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Quantitative evaluation of uncertainties in satellite retrieval of dust-like aerosols induced by spherical assumption

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ABSTRACT

It has been frequently pointed out the necessity to consider non-sphericity of dust-like aerosols in modeling their optical properties. However, most existing aerosol retrieval algorithms still utilize the Mie theory in defining aerosol models and creating look up tables (LUTs) for simplicity. Neglecting non-sphericity can severely influence aerosol optical depth (AOD, τ) retrieval in case of dust-like aerosols—largely due to the difference of derived phase functions under spherical and non-spherical assumptions—whereas this uncertainty has rarely been quantitatively studied. This paper aims at a better understanding of uncertainties on AOD retrieval caused by aerosol non-sphericity. From a dust aerosol model, we adopt different methods to simulate and compare aerosol optical properties on the basis of spherical and non-spherical assumptions respectively. Consequently we generate two LUTs under varieties of observing conditions, aerosol loadings, and surface brightness using radiative transfer (RT) code. From the obtained LUTs we thoroughly evaluate and analyze the differences of TOA reflectance ($\Delta\rho_{TOA}$) and AOD retrieval errors ($\Delta\tau$) induced by straightforwardly utilizing the Mie theory in dust-like aerosol retrieval. Errors may be positive or negative, depending on the specific geometry. For low aerosol loading ($\tau\sim0.25$) and black surface, $|\Delta\rho_{TOA}|$ could be greater than 0.06, with maximum $|\Delta\tau|$ of $\sim$0.12. Moreover, this error can increase more than ten times and become even irregular as aerosol loading gets higher and surface gets brighter. Mean $\Delta\tau$ statistics show that this uncertainty significantly influences derived aerosol climatology as well. Therefore we conclude that the neglect of non-sphericity introduces substantial errors on RT simulation and AOD retrieval, and a representative aspheric aerosol model other than Mie calculation is recommended for inversion algorithms related with dust-like non-spherical aerosols.

1. Introduction

Satellite remote sensing has long been recognized as an ideal way to monitor global properties and spatio-temporal distribution of the extremely uncertain atmospheric component which significantly influences the global climate change—tropospheric aerosols [1,2]. However, the accuracy and consistency of existing aerosol products from satellite retrieval are limited [3–5]

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because of several unresolved obstacles, including radiance calibration, cloud screening, aerosol optical property (AOP) modeling and surface signals decomposition [6,7]. Among these uncertainties, AOP modeling is of great importance—especially for single-view and intensity-only measurements—to constrain the ill-posed inversion problem [8]. In such satellite retrievals, the AOP constraints were usually accomplished via deriving a set of aerosol types with similar AOPs including size distribution, scattering, absorption and their spectral dependence [9]. Based on sensitivity studies it was found that changing AOP input in a retrieval case can create substantial bias in the retrieved aerosol optical depth (AOD) [4,10]. One of the heated topics of this issue recently is the difficulty of modeling the AOP of non-spherical dust-like aerosols.

Unlike moist sea salt, sulfate and biomass burning aerosols, AOPs of non-spherical particles (including mineral dust and dry sea salt in the upper part of marine boundary layer) are proved from laboratory measurements [11] and field campaigns [12,13] to be deviated from those modeled by the Mie theory which requires homogeneous spherical shape, arousing prevalent researches on modeling AOP accounting for non-sphericity (e.g. [13–21]). For remote sensing applications, spheroid model is preferable for its simplicity required by operational utility and the accuracy of reproducing real dust AOP after integration over size and shape from a shape mixture of randomly oriented spheroids [14,22]. These contributions had been compiled in some inversion algorithms for both ground-based [23,14] and satellite [24–26] aerosol retrieval. Nevertheless, many existing algorithms still rely on the spherical assumptions (e.g. [7,27–29]) which, as cited by Mishchenko et al. [18], can severely influence aerosol optical depth (AOD, τ) retrieval in case of dust-like aerosols even for low aerosol loadings because of large discrepancy between modeled and actual phase functions. Mishchenko et al. [30] also conducted some preliminary studies on this influence on aerosol climatology study employing long-term AOD retrieved based on different phase functions of spherical and non-spherical aerosols, whereas this study is limited within retrieval cases over ocean with dark reflectivity. To our knowledge the uncertainties in a single AOD retrieval for a complete set of situations, including higher aerosol loadings, complete observing geometries and different surface brightness, have not been thoroughly investigated before, resulting an incomplete knowledge in related fields of study.

This paper aims at a better understanding of the above mentioned uncertainties caused by neglecting aerosol non-sphericity by addressing the resultant error in top of atmosphere (TOA) reflectance ($\Delta\rho_{TOA}$) and AOD retrieval ($\Delta\tau$) induced by AOP modeling under spherical and non-spherical assumptions. We introduce the employed dust aerosol type, then present and compare its AOP modeled under two assumptions in Section 2. Section 3 describes the radiative transfer (RT) simulation and the results of $\Delta\rho_{TOA}$ and $\Delta\tau$, with a quantitative and depict discussion of the influencing factors. In Section 4 we conclude our studies, and afterwards give some practical suggestions.

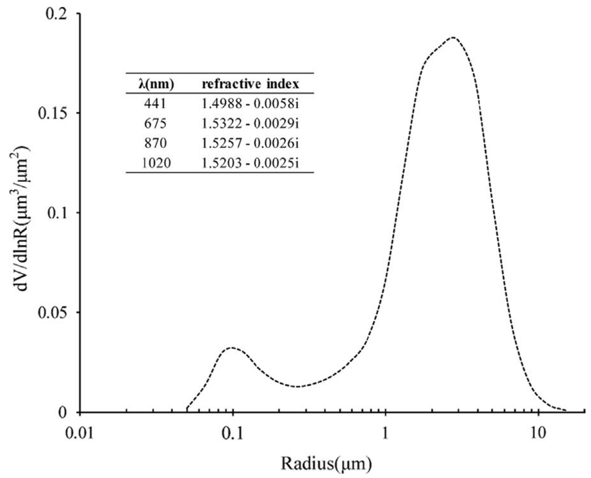

Fig. 1. Size distribution and refractive index of employed dust aerosol type.

2. Dust aerosol type and AOP modeling

In order to generate a representative dust aerosol type, we exploit Aerosol Robotic Network (AERONET) Level 2.0 post-calibrated and quality assured inversion data over China since 1999. After initial cloud screening and quality control, Level 2.0 data were selected based on criteria like solar zenith angle greater than 50° and AOD_{440} higher than 0.4 [31]. Data from coastal sites are eliminated to avoid contamination of dry sea salt. Only data with a percentage of sphericity less than 5% (close to "pure" dust) are used for cluster analysis. Two clusters are classified from the 1705 qualified records, among which one is dominant (1513 records). Thus we choose this aerosol type for dust AOP modeling. Fig. 1 presents the size distribution ($dV(r)/d\ln r$) and refractive index (RI) of the derived aerosol type. Obviously it is dominated by the coarse mode, with RI of low spectral dependence in the visible spectrum, showing a typical dust characteristic. Besides, our results of $dV(r)/d\ln r$ and RI values are quantitatively close to those from other similar studies [9,32], and those adopted in generating the NASA MODIS aerosol products [26], confirming the reasonability of the derived dust model parameters.

Based on the known RI and $dV(r)/d\ln r$ of this dust type we can calculate columnar AOPs via particle scattering theories. Mie calculation is carried out for spherical assumption using the Mie module in the Second Simulation of a Satellite Signal in the Solar Spectrum—Vector (6SV) code [33]. On the other hand, for non-spherical aerosol modeling, we adopt the pre-calculated scattering kernels and software package presented by Dubovik et al. [14,23] to calculate columnar AOPs. As mentioned above, dust aerosol and its AOP can be adequately described and reproduced as a shape mixture of randomly oriented poly-disperse spheroids, while direct modeling based on this theory is complicated and time-consuming because it requires integrating single particle cross sections over size and shape [22]. Even though spheroid is the simplest non-spherical model with only one extra parameter required by modeling—aspect ratio (ε) distribution ($dn(\varepsilon)/d\ln\varepsilon$)—