

Simulation of the influence of aerosol particles on Stokes parameters of polarized skylight

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Abstract. Microphysical properties and chemical compositions of aerosol particles determine polarized radiance distribution in the atmosphere. In this paper, the influences of different aerosol properties (particle size, shape, real and imaginary parts of refractive index) on Stokes parameters of polarized skylight in the solar principal and almucantar planes are studied by using vector radiative transfer simulations. The results show high sensitivity of the normalized Stokes parameters due to fine particle size, shape and real part of refractive index of aerosols. It is possible to utilize the strength variations at the peak positions of the normalized Stokes parameters in the principal and almucantar planes to identify aerosol types.

1. Introduction

Similar to radiance, propagation direction and frequency, polarization is also an intrinsic property of electromagnetic waves [1,2]. Solar radiation incident at the top of atmosphere is unpolarized, but interactions with molecules, aerosols, water droplets and ice crystals in the atmosphere change not only radiance but also the state of polarization of the incident solar radiation. After transferring through the atmosphere, the scattered skylight is partially polarized [1,3].

Previous studies have shown that the polarization pattern of skylight is dominated by Rayleigh scattering of small particles. However, it is highly sensitive to the influence of different aerosol types [4]. Aerosol types are classified by their microphysical properties and chemical compositions (particle size, shape, size distribution, the mixing status, real and imaginary parts of refractive index). The aerosol optical properties (e.g., optical thickness, single scattering albedo, asymmetry factor or scattering matrix) can be calculated from these properties. The effects of aerosol microphysical properties on polarization of skylight are not equal; the behavior of degree of linear polarization (DoLP) is shown to be highly sensitive to both small mode of bimodal size distribution and real part of refractive index of aerosols. DoLP is less sensitive to the imaginary part than radiance; correspondingly, polarization seems to have some potential to improve aerosol retrievals mainly of the fine mode size distribution and real part of the refractive index. Furthermore, polarization is more sensitive to particle shape than radiance [5,6]. Therefore, ground-based polarized skylight measurements that are usually performed in the solar principal and almucantar planes have high potential to derive the microphysics of aerosols and can be used to identify the type of aerosol [4].

Unlike DoLP, Stokes parameters Q and U contain all the information (not only the degree but also the orientation) about the linear polarization [7]. In this study, we simulate the influences of aerosol



particle size, shape, real and imaginary parts of refractive index on normalized Stokes parameters of polarized skylight in the principal and almucantar planes to study the sensitivity of normalized Q and U to changes of aerosol microphysics.

2. Polarized radiative transfer simulation

2.1. Definition of Stokes parameters of polarized light

The polarization of electromagnetic waves can be described in different ways, the most common was proposed by G. Stokes in 1852. He introduced the Stokes vector with four parameters I, Q, U and V to completely specify the polarization state of light beam [8]. For skylight in the Earth's atmosphere, the circular polarization parameter V is very small and can be neglected, so only linear polarization parameters Q and U need to be considered [7]. They can be expressed in terms of DoLP and the orientation of polarization χ in the following way [9]:

$$Q/I = DoLP \cdot \cos 2\chi \quad (1)$$

$$U/I = DoLP \cdot \sin 2\chi \quad (2)$$

where Q and U are normalized to total radiance I. The degree of linear polarization is defined as:

$$DoLP = \frac{\sqrt{Q^2 + U^2}}{I} \quad (3)$$

For skylight within the principal plane, $U \approx 0$. Then DoLP in principal plane can also be written as [5]:

$$DoLP = -\frac{Q}{I} \quad (4)$$

where minus is to preserve the sign of Q.

2.2. Simulation of Stokes parameters of polarized skylight

To simulate the Stokes parameters of polarized skylight affected by different aerosol properties, a Mie code is used to calculate the single scattering by sphere particles while T-matrix code is applied to calculate the single scattering by non-spherical particles. Then the optical properties (e.g., extinction coefficient, asymmetry factor, single scattering albedo and expansion coefficient of scattering matrix) of aerosol particle are put into the vector radiative transfer model SCIATRAN to calculate the Stokes parameters [10].

In this simulation, we consider the influences of aerosol particle size, shape, real and imaginary parts of refractive index on Stokes parameters Q and U in the principal plane and almucantar plane, respectively. The input parameters are listed in Table 1.

Table 1. The input parameters for simulation

Parameter	Standard value	Changes of the value
Wavelength(λ)	0.55 μ m	constant
Aerosol particle effective radius (r)	0.1 μ m	0.02, 0.04, 0.48, 1.28 μ m
Particle size distribution	power law	constant
Shape parameter of spheroid (a/b)	1(sphere)	0.5, 1, 2, 3
Real part of refractive index (n)	1.53	1.33, 1.4, 1.53, 1.75
Imaginary part of refractive index (k)	0.007	0.1E-7, 0.007, 0.02, 0.44
Aerosol optical thickness	0.5	constant
Rayleigh optical thickness	0.097069	constant
Surface albedo	0.1	constant
Solar zenith angle	45 degree	constant
Viewing zenith angle	45 degree	-85~85 degree
Relative azimuth angle	0,180 degree	30~330 degree

3. Results

The simulated results are plotted in Fig.1 to Fig.4. The Stokes parameters Q and U are normalized to radiance I and then multiplied by 1000. Note that Q/I implies a negative DoLP within the principal plane. The influence of aerosol particle size on normalized Stokes parameters Q/I and U/I is shown in Fig.1, where Fig.1a and Fig.1b illustrate Q/I and U/I as a function of viewing zenith angle (VZA) in the principal plane of anti-solar direction, respectively. Q/I is mostly negative, it drops to its minimum around 45 degree (i.e., scattering angle is about 90 degree in this case) and then pick up again, while U/I is really close to 0, so the measurement of U in the principal plane is hard to utilize.

Fig.1c and Fig.1d represent Q/I and U/I as a function of relative azimuth angle (RAA) in the almucantar plane. As can be seen from these figures, Q/I is symmetric to the principal plane. It increases slowly with the increase of RAA before reaching to 70 degree then falls sharply reaching the bottom at 180 degree (i.e., scattering angle equals to 90 degree in this case). U/I is antisymmetric to the principal plane. U/I is negative for RAA less than 180 degree. It falls before 120 degree and then increases again with increasing of RAA. U/I nearly equals to 0 at 180 degree which indicates the principal plane. To the contrary, U/I is positive for RAA larger than 180 degree. It goes up to peak at 240 degree and then decreases again.

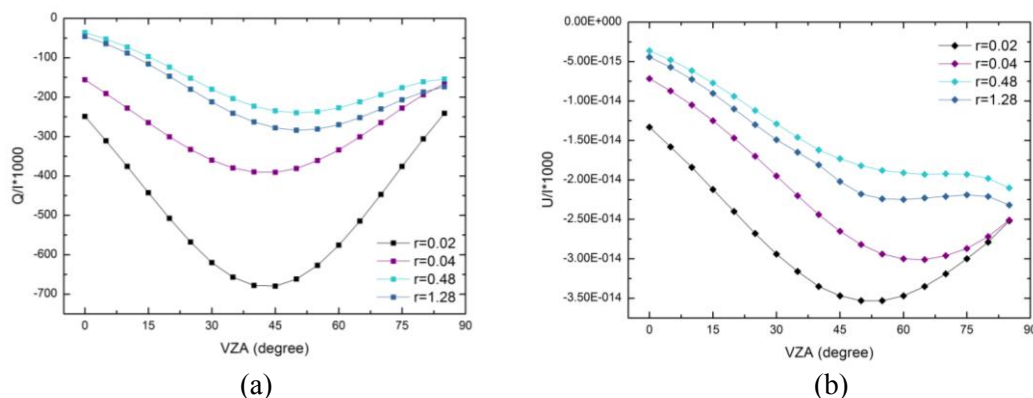
The patterns of Q/I and U/I are ubiquitous for all aerosol particles in Fig.1 to Fig.4 and are in agreement with previous observations [2]. In general, the discrepancies of Q/I or U/I for different values of aerosol properties in Fig.1 to Fig.4 are large at the peak positions. The strengths of the peaks vary with different values of aerosol properties, nevertheless, the peak positions are almost unchanged. So it's recommended to utilize the polarization measurements at peak positions in the principal and almucantar planes to get the information of different aerosol properties.

As we can see from Fig.1, for fine particles (e.g., $r=0.02$, $0.04\mu\text{m}$), Q/I and U/I change strongly with increasing of particle size; but for coarse particles (e.g., $r=0.48$, $1.28\mu\text{m}$), they do not change a lot, especially in the almucantar plane. Moreover, Q/I and U/I change less significant with VZA and RAA compared with that of fine particles.

Fig.2 illustrates the influence of aerosol shape on Stokes parameters. For non-spherical particles, Q/I and U/I change more considerable with VZA and RAA compared with that of sphere particles (i.e., $a/b=1$). In addition, results of oblate spheroid (e.g., $a/b=0.5$) and prolate spheroid (e.g., $a/b=2$) those with inverse axial ratio are close to each other.

The influence of real part of refractive index on Stokes parameters is shown in Fig.3. For all viewing zenith angles in the principal plane, Q/I and U/I decrease remarkably with decreasing of real part of refractive index. In the almucantar plane, Q/I and U/I change more sharply with different real parts at the peak positions than other positions.

Fig.4 illustrates the influence of imaginary part of refractive index on Stokes parameters. Both in the principal and almucantar planes, Q/I and U/I change slightly for imaginary parts from $0.1\text{E-}7$ to 0.02 . But for strongly absorbing particle, such as black carbon with imaginary part of 0.44 , Q/I and U/I are distinct from others and they change dramatically with VZA and RAA.



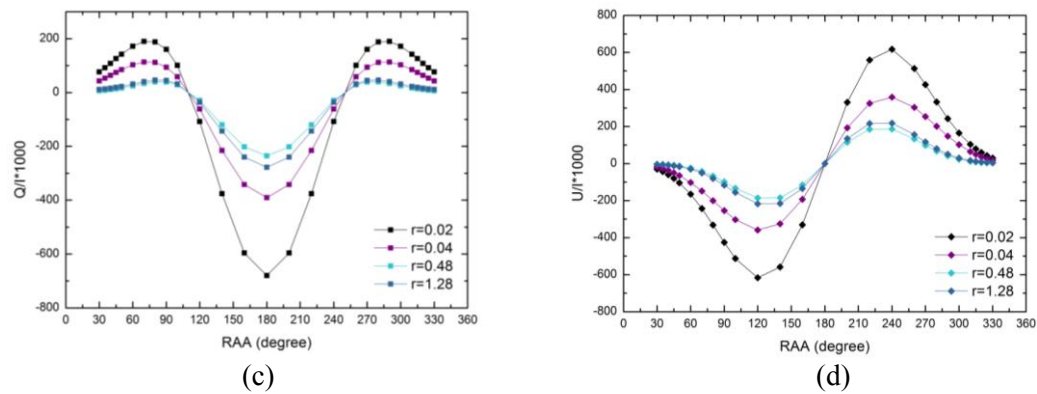


Figure 1. The influence of aerosol particle size on Stokes parameters (a) Q/I in the principal plane, (b) U/I in the principal plane, (c) Q/I in the almucantar plane, (d) U/I in the almucantar plane. Where VZA denotes viewing zenith angle that is defined as positive in anti-solar direction; RAA denotes relative azimuth angle of line-of-sight with respect to sun; r denotes the radius of aerosol particle.

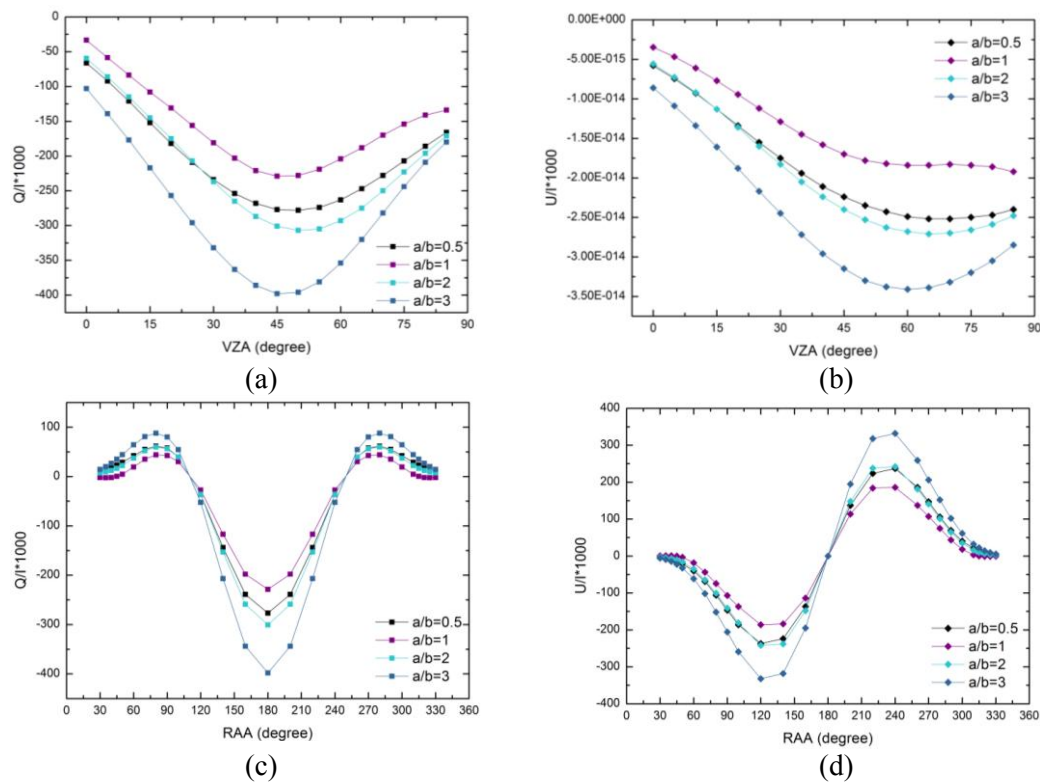


Figure 2. The influence of aerosol particle shape on Stokes parameters (a) Q/I in the principal plane, (b) U/I in the principal plane, (c) Q/I in the almucantar plane, (d) U/I in the almucantar plane. Where VZA and RAA are same as in Fig.1; a/b denotes the shape parameter of aerosol that is defined as the ratio of the horizontal to rotational axes of spheroid particle.

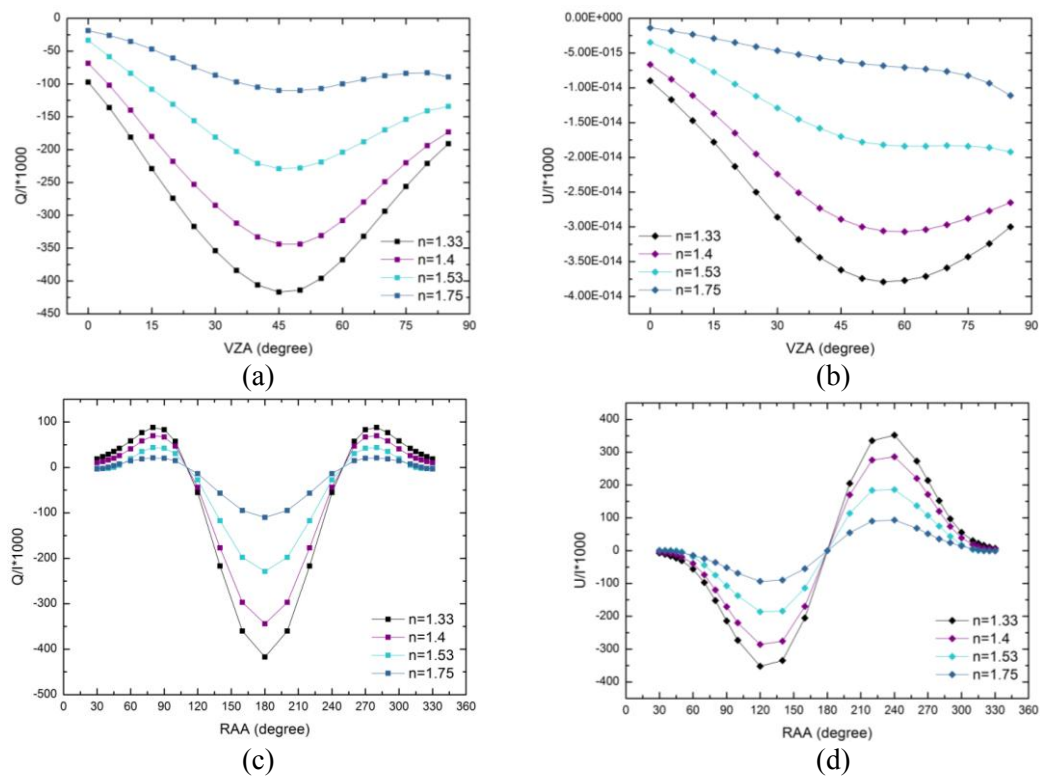


Figure 3. The influence of real part of aerosol refractive index on Stokes parameters (a) Q/I in the principal plane, (b) U/I in the principal plane, (c) Q/I in the almucantar plane, (d) U/I in the almucantar plane. Where VZA and RAA are same as in Fig.1; n denotes the real part of refractive index.

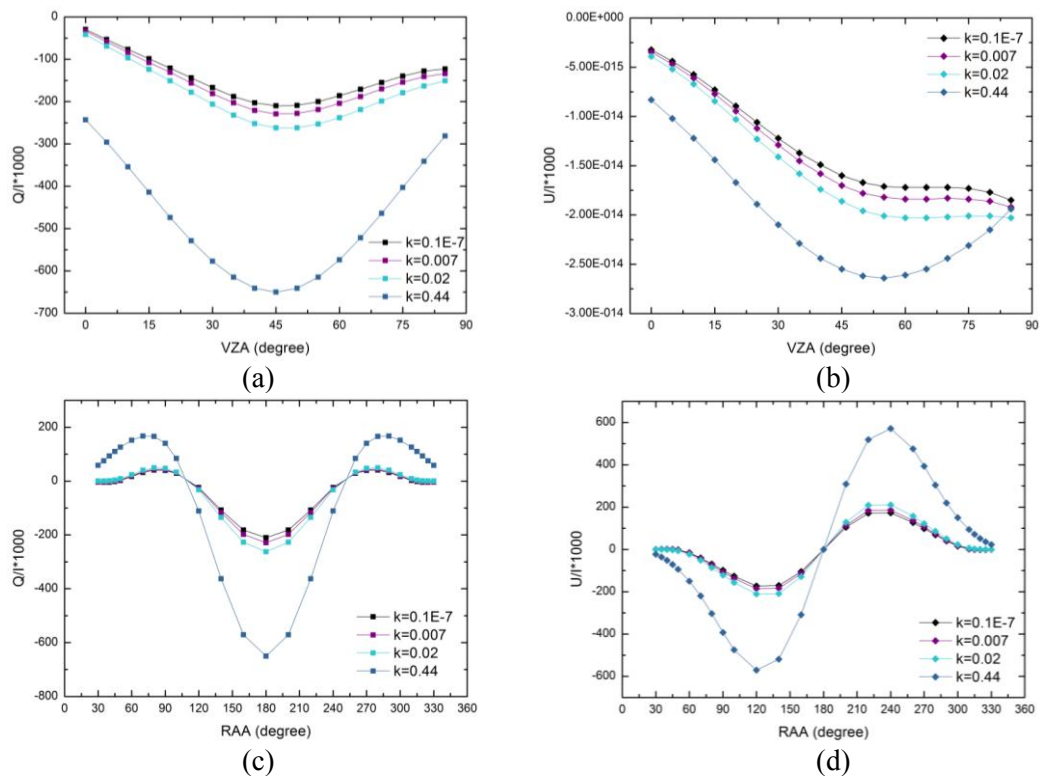


Figure 4. The influence of imaginary part of aerosol refractive index on Stokes parameters (a) Q/I in

the principal plane, (b) U/I in the principal plane, (c) Q/I in the almucantar plane, (d) U/I in the almucantar plane. Where VZA and RAA are same as in Fig.1; k denotes the imaginary part of refractive index.

4. Summary

The influences of aerosol particle size, shape, the real and imaginary parts of refractive index on the normalized Stokes parameters Q/I and U/I of polarized skylight have been studied in this paper. In general, for different values of aerosol properties, the peak positions of Q/I and U/I vary little, while the strengths of peaks change significantly.

Q/I at VZA of 45 degree in the principal plane and at RAA of 180 degree in the almucantar plane (i.e., the scattering angles equal to 90 degree in both cases) and U/I around RAA of 120 degree and 240 degree in the almucantar plane change most significantly with different values of fine particle size, shape and real part of refractive index of aerosols. For strongly absorbing particle with large imaginary part of refractive index, it is also possible to distinguish it with others by using Q/I and U/I. So we can utilize the strength variations at the peak positions of Q/I and U/I in the principal and almucantar planes to get the information of different aerosol properties and then identify aerosol types in future.

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References

- [1] Kokhanovsky A A 2003 *Polarization optics of random media* (UK:Springer Praxis)
- [2] Liu Y and Voss K 1997 *Applied Optics* **36** 8753-64
- [3] Smith G S 2007 *Am.J.Phys.* **75** 25-35
- [4] Emde C, Buras R, Mayer B and Blumthaler M 2010 *Atmos. Chem. Phys.* **10** 383-396
- [5] Boesche E, Stammes P, Ruhtz T, Preusker R and Fischer J 2006 *Applied Optics* **45** 8790-8805
- [6] Li Z Q, Goloub P, Dubovik O, Blarel L, Zhang W X, Podvin T, Sinyuk A, Sorokin M, Chen H B, Holben B, Tanré D, Canini M and Buis J P 2009 *Journal of Quantitative Spectroscopy & Radiative Transfer* **110** 1954-61
- [7] Tilstra L G, Schutgens N A J and Stammes P 2003 *Scientific Report WR2003-01* 1-13
- [8] Wendisch M and Yang P 2012 *Theory of Atmospheric Radiative Transfer* (Weinheim:Wiley)
- [9] Van de Hulst H C 1957 *Light Scattering by Small Particles* (New York:Wiley)
- [10] Rozanov V V, Buchwitz M, Eichmann K U, Beek R de and Burrows J P 2002 *Adv. Space Res.* **29** 1831-35