Aerosol optical properties assessed by an inversion method using the solar principal plane for non-spherical particles

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Abstract

Adequate modeling of light scattering by nonspherical particles is one of the major difficulties in remote sensing of atmospheric aerosols, mainly in desert dust events. In this paper we test a parameterization of the particle shape in size distribution, single scattering albedo, phase function and asymmetry parameter retrieval from direct and sky-radiance measurements, based on the model skyrad.pack taking into account the principal plane measurements configuration. The method is applied under different Saharan dust outbreaks. We compare the results with those obtained by the almucantar measurements configuration. The results obtained by both methodologies agree and make possible to extend the parameter retrieval to different zenith angles.

1 Introduction

Modeling the impact of mineral dust aerosols on radiative net flux is of particular interest in climate research, because mineral dust aerosols can have a strong direct climate forcing effect. Thus, this is especially relevant in southern Europe and in some Atlantic islands [1]. North African dust is injected into the atmosphere through resuspension processes at the source areas, and it is then transported at different altitudes (from sea level up to 4-6 km), being the maximum dust transport in summer when large quantities of dust are carried across the Mediterranean basin to Europe and the Middle East and across the Atlantic ocean to the Caribbean, the southeastern United States, and the midlatitude western North Atlantic. In winter, there is also considerable transport when large quantities of dust are carried toward South America and sporadically to Western Europe. As example, in 2001 was recorded 77 days with African episode at the Iberian Peninsula [1].

The satellite sensors provide a global coverage, but the retrieval algorithms to determine atmospheric aerosol characteristics used need validation so they can be tested and improved. In the last decades, there have been continuous efforts to establish inversion algorithms for determining the columnar aerosol optical properties of suspended aerosol polydispersions from ground measurements of solar extinction and almucantar sky radiance, taking into account spherical or spheroid particles approximation (i.e. [2-5]). The columnar aerosol properties of interest are: size distribution, phase function, asymmetry parameter, single scattering albedo and refraction index. Nevertheless it would be convenient to include nonsphericity features for improving the retrieval qualities in particular for large dust particles. Scattering phase function, including scattering angles larger than 90º, are important because this angular range of scattering determines the aerosol effect on climate and is used for remote sensing. Aerosol scattering at large angles 100º-140º is affected by the particle shape. The results show that the use of spheres causes considerably larger sky radiance errors for mineral particles than the use of spheroids, and the effect is particularly pronounced at Top of Atmosphere (TOA), which is most relevant for satellite remote sensing computations. Thus, different authors have shown that in presence of mineral particles the modeled phase function of spheres strongly deviates from that of non-spherical particles. Simulations based on spherical model particles were found to give TOA spectral radiance results with an error range that is larger by a factor of 4 than those results obtained with spheroidal shape distributions [6].

On the other hand, using the almucantar sky radiance data the authors show that the single scattering albedo can be retrieved with reasonably high accuracy only for high aerosol loading and large solar zenith angles (i.e. [3], [7]). But the aerosol load can change along the day also due to the different local sources or meteorological conditions. To extend the columnar aerosol properties derived by inversion methods along the day, including scattering angles larger than 90º, in this work we test a parameterization of the particle shape in size distribution, phase function, single scattering albedo and asymmetry parameter retrievals from direct and sky-radiance measurements, based on the model skyrad.pack using the principal plane approximation. The method is applied under different atmospheric conditions, including Saharan dust outbreak. We compare the results with those obtained by the well tested almucantar inversion using the spheroids particles approximation [3-5].

2 Instrumentation

For this study we use solar extinction and diffuse sky radiance measured with a CIMEL CE-318 at Granada, Spain (37.18ºN, 3.58ºW and 680 m a.m.s.l.). The instrument is part of AERONET network [8]. This instrument obtains solar transmissions, aureole and sky radiances observations through a large range of scattering angles from the Sun through a constant aerosol profile. The solar transmission measurements are performed at 340, 380, 440, 500, 670, 870, 940 and 1020 nm to retrieve the aerosol optical depth, and the sky radiance measurements are carried out at 440, 670, 870 and 1020 nm by means of almucantar and principal plane observations. Together with the AERONET calibration procedures, Langley plots at high location in Sierra Nevada Range (2200 m msl) have been made to determinate the spectral extraterrestrial voltage for this instrument. The aerosol optical depth was derived from the total optical depth subtracting the Rayleigh, O_3 and NO_2 contributions. The total uncertainty in aerosol optical depth and sky radiance measurements are $<\pm 0.01$ and $<\pm 5\%$, respectively [8].

3 Methods

The retrieved information from sky radiance at large scattering angles requires accurate correction for the effects of multiple scattering and for the contribution of light reflected from the Earth's surface and scattered downward in the atmosphere. Nakajima et al. [2] developed and applied an inversion scheme that includes accurate radiative transfer modeling to account for multiple scattering (Skyrad.pack code). The method use specified wavelengths, selected outside the gas absorption bands, in order to reduce the radiative transfer problem to a pure scattering problem. The inversion procedure uses the normalized sky radiance (almucantar and principal plane configuration) and the aerosol optical depth measured by means of a method that requires absolute calibration. The connection between the optical measurements and the aerosol features occurs through the radiative transfer equation in a multiple-scattering scheme for a one-layer plane-parallel atmosphere. The code is developed originally for spherical particles and Olmo et al. [5] was adapted the methodology including a shape mixtures of randomly oriented spheroids using the almucantar measurement configuration. In this paper, we also modified this method including the same parameterization of the particle shape to calculate the efficiency factor for extinction and the phase function using the principal plane measurement configuration. All scattering angles in the range measured, which depend on the measurement time, were used to retrieve the aerosol volume radius distribution in the radius interval 0.06-10 μm.

The EBCM, or T-matrix [9], theory has been used to calculate light scattering calculations for nonspherical matrices (kernel matrices) instead of previously used Mie simulations by Nakajima. Both incident and scattered electric fields can be expanded in vector spherical wave functions. Incident and scattered expansion field coefficients can be related by means of a transition (T) matrix, whose elements depend on the particle's size, shape and orientation. In the case of randomly oriented, axially symmetric particles, the T-matrix is calculated for the so-called natural reference frame (z axis along the particle symmetry axis) and results are then averaged for all particle orientations. T-matrix sizes have been chosen so that phase matrix elements are calculated with an accuracy of 10^{-3}; cross sections are accurate to within one part in 10^4 [10]. Accordingly, we defined in code the aerosol single-scattering properties as functions of the volume size distribution of randomly oriented polydisperse spheroids, and we have computed the kernel matrices for randomly oriented prolate and oblate spheroids, using equiprobable distributions, following the recommendations of Dubovik et al [3].

For the complex refractive index we have selected for each experimental case a unique value independent of wavelength. The selected value is the one that minimize the residuals between the measured and the simulated radiances. We assumed a Lambertian surface with a constant albedo in the wavelength range. The procedure allows the retrieval of particle size distributions, the complex refractive index, the single scattering albedo, the phase function and the asymmetry parameter.

4 Results

In order to verify how representative are the retrieval improvements of the method using the principal plane configuration we processed several measurements data (extinction and sky radiance –almucantar and principal plane-) collected at Granada in different atmospheric conditions. Figure 1 shows the comparison of the aerosol size distributions retrieved using the two spheroids scattering models in a day influenced by desert dust. We can appreciate the good agreement for the range of radius where the codes are applicable. Figure 2 shows the codes comparison for the columnar single scattering albedo (670nm) for July 31 (2006), also influenced by a Saharan dust outbreak. In addition, this day is influenced by the local pollution due to the traffic emissions that affect the aerosol absorption proper-

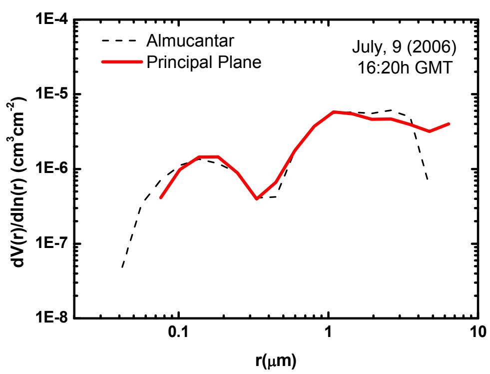

Fig. 1.- Aerosol size distribution at Granada in a day with Saharan dust influence.

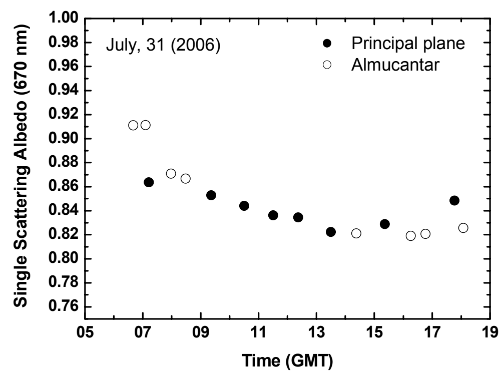

Fig. 2.- Single scattering albedo evolution at Granada in a day with Saharan dust influence.

ties decreasing the single scattering albedo along the day. Figures 3 shows the asymmetry parameter evolution (670nm) derived by the two methods for July 31 (2006). Both results display that the columnar aerosol properties derived by the principal plane inversion agree with the almucantar inver-

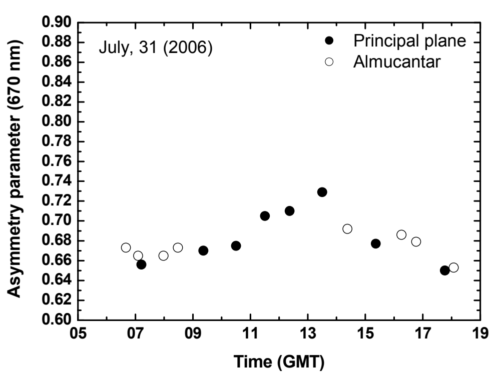

Fig. 3.- Asymmetry parameter evolution at Granada in a day with Saharan dust influence.

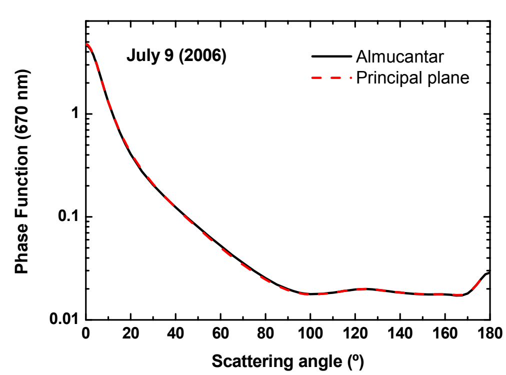

Fig. 4.- Aerosol phase function at Granada in a day influenced by desert dust.

sion using the spheroids approximation. Figure 4 shows the comparison of the phase function (670nm) also derived by the two methods for measurements close in time. As we can observe, the result for the phase function also agrees from sky-radiance aureole and for scattering angles higher than 90^o.

5 Conclusions

We have modified the skyrad.pack code to take into account the non-sphericity of the aerosol particles as polydisperse, randomly oriented spheroids (equiprobable distributions of oblate and prolate), to retrieve the columnar aerosol optical properties from measurements of extinction and sky atmospheric radiances –almucantar and principal plane- at Granada (Spain). The aerosol size distributions, single scattering albedo, asymmetry parameter and phase function obtained by the two methods have been compared for different atmospheric conditions (Saharan dust influence). The results of the two methods agree well, showing the feasibility of extending the retrieval of atmospheric aerosol optical properties along the day, not only for large solar zenith angles. Nevertheless, this study is only a first attempt to explore the columnar aerosol optical properties with this method. We also plan to explore the parameters taking into account different particle aspect-ratio and computing more accurate spheroids kernel matrices.

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References

[1] M. Escudero et al., "Wet and dry African dust episodes over eastern Spain", J. Geophys. Res., 110, D18S08, doi: 10.1029/2004JD004731 (2005).

[2] T. Nakajima, G. Tonna, R. Rao, P. Boi, Y.J. Kaufman, B.N. Holben, "Use of sky brightness measurements from ground for remote sensing of particulate polydispersions", App. Opt., **35**, 15, 2672-2686 (1996).

[3] O. Dubovik, B.N. Holben, T. Lapyonok, A. Sinyuk, M.I. Mishchenko, P. Yang, I. Slutsker, "Non-spherical aerosol retrieval method employing light scattering by spheroids", Geophys. Res. Lett., **29**, N10, 10.1029/2001GL014506 (2002).

[4] O. Dubovik et al., "Application of spheroid models to account for aerosol particle nonsphericity in remote sensing of desert dust", J. Geophys. Res., 111, D11208, doi: 10.1029/2005JD006619 (2006).

[5] F.J. Olmo, A. Quirantes, A. Alcántara, H. Lyamani, L. Alados-Arboledas, "Preliminary results of a non-spherical aerosol method for the retrieval of the atmospheric aerosol optical properties", J. Quant. Spectr. Radiat. Transfer, 100, 305-314 (2006).

[6] M. Kahnert, T. Nousiainen, B. Veihelmann, "Spherical and spheroidal model particles as an error source in aerosol climate forcing and radiance computations : A case study for feldespar aerosols", J. Geophys. Res., 110, D18S13, doi: 10.1029/2004JD005558 (2005).

[7] D.H. Kim et al., "Aerosol optical properties over east Asia determined from ground-based sky radiation measurement", J. Geophys. Res., 109, D02209 (2004).

[8] B.N. Holben, T.F. Eck, I. Slutsker et al., "AERONET-A federated instrument network and data archive for aerosol characterization". Rem. Sens. Environ., **66**, 1-16 (1998).

[9] M.I. Mishchenko, "Light scattering by randomly oriented axially symmetric particles", J. Opt. Soc. Am. A **8**, 871-882 (1991); Errata **9**, 497 (1992)

[10] M.I. Mishchenko, "Light scattering by size-shape distributions of randomly oriented axially symmetric particles of a size comparable to a wavelength", Appl .Opt. **32**, 4652-4666 (1993)