279, 2009.

Sakai ,T., Orikasa, N., Nagai, T., Murakami, M., Tajiri, T., Saito, A., Yamashita, K., and Hashimoto, A.: Balloon-borne and Raman lidar observations of Asian dust and cirrus cloud properties over Tsukuba, Japan, J. Geophys. Res.- Atm., 119, 6, 3295 – 3308, 2014.

Shettle¸ E.P. and Fenn, R.W.: Models for the aerosols of the lower atmosphere and the effects of humidity variations on their optical properties, Report AFGL-TR-79-0214, AFGL, Hanscom AFB, Mass, USA, pp.94, 1979.

Sokolik, I.N., Winker, D.M., Bergametti, G., Gilette, D.A., Carmichel, G., Kaufmann, Y.J., Gomes, L., Schmetz, l., and Penner, J.E.: Introduction to special section: outstanding problems in quantifying the radiative impacts of mineral dust, J. Geophys. Res. –Atmos., 106, D16, 18015 – 18027, 2001.

Tanré, D., Devaux, C., Herman, M., and Santer, R.: Radiative properties of desert aerosols by optical ground-based measurements at solar wavelengths, J. Geophys. Res. – Atmos., 93, D11, 14223 – 14231, 1988.

Waterman, P.: Symmetry, unitarity, and geometry in electromagnetic scattering, Phys. Rev., D4, 825 – 839, 1971.

Weinzierl, B., Petzold, A., Esselborn, M., Wirth, M., Rasp, K., Kandler, K., Schütz, L., Koepke, P., and Fiebig, M. : Airborne measurements of dust layer properties, particle size distribution and mixing state of Saharan dust during SAMUM 2006, Tellus B, 61, 96-117, 2009.

Formatiert: Einzug: Links: 0 cm, Hängend: 1,25 cm

Feldfunktion geändert

Wiegner, M., Gasteiger, J., Kandler, K., Weinzierl, B., Rasp, K., Esselborn, M., Freudenthaler, V., Heese, B., Toledano, C., Tesche, M., and Althausen, D.: Numerical simulations of optical properties of Saharan dust aerosols with emphasis on lidar applications, Tellus B, 61, 180 – 194. 2009.

Wiegner, M., Madonna, F., Binietoglou, I., Forkel, R., Gasteiger, J., Geiß, A., Pappalardo, G., Schäfer, K., and Thomas, W.: What is the benefit of ceilometers for aerosol remote sensing? Atmos. Meas. Tech. 7, 1979 – 1997, 2014.

Yang, P., Feng, Q., Hong, G., Kattawar, G.W., Wiscombe, W.J., Mishchenko, M.I., Dubovik, O., Laszlo, I., and Sokolik, I.N.: Modeling of the scattering and radiative properties of nonspherical dust-like aerosols, J. Aerosol Sci., 38, 995-1014, 2007.

Yi, B., Hsu, C.N., Yang, P., and Tsay, S.-C.: Radiative transfer simulation of dust-like aerosols: Uncertainties from particle shape and refractive index, J. Aerosol Sci., 42, 631 – 644, 2011.

Zerull, R.H., Giese, R.H., Schwill, S., and Weiss, K.: Scattering by particles of nonspherical shape, In: Light scattering by irregularly shaped particles [Schuerman, D.W. (ed.)], Plenum Press, New York, USA, 273 – 282, 1980.

Feldfunktion geändert