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THE WHITEHOUSE EFFECT: SHORTWAVE RADIATIVE FORCING OF CLIMATE BY ANTHROPOGENIC AEROSOLS

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ABSTRACT

Loadings of tropospheric aerosols have increased substantially over the past 150 years as a consequence of industrial activities. These aerosols enhance reflection of solar radiation by the earth-atmosphere system both directly, by scattering light and, indirectly, by increasing the reflectivity of clouds. The magnitude of the resultant decrease in absorption of solar radiation is estimated to be comparable on global average to the enhancement in infrared forcing at the tropopause due to increases in concentrations of CO_2 and other greenhouse gases over the same time period. Estimates of the aerosol shortwave forcing are quite uncertain, by more than a factor of two about the current best estimates. At the high end of the uncertainty range the aerosol forcing is comparable to the anthropogenic greenhouse forcing, and substantially greater in industrialized regions. Even at the low end of the range the aerosol forcing cannot be neglected in considerations of influences on climate over the industrial period.

DISCLAIMER

INTRODUCTION

Increases in atmospheric concentrations of carbon dioxide and other infrared active gases over the industrial period are thought to have increased the average flux of longwave (thermal infrared) radiation between the surface of the earth and the lower atmosphere, leading to an increase in global mean temperature. Over the same period it is thought that concentrations of aerosol particles in the troposphere have similarly increased as a consequence of industrial emissions and that these increased concentrations of particles have increased the earth's reflectivity of shortwave (solar) radiation incident on the planet both directly, by scattering radiation, and indirectly, by increasing the reflectivity of clouds. The term "whitehouse effect" is introduced to refer to this increased scattering of shortwave radiation by analogy to the term "greenhouse effect," which refers to the enhanced trapping of longwave radiation resulting from increased concentrations of infrared active gases. Each of these phenomena is referred to as a "forcing" of the earth's climate, that is a secular change imposed on the system; such a forcing is to be distinguished from a "response" of the system, such as a change in global mean temperature or other index of global climate. The forcing due to the direct and indirect effects induced by anthropogenic aerosols has been estimated to be comparable in global-average magnitude to that due to increased concentrations of greenhouse gases, but it is of opposite direction, that is exerting a cooling influence. The shortwave radiative influence of anthropogenic aerosols may thus be considered to be offsetting some, perhaps a great fraction, of the longwave radiative influence of anthropogenic greenhouse gases.

In order for the magnitude of the whitehouse effect to be accurately evaluated, the processes that control this magnitude must be well characterized. Examination of the uncertainties associated with description of these processes allows estimation of the uncertainty associated with estimates of the magnitude of the forcing. These uncertainties result in an overall uncertainty range associated with estimates of the global average direct aerosol forcing of about a factor of four--that is, the estimates are consistent with a forcing that may be half as great, or twice as great, as present "best" estimates. At the high end of this range the whitehouse forcing is comparable to the anthropogenic greenhouse forcing on global average, and substantially

greater in regions proximate to industrial emissions of aerosols and aerosol precursors. Even at the low end of the range the whitehouse forcing is sufficiently great that it cannot be neglected in considerations of net anthropogenic influences on climate over the industrial period. Examination of uncertainties associated with the controlling processes allows identification of processes which must be better described in order to improve estimates of the climate forcing.

Aerosol species that are thought to contribute substantially to this forcing include sulfates, arising from emissions of SO_2 associated mainly with fossil fuel combustion, and organic aerosols arising from biomass combustion. Nitrates and organics associated with industrial emissions may also be important. These aerosol species have received much attention from the air pollution research community because of their possible contribution to acid deposition, health impairment, and visibility reduction, and the ability to describe the climate forcing relies heavily on the results of that research.

DIRECT FORCING

An initial approach to estimating the magnitude of the direct forcing is given by a box-model description of the phenomenon. Although such a model is incapable of describing the geographical distribution of the forcing and of accounting for correlations among controlling variables, it is a useful first approximation, especially as the forcing is linear in aerosol loading for an optically thin aerosol in which single scattering dominates. This model yields for the areal mean shortwave forcing $\overline{\Delta F_R}$ resulting from an increase in sulfate aerosol concentration:

$$\overline{\Delta F_R} = -\frac{1}{2} F_T (1 - A_c) T^2 (1 - R_s)^2 \bar{\beta} \alpha_{SO_4^{2-}} f(\mathrm{RH}) Q_{SO_2} Y_{SO_4^{2-}} \tau_{SO_4^{2-}} / A. \qquad (1)$$

Here F_T is the solar radiative flux at the earth's orbit,

A_c is the fractional cloud cover in the area of concern,

T is the fraction of incident light transmitted through the atmosphere above the aerosol layer,

R_s is the albedo of the underlying surface,

$\bar{\beta}$ is the fraction of the radiation scattered upward by the aerosol,

$\alpha_{SO_4^{2-}}$ is the light-scattering cross section of sulfate at a reference low relative humidity (30%),

f(RH) is the relative increase in scattering cross-section with increasing humidity,

Q_{SO_2} is the source strength of anthropogenic SO_2,

$Y_{SO_4^{2-}}$ is the fractional yield of emitted SO_2 that reacts to produce sulfate aerosol,

$\tau_{SO_4^{2-}}$ is the mean residence time of sulfate aerosol in the atmosphere, and

A is the area of the geographical region to which the material is confined--the entire earth, or some smaller region.

Equation (1) has the advantage of explicitly delineating the dependence of $\overline{\Delta F_R}$ on all of the variables on which it depends, thereby allowing identification of key uncertainties. The negative sign denotes that the forcing represents a cooling tendency. The factor $(1 - A_c)$ is introduced because the albedo enhancement is applicable only for cloud free regions.

Table 1 presents estimates of values for the several parameters in equation (1). The global mean direct radiative forcing due to sulfate aerosol evaluated by this equation, about -1 W m^{-2}, may be compared to the estimate of the longwave forcing due to enhanced concentrations of greenhouse gases over the industrial period, about 2.5 W m^{-2}.

The box-model approach is even more valuable in identifying and quantifying sources of uncertainty in estimates of the magnitude of the forcing. Key sources of uncertainty are parameters describing the atmospheric chemistry of the aerosol species--source strength and mean atmospheric residence time--both of which contribute linearly to the atmospheric burden and to the resultant forcing. In the case of sulfate aerosols the fraction of emitted SO_2 that is converted in the atmosphere to sulfate aerosol is considered uncertain to a factor of about 1.5. Likewise the mean residence time of this aerosol is also considered uncertain to a factor of about 1.5. The remaining major source of uncertainty is associated with the microphysical and optical properties of the aerosol--the light scattering efficiency (cross-section per unit mass), which depends on the size distribution of the aerosol, and in turn on the state of dispersion of the material, the degree of neutralization by ammonia, and, through accretion of water, the relative humidity. The aerosol size distribution also influences the angular distribution of light scattering, thereby influencing the fraction of scattered radiation that is scattered into the upward

hemisphere and that consequently leaves the earth-atmosphere system, resulting in the cooling influence that is the whitehouse forcing. Together these uncertainties in microphysical properties are thought to contribute a further factor of about 1.7 uncertainty to estimates of the whitehouse forcing Propagation of the several uncertainties under assumption that they are uncorrelated leads to an estimated uncertainty in the forcing of a factor of about 2.4. Similar uncertainties govern estimates of the climate forcing due to aerosols from biomass combustion and other sources.

INDIRECT FORCING

The indirect forcing by anthropogenic aerosols is due to enhanced dispersion of cloud liquid water under conditions of enhanced loading of aerosols. For a given liquid water content, the cloud-top reflectivity is increased as the liquid water is dispersed in a greater number of (smaller) droplets. Quantitative description of the phenomenon requires consideration of the influence of aerosol particles on cloud droplet concentrations and consideration of the influence of the enhanced dispersion on the cloud-top reflectivity in addition to knowledge of increases in aerosol loading.

Clouds form when air is cooled to a temperature below its thermodynamic dew point, leading to condensation of water on existing aerosol particles. Other things being equal (such as the cooling rate, which is governed largely by updraft velocity), the greater the number of aerosol particles that are present to serve as the particles on which cloud droplets form (cloud condensation nuclei), the greater the number of cloud droplets that are formed. In contrast, the liquid water content, which, in the absence of precipitation, is governed mainly by the large-scale thermodynamics, is relatively uninfluenced by the aerosol loading. The magnitude of the enhancement in cloud droplet concentration due to an increase in aerosol loading is quite uncertain. Several studies have indicated that the droplet concentration increases nearly linearly with aerosol particle loading, at least at fairly low particle concentrations characteristic of nonurban locations. Thus this phenomenon depends sensitively on the state of dispersion of the aerosol, not simply on the mass loading.

In contrast to the direct forcing, the indirect forcing is inherently nonlinear, because clouds are not optically thin. An approximate treatment of multiple scattering in clouds indicates a logarithmic dependence of cloud-top reflectivity on cloud droplet number concentration for clouds of intermediate thickness (cloud-top reflectivity roughly between 0.3 and 0.7) characteristic of prevalent marine stratus clouds. Estimates that have been given of the global-average indirect forcing due to anthropogenic aerosols are based on observed frequencies of such clouds and on estimates of anthropogenic enhancement of the mass loading of sulfate aerosol in remote regions derived from measurements. These estimates suggest that the magnitude of the indirect forcing by anthropogenic sulfate aerosol is comparable to that of the direct forcing. In view of their fairly primitive basis, these estimates must be regarded as quite uncertain, and indeed it is difficult even to give an estimate of the uncertainty.

Enhanced dispersion of cloudwater is thought also to inhibit development of precipitation. This could result in longer cloud lifetimes, leading to a further cooling influence on climate, since for low clouds, which are most susceptible to influences of anthropogenic aerosols, the shortwave influence exceeds the longwave influence. The situation is further complicated, however, because inhibition of precipitation may result in water that would otherwise have been removed from the atmosphere in precipitation remaining in the atmosphere upon cloud evaporation, leading to a warming influence through the greenhouse effect of this water vapor.

DISCUSSION

In view of correlations among the several variables governing the aerosol forcing, for example mass loading, particle size, cloud cover, and relative humidity, it seems that accurate estimates of the forcing on global as well as regional scales will require application of models that describe the transport, transformation, and removal processes that control the loadings of these aerosols in the atmosphere. Confident application of such models in turn requires evaluation of their accuracy by comparison of modeled and measured aerosol loadings and other properties such as size distribution and state of neutralization. Because of the high degree of spatial and temporal variability of this loading, it appears that sensitive evaluations of chemical models will be obtainable only when comparing observations to quantities calculated with

models driven by meteorological wind and precipitation fields that are derived from observations. Investigations with such models are now being undertaken for this purpose. Results from these models can be compared to *in situ* measurements and to measures of aerosol optical depth derived from satellite instruments. Once suitable evaluated chemical models are at hand, they can be used with confidence in examining the climatic influence of these aerosols.

Despite the importance of these aerosol influences on climate change inferred from estimates of the magnitude of the forcing, there is as yet relatively little observational information that reliably and confidently be used to support these estimates. Locally and in a few instances the direct radiative influence of atmospheric aerosols has been demonstrated and its magnitude related to the aerosol loading. There is also indication from satellite measurements of enhanced aerosol loading over the western North Atlantic and western North Pacific that is attributed to aerosols exported from industrial regions. (There is also rather convincing evidence of the radiative influence of stratospheric aerosols arising from the 1991 eruption of the volcano Pinatubo in the Philippines, which confirms, in a broad way, the phenomenon of shortwave radiative forcing by aerosols.) However much more work is required to substantially narrow the uncertainty in forcing due to anthropogenic aerosols. Unfortunately the existing class of satellite radiometers is only marginally sensitive to contributions to radiance due to these aerosols. Ultimately a variety of closure experiments that test models of components of the process is required to build confidence in model evaluations of the aerosol forcing.

With respect to the indirect forcing, recent interhemispheric comparisons of cloud drop sizes in low clouds inferred from satellite measurements have indicated a systematically smaller drop radius in the northern hemisphere than the southern, in both continental and marine clouds, consistent with a possible influence of anthropogenic aerosols; anthropogenic emissions of aerosols and aerosol precursors such as SO_2 are much greater in the northern hemisphere than the southern. Again more work is needed to substantiate quantitative estimates of the forcing.

A potentially attractive alternative approach to looking for evidence of aerosol forcing of climate is through examination for possible climate changes that may be attributable to this forcing. Such influences might be manifested through interhemispheric differences or regional

patterns in temperature anomaly trend, or in seasonal or diurnal patterns in these trends. Indeed several such patterns have been identified as plausibly attributable to aerosol forcing. Unfortunately, at the present stage of understanding of climate response to forcing, taking into account processes such as heat transport through atmospheric and oceanic circulation patterns, it does not appear possible to unequivocally ascribe such patterns to aerosol forcing. A possible exception may be the response to large, short-term perturbations, i.e., volcanoes, such as Pinatubo, for which the time signature of the forcing and response may permit such unequivocal attribution. Recent climate modeling studies indicate that the apparent global cooling in the two years following the Pinatubo eruption is consistent with a response to this aerosol forcing and thereby lend credibility to the theoretical arguments indicating substantial climate forcing by anthropogenic tropospheric aerosols.

One final point that should be noted regarding the aerosol forcing in the context of the broader climate change issue has to do with the vastly different atmospheric residence times of the aerosol particles responsible for the whitehouse effect (about a week) compared to the infrared gases responsible for the greenhouse effect (decades to centuries). This difference in lifetimes means that to whatever extent shortwave radiative forcing by anthropogenic aerosols is offsetting longwave forcing by anthropogenic greenhouse gases, it is aerosols from a week's worth of emissions that are offsetting forcing by greenhouse gases resulting from decades' worth of emissions. Recognition of this leads to the immediate realization in the inherent unworkability of any scheme to take deliberate advantage of the aerosol forcing as a mechanism for offsetting the forcing due to increased concentrations of greenhouse gases.

TABLE 1. Evaluation of global mean direct radiative forcing due to anthropogenic sulfate aerosol.

Quantity	Value	Units	Uncertainty Factor
F_T	1370	W m^{-2}	—
$1\text{-}A_C$	0.4	—	1.1
T	0.76	—	1.15
$1\text{-}R_S$	0.85	—	1.1
$\bar{\beta}$	0.29	—	1.3
$\alpha_{SO_4^{2-}}$	5	m^2 (g SO_4^{2-})$^{-1}$	1.5
f(RH)	1.7	—	1.2
Q_{SO_2}	80	Tg S yr^{-1}	1.15
$Y_{SO_4^{2-}}$	0.4	—	1.5
$\tau_{SO_4^{2-}}$	0.02	yr	1.5
A	5×10^{14}	m^2	—
$\overline{\Delta F_R}$	-1.1	W m^{-2}	2.4