Applicability of a Simple Model for Computing Direct Shortwave Climate Forcing by Sulfate Aerosols

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Recent estimates of global average forcing of climate caused by direct scattering of shortwave radiation by anthropogenic sulfate aerosol are -0.4 W m^{-2}, uncertain to a factor of somewhat greater than 2. For an aerosol optical depth of 0.1, characteristic of regions, including the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site, which are influenced by proximate anthropogenic emissions, the instantaneous forcing under cloud free sky is approximately 10 W m^{-2}. It is therefore necessary to represent this forcing in climate models, specifically including spatial and temporal variability. Here we examine the accuracy of simple algebraic expressions for representing the direct local and global average shortwave forcing by anthropogenic sulfate, which takes explicit account of the aerosol microphysical and optical properties, to determine their accuracy and applicability for use in climate models. The expressions, which are based on the approach of Charlson et al. (1991, 1992), give the forcing (W m^{-2}) in terms of the solar constant, F_T the sulfate column burden, $B_{SO_4^{2-}}$, mass scatter ing efficiency, α^*, and upscatter fraction, β, (both dependent on particle radius, r, and wavelength, λ) and on such local properties as solar zenith angle, θ_o and surface albedo, R_s;

$$\Delta F_{SO_4^{2-}} = -F_T \alpha_\lambda^* \beta_\lambda(\theta_o) T^2 (1-R_s)^2 B_{SO_4^{2-}} \qquad (1)$$

In the present study, the scattering efficiency is evaluated relative to the mass of sulfate in the aerosol and is expressed as $\alpha^* = \alpha$ x F(RH) (Charlson et al. 1992). Atmospheric transmission, T, is expressed as a function of wavelength (Coakley et al. 1983: Nemesure et al. 1995). The global average forcing for uniformly distributed aerosol is defined as

$$\overline{\Delta F}_{SO_4^{2-}} = \frac{1}{2} \int \Delta F_{SO_4^{2-}} \, d\mu_o; \qquad \mu_o = \cos\theta_o \qquad (2)$$

The factor $\frac{1}{2}$ is included because only half the planet is illuminated at any time.

A doubling and adding multiple scattering model (Hansen and Travis 1974) was used as the reference for comparison. The doubling and adding model is based on the fact that if reflection and transmission are known for two layers in the atmosphere, then the resultant reflection and transmission of the two layers can be obtained by computing the successive orders of scattering between the two layers.

A Mie scattering model (Hansen and Travis 1974) was used to determine the optical properties ($\alpha^*(\lambda)$ and aerosol phase function, $P_\lambda(\theta)$ used in both the algebraic expression and the multiple scattering model. We chose a gamma particle size distribution ("effective variance" equal to 0.01[(a)]) wide enough to remove any resonances in the particle size range considered, yet narrow enough that the Mie scattering properties were calculated essentially for monodisperse aerosols. The refractive index was assumed to be real, that is, no absorption ($n = n_r - in_i$ with $n_r = 1.4$ and $n_i = 0$). An ammonium sulfate particle at RH = 80% was considered and the atmospheric absorption was assumed to be 30%, i.e., T = 0.7.

In addition to comparing the algebraic expression to the multiple scattering model, we compare an even simpler expression for global average forcing suggested by Lacis et al. (1992), whereby the forcing by stratospheric sulfuric acid aerosols for a small optical thickness ($\tau < 1$) is linear and approximately 30 times the optical thickness.

$$\overline{\Delta F}_{SO_4^{2-}} (Wm^{-2}) = -30\tau_{SO_4^{2-}} \qquad (3)$$

Differences between the forcing computed for ammonium sulfate aerosols and sulfuric acid aerosols are due primarily to the difference in refractive index between the two compositions (Nemesure et al. 1995) and can be ignored for the purpose of this comparison. Figure 1 shows global average forcing as a function of aerosol optical thickness for the three representations of forcing being considered. The first panel, representing the forcing for a 0.12 μm radius particle, shows that the Lacis et al. (1992) underestimates the forcing by as

(a) Relative standard deviation ≈ 0.1.

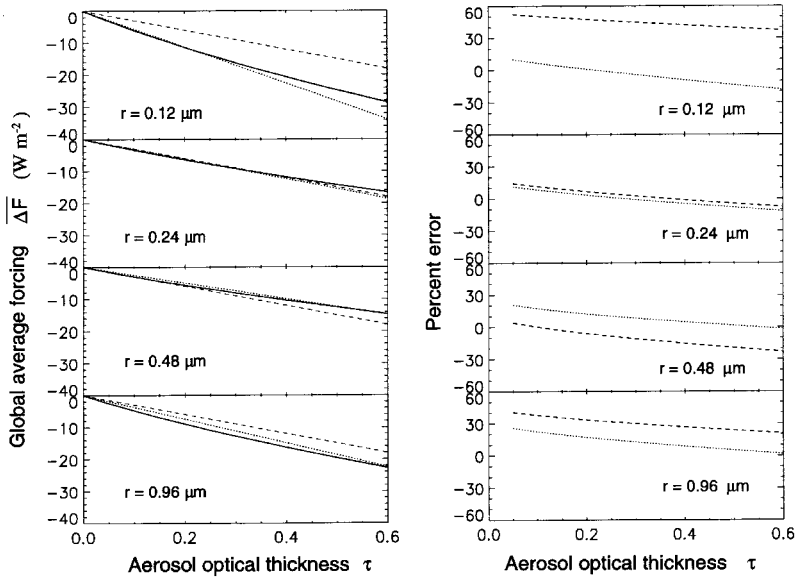

Figure 1. Left panel: dependence of global average forcing (W m^{-2}) on aerosol optical thickness for indicated values of radius and a surface albedo, R_s = 0.15. Solid line represents multiple scattering model, dotted line is Eq. (2), and dashed line is Eq. (3). Right panel: percent error relative to the multiple scattering model.

much as 50%, consistent with the investigators' caveat that this approximation does not hold for particles smaller than about 0.2 μm. This is due to the lack of sensitivity of the Lacis et al. (1992) approximation to the high degree of upscatter associated with smaller particles (Nemesure et al. 1995). The algebraic expression (1) slightly overestimates the forcing at larger aerosol optical thickness because of its linear nature versus the nonlinear nature of the global average forcing calculated using a multiple scattering model. This nonlinearity is due to the fact that the forcing becomes less sensitive to increases in the aerosol loading when $\tau > \approx 0.4$. In the remaining three panels both approximations to the forcing computed by the multiple scattering model do well, with Lacis et al. (1992) within about 40% of the multiple scattering model and Eq. (2) within about 20%, even for τ up to 0.6.

The forcing calculated for an individual particle size is not very realistic when estimating the global average forcing of actual aerosols. Rather, the forcing for an actual aerosol needs to be evaluated by integrating the radius-dependent forcing over the size distribution of the aerosol. Here for illustration, we carry out such an evaluation using the four different size distributions shown in Figure 2. Figure 3 shows the global average forcing averaged over these four size distributions. For three of the four distributions, both Eq. (2) (within 15%) and Eq. (3) (within 30%) agree quite well with the multiple scattering model. The Lacis et al. (1992) approximation

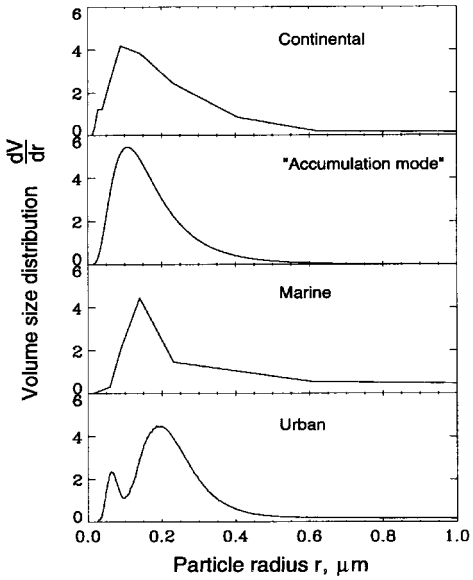

Figure 2. Volume size distributions corresponding to measurements of marine and continental aerosol (Hoppel et al. 1990), urban sulfate aerosol (John et al. 1990), and the classical accumulation mode distribution of Whitby (1978) (volume size distribution with r_g = 0.15 μm and σ_g = 0.57).

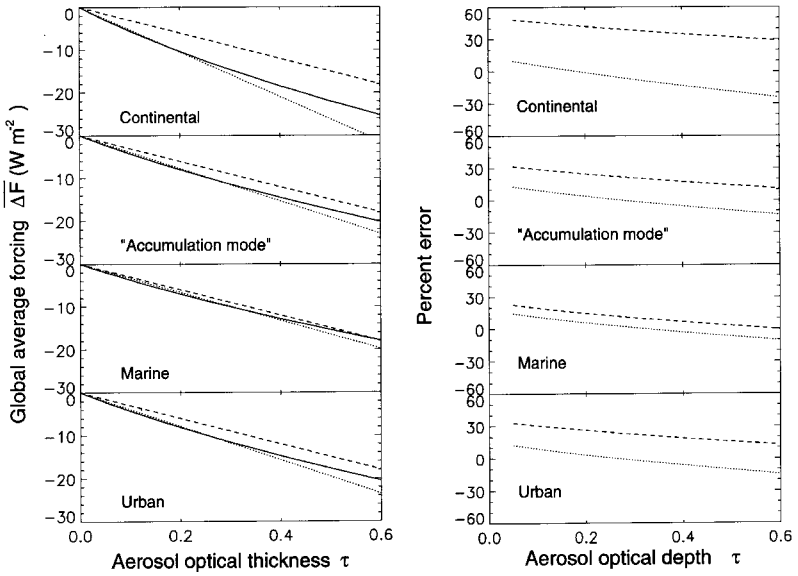

Figure 3. Left panel: dependence of global average forcing (W m^{-2}) on aerosol optical thickness integrated over four different size distributions as indicated on the figure. Solid line represents multiple scattering model, dotted line is Eq. (2), and dashed line is Eq. (3). All calculations made with $R_s = 0.15$. Right panel: percent error relative to the multiple scattering model.

underestimates the forcing by 50% for the continental aerosol, which is consistent with the accuracy given by Sato et al. (1993). As noted earlier, the apparent divergence at large aerosol optical thickness between Eq. (2) and the multiple scattering model is due to the nonlinearity of the multiple scattering that can only be captured by the multiple scattering model.

Estimates of instantaneous forcing at specific times are important for the purpose of comparing to measured quantities at specific locations such as at ARM sites. Figure 4 shows instantaneous forcing for four particle sizes as a function of μ_o, with $R_s = 0.15$ and $\tau = 0.2$. The algebraic expression (1) does not accurately represent the actual forcing for $\mu_o < \approx 0\ 3$, reaching an absolute maximum at the limb rather than zero as the multiple scattering model indicates. Eq. (1) fails to accurately represent the instantaneous forcing as $\mu_0 \rightarrow 0$, even at low aerosol optical thickness, because at high solar zenith angles the incident flux is decreased substantially by Rayleigh scattering. This Rayleigh scattering is not appropriately represented in Eq. (1).

The accuracy of both the linear approximation derived here and that of Lacis et al. (1992) might be sufficient (within ≈ 15-30%) for estimating the global average forcing, derived from an arbitrary size distribution, in a general circulation model (GCM). Using either of these approximations in a GCM can save valuable CPU time without losing much of the accuracy of the more CPU-intensive multiple scattering model. Estimates of the instantaneous forcing using an expression similar to Eq. (1) however, will need to be examined further so that Rayleigh scattering is sufficiently represented for large solar zenith angles, making it possible to reduce the time needed to make instantaneous measurements of forcing.

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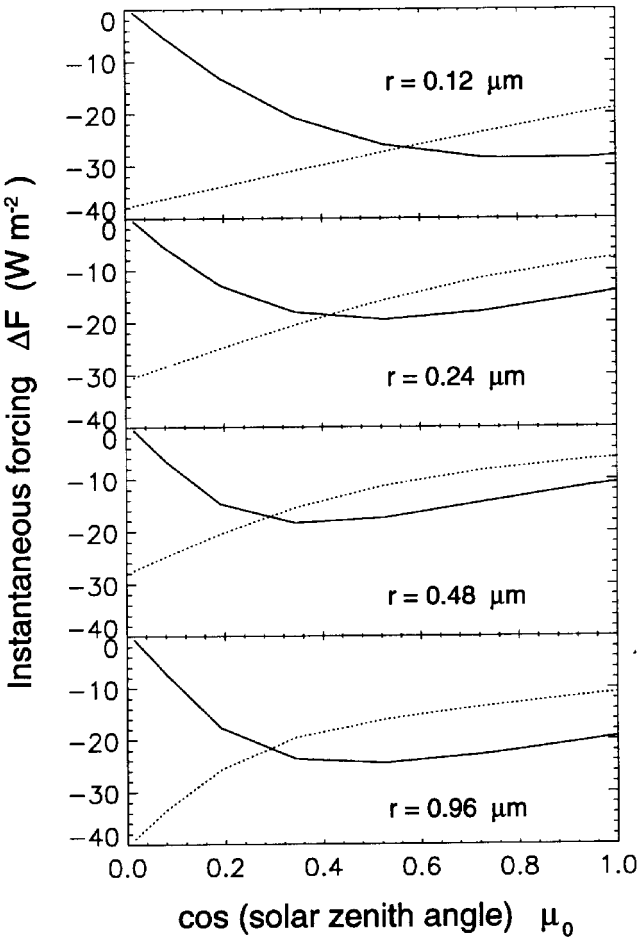

Figure 4. Instantaneous forcing (W m^{-2}) as a function of the $\mu_o = \cos\theta$ for $R_s = 0.15$ and $\tau = 0.2$ as computed by the multiple scattering model (solid line) and Eq. (1) (dotted line).

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