Modeling UV sky radiance during twilight with taking into account the sunlight polarization

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Abstract – Intensity and polarization of the solar light may be characterized completely by a vector of the four Stokes parameters. Therefore, accurate description of the radiation field in the Earth atmosphere requires a solution of the transfer equation in the unknown vector of the Stokes parameters. A simplified theory treats light as a scalar being equal to the radiance intensity only. Several studies have compared results of the accurate vector and simplified scalar radiative transfer models and have shown that the scalar treatment of light may have only restricted application. Though several observational conditions were exploited, an effect of polarization on modeling of UV radiance has not been investigated yet for twilight. The paper briefly presents a study of modeled UV radiance during twilight taking into account polarization. The intensity and the degree of linear polarization of the scattered UV radiance for two cases of the ground-based observations are discussed. In the first case, radiation incoming from the zenith for the solar zenith angles (SZA) from 90^{O} to 96^{O} is under investigation. Radiation in the solar principal plane for the beginning of twilight (SZA=90.1^{O}) was calculated in the second case.

Keywords: Polarization, Degree of linear polarization, Vector radiative transfer, Twilight, Zenith sky radiance, Scattering of radiance

1. INTRODUCTION

The solar light in the Earth atmosphere may be characterized completely by a vector of the four Stokes parameters. The Stokes parameters characterize the radiance intensity and the degree, plane and ellipticity of the radiance polarization (Chandrasekhar, 1950). A simplified theory treats light as a scalar being equal to the radiance intensity only but has limited area of applicability. Indeed, the light comes from the Sun being originally unpolarized, then scattered from air molecules or aerosol becomes partially polarized. It produces different source functions of the components in two perpendicular polarization directions for the second scattering, which the scalar theory neglects. Several studies (Chandrasekhar, 1950, Lacis et al., 1998, Lenoble, 1986, Marchuk et al., 1980, Mishchenko et al., 1994, Postylyakov et al., 2001a) compared solutions of the vector and scalar radiative transfer equations for various observational geometries. They showed that scalar calculations of the radiance intensity are in error by up to 10% for many cases, depending on geometry of observations, aerosol loading and surface albedo.

The radiation field in the atmosphere permanently varies during twilight because the height of the atmospheric layer, dominantly forming it, changes with movement of the Earth's shadow (Rosenberg, 1963). That manifests both in the intensity (Fesenkov, 1923) and in the polarization of scattered light (Linke 1951, Fesenkov, 1966). More recent investigations have shown that twilight observations of the intensity (Solomon et al., 1987) and the degree of polarization (Postylyakov et al., 2001b, Ugolnikov et al. 2004) can be applied for investigation of the vertical distribution of gas and aerosol compositions in the atmosphere. The twilight method, employing the intensity measurements at visible wavelengths, is well recognized now and successfully used for the determination of NO_2 and other trace gas contents at the Network for the Detection for Stratospheric Change, which integrates high-quality remote-sounding research stations (Schofield et al., 2004).

However, the interpretation of the UV twilight ground-based observations remains still a difficult problem. Indeed, quantitative understanding of UV twilight radiance must include polarization and multiple scattering, what has become possible due to progress in computer equipment only recently. Besides application to remote sensing of the atmosphere, modeling of the UV radiation field during twilight is interesting for radiative budget study and for climatic researches. Differ to other observational conditions, effect of polarization on accuracy of UV modeling has not been investigated yet for twilight.

This paper presents briefly a study of modeled UV radiance during twilight taking into account polarization. Section 2 briefly introduces values characterizing polarized radiance, describes a radiative transfer model used for numerical simulations, and gives a model atmosphere exploited. The intensity and the degree of linear polarization of scattered UV radiance are discussed in Section 3 for two cases of the ground-based observations. In the first case, observations in the zenith direction for solar zenith angles (SZAs) from 90^{O} to 96^{O} are under investigation. Measurements in the solar principal plane for SZA=90.1^{O} correspond to the second case. To understand better importance of the complete vector treatment of radiance in these cases, we quantified errors of scalar calculation relative to more accurate vector modeling here. Section 4 concludes the paper.

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2. RADIATIVE TRANSFER MODEL

Polarized light in the atmosphere can be characterized by a vector of the four Stokes parameters (Chandrasekhar, 1950):

$$\mathbf{I} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}. \quad (1)$$

The first element I of the Stokes vector (1) describes the intensity measured by a polarization non-sensitive instrument, and the others define the plane and ellipticity of polarization. The Stokes parameters are defined relative to a certain coordinate frame. Using a calculated Stokes vector the degree of linear polarization

$$P_{lin} = \sqrt{Q^2 + U^2} \big/ I \quad (2)$$

and the ellipticity

$$\sin 2\beta = V \Big/ \sqrt{Q^2 + U^2 + V^2} \ , \quad (3)$$

can be determined. These polarization quantities are invariant under a rotation of axis. The plane of polarization, depended on a rotation of axis, is given by

$$\tan 2\chi = U \big/ Q \ . \quad (4)$$

Solar radiance incidents to the atmosphere is completely unpolarized. The first scattering can gives only the linear polarization. A source of the elliptical polarization can become the second and higher orders of scattering only. But scattering by aerosol and clouds produces a minor elliptical component V in comparison with linear polarization, while Rayleigh scattering gives zero ellipticity at all. So the fourth Stokes parameter V is usually very small in the Earth atmosphere and will not be an issue of this paper. So, it will be necessary to obtain the degree of linear polarization for cases under investigation.

To simulate the radiance field, the radiative transfer model MCC++ for a spherical atmosphere has been applied (Postylyakov 2004a, 2004b). The vector and scalar versions of the MCC++ model, which employs the Monte Carlo method of conjugate walk, were used. The model may take into account molecular and aerosol elastic scattering, gas and aerosol absorption, and a surface characterized by the Lambertian reflectance or the bidirectional reflectance distribution function. Refractive bending was ignored in current calculations. The MCC++ model was repeatedly validated against other model (see overview in Postylyakov (2004a)), in particular, for twilight (Postylyakov et al., 2001a).

The air density and the ozone concentration profiles corresponding to a mid-latitude winter model were taken for the calculations from monograph of Zuev and Komarov (1986). The total ozone column was normalized to 345 DU. The ozone cross section taken from Burrows et al (1999) and Rayleigh scattering cross section from Bates (1984) were used. We neglected the molecular depolarization factor. The Mie theory was applied for calculations of the aerosol phase matrixes. The aerosol particle size distribution and the refraction index recommended by WMO (1986) for the background stratospheric condition were used above 12 km. The aerosol properties corresponding to the continental type of aerosol (WMO, 1986) were exploited below 12 km. The aerosol extinction profile, showing the best correlation with polarization observation of paper (Ugolnikov et al., 2004), was used. This aerosol extinction profile corresponds to very clear troposphere and the background aerosol concentration in the stratosphere. The surface albedo was equal to 0. The altitude of the observation was 200 m.a.s.l.

3. SIMULATION RESULTS AND DISCUSSION

The Stokes vector of scattered UV radiance observed from the ground during twilight was calculated using the radiative transfer model MCC++ (Postylyakov 2004a, 2004b). The statistical accuracy of the Monte Carlo calculations is better than 1%.

Intensity and polarization characteristics of radiance scattered in the zenith are shown in Figure 1. That case corresponds to the single scattering angle near 90^O when the light scattered by air molecules is almost completely polarized. The multiple scattering and to a lesser degree the aerosol scattering reduce the degree of linear polarization. The zenith radiance is strongly polarized during twilight and changes slightly from SZA=90^O to SZA=95^O. The degree of linear polarization P_{lin} reaches 83% at 305 nm, and decreases up to 63% at longer wavelength 330-340 nm. The intensity of radiance decreases faster than exponentially with the SZA. The wavelength dependence of P_{lin} in UV is opposite to this observed in visible (Ugolnikov et al., 2004). The shorter wavelength has the smaller P_{lin} in visible due to the stronger molecular scattering, what increases the part of multiple scattering. On the contrary, the shorter wavelength has the larger P_{lin} in UV. The point is that the stronger ozone absorption leads to the increase of the part of the single scattered (SS) radiance despite the stronger molecular scattering.

The ratio of the single scattered radiance to the total radiance changes slightly up to SZA=95^O. It begins to decrease strongly since SZA=95^O. That changes the behavior of the polarization and the intensity. The degree of linear polarization begins to reduce fast. To all appearance, still rather high the degree of linear polarization for the part of the SS radiance about 3-5% is caused by significant contribution of photons with trajectories differing a little from the SS photon trajectory though these photons experienced multiple scattering.

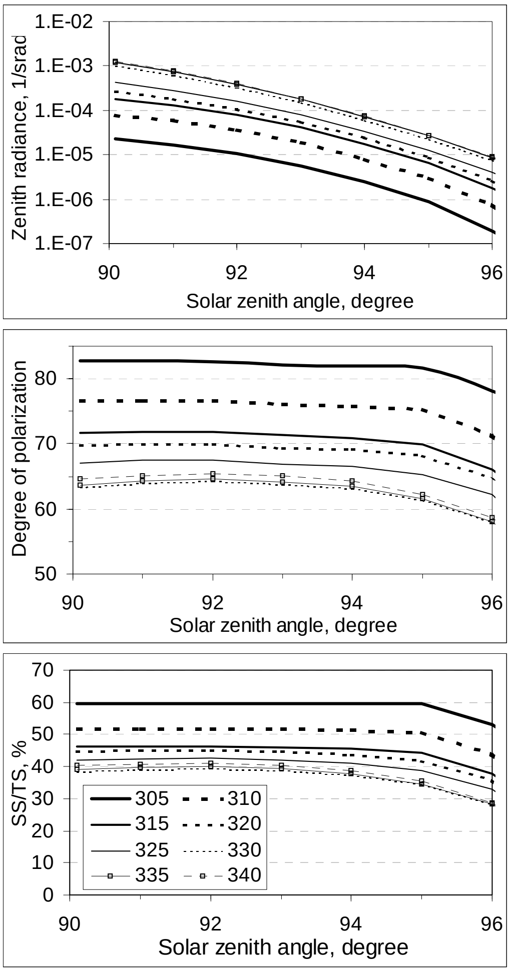

Figure 1. The zenith radiance for the twilight solar zenith angles and the UV wavelengths: the intensity (for the unit incoming radiance), the degree of linear polarization, and the ratio of the single scattered radiance to the total radiance (SS/TS).

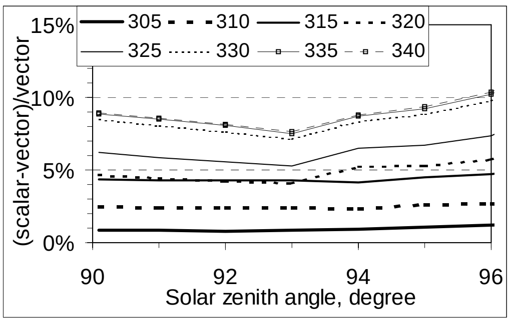

Figure 2. Error of the scalar calculation of the intensity for the twilight solar zenith angles and the UV wavelengths.

The error of the scalar calculation of the intensity is shown in Figure 2. It significantly depends on the wavelength and the solar zenith angle. The single-scattered radiance fields given by the both vector and scalar radiative transfer theories are equivalent. Therefore, the calculations for the longer wavelength and the large solar zenith angle, which has the smaller part of the single scattered radiance, differ more. The error of the scalar calculation for the zenith observation reaches maximum of 10% for SZA=96^{O} at 340 nm, but remains near 1% from SZA=90^{O} to SZA=96^{O} at 305 nm.

Radiance in the principal plane for the beginning of twilight has been calculated by using the vector and scalar versions of the MCC++ radiative model. Figure 3 shows errors of the scalar calculation for the wavelengths 320-340 nm, which have the stronger polarization (but the smaller error) than the shorter wavelengths. The <u>o</u>bservation <u>z</u>enith <u>a</u>ngle (OZA) equal to 90^{O} corresponds a view to the Sun. If OZA=-90^{O}, the Sun is behind the looking direction. Figure 3 shows that the scalar description of radiative transfer gives strongly distorted diffuse UV radiance field for SZA=90.1^{O}. The error of the scalar description varies from -17% for the directions to the horizon to +9% for observation to the zenith. The error for the zenith direction depends on the wavelength, while the error for the absolute observation zenith angle greater than 50^{O} changes with wavelength negligibly. Integrating the intensities within the principal plane we obtain that scalar models overestimate the integral radiance in the principal plane up to 3-4%±0.5%.

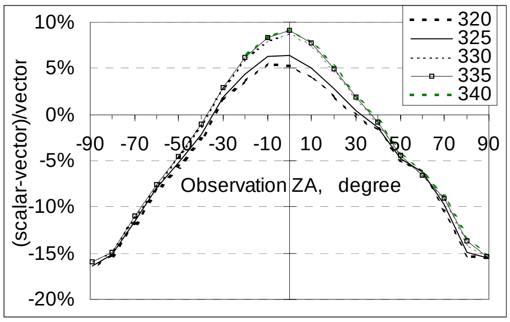

Figure 3. Errors of the scalar calculation of the intensity for different directions of observations in the principal solar plane for the beginning of twilight, SZA=90.1^{O}.

4. CONCLUSION

The first results of the study of effect of polarization showed that the UV radiative field in the twilight atmosphere can be handled correctly only using the vector theory. Scalar radiative transfer models calculate the UV intensity with significant error. The error strongly varies with the wavelength, the line of an observation, and the solar position. The revealed distortion of the zenith radiance by a scalar model reaches maximum of 10% at 340 nm for the solar zenith angle (SZA) equal to 96^{O}. The shorter wavelengths have the smaller error, about 1% at 305 nm for SZA=96^O, due to the larger part of the single scattered radiance. The error of scalar modeling may be as more as -17% if looking to the horizon for SZA=90.1^O. Scalar radiative transfer models underestimate the integral intensity in the principal plane up to 4%±0.5% at SZA=90.1^O for the wavelengths from 320 to 340 nm. That should be taken into account in problems of radiative budget estimation and of remote sensing of the atmosphere exploiting the twilight period.

An investigation of effects of ozone distribution, aerosol loading and microphysics, surface reflectance, and more detailed comparison of influence of the vector and scalar description on the UV twilight radiance are a subject of interest and of the future work, as well as comparisons with UV measurements.

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