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

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[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.

1. Introduction

[2] Accurate measurements of aerosol optical depth (AOD) are important for many studies, such as climate change, remote sensing and environment monitoring [*Li et al.*, 2009; *Intergovernmental Panel on Climate Change*, 2007; *Kaufman et al.*, 1997; *Hansen et al.*, 1997]. The long-term and quality-assured set of AOD data from the Aerosol Robotic Network (AERONET) [*Holben et al.*, 1998, 2001] are among the most widely employed geophysical measurements. AERONET consists of ~500 stations worldwide at which spectral solar and sky radiation are measured using automated scanning Cimel Sun photometers that are routinely calibrated. The total uncertainty of the calibration is less than ± 0.01 for wavelengths (λ) greater than 440 nm and ± 0.02 for shorter λ [*Holben et al.*, 1998]. Such ground-based AOD measurements are essential to studying aerosol radiative forcing and climate effects, development of atmospheric physical/chemical models, validation of satellite remote sensing products, and atmospheric correction.

[3] The CE-318 Sun photometer has a 1.2° field-of-view (FOV) and measures direct solar irradiances at 440, 670, 870, and 1020 nm. When the instrument receives direct solar irradiance, the irradiance from atmospheric forward scattering is also included but not accounted for in retrieving the AOD. In general, the forward scattering irradiance inside the field of view is much smaller in magnitude than the direct solar irradiance, so can be safely ignored. However, in cases of heavy dust loading, the direct solar irradiance decreases quickly with increasing solar zenith angle (θ_o). In such cases, the effect of atmospheric forward scattering on the measurement of direct solar irradiance cannot always be ignored. The purpose of this study is to examine and quantify the effect.

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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 θ_o, 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

$$dv(r)/d\ln r = \begin{cases} c(r/0.1)^4 & r \le 0.1\mu m \\ c(r/0.1)^{-(p-4)} & r > 0.1\mu m \end{cases}, \quad (1)$$

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, α, and the exponent in the Junge power law is

$$\alpha = p - 3. \quad (2)$$

[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 μm and 15 μm, 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 θ_o = 40° and 70°, respectively. As expected, the direct solar spectral irradiance decreases exponentially with increasing AOD. The decrease at large θ_o is faster than at small θ_o.

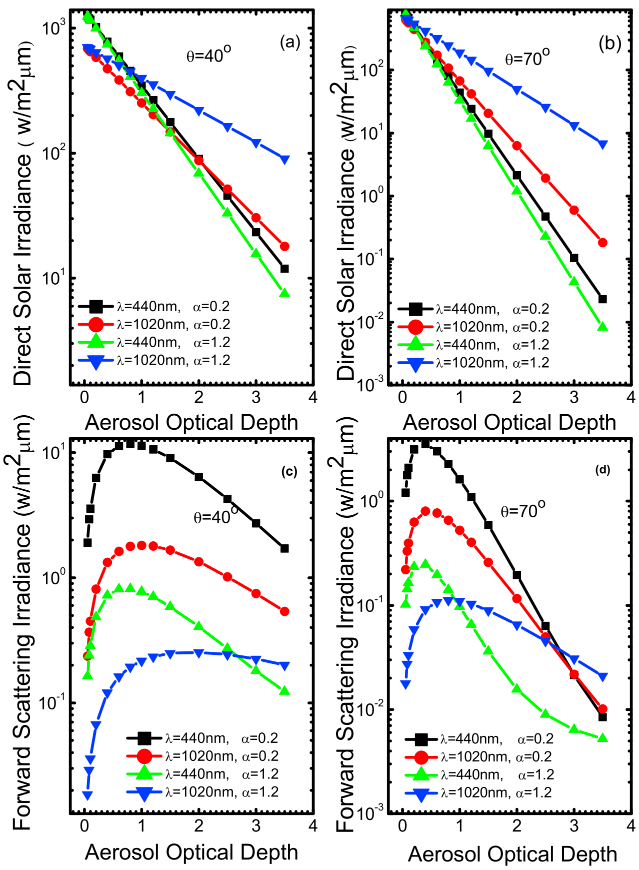

Figure 1. (a, b) Direct solar and (c, d) forward scattering spectral irradiances as a function of AOD.

Because α is generally larger than zero, the direct solar spectral irradiance decreases faster at shorter λ than at longer λ. 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 θ_o and λ. 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

[6] 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, θ_o and particle size, and decreases with increasing λ, as can be seen from Figure 1. For example, for $\lambda = 440$ nm, $\alpha = 0.2$ and $\theta_o = 40°$, the ratio of the forward scattering irradiance to that of the direct solar irradiance is 0.05 at AOD = 1.5. The ratio increases to 0.07 as AOD increases to 2. At the same AOD of 2, the ratio increases from 0.07 to 0.09 as θ_o increases from 40° to 70°.

[7] 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

$$\text{relative error} = R_s/R_d. \tag{3}$$

[8] Figures 2 and 3 show relative errors as a function of AOD at different λ and θ_o for $\alpha = 1.2$ and 0.2, respectively. As expected from the above discussions, the error increases with increasing AOD, θ_o and particle size, or fraction of coarse aerosols. For $\alpha = 1.2$, the errors are negligible for $\theta_o < 60°$. For $\theta_o = 70°$, the errors are significant only at very large AOD and short wavelength, say $\lambda = 440$ nm for which the relative error exceeds 0.1 for AOD larger than 3. The error increases with increasing θ_o. For $\theta_o = 80°$, the error can reach 1 at AOD = 2 for $\lambda = 440$ nm. The error decreases with increasing λ. Errors are negligible at $\lambda = 870$ and 1020 nm, even for $\theta_o = 80°$. For mineral dust-dominant polydispersions, α 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 $\theta_o = 40°$, as AOD increases from 0.4 to 3.5, the ranges of relative errors are 0.013–0.144,

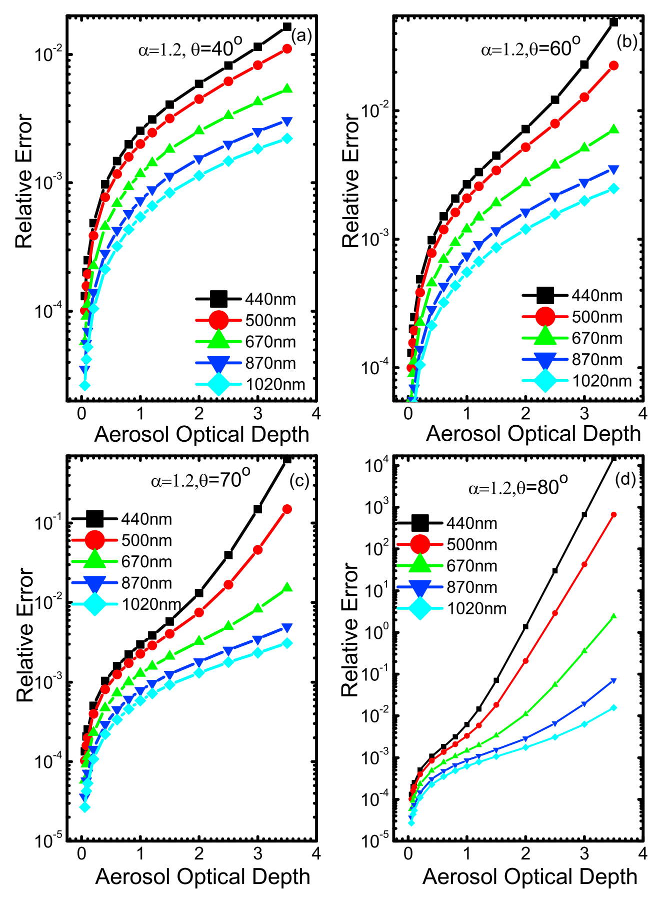

Figure 2. Relative errors in derived AOD arising from forward scattering for $\alpha = 1.2$.

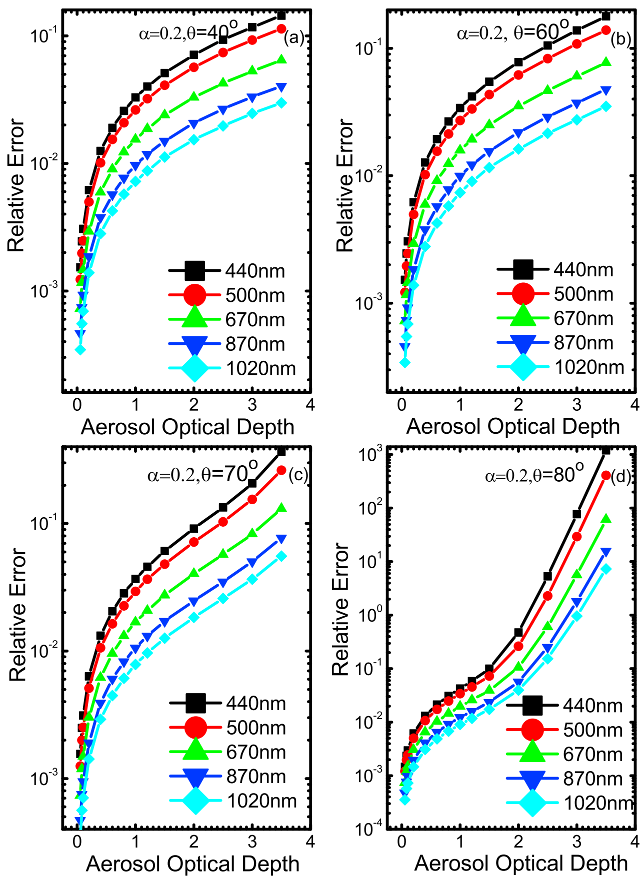

Figure 3. Same as in Figure 2, but for α = 0.2.

0.01–0.114, 0.006–0.06, 0.004–0.04, and 0.003–0.03 at λ = 440, 500, 670, 870 and 1020 nm, respectively. The errors increase with increasing θ_o. For θ_o = 70°, errors range from 0.013–0.367, 0.011–0.262, 0.006–0.131, 0.004–0.077, and 0.003–0.056 at λ = 440, 500, 670, 870 and 1020 nm, respectively.

4. Analyses of Observed Data

[9] 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 Minqin (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 α over these sites are 0.092 ± 0.012, 0.158 ± 0.016 and 0.208 ± 0.021 in spring, summer and autumn, respectively. Negative α was also observed. In spring, up to 10% of α 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 λ. 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 α 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, θ_o and α 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 λ.

[10] 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

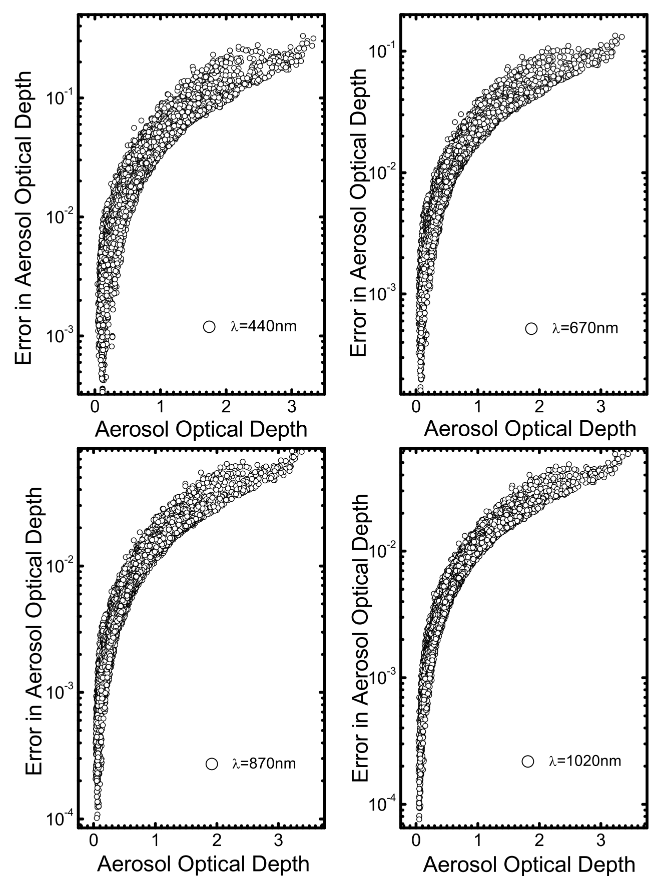

Figure 4a. Errors in AOD retrieved at Tazhong, Hetian, Mingqin and Dunhuang. The abscissa is AOD at 0.5 μm.

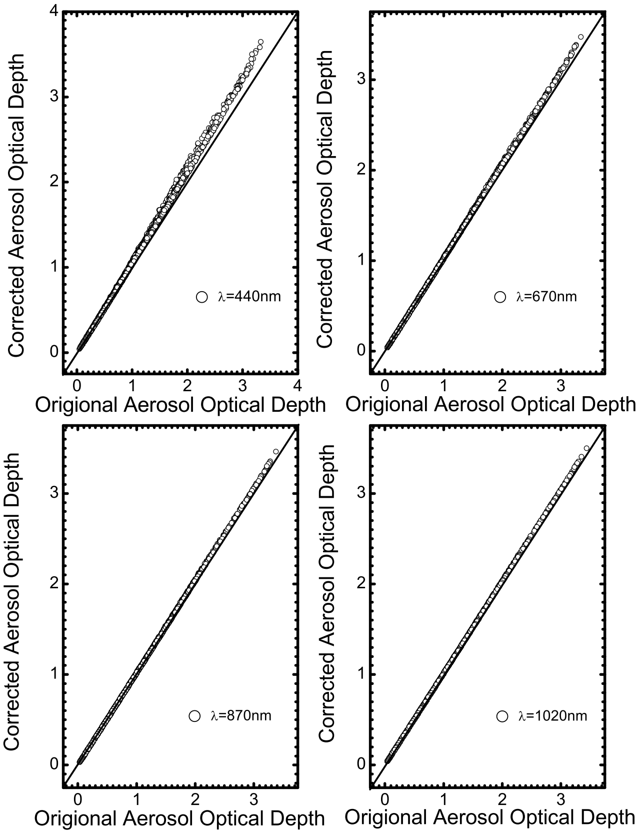

Figure 4b. Comparison between original and corrected AOD retrieved at Tazhong, Hetian, Mingqin and Dunhuang.

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 θ_o. 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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