Evaluating Aerosol Indirect Effect Through Marine Stratocumulus Clouds

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Introduction

During the last decade much attention has been focused on anthropogenic aerosols and their radiative influence on the global climate. Charlson et al. (1992) and Penner et al. (1994) have demonstrated that tropospheric aerosols and particularly anthropogenic sulfate aerosols may significantly contribute to the radiative forcing exerting a cooling influence on climate (-1 to -2 W/m^2) which is comparable in magnitude to greenhouse forcing, but opposite in sign.

Aerosol particles affect the earth's radiative budget either directly by scattering and absorption of solar radiation by themselves or indirectly by altering the cloud radiative properties through changes in cloud microstructure. Marine stratocumulus cloud layers and their possible cooling influence on the atmosphere as a result of pollution are of special interest because of their high reflectivity, durability, and large global cover.

In this paper we present an estimate of the aerosol indirect effect. More specifically, we focus on the forcing due to anthropogenic sulfate aerosols. In our evaluation of the short wave forcing, we use the data by Warren et al. (1988) on global stratocumulus cloud climatology, the data on pollution due to sulfate aerosols from the 3-D chemical model of Langner and Rodhe (1991), and the parameterization of stratocumulus cloud albedo susceptibility developed using the Cooperative Institute of Mesoscale Meteorological Studies (CIMMS) large-eddy simulation (LES) cloud model with explicit microphysics and radiation (Kogan et al. 1994).

Model Description

In the study we employed the 3-D fields of cloud drop size distributions generated by the CIMMS/National Center for Atmospheric Research (NCAR) cloud model (Kogan et al. 1994). The dynamical framework of the model is based on a LES code developed by Moeng (1984). The cloud physics formulation follows that of Kogan (1991) and includes explicit formulation of the processes of nucleation, condensation, evaporation, and coalescence. The long wave radiation is parameterized according to Herman and Goody (1976), while the radiation code developed by Bretherton (1994) is used to compute the short wave heading rates. The simulations have been made with 40^3 grid points covering the $(2\ \mathrm{km})^3$ domain with equal spacing of 50 m in all directions. From each cloud simulation, we extracted 1600 vertical profiles of cloud drop spectra corresponding to each cloud grid-column. These profiles represented a wide range of dynamical conditions existing at various spatial locations within the cloud layer.

The developed cloud albedo susceptibility parameterization can be rather accurately represented by the formula:

$$dA / dN = C N^k \qquad (1)$$

where $C = 0.044$ and $k = -0.86$. As can be seen from Figure 1, the developed parameterization agrees very well with the calculations based on measurements by Taylor and McHaffie (1994) made during the Atlantic Stratocumulus Transition Experiment field program. The total column sulfate mass loading was obtained from the 3-D chemical Eulerian transport model of Langner and Rodhe (1991). The model simulations were made with horizontal resolution of 10 by 10 degrees in both longitude and latitude and with ten layers in the vertical between the surface and 100 hPa. The difference between distributions of total sulfate aerosols and sulfate aerosols from natural sources only provides the distributions of sulfates due to anthropogenic sources.

Finally, to calculate the spatial distribution of low layer cloud amounts over the globe, we used the two-dimensional climatological data for stratus/stratocumulus clouds (St, Sc), and fog situations by Warren et al. (1988).

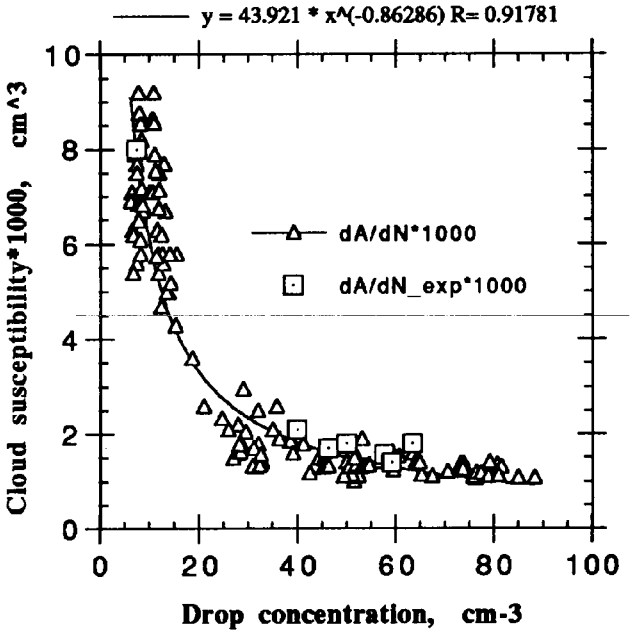

Figure 1. Cloud albedo susceptibility versus drop concentration derived using LES model data (triangles) and the experimental data of Taylor and McHaffie (1994) (squares).

Results

Figure 2 shows zonal averages of sulfate aerosols from all sources as well as from natural sources only. As one may expect, the strongest pollution is in the Northern Hemisphere within the 30°–70°N zone. These areas correspond to the pollution caused by major industrial sources from Europe and the East Coast of the United States. The cleanest air is in the Southern Hemisphere within the 40°–80°S zone; the concentration of particles there is smaller, by approximately a factor of 2, than in the Northern Hemisphere. The level of pollution which may be estimated by the difference between the two lines in Figure 2 is about 5 times less in magnitude in the Southern Hemisphere compared with the Northern Hemisphere. These well-pronounced differences result in a much larger cloud albedo susceptibility of the Southern Hemisphere clouds. As Figure 3 shows, the susceptibility of the Southern Hemisphere clouds is more than twice as large as the susceptibility of the Northern Hemisphere clouds. This result is consistent with our parameterization in Equation 1. Namely, for very clean clouds with drop concentrations on the order of 20 cm^{-3} the susceptibility is about 2 times larger than for the Northern Hemisphere clouds with drop concentrations on the order of 50 cm^{-3}.

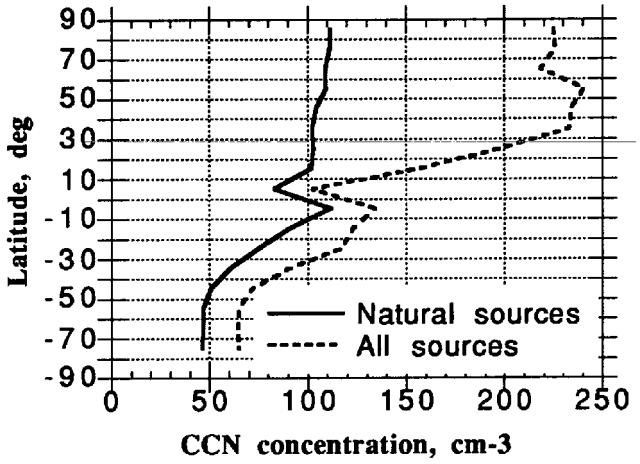

Figure 2. The zonally averaged profiles of the sulphate aerosols. The solid line shows contribution from natural sources only, while the dashed line from all sources.

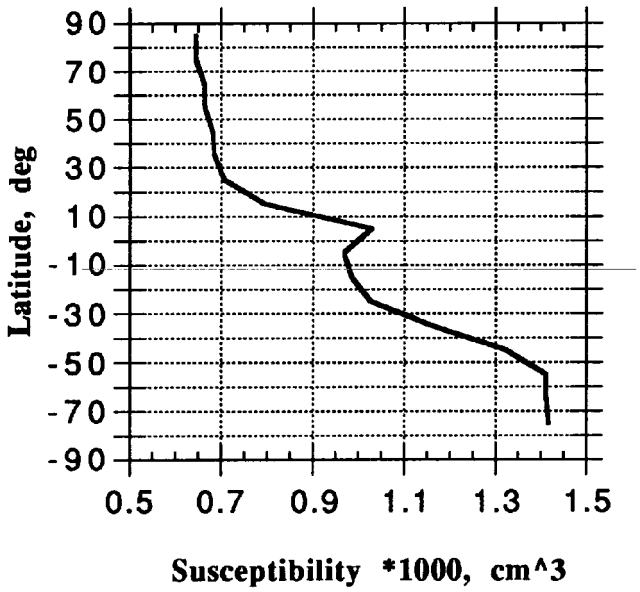

Figure 3. The zonally averaged profile of the cloud albedo susceptibility.

Figure 4 shows the variation with latitude of zonally averaged short-wave forcing due to sulfate aerosol pollution, while Figure 5 shows the distribution of this forcing over the globe (ocean areas only). Figure 4 shows that the maximum forcing is given by regions within the 50°–60°N zone, which is consistent with the high pollution in these areas.

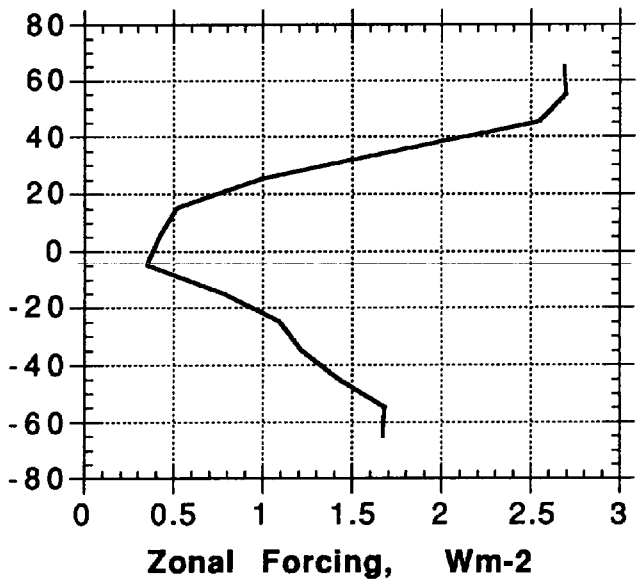

Figure 4. The zonally averaged profile forcing due to the indirect effect of anthropogenic sulphate aerosols.

A striking feature of this figure is the rather large contribution from the high latitudes in the Southern Hemisphere. This is evidently due to the high cloud albedo susceptibility in that zone (Figure 3). Figure 4 shows that, although the pollution level in the Northern Hemisphere is about 5 times larger than in the Southern Hemisphere, the peak forcing here is only 1.6 times larger than the peak forcing in the Southern Hemisphere. Again, this fact can be explained by the negative feedback between sulfate loading and albedo susceptibility.

Our calculations show that the total contribution to the forcing term from each hemisphere differs insignificantly. Namely, the average cooling rate over the whole globe is 1.1 W/m^2, while the averages for Northern and Southern Hemispheres are 1.3 W/m^2 and 0.9 W/m^2, respectively. Thus, in spite of the large difference in the pollution loading between the two hemispheres, the difference in climate cooling rates is rather small.

Figure 5 shows that forcing (cooling) may vary substantially over the globe from 0.08 W/m^2 near the equator to about 5.6 W/m^2 near the major pollution sources in the United States and Europe.

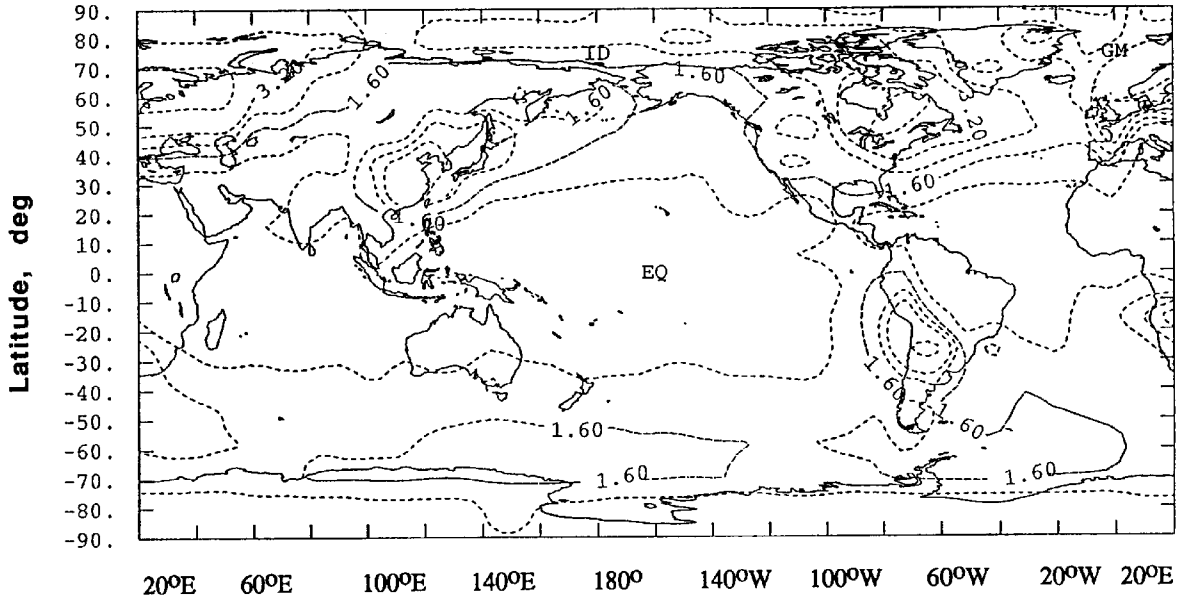

Figure 5. Global distribution of the radiative forcing due to the indirect effect of anthropogenic sulfate aerosols. The isoline increment is 0.8 W/m^2.

Conclusions and Future Work

We have evaluated the indirect radiative forcing caused by sulfate aerosols using the data on pollution from the 3-D chemical transport model of Langner and Rodhe (1991), cloud climatological data by Warren et al. (1988), and parameterization of cloud albedo susceptibility developed using the CIMMS/NCAR LES cloud model with explicit microphysics (Kogan et al. 1994). The results show that the global average cooling due to indirect forcing is 1.1 W/m^2, with averages 1.3 W/m^2 and 0.9 W/m^2 over the Northern and Southern Hemispheres, respectively. Our results also show that forcing (cooling) may vary over the globe from 0.08 W/m^2 near the equator to 5.6 W/m^2 near major pollution sources in United States and Europe. These estimates are consistent with those obtained previously by Charlson et al. (1992) and Jones et al. (1994). Our results also show a large difference in cloud albedo susceptibility between the two hemispheres. This leads to a rather small difference in the cooling rates (0.4 W/m^2) between the two hemispheres. As a result, in spite of the large differences in pollution loading, the contribution to the climatic forcing due to anthropogenic aerosols from each hemisphere differs only by about 25%. In our future work we will study the sensitivity of the climatic forcing due to anthropogenic sulfur aerosols to the uncertainties and variability in the input data.

Acknowledgments

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