The effect and correction of aerosol forward scattering on retrieval of aerosol optical depth from Sun photometer measurements

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1. Introduction

[1] The Sun photometer is widely used to retrieve aerosol optical depth (AOD). In this study, the effect of atmospheric forward scattering on the measurement of direct solar irradiance is analyzed. In most cases, this effect can be safely neglected. However, in the case of heavy dust loading, errors in AOD derived from Sun photometer measurements can be significant which warrants a correction of the forward scattering to derive accurate values of AOD. An algorithm is presented for such a correction. Citation: Zhao, F., Y. Tan, Z. Li, and C. Gai (2012), The effect and correction of aerosol forward scattering on retrieval of aerosol optical depth from Sun photometer measurements, Geophys. Res. Lett., 39, L14805, doi:10.1029/2012GL052135.

2. Direct Solar and Atmospheric Forward Scattering Spectral Irradiances

[4] To gain insight into variations in direct solar and atmospheric forward scattering spectral irradiances with AOD and \( \theta_a \), radiative transfer calculations were performed using the code described in Zhao and Li [2007], which is a combination of the radiative transfer code for TMS algorithm developed by Nakajima and Tanaka [1988] and the K-distribution method described in Kneizys et al. [1988]. In the calculations, the U.S. standard atmosphere gas vertical profile is chosen [McClatchey et al., 1972]. The complex index of refraction is 1.5-0.003i. The aerosol size distribution is the Junge power law expressed as

\[
dv(r)/d\ln r = \begin{cases} c(r/0.1)^4, & r \leq 0.1\mu m, \\ c(r/0.1)^{- (p-4)}, & r > 0.1\mu m. \end{cases}
\]

where \( dv(r)/d\ln r \) is the aerosol volume spectrum at a particle radius \( r \), \( c \) is a constant, and \( p \) is the exponent of the Junge power law. The smaller the exponent, the larger the particles contained in the polydispersion. The relationship between the Angstrom parameter, \( \alpha \), and the exponent in the Junge power law is

\[
\alpha = p - 3.
\]

[5] The radiative transfer calculations were performed with 32 streams in each hemisphere. The lower and upper limits of the particle radius for integration to aerosol size distribution are 0.01 \( \mu m \) and 15 \( \mu m \), respectively. To test the validity of the forward scattering, we performed radiative transfer calculations with 4, 8, 16, 24, 32 and 36 streams in each hemisphere. The results showed that the selection of 32 streams is suitable for the present study. For the calculations of forward scattering irradiance, we assumed the response is homogeneous and zero within and out of the instrument field of view, respectively. The forward scattering irradiance is obtained by integral of the scattering radiance within the instrument field of view. The integration steps for zenith and azimuthal angles are 0.1°. Figures 1a and 1b show direct solar spectral irradiances as a function of AOD (500 nm) at \( \theta_a = 40° \) and 70°, respectively. As expected, the direct solar spectral irradiance decreases exponentially with increasing AOD. The decrease at large \( \theta_a \) is faster than at small \( \theta_a \).
Because $\alpha$ is generally larger than zero, the direct solar spectral irradiance decreases faster at shorter $\lambda$ than at longer $\lambda$. Figures 1c and 1d show forward scattering spectral irradiances as a function of AOD, where forward scattering is calculated by integrating scattered radiative intensities over all directions within the instrument field of view. Scattered radiation is affected by increases in AOD in two ways. On one hand, an increase in AOD increases forward scattering. On the other hand, increasing AOD decreases the direct solar spectral irradiance, as mentioned above, so decreases the forward scattering. As a result, the forward scattering irradiance has a maximum value located at an AOD which varies with $\theta_0$ and $\lambda$. We can see from Figure 1 that forward scattering spectral irradiances are not always negligible when retrieving AOD from measurements of direct solar spectral irradiance.

3. Effect of Forward Scattering on AOD Retrievals Using Simulated Data

The effect of forward scattering depends on the ratio of the forward scattering irradiance to that of the direct solar irradiance. In general, this effect increases with increasing AOD, $\theta_0$, and particle size, or fraction of coarse aerosols. For $\alpha = 1.2$, the errors are negligible for $\theta_0 < 60^\circ$. For $\theta_0 = 70^\circ$, the errors are significant only at very large AOD and short wavelength, say $\lambda = 440\,\text{nm}$ for which the relative error exceeds 0.1 for AOD larger than 3. The error increases with increasing $\theta_0$. For $\theta_0 = 80^\circ$, the error can reach 1 at AOD = 2 for $\lambda = 440\,\text{nm}$. The error decreases with increasing $\lambda$. Errors are negligible at $\lambda = 870$ and 1020 nm, even for $\theta_0 = 80^\circ$. For mineral dust-dominant polydispersions, $\alpha$ can be very small [e.g., Dubovik et al., 2002a; Gai et al., 2006; Dey et al., 2004; Longtin et al., 1988; D’Almeida et al., 1991; Prasad and Singh, 2007]. As shown in Figure 3, for $\alpha = 0.2$ and $\theta_0 = 40^\circ$, as AOD increases from 0.4 to 3.5, the ranges of relative errors are 0.013–0.144.

Figure 1. (a, b) Direct solar and (c, d) forward scattering spectral irradiances as a function of AOD.

Figure 2. Relative errors in derived AOD arising from forward scattering for $\alpha = 1.2$.

At the same AOD of 2, the ratio increases from 0.07 to 0.09 as $\theta_0$ increases from 40° to 70°.

Let $R_s$ and $R_d$ represent the spectral irradiances of forward scattering and direct solar irradiance, respectively. The relative error in the measurement of direct solar spectral irradiance resulting from forward scattering, which is just equal to the absolute error in derived AOD, can be expressed by

$$\text{relative error} = \frac{R_s}{R_d}.$$
error is about 0.02. So it is necessary to correct the effect of forward scattering, especially for the direct solar irradiances measured at shorter wavelengths. To do this, we generated a lookup table for forward scattering irradiances. In the calculations, the aerosol size distribution follows the Junge power law, as defined in equation (1). The library values of AOD at 500 nm are 0.05, 0.08, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.5, 2.0, 2.5, 3.0 and 3.5 and values for $\alpha$ are 0.0, 0.2, 0.7, 1.2 and 1.7. The corresponding AOD at other wavelengths is derived from the Angstrom relationship. Solar zenith angles range from 20° to 80° in 10° increments. The forward scattering irradiance at any AOD, $\theta_o$ and $\alpha$ is interpolated from the look-up table. Figure 4b shows the comparison of original and corrected AOD after removal of the forward scattering effect. It illustrates how corrections are needed to get accurate values of AOD, especially in the case of large AOD at short $\lambda$.

It should be noted that the corrections described above are based on the radiative transfer calculations assuming that particles are spherical. The non-spherical effect may affect the correction accuracy more or less. Dubovik et al. [2002b, 2000] analyzed the non-spherical effect on aerosol properties retrieved from a Sun-sky scanning radiometer. They indicated that, in the region of scattering angles larger than 30°–40°, there are significant differences between the retrieved scattering phase functions of spherical particles and spheroids. But in the region of scattering angles less than 30°, the differences are not

4. Analyses of Observed Data

[7] Mineral dust properties in the northwest region of China were measured and analyzed by Gai et al. [2006]. The observation sites are Tazhong (83.66°E, 39.00°N) and Hetian (79.93°E, 37.13°N) in the Taklamakan Desert and Dunhuang (94.68°E, 40.15°N) and Mingqin (103.08°E, 38.63°N) in the Hexi Corridor region. These sites are located in the source regions of mineral dust aerosols in China. Measurements from CE-318 Sun photometers installed at the sites were used to retrieve aerosol properties. Mean $\alpha$ over these sites are 0.092 ± 0.012, 0.158 ± 0.016 and 0.208 ± 0.021 in spring, summer and autumn, respectively. Negative $\alpha$ was also observed. In spring, up to 10% of $\alpha$ values are negative. AOD estimates may be significantly affected by strong forward scattering. Figure 4a shows errors arising from forward scattering. In this figure, the abscissa shows AOD at 500 nm interpolated from those measured at 440 nm, 670 nm, 870 nm and 1020 nm. As expected from model simulations, the error increases with increasing AOD and decreases with $\lambda$. For AOD = 2, the maximum error at 440 nm can reach about 0.2 while at 1020 nm, the maximum error is about 0.02. So it is necessary to correct the effect of forward scattering, especially for the direct solar irradiances measured at shorter wavelengths. To do this, we generated a lookup table for forward scattering irradiances. In the calculations, the aerosol size distribution follows the Junge power law, as defined in equation (1). The library values of AOD at 500 nm are 0.05, 0.08, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.5, 2.0, 2.5, 3.0 and 3.5 and values for $\alpha$ are 0.0, 0.2, 0.7, 1.2 and 1.7. The corresponding AOD at other wavelengths is derived from the Angstrom relationship. Solar zenith angles range from 20° to 80° in 10° increments. The forward scattering irradiance at any AOD, $\theta_o$ and $\alpha$ is interpolated from the look-up table. Figure 4b shows the comparison of original and corrected AOD after removal of the forward scattering effect. It illustrates how corrections are needed to get accurate values of AOD, especially in the case of large AOD at short $\lambda$.

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significant. This may imply that the correction errors caused from non-spherical effect play a secondary role.

5. Conclusions

[11] In this study, the effect of forward scattering on AOD derived from CE-318 Sun photometers is analyzed. The effect depends on AOD, α, λ, and φ. In general, such an effect is not significant. But for large AOD and small α, typical for dust storms, errors caused by forward scattering cannot be ignored. This is illustrated at four dusty stations in western China where the relative retrieval errors could be up to more than ten percent. A simple correction algorithm is presented to account for the effect of forward scattering on AOD retrievals from measurements made by the CE-318 Sun photometer.

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References


