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Vertical profile of polarization over Vladivostok using horizon shadowing: Clues to understanding the altitude variation of reflectance of aerosol particles

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ABSTRACT

We report polarimetric measurements of atmospheric aerosol in evening and morning twilight over Vladivostok (Russia) in late winter–early spring of 2017 using a horizon-shadowing technique. Motion of the Sun beneath the horizon changes the altitude of the boundary of the shadowed atmosphere h, making it possible to constrain the altitude of aerosol particles contributing to the polarimetric response. We investigate the degree of linear polarization P in aerosol particles at different altitudes, ranging from 0 km up to 17 km. In two out of four experiments we found significant variations of the polarimetric response ($\Delta P \sim 10\%$) with altitude; whereas, in the other measurements, the polarization appeared nearly the same ($\Delta P \sim 2$–3%) throughout the entire range of the studied altitude. Polarization P was measured in the zenith direction with the scattering angle being $\theta \sim 90°$ At such a scattering angle, the polarization is near its maximum value $P_{\max}$. We analyze our measurements using the Umov effect that describes an inverse correlation between $P_{\max}$ and the geometric albedo A. On 2017-02-21, we estimate $A \approx 0.0120 \pm 0.0004$ at $h = 0$ km and $A \approx 0.0154 \pm 0.0026$ at $h = 10$ km. On 2017-02-27, we find the opposite trend, $A \approx 0.0108 \pm 0.0003$ ($h = 0$ km) and $A \approx 0.0084 \pm 0.0006$ ($h = 10$ km). On 2017-03-02 and 2017-03-03 we find $A \approx 0.0084 \pm 0.0009$ and $A \approx 0.0090 \pm 0.0010$, respectively. Conclusions drawn from polarimetric measurements appear in qualitative accordance with results of remote sensing with a three-wavelength lidar.

1. Introduction

Active remote sensing of atmospheric aerosols is based on measurements of their light-scattering response when irradiated by a laser beam using lidar systems. This approach, however, suffers from a few important limitations. The first limitation concerns the characteristics of the scattered light that are available within the lidar technique. At best, these are the scattered light *flux* and its *linear depolarization ratio* measured at a few wavelengths (e.g., [1]). However, only the linear polarization ratio directly corresponds with the microphysics of aerosols; whereas, the flux results from a product of the *backscattering efficiency* and the number of aerosol particles within the field of view. The latter makes it difficult to attribute the measured flux immediately to microphysical properties, requiring some modeling and/or a priori knowledge about the aerosol cloud.

The second limitation is that the lidar measurements are conducted predominantly in the backscattering regime when the scattering angle is equal to $\theta = 180°$. Such geometry is convenient to implement in practice because the laser and the detector are located in the same place. It does not provide access to interesting phenomena in the linear depolarization ratio arising at $\theta \neq 180°$ that could provide better clues to microphysics of aerosols (e.g., [2]).

These difficulties are avoided in passive remote sensing, when physical and chemical properties of aerosol particles are retrieved from their sunlight-scattering response. For instance, when initially unpolarized sunlight is scattered by aerosol particles, it acquires partial linear polarization that is characterized with the degree of

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linear polarization P:

$$P = \left(I_\perp - I_\|\right)/\left(I_\perp + I_\|\right). \quad (1)$$

Here, $I_\perp$ and $I_{||}$ denote the intensity of two components of the scattered sunlight that are polarized perpendicular to and within the scattering plane, respectively. P is a function of the scattering angle θ.

Numerous laboratory experiments and modeling studies on single light scattering by dust particles reveal two common trends (e.g., [3–5]). Near the backscattering regime, at $\theta > 150°$, dust particles systematically produce negative polarization in the scattered light; in terms of Eq. (1), this implies $I_\perp < I_{||}$. At smaller scattering angles, the degree of linear polarization is positively polarized (i.e., $I_\perp > I_{||}$). In the scattering-angle profile of polarization, these phenomena appear as a branch of negative polarization and a branch of positive polarization. In general, the angular profile of polarization is characterized with five parameters: the amplitudes of the negative polarization $|P_{\min}|$ and of the positive polarization $P_{\max}$; the scattering angles where those extreme values are achieved, $\theta_{\min}$ and $\theta_{\max}$, respectively; and the scattering angle where P changes its sign θ_{inv}. These five characteristics vary from one sample to another, and makes it possible to constrain their microphysical properties from polarimetric measurements.

Interestingly, the phenomenon of the negative polarization has been successfully exploited in remote-sensing applications to the Martian aerosols [6] and to terrestrial aerosols (e.g., [7]). Accurate measurements of the negative polarization make it possible to constrain the refractive index of target particles [8]. However, the phenomenon of the positive polarization is also a powerful tool for remote sensing. For instance, the maximum of positive polarization $P_{\max}$ inversely correlates with the reflectance of target particles. The significance can be found within the interrelation of $P_{\max}$ with the reflectance, which takes on an extremely simple form that obeys to the *Umov law* or *Umov effect* [9,10]. Therefore, experimental measurements of $P_{\max}$ in atmospheric aerosols can be directly attributed to their reflectance. In this work, we investigate the positive polarization of atmospheric aerosols over Vladivostok at the scattering angle $\theta = 88°–94°$. Near this geometry of light scattering, the positive polarization typically acquires its maximum value $P_{\max}$, making the retrieval of reflectance in aerosol particles using the Umov law possible.

2. Polarimetry technique and data processing

An important shortcoming of passive remote sensing is that the degree of linear polarization, as well as any other light-scattering characteristic, is always integrated over the line of sight; however, it is of high practical interest to discriminate the signals that originate at different distances from the radiometer. This problem can be partially resolved by conducting measurements shortly after sunset and/or before sunrise. In twilight, air is illuminated by sunlight only above some altitude and aerosol particles located at lower altitudes are shadowed and, as a consequence, they do not contribute to the light-scattering signal. The advantages of twilight polarimetry of the atmosphere were recognized long ago (e.g., [11]) and, nowadays, this technique is utilized, for instance, in the study of noctilucent clouds [12].

The zenith height of the shadow boundary h is determined by the Earth radius $R = 6371$ km and the angle γ that specifies the depth of the Sun beneath the horizon (see scheme in Fig. 1):

$$h = R(1 - \cos\gamma)/\cos\gamma \quad (2)$$

The Sun has a noticeable angular extent of about 0.5°; therefore, we count the angle γ from its top edge. The angle γ was computed using the astronomical software *Stellarium* ver. 0.15.1 (freely available at http://www.stellarium.org/) for given place and local time. Note also that the apparent location of the Sun is somewhat displaced from the real one due to *atmospheric refraction*. Such displacement is a complex function of atmospheric conditions and elevation of the Sun. Local relief further affects the shadow height. The latter effect, however, is limited only to the near-horizon position of the Sun. We compute the height of the shadow h solely on the basis of the true location of the Sun for a perfectly spherical Earth because, in practice, it is difficult to take these additional factors accurately into account. This places some uncertainty, about ~0.5°, on our calculation of the angle γ. It is worth noting that the displacement of the Sun can be determined from our measurements, the significance of which is that it does not affect our principal conclusions.

We place a radiometer equipped with a linear polarizer on the loft of the six-floor building of the Institute of Automation and Control Processes (Far Eastern Branch of the Russian Academy of Science, Vladivostok). We measure the location of the radiometer with the help of GPS at 43° 11′ 54.36″ N and 131° 55′ 28.53″ E (± 15 m) and an altitude of 45 m (± 5 m) above the sea level. Time was also determined using GPS.

We utilize a commercially available radiometer (*Ocean Optics Maya2000 Pro UV-VIS-NIR*) and a linearly polarizing filter on a photographic camera. The polarizing filter is installed in front of the radiometer and is held by a ring with four fixed positions (step of 45°). The orientation of the filter is changed manually once the signal is recorded at the given location. A one-cycle measurement with four consequent orientations of the polarizing filter takes 10 –20 s. Note that one cycle provides redundant information because the degree of linear polarization can be inferred using only three orientations of the linear polarizer (e.g., [13]). We use the fourth measurement to check the quality of the obtained value of polarization and calculate the corresponding error bars.

3. Experimental results

Over a ten-day time period in the late winter – early spring of 2017, we conducted four series of polarimetric measurements on February 21 (18:42:20 – 19:04:52 local time (LT)), February 27 (18:49:58 – 19:15:10 LT), March 2 (18:54:00 – 19:19:29 LT), and March 3 (07:26:59 – 8:14:56 LT). The first three experiments embraced the sunset that occurred according to *Stellarium* at the model conditions, on 18:47:30, 18:55:15, and 18:59:05, respectively. The last experiment commenced in the morning twilight and covered the sunrise that occurred on 07:48:54 (LT). In all the cases, the atmosphere toward zenith was free of optically thick clouds during the entire experiment.

Fig. 2 shows the shadow height as a function of local time that is computed using the *Stellarium* software at the model conditions. The shadow height is set to zero when the sun is above the horizon. The extent of the black solid line in each panel represents the duration of the measurement on the given epoch. On the first epoch, it can be seen that we conducted polarimetric measurements until the shadow height reached an altitude of ~12 km. In the two next measurements, it was increased to ~15 km. On the latest epoch, the measurements commenced when the shadow boundary was at almost 17 km.

In Fig. 3, we show the degree of linear polarization measured in red light (wavelength $\lambda = 0.65$ μm, bandpass $\Delta\lambda = 0.002$ μm). Note that the red part of the spectrum is chosen to reduce the relative contribution of the blue sky as a light source. Consequently, the relative contribution of skylight as a source is nearly two orders of magnitude below that of the sun [14], and the response from aerosol particles should dominate the response. When measuring aerosol particles in twilight one also needs to take into account that the solar radiation propagates through a significant