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Climate response to radiative forcings by sulfate aerosols and greenhouse gases

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Abstract. The annual, global mean radiative forcing for the troposphere-surface system has been used to rank the global warming influences of atmospheric trace gases. The approach was also used recently to compare the cooling influence of tropospheric sulfate aerosols with the warming influence of greenhouse gases. However, the spatial inhomogeneity of sulfate aerosols (concentrated mainly in the continental Northern Hemisphere) may induce climate responses which differ other than just in sign from those induced by increased concentrations of the more homogeneously distributed greenhouse gases. Here we use a general circulation model to further examine the suitability of global mean radiative forcing as a predictor of differences in global, hemispheric, and regional climate responses to differing spatial and temporal forcing patterns. The calculated responses indicate that changes of the global and annual mean surface air temperature depend only on global average net forcing and are not highly sensitive either to the details of the spatial and seasonal patterns in forcing or to the nature of the forcing (shortwave vs. longwave). Thus in global and annual mean the negative aerosol forcing may be viewed as a scaleable anti-greenhouse forcing. However substantial responses to nonuniformly distributed aerosol forcing were observed at hemispheric and regional scales. Further, the patterns of response differ from the patterns of forcing, leading to the conclusion that the spatial distribution of all significant forcings must be accurately represented when studying regional climate changes.

Introduction

Radiative forcing is commonly defined as the instantaneous change in radiative flux, given an instantaneous change in a substance of radiative importance, e.g., greenhouse gases or sulfate aerosols [*Houghton et al.*, 1992]. The strong coupling between the surface and troposphere has led to the choice of the tropopause as the level at which radiative forcing is defined and used to study the relative importance of different forcings for climate change studies [*Houghton et al.,* 1990]. For sulfate aerosols, the change in solar radiative flux results from two processes: a direct backscattering of solar radiation by the particles, and an indirect effect of enhanced cloud albedo due to increased cloud droplet numbers in the presence of enhanced concentrations of aerosol particles [*Wigley and Raper*, 1992; *Charlson et al.,* 1992]. The indirect effect is not well characterized and in this study we treat only the direct effect. *IPCC* [1994] indicates that shortwave aerosol forcing may be offsetting longwave greenhouse gas forcing to a substantial extent in global and annual average. However, the compensation in forcing is only in the mean, and the spatial and seasonal response to such a nonuniform cancellation is unknown.

The radiative forcing of sulfate aerosols exhibits a strong spatial and seasonal variation, in comparison to the more uniform longwave forcing due to enhanced greenhouse gas concentrations [*Kiehl and Briegleb*, 1993; *Charlson et al.*, 1991]. In addition, the vertical partitioning of the forcings is quite different. The greenhouse gas forcing is partitioned roughly equally among the upper troposphere, lower troposphere, and surface, whereas the aerosol forcing is active primarily at the surface. Different vertical partitionings may lead to different regional climate response [*Wang et al.*, 1991]. Thus, response to the presence of both aerosols and enhanced greenhouse gases may differ substantially in both global mean and regional detail compared to a case where neither forcing is present. *Taylor and Penner* [1994] studied the response to varying amounts of both aerosols and greenhouse gases. Here we examine a case where the two cancel each other in the mean in order to explicitly examine differences in response to these different spatial and seasonal distributions of forcing.

GCM Simulations

Two general circulation model (GCM) runs were performed (Table 1). The terms "forcing" and "response" in this paper refer to differences between the two. Case A is a reference case, similar to that documented in *Wang et al.* [1992], with observed year-1990 concentrations of greenhouse gases, and no explicit aerosol effect included. Case B contains year-2000 levels of greenhouse gases [*Houghton et al.* 1990], which gives a global annual longwave forcing of 0.494 Wm^{-2} relative to Case A, and an anthropogenic sulfate aerosol layer which just balances the longwave forcing. The sulfate aerosol column burdens were calculated [*Charlson et al.*, 1991] by a 3-d transport and transformation model with geographically distributed emissions and monthly mean winds. Figure 1 shows the seasonal distributions of aerosol column burden. The aerosol is heavily biased towards the continental midlatitude regions of the NH. Maxima are located in the midwestern U.S., central Europe, and eastern Asia.

We incorporate these burdens into a version of the National Center for Atmospheric Research Community Climate Model, version 1 (NCAR CCM1), with a mixed-layer ocean, calculated sea ice, and incorporation of the radiative effect of the major greenhouse gases [*Wang et al.*, 1992; *Williamson et al.*, 1987]. The transmissivity and reflectivity of the aerosol layer are calcu-

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Table 1. Gas Concentrations for GCM Experiments, and Global and Annual Mean Climate Parameters.

	Concentration						GCM simulated climate		
Case	CO_2	CH_4	N_2O	$CFCl_3$	CF_2Cl_2	Aerosol	T_s	P	C
A	354	1.72	0.31	0.28	0.48	0	289.69±.01	3.48	.428
B	374	1.97	0.32	0.36	0.61	see Fig. 1	289.68±.01	3.49	.428

Concentration unit is ppmv for CO_2, CH_4, and N_2O, ppbv for $CFCl_3$ and CF_2Cl_2. The aerosols and additional trace gases of case B cause radiative forcings at the tropopause of +.494 Wm^{-2} in the longwave, and -.494 Wm^{-2} in the shortwave, compared to case A. Climate parameters are surface air temperature T_s (K), cloud cover C (fraction) and precipitation P (mm/day). Case B contains greenhouse gas concentrations at the year 2000 level as prescribed by the business-as-usual scenario, and sulfate aerosols as described in the text. The last 24 years of a 35-year run are averaged. The uncertainty in T_s represents standard error of the mean.

lated using a delta-Eddington scheme. The optical properties of the aerosol layer are then combined with those of the surface [*Briegleb*, 1992], effectively increasing the surface albedo. The vertical distribution of the aerosols is thus ignored; it has been shown [*Coakley et al.*, 1983] that if an aerosol layer is non- or weakly absorptive, the radiation profile is insensitive to vertical distribution. We use a single scattering albedo of 0.99, and an asymmetry parameter of 0.8. We ignore the effect of the aerosols on the longwave radiation, which is small because of the low altitude and resultant small temperature contrast with the surface.

The annual global mean longwave radiative forcing at the tropopause due to the increased greenhouse gases is calculated to be +0.494 Wm^{-2}. The calculated global and annual mean radiative forcing at the tropopause caused by the aerosol layer is -0.430 Wm^{-2}. In order to exactly offset the greenhouse gas forcing, the specific extinction is increased from a reference value of 8.5 m^2 $(g\ SO_4^{2-})^{-1}$ [*Charlson et al.*, 1991] to 9.8 m^2 $(g\ SO_4^{2-})^{-1}$. This value may be too high, given the falloff of specific extinction with increasing wavelength [*Kiehl and Briegleb*, 1993; *Haywood and Shine*, 1995]; however the purpose here is not to exactly model the magnitude of the aerosol forcing, but rather to match the longwave forcing in global and annual average magnitude, while maintaining the spatial and seasonal radiative forcing distribution of the aerosols. The global and annual mean

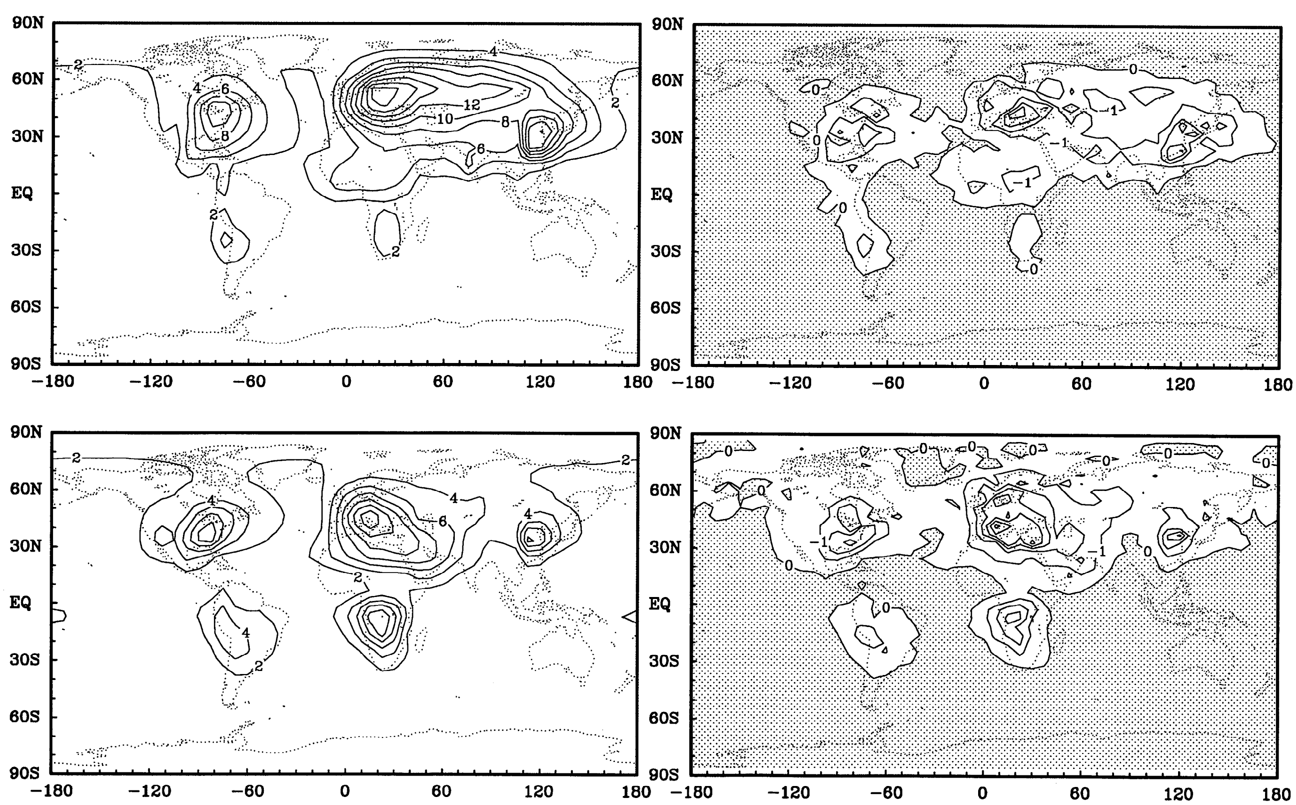

Figure 1. Anthropogenic sulfate aerosol column mass burden (mg SO_4^{2-} m^{-2}, left panels) and net radiative forcing at the tropopause (Case B-Case A, Wm^{-2}, right panels, contour interval 1 Wm^{-2}, shaded where forcing is positive, i.e. warming) for DJF (top) and JJA (bottom). Aerosol data file, provided by J. Langner (Stockholm University), is similar to that of *Charlson et al.* [1991]. Maxima in northeast North America, central Europe, and eastern China are due to industry and fossil fuel combustion. Net forcing is the algebraic sum of the negative (cooling) by sulfate localized primarily in continental midlatitudes of the Northern Hemisphere and the more uniform positive (warming) forcing by the greenhouse gases.

Table 2. Hemispheric Annual Breakdown of Forcing and Surface Temperature Response.

	global	NH	SH
Aerosol forcing (Wm^{-2})	-0.494	-0.788	-0.200
Greenhouse forcing (Wm^{-2})	0.494	0.492	0.497
Net forcing (Wm^{-2})	0	-0.297	0.297
Expected ΔT_s (K)	0	-0.37	0.37
Model ΔT_s (K)	-0.01	-0.14	0.12

The expected values are determined using a model sensitivity of 1.25 K/Wm^{-2} and the assumption that the hemispheres are decoupled.

net forcing at the tropopause (a superposition of the shortwave cooling by the aerosol layer and longwave warming by the greenhouse gases) is thus zero. This cancellation in the mean emphasizes the sensitivity to differences in spatial and seasonal patterns of forcing. The strong regional signature of the shortwave forcing is evident, compared to the more evenly distributed greenhouse forcing (Fig. 1). The forcing is greatest in the Northern Hemisphere (NH) summer (Table 2), when incoming solar radiation is greatest. Each case was run for 35 years, and the last 24 years of data were used.

The global annual mean surface temperature for case B is 0.01±0.01 K cooler than for case A, suggesting a near cancellation of longwave and shortwave effects in global mean; for a global sensitivity of CCM1 of 1.25 K/Wm^{-2} [*Wang et al.*, 1991] the response to either forcing alone would be ~0.6 K. However, there is a pronounced regional and seasonal response. In the annual mean, the Northern Hemisphere is 0.14 K cooler, whereas the Southern Hemisphere is 0.12 K warmer, qualitatively consistent with the hemispheric partitioning of the forcings. Figure 2 shows the seasonal temperature response. The broad pattern shows a greater model response in the higher latitudes, consistent with previous GCM simulations of a 2xCO_2 climate [*Houghton et al.*, 1990]. The NH cooling is greatest during June-July-August (JJA), i.e. the period of maximum aerosol forcing. Additionally, the pattern of response exhibits a high degree of regional variability, which differs considerably from season to season. Strong cooling is generally exhibited over the North American and European forcing centers, although the strongest cooling occurs well to the northwest of the North American center. The east Asian center is not reflected in the response as clearly, and is displaced to the north in those seasons when it does appear. The African and South American centers do not appear strongly in the response. Examination of interannual variability indicate that the magnitudes of the regional responses are robust. For example, the European temperature is 0.69 K cooler than the NH JJA mean cooling of 0.20 K, with a standard error of 0.12 K, and the JJA North American center is 0.72 K cooler, with a standard error of 0.14 K. Note that prior studies [*Wang et al.*, 1992] have shown that model variability exhibits a seasonal and latitudinal dependence, and that signal-to-noise ratio may vary across different models. Table 2 summarizes the seasonal and hemispheric response.

If the hemispheres could be treated as decoupled, the expectation would be that each would respond independently to the forcings imposed on it, with the sensitivity of the model, 1.25 K/Wm^{-2}. With equal but opposite forcings of 0.30 Wm^{-2} (Table 2), each hemisphere would be expected to respond by 0.37 K. The actual model response was much smaller in

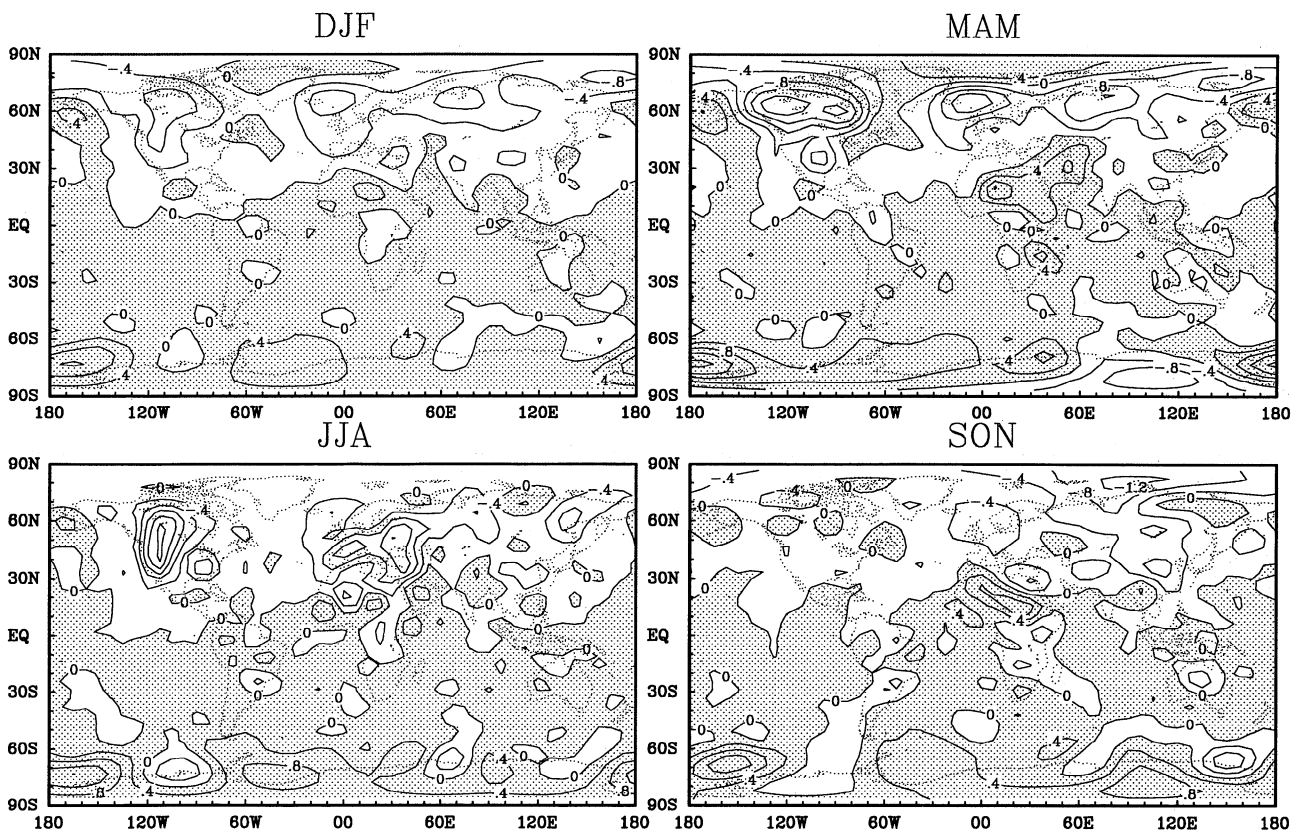

Figure 2. Distribution of surface temperature difference (Case B-Case A, K). The values are averages over the last 24 years of a 35 year run for both cases. Shaded where $\Delta T > 0$ K. Contour interval is 0.4 K.

magnitude than this; -0.14 K in the NH and +0.12 K in the SH, indicative of substantial net heat flow from the SH to the NH.

Conclusions and Discussion

The principal motivation for the present study was to examine the climatic effect of a horizontally inhomogeneous perturbation in radiative forcing resulting from the inhomogeneous distribution of anthropogenic aerosols. In global and annual mean we find essentially equal sensitivity to equal but opposite forcings by greenhouse gases and aerosols, evidenced by a near zero global and annual response of the system to zero net forcing. This result supports the suggestion [*Houghton et al.*, 1992] that cooling forcing by anthropogenic aerosols may be offsetting a substantial fraction of the global mean response to forcing due to greenhouse gases.

When temperature response is examined by hemispheres we find that the hemispheres respond qualitatively as expected (cooling in the NH, warming in the SH). However the magnitude of the response in either hemisphere is substantially less than would be expected if the hemispheres were completely decoupled, because a major fraction of the negative forcing in the NH is expressed as a decrease in the magnitude of SH warming. Such lesser hemispheric response suggests that inferring global temperature sensitivity from the interhemispheric difference in magnitudes in temperature anomaly trends under assumption that the hemispheres are decoupled will lead to substantial underestimation of this sensitivity. Finally, in examining regional temperature response we find considerable spatial displacement between the loci of regional forcing and temperature response. This result again suggests that heat transport by atmospheric circulation processes will confound attempts to empirically infer temperature sensitivity from the relation between regional forcing and regional temperature anomaly trends.

The finding of the present study of essentially equal sensitivity to greenhouse gas and aerosol forcings differs from that of an earlier study by *Taylor and Penner* [1994], which found greater sensitivity to greenhouse gas than aerosol forcing. However, extension of that work [*K. Taylor*, private communication, 1995; *Santer et al.*, 1995] has indicated that the earlier result was an artifact of the calculation and that the sensitivities are essentially identical and nearly the same as that reported by *Wang et al.* [1992], 1.25 K/Wm^{-2}. Thus, both studies can be taken as indicating that the global and annual mean temperature respond to the algebraic sum of longwave greenhouse forcing and shortwave aerosol forcing. The two studies also concur in the finding of substantial differences between regional and hemispheric patterns of forcing and response, and can be taken as indicating the need to explicitly represent the spatial and seasonal distribution of aerosol forcing when examining climate response at a level more detailed than the global and annual mean.

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