Comparison of Seasonal and Zonal Patterns of the Direct and Indirect Radiative Forcing of Climate by Aerosols

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Aerosols have a climatically significant influence on the absorption of shortwave radiant energy in the troposphere, both directly through enhanced scattering of sunlight in the absence of clouds and indirectly through their fundamental role in controlling cloud microphysical properties. Quantitative estimates of the magnitudes of both effects are very uncertain (Charlson et al. 1992). In order to possibly distinguish these effects, we calculated the monthly and zonally averaged forcing for two idealized cases representing the direct and indirect forcing for a spatially uniform and seasonally constant perturbation in aerosol and cloud optical properties.

The model atmosphere was divided into two layers: a surface layer with a Lambert albedo of 0.15 and a homogeneous atmospheric layer consisting of molecular Rayleigh scattering and Mie scattering on either sub-micron size particles (direct effect) or cloud droplets (indirect effect). The doubling and adding radiative transfer was calculated at seven wavelengths (from 0.34 nm to 0.99 nm) with the weight of each wavelength interval proportional to the solar flux. The sum of the weights (0.7) is less than 1 to account for the fraction of the solar flux that is absorbed shortward and longward of the above wavelength range (Coakley et al. 1983). The microphysical properties of the aerosol were chosen as effective particle radius r_e=0.25 μm and variance v_r=0.01 in a modified gamma distribution (Hansen and Travis 1974), refractive index n_r=1.4 [corresponding to $(NH_4)_2SO_4$ particles at a relative humidity RH=0.8; Nemesure et al. 1995]. The direct forcing was determined as the difference in the net downward flux at the top of the atmosphere between a case with an aerosol optical depth of $\tau_a = 0.1$ and one with $\tau_a =$ 0.05, corresponding to the background aerosol burden. The hemispheric mean of the direct forcing is -1.1 Wm^{-2} for a 40% cloud free planet.

The cloud layer consists of droplets (refractive index 1.33) with a narrow size distribution having an effective radius r_e= 8 μm and an optical depth τ_c = 6 for the unperturbed case and r_e= 7.3μ and τ_c= 6.6 for the anthropogenically perturbed case, corresponding to a cloud droplet number density increase by a factor of 1.3 and a constant liquid water path. The geometric albedo increased by 0.02 from 0.46 for the unperturbed case to 0.48 for the perturbed case. The hemispheric mean of the indirect forcing is -1.8 Wm^{-2} for 20% perturbed cloud cover.

The resulting zonal and seasonal direct and indirect forcings, normalized to a mean of -1 Wm^{-2}, are presented in Figure 1. The seasonal variability and the peak of the direct aerosol forcing are confined to the high latitudes, whereas the indirect forcing extends to much lower latitudes.

The marked difference between Figure 1a and 1b is a direct consequence of the fact that the direct effect operates in the optically thin regime, whereas the cloudy atmosphere of the indirect effect is optically thick. To illustrate this point, Figure 2 shows normalized direct and indirect forcing vs. μ_0, the cos(solar zenith angle). Also shown are the “results” of the two extreme optical thickness regimes in the radiative transfer. In the optically thin limit (dashed line marked “direct”) the forcing is proportional to the upscatter fraction (the integral of the phase function over the upward hemisphere) because the decrease of downward flux due to the projection of the solar irradiance onto the earth’s surface ($\propto \mu_0$) is compensated by the increase in path length through the aerosol layer ($\propto \mu_0^{-1}$). Since the effective path length approaches a finite value as μ_0 goes to 0, the forcing should go to 0 for μ_0 = 0 as indicated by the doubling and adding model result.

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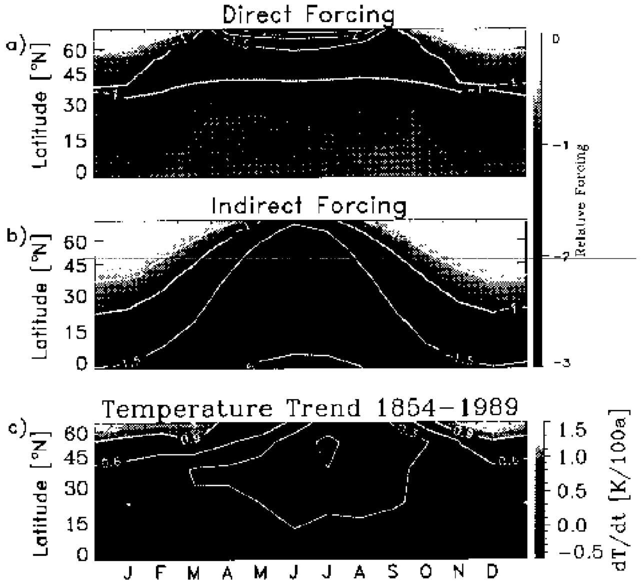

Figure 1. a) Direct aerosol forcing due to a uniform increase of aerosol optical depth over a uniform surface; b) Indirect aerosol forcing due to a uniform increase in cloud optical depth and decrease of cloud droplet radius; c) Zonal average of the monthly mean surface temperature anomaly trends (1854-1989) in K/century.

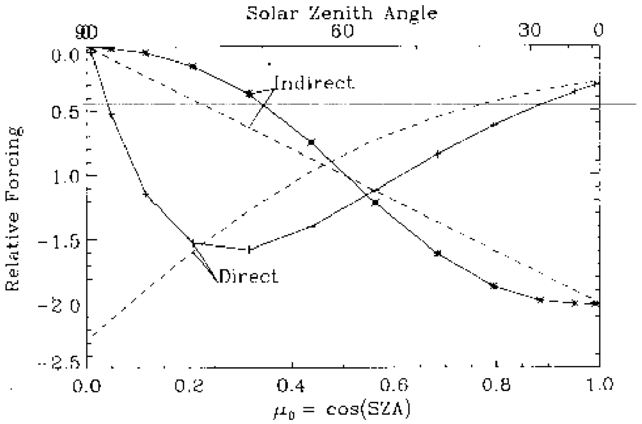

Figure 2. Relative forcing, normalized to a global average of -1, vs cos(solar zenith angle). Solid lines: Direct (plus symbols) and indirect (asterisks) forcing as computed with the doubling and adding model (see text). Dashed lines: heuristic "models" explaining the main differences between the direct and indirect forcing functional dependence on μ_0 (see text).

The direct and indirect forcing patterns of Figure 1a and 1b may be compared to the seasonal pattern in observed monthly mean surface temperature anomaly trends (Hunter et al. 1993) shown in Figure 1c. This pattern lies between the two patterns exhibited by the direct and indirect forcing and can be matched very well through a linear combination of the two, time lagged by one month. The indirect effect is statistically more significantly correlated to the temperature anomaly trends than the direct effect, indicating that the indirect effect is more important in establishing the seasonal and zonal forcing patterns and that its magnitude is equal to or greater than the direct forcing.

Such a match would only be expected, however, if dynamical effects can be ignored in the climatic surface temperature response to the aerosol forcings on a zonal and monthly mean basis. Quantitative attribution also requires consideration of the seasonal and zonal distributions of low-altitude clouds, cloud free areas, relative humidity, and anthropogenic sulfate aerosol burden and particle size distribution.

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