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The reflection and polarization properties of non-spherical aerosol particles

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ABSTRACT

In this paper, we investigate the capability of multi-angle TOA reflectance and polarized reflectance for the retrieval of aerosol properties including aerosol mode (fine mode and coarse mode), aerosol shape (sphere and non-spherical), and aerosol optical thickness. Single-scattering parameters and phase-matrix elements were computed for randomly oriented non-spherical aerosol particles. Sensitivity indices were introduced to quantify the sensitivity of the TOA total reflectance and polarized reflectance to aerosol parameters. Finally, on the basis of the sensitivity study, this paper presents a conceptual approach toward the remote sensing of non-spherical aerosol three parameters (aerosol mode, aerosol shape, and aerosol optical thickness) using the TOA total reflectance and TOA polarized reflectance for the 0.865 μm spectral bands measured at multiple viewing angles.

1. Introduction

Aerosol particles in the atmosphere are known to play an important role in the climate system by altering the earth's energy budget through the scattering and absorption of radiation [1,2]. Knowledge of aerosol particles properties is crucial for studying the radiation budget and climate change, thus studies of the optical, microphysical properties of aerosol particles have become the popular issue. Yet accounting for aerosol particles has been known to be a source of significant uncertainties in studies of earth's climate, which is explained by difficulties in monitoring spatially and temporally variable aerosol properties [3]. The only way to obtain the aerosol particles properties on a global scale is by means of satellite remote sensing.

Several approaches to the satellite remote sensing of aerosol particles optical and microphysical properties using measurements of solar reflectance have been developed [4–7]. The general approach is to compare measured radiances with radiative transfer (RT) calculations. The TOA radiance is the sum of contributions from different sources—scattering from air molecules and aerosol particles, reflections from the surface. Scattering processes at air molecules are well understood, so their contribution to the TOA radiance can be calculated easily from the mean altitude of pixel and the viewing geometry. However, a remaining problem is the separation of the aerosol signal from the surface signal [8]. Both are known to change and depend on various parameters not all of which are known. For example, the aerosol signal depends on the aerosol particles shape, which is not directly available. The surface reflectance depends, for instance, on the viewing geometry, on the vegetation cycle, and on ground humidity. Several approaches are being followed

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Nomenclature

AOT	aerosol optical thickness
TOA	top of atmosphere
I	first Stokes parameter
Q	second Stokes parameter
U	third Stokes parameter
V	fourth Stokes parameter
R	TOA reflectance
R_p	TOA polarized reflectance
F_0	incident solar flux density at the given wavelength
L	radiant flux crossing a unit area perpendicularly into a unit solid angle
RT	radiative transfer
r_{eff}	effective radius of a size distribution
v_{eff}	distribution standard deviation
θ_s	solar zenith angle
θ_v	view zenith angle
$\phi_s - \phi_v$	relative azimuth angle

to separating the aerosol contribution from that of the surface [9].

Despite this multitude of approaches, the AOT retrieval from satellite data is still not satisfactory [10]. The accuracy of remote sensing aerosol characterization is limited by the difficulty modeling the optical properties of non-spherical aerosol particles [11,12]. Earlier on, and in some applications even today, aerosol particles have been assumed to be isotropic, homogeneous, and spherical. With these assumptions one can apply the Mie theory to compute the exact single-scattering properties of aerosol particles of any size and refractive index. The main problem with this approach is that aerosol particles are not spherical and also are seldom isotropic or homogeneous. There is sufficient experimental evidence that the non-spherical of aerosol particles can cause scattering properties significantly different from those predicted by the Mie theory [13–15]. Many research efforts have focused on improving the accuracy of aerosol retrievals in the presence of non-spherical particles. However, dealing with non-sphericity is not a completely resolved issue.

The aerosol particles shape is important in climate studies and also in remote sensing of environment [16–18]. It is therefore a sufficient motivation to evaluate the degree of non-sphericity of aerosols. Indeed, incorporating non-spherical scattering in remote sensing retrievals is problematic methodologically and technically.

Multi-angle polarized measurements provide an alternative and robust approach for the study of aerosol. Indeed the polarized surface contribution is smaller than, or equal to, that of the atmosphere. Moreover polarized surface contribution shows little spectral dependence and generally weak spatial contrast [19,20]. Retrievals aerosol particles properties from multi-angle polarized measurements can take advantage of the different angular reflectance and polarized reflectance signatures of the surface and aerosol properties [21,22]. The main motivation for this research stems from the need to explore the ability of multi-angle measurements of intensity and polarization to retrieve the non-spherical aerosol properties, including the aerosol mode, the shape of aerosol particles and optical thickness. Because 0.865 μm is in the spectral regions at which absorption by water vapor and other gases is minimal, the effect of water vapor and other gases is negligible. In this paper, the optical properties of non-spherical aerosol particles at the wavelengths 0.865 μm are studied. TOA total and polarized reflectance at 0.865 μm are evaluated, the sensitivity studies to aerosol mode, aerosol particles shape, and AOT is investigated.

This paper is organized as follows: Section 2 describes the non-spherical aerosol model and modeling multi-angular reflectance and polarized reflectance of non-spherical aerosol particles. In Section 3, the ability of multi-angle measurements of intensity and polarization to retrieve the non-spherical aerosol properties, including aerosol mode, aerosol particles shape, and AOT is studied. Results and discussion are given in Section 4.

2. Modeling multi-angular reflectance and polarized reflectance of non-spherical aerosol particles

Natural aerosol particles in the atmosphere show a great variety of shapes, resulting from different sources, which making difficult a realistic choice of a particle shape model [23]. Indeed, it is very difficult to treat realistically the physical properties of aerosol particles, such as morphology and composition. Further, there is no exact analytical solution for light scattering by non-spherical aerosol particles, and testing different modeling approaches is complicated by the lack of reliable and accurate references. Hence, non-spherical aerosol particles optical modeling requires that one simplifies the particles model. In this study, the aerosol particles shapes are assumed as spheroids. It should be pointed out that the particle geometries defined here is highly simplified in comparison with shapes of real aerosol particles. Thus, aerosol particles defined in this study should be understood as simulated aerosol particles.

Theoretical computations of light scattering by non-spherical particles with size comparable to the wavelength are very complicated. We have chosen for this study the method that is based on T-matrix approach [24], the justification being that this method is one of the most efficient and widely used techniques for rigorous calculations of single-scattering characteristics of non-spherical particles in random orientation. In principle, this method can be applied to an arbitrary geometry. A unique advantage of the T-matrix method is that the random orientation condition can be efficiently and exactly