Intercomparison of Radiation Transfer Models Representing Direct Shortwave Forcing by Sulfate Aerosols

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Abstract

A study has been conducted, involving 15 models by 12 groups, to compare modeled forcing (change in shortwave radiation budget) due to sulfate aerosol for a wide range of values of particle radius, optical depth, surface albedo, and solar zenith angle (SZA). The models included high- and low-spectral resolution models, incorporating a variety of radiative transfer approximations, as well as a line-by-line model. The normalized forcings (forcing per sulfate column burden) obtained with the radiative transfer models were examined and the differences characterized. All models simulate forcings of comparable amplitude and exhibit a similar dependence on input parameters. As expected for a non-light-absorbing aerosol, forcings were negative (cooling influence), except at high surface albedo combined with low SZA. The relative standard deviation of the zenith-angle-average normalized broadband forcing for 15 models was 8% for particle radius near the maximum in magnitude of this forcing (ca. 200 nm) and at low surface albedo. Somewhat greater model-to-model differences were exhibited at specific SZAs. Still greater differences were exhibited at small particle radii, and much greater discrepancies at high surface albedos, at which the forcing changes sign; in these situations, however, the normalized forcing is quite small. Differences among the models arise mainly from differing treatment of the angular scattering phase function, differing wavelength and angular resolution, and differing treatment of multiple scattering. The relatively small spread in these results suggests that the uncertainty in forcing arising from treatment of radiative forcing of a well characterized aerosol at well specified surface albedo is a minor source of uncertainty compared to that from representing other processes influencing direct forcing by anthropogenic sulfate aerosols and anthropogenic aerosols generally. A journal article describing this intercomparison project has recently been accepted for publication (Boucher et al. 1998), and reference should be made to that publication for the details of the study. The project and results are briefly summarized.

Introduction

Shortwave radiative forcing by direct light scattering by anthropogenic sulfate aerosol has been suggested to be substantial in the context of longwave forcing by anthropogenic greenhouse gases over the industrial period (Charlson et al. 1991, 1992). Relatively simple expressions were used to estimate this forcing based on atmospheric loading (column burden) of sulfate, but such estimates are subject to concern from the perspective of the accuracy of their representation of the radiative transfer. Issues of concern include mass scattering efficiency (m^2 [g sulfate]$^{-1}$), upscatter fraction, wavelength dependence, dependence on surface albedo, and linearity in optical depth. Penner et al. (1994) suggested that the uncertainties arising from these issues amounted to a factor of 2. Other contributions to uncertainty in aerosol forcing include loading, geographical distribution, composition, optical properties, and cloud nucleating properties of the aerosol contributing to the "indirect" effect. Uncertainties in aerosol radiative forcing are thought to represent the greatest contribution to uncertainty in climate forcing over the industrial period (IPCC 1996; Schwartz and Andreae 1996).

Several groups have recently addressed radiative forcing by sulfate aerosol, but significant unresolved differences remain. Comparison of these studies suggests that part of the difference may be due to differences in the treatment of radiation. However, it is difficult to confirm this because of differences in the approaches. Boucher and Anderson (1995), using a global model, computed aerosol forcing for accumulation-mode sulfate aerosols. Nemesure et al. (1995) reported forcing for column burdens of monodisperse sulfate aerosols. Pilinis et al. (1995) reported forcing for a "global mean" aerosol consisting of fine and coarse modes.

Consequently it was necessary to back out the effects of differences in cloud and surface albedo, aerosol size distributions employed, and the like.

In view of the importance of aerosol forcing generally, sulfate aerosol in particular, and the resultant need to identify and reduce uncertainties in such estimates, it is considered desirable to ascertain the extent of the differences in these estimates due solely to the treatment of aerosol radiative forcing for specified conditions by means of an intercomparison by several groups conducting such calculations. The participants in this intercomparison project are listed in Table 1 along with the characteristics of the models that were used. A total of 19 different sets of calculations were submitted for comparison from 12 different groups and involving 15 different radiative transfer models, albeit several of them closely related. Several of the codes are presently used in general circulation models (GCMs); whereas some are too detailed to be used in GCMs.

A further motivation for this study arises from the need to represent aerosol forcing in GCMs and therefore the desire to evaluate errors arising from simplified treatments of this forcing that might be suitable for inclusion in GCMs.

There is some precedent for an intercomparison of shortwave aerosol forcing. Fouquart et al. (1991) intercompared shortwave radiation codes for climate studies as part of the Intercomparison of Radiation Codes used in Climate Models (ICRCCM) activity. Several of the cases that incorporated aerosols were reported briefly. Examination of the published paper and of unpublished results (Fouquart, personal communication, 1996) indicates (Figure 1) that the top-of-atmosphere (TOA) forcing, due to incremental aerosols in that intercomparison differed substantially in magnitude and even in sign for a certain number of the cases examined. The reasons for this are not clear and apparently were not extensively pursued subsequent to that intercomparison.

For the present intercomparison, a protocol was initially formulated by O. Boucher and S. Schwartz and circulated to groups engaged in such calculations. Models examined included a line-by-line model as well as high- and low-spectral resolution models with various radiative transfer approximations.

Table 1. Participants in the Project.

O. Boucher[1,2], S. E. Schwartz[3], T. P. Ackerman[4], T. L. Anderson[5], B. Bergstrom[6], B. Bonnel[1], P. Chlek [7], A. Dahlback[8], Y. Fouquart[1], Q. Fu[7], R. N. Halthore[3], J. M. Haywood[9,10], T. Iversen[11], S. Kato[4], S. Kinne[6], A. Kirkevåg[11], K. R. Knapp[12], A. Lacis[13], I. Laszlo[14], M. I. Mishchenko[13], S. Nemesure[3], V. Ramaswamy[10], D. L. Roberts[9], P. Russell[6], M. E. Schlesinger[15], G. L. Stephens[12], R. Wagener[3], M. Wang[7], J. Wong[7], and F. Yang[15]

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5. Joint Institute for the Study of the Atmosphere and the Oceans, University of Washington, Seattle
6. NASA-Ames Research Center, California
7. Department of Oceanography and Physics, Dalhousie University, Canada
8. Norwegian Institute for Air Research, Norway
9. Hadley Centre for Climate Prediction and Research, Meteorological Office, Bracknell, United Kingdom
10. Geophysical Fluid Dynamics Laboratory, New Jersey
11. Department of Geophysics, University of Oslo, Norway
12. Colorado State University, Colorado
13. NASA-Goddard Institute for Space Studies, New York
14. University of Maryland, Maryland
15. University of Illinois at Urbana-Campaign, Illinois

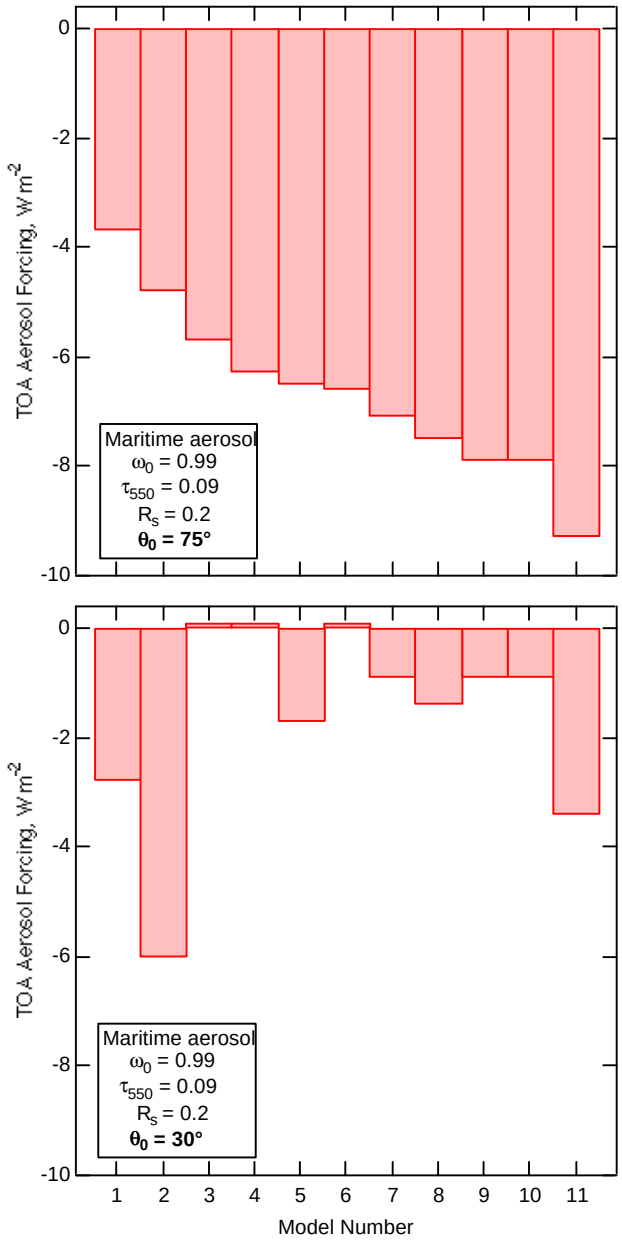

Figure 1. Shortwave radiative forcing evaluated for specified aerosol and surface properties during the ICRCCM (Fouquart et al. 1991; Fouquart, personal communication, 1996). Negative forcing denotes cooling influence. R_s is surface reflectance; in ω_0 is single scattering albedo; τ_{550} denotes aerosol optical depth at 550 nm; θ_0 denotes SZA. Note different relative magnitudes of forcing at different SZAs and differences in sign for different models at ω_0 = 30°. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/schwartz-98.pdf*).

Approach

Comparison of radiative forcing (change in net radiative flux at the TOA) by sulfate aerosol by different models, required specification of the conditions of the calculations covering a wide range of values of particle radius, aerosol optical depth, surface albedo and SZA. These conditions are summarized in Figure 2. In order to avoid influence of high-frequency Mie resonances associated with monodisperse aerosols, calculations were performed for a narrow size distribution (geometric standard deviation σ_g = 0.01) as shown in Figure 3. All calculations were performed for an aerosol having optical properties corresponding to a saturated solution of ammonium

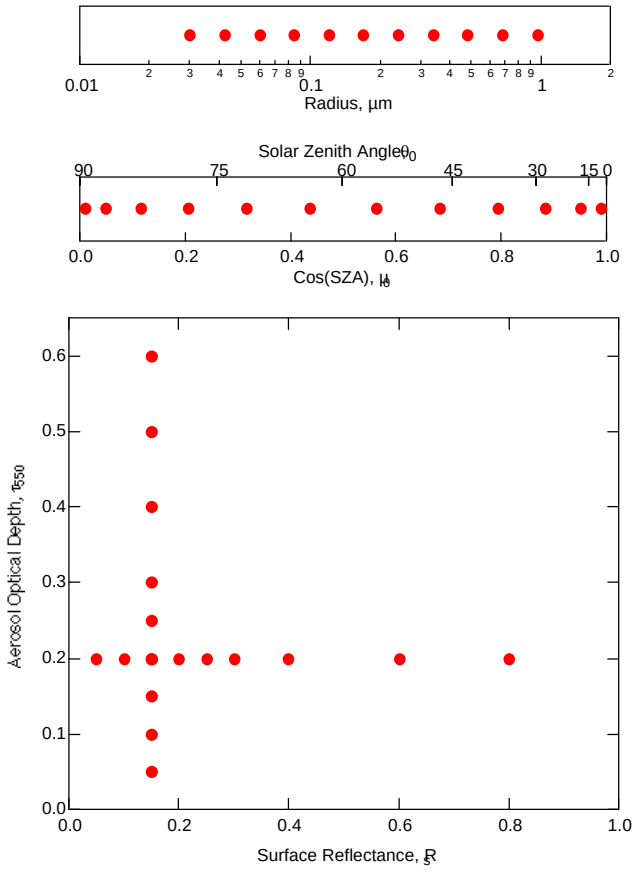

Figure 2. Conditions of the calculations, showing values of radius, SZA, aerosol optical depth, and surface reflectance for which the calculations were performed by the participating modeling groups. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/schwartz-98.pdf*).

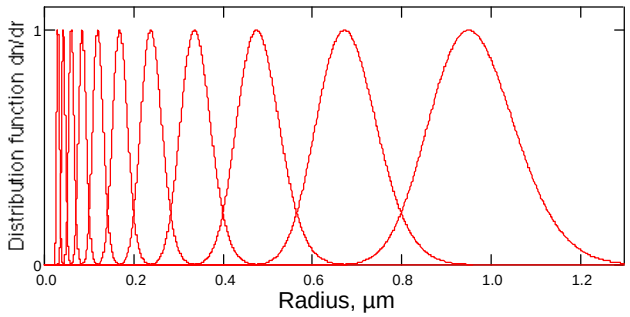

Figure 3. Particle size distributions employed in the calculations. From Boucher et al. (1988). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/schwartz-98.pdf*).

sulfate, specifically an index of refraction taken as 1.40 - 0*i*. Surface reflectance function and solar spectrum were specified by the participating groups according to their practice. Results were to be specified as normalized forcing, evaluated as the forcing divided by the column burden of sulfate and having units $Wm^{-2}/g(sulfate)$ m^{-2} or W $g(sulfate)^{-1}$. In addition to calculating broadband shortwave forcing, each group was asked to evaluate narrowband partial forcing at 550 nm, units W $g(sulfate)^{-1}$ nm^{-1}, and the ratio of broadband to partial forcing, forcing ratio, units nm.

Results

Results are presented in detail in Boucher et al. (1998), in which the discrepancies among the results obtained with the several radiative transfer models are investigated. All models simulate forcings of comparable amplitude and a similar dependence on input parameters. For most conditions, forcing is negative (cooling influence) as expected for a non-absorbing, light scattering aerosol.

However, the forcing is positive at low SZA and high surface albedo even for non-absorbing aerosols. Differences among results for the several models are attributed to differences in treatment of the spectral dependence of the aerosol scattering and representation of the solar spectrum by low spectral-resolution models.

Figures 4 and 5 present some highlights. Figure 4 shows close agreement among the several models in global average mass scattering efficiency and broadband and narrowband forcing. For particle radius near the maximum in this forcing, *ca*. 200 nm, the standard deviation among the models was about 8%. However, as indicated in Figure 5, the spread among the models was substantially greater under certain conditions. For example, high surface albedo has a range of zenith angle where the sign of forcing differs among the several models.

Conclusion

The present study indicates that a relatively small spread in forcing is due to differences in treatment of the optical and radiative components of the aerosol forcing, for specified aerosol properties and albedo. This situation represents a substantial improvement in the situation that was indicated in limited comparisons in ICRCCM (Fouquart et al. 1991). The model-to-model spread in forcing contributes relatively little to the overall uncertainty in sulfate aerosol forcing. Major reduction of the overall uncertainty in this forcing will require reduction in the larger uncertainties in the input parameters of radiative calculations, specifically the loading, distribution, and optical properties of the aerosol and the relation of these properties to other radiative influences such as relative humidity, surface albedo, SZA, and length of day, the latter governed by latitude and season.

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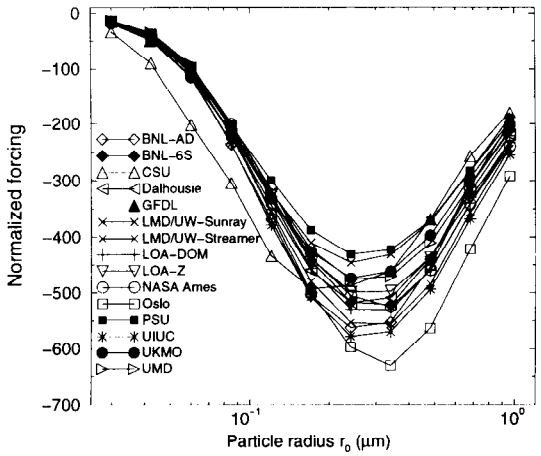
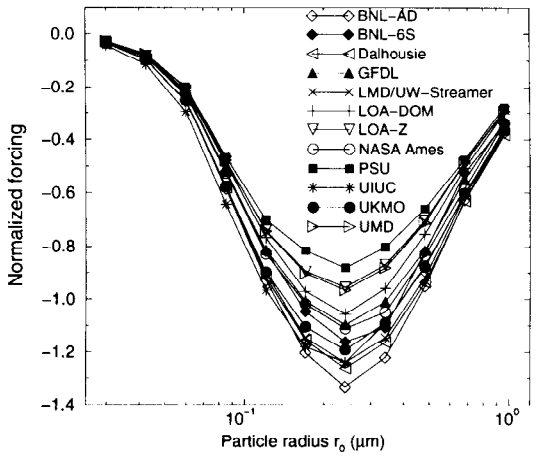
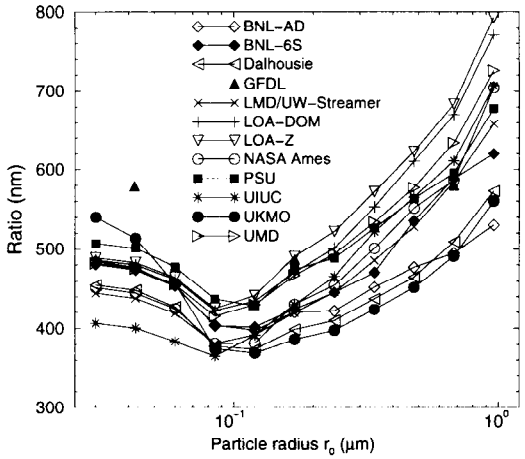


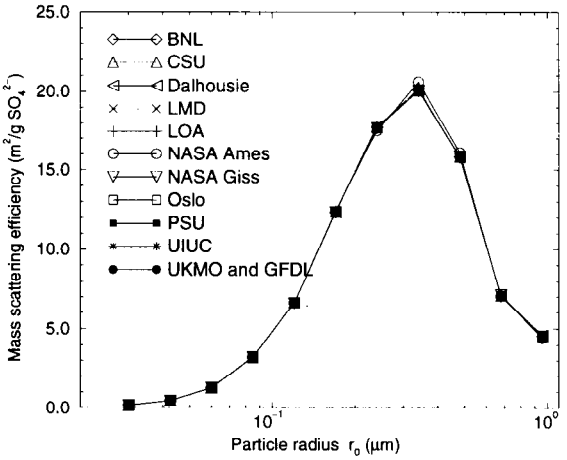
(a) Broadband forcing (W (g sulfate)$^{-1}$)



(b) 550 nm partial forcing (W (g sulfate)$^{-1}$ nm^{-1})



(c) Forcing ratio (nm)



(d) Mass scattering efficiency at 550 nm (m^2 (g SO_4^{2-})$^{-1}$)

Figure 4. Examples of results from intercomparison. Broadband normalized forcing, W m^{-2}/g sulfate m^{-2} or W g (sulfate)$^{-1}$. Partial forcing, W g (sulfate)$^{-1}$ nm^{-1}. Aerosol optical depth, 0.2; surface reflectance, 0.15. From Boucher et al. (1998).

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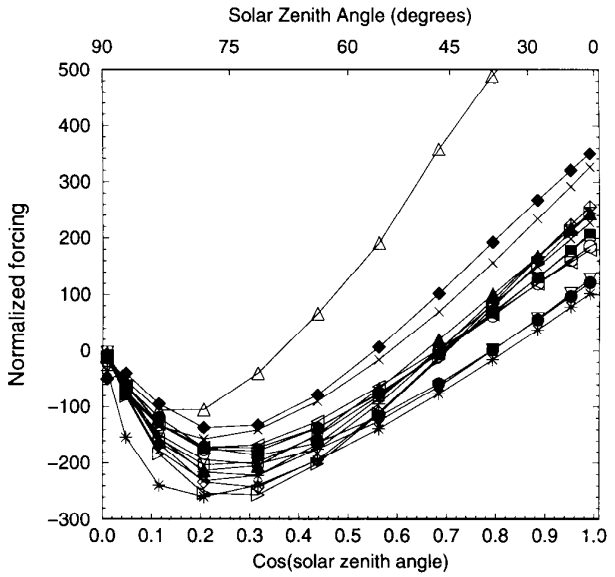
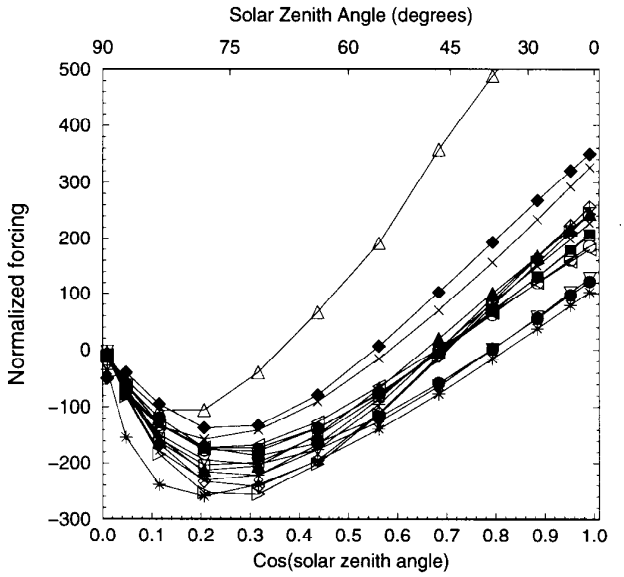


(a) Broadband forcing



(b) 550 nm partial forcing

Figure 5. Zenith angle dependence of broadband and partial forcing at high surface reflectance. Broadband normalized forcing, W m^{-2}/g sulfate m^{-2} or W g $(sulfate)^{-1}$. Partial forcing, W g $(sulfate)^{-1}$ nm^{-1}. Radius, 0.17 µm; aerosol optical depth, 0.2; surface reflectance, 0.60. From Boucher et al. (1998).

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