Role of Aerosols in Radiative Forcing of Climate Change: Global Mean and Uncertainties

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Anthropogenically induced climate change is of great current interest because of increases in atmospheric loading of infrared active (greenhouse) gases over the past 150 years and the inferred resultant increase in infrared radiation flux in the troposphere. However the climate change ascribed to such increases, not to mention predictions of future climate change in response to prospective changes in the earth's radiation budget, is based virtually entirely on climate model simulations of how the earth's climate would respond to changes in radiation rather than on empirically established relationships between changes in the earth's radiation budget and climate change. There is thus an urgent need to evaluate the performance of climate models to ascertain the accuracy with which they represent the changes in temperature and other indicia of climate that have been observed over the industrial period. Such an evaluation, however, requires an accurate assessment of the totality of changes in the earth's radiation budget in both the longwave (thermal infrared) and shortwave (solar) spectral regions, not just of changes in the longwave due to increased concentrations of long-lived greenhouse gases.

Changes in downwelling thermal infrared radiation arise from changes in tropospheric and stratospheric ozone in addition to the long-lived gases, mainly CO_2, methane, nitrous oxide and chlorofluorocarbons. Changes in shortwave radiation absorbed by the earth-atmosphere system are thought to arise mainly from changes in the loading and properties of tropospheric aerosols. These aerosols scatter shortwave radiation, decreasing the fraction of incident solar radiation that is absorbed, thereby exerting a cooling influence on climate (referred to as the direct effect). However absorbing aerosol particles decrease reflection of shortwave radiation, especially over bright surfaces such as snow or clouds, exerting a warming influence. Aerosol particles also serve as nuclei for cloud droplets (cloud condensation nuclei, CCN); an increase in CCN concentration leads to an increase in cloud droplet concentration, enhancing multiple scattering within clouds and leading in turn to an increase in cloud albedo (indirect aerosol effect). Each of these phenomena has been estimated to have exerted an influence on the earth's radiation budget that is appreciable in the context of the longwave perturbation due to increased concentrations of the long-lived greenhouse gases over the industrial period (Charlson *et al*., 1992; IPCC, 1996). Additionally appreciable radiative influences may arise from an increase in the solar constant.

Climate modeling studies have indicated, at least to first approximation, that equal changes in global-average net radiation at the tropopause from the several phenomena result in equivalent global-average temperature response (Wang *et. al*., 1991; Cox *et al*., 1995), although there is no *a priori* reason that this should be the case. This finding makes it useful to quantify and compare the radiative "forcing" of climate change due to the several phenomena and to assess the total forcing as the sum of the several forcings. Here we use the term "forcing" as it has been employed by the Intergovernmental Panel on Climate Change (IPCC, 1996), namely "a *change* in the energy available to the global earth-atmosphere system." A key assumption underlying the concept of radiative forcing is that the forcing is the change in radiation budget due only to the imposed radiative change, without any accommodation by the climate system to the imposed change. Within this assumption the task is to quantify each of the several forcings and to estimate their uncertainties.

The IPCC has summarized the forcings over the industrial period due to the several identified mechanisms together with the estimated uncertainties associated with each of these quantities,

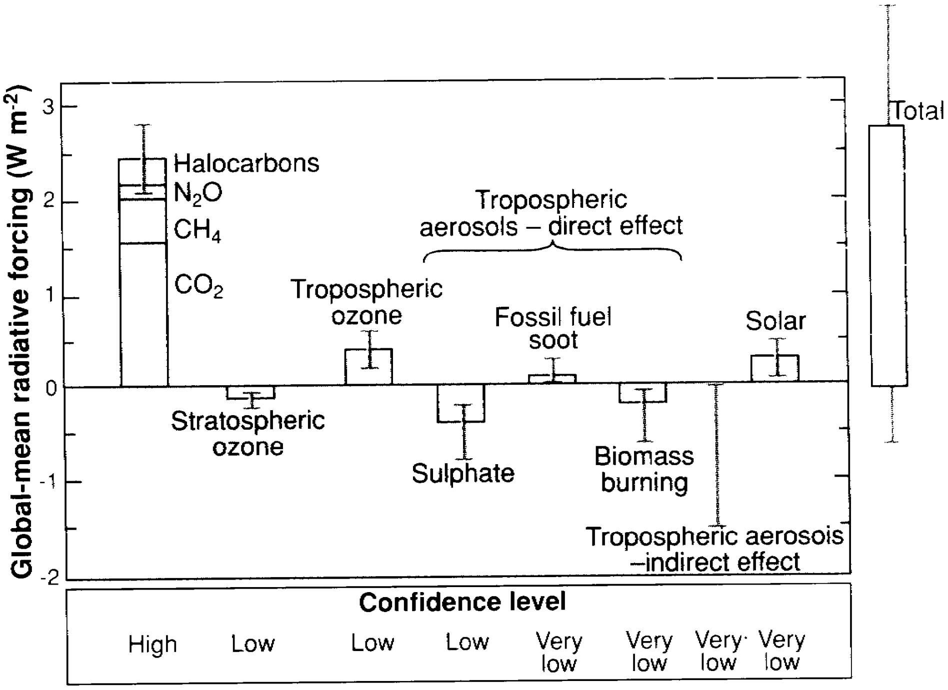

Figure 1. IPCC (1996) estimates of the globally and annually averaged anthropogenic radiative forcing of climate due to changes in concentrations of greenhouse gases and aerosols from preindustrial times to the present and to natural changes in solar output from 1850 to the present. The bars denote a mid-range estimate for each forcing (an upward bar denotes a positive forcing or warming influence; a downward bar, a cooling influence); the I-beams show an estimate of the uncertainty range. Bar at right shows the total forcing as the algebraic sum of the individual component forcings and the uncertainty range for the total forcing as the sums of the upper and lower ends of the individual uncertainty ranges. The lower panel indicates the IPCC's subjective confidence that the actual forcing lies within the indicated uncertainty range. From Schwartz and Andreae (1996).

Figure 1. Note that the IPCC gave no estimate for the aerosol indirect forcing, only an uncertainty range Not shown is forcing due to dust aerosols, which has been estimated as 0.1 W m^{-2} (Tegen *et al.*, 1996). The bar denoted "Total", which Andreae and I added to the IPCC figure, is roughly the same as that for the long-lived greenhouse gases alone. The picture changes, however, when the very large uncertainties in current estimates of aerosol forcing are considered. If the magnitude of aerosol forcing is at the low end of the uncertainty range, aerosols are negating only a small fraction of the greenhouse forcing. However, if the aerosol forcing is at the high end of the uncertainty range, aerosols could be negating virtually all of the present greenhouse forcing. This has great implications on empirical inferences of climate model accuracy and requires that the uncertainty in aerosol forcing be greatly reduced.

An expression (Charlson *et al.*, 1992; Haywood and Shine, 1995) for global average aerosol direct forcing, that takes into account both scattering and absorption, is:

$$\Delta F = -\frac{1}{2} F_0 T^2 (1 - A_c) \tau \bar{\beta} \omega \left\{ (1 - R)^2 - 2R(1 - \omega) / \bar{\beta} \omega \right\}. \tag{1}$$

Here ΔF is the change in outgoing shortwave flux at the top of the atmosphere, F_0 is the incoming solar flux at the top of the atmosphere, T is the transmittance of the atmosphere above the aerosol layer, A_c is the fractional cloudiness, τ is mean aerosol optical depth, $\bar{\beta}$ is the mean upscatter fraction (fraction of radiation scattered into the upward hemisphere), ω is the single scattering albedo, and R is the surface reflectance.

The minus sign denotes the convention that a negative forcing is a cooling influence. The factor $\frac{1}{2}$ arises from the fact that only half the planet is illuminated at any time. The factor $(1-R)^2$ accounts for multiple reflection between the aerosol layer and the surface. The factor $(1-A_c)$ denotes the absence of direct forcing in the presence of clouds; actually the forcing due to aerosol absorption above bright clouds must also be evaluated. It must be recognized that the aerosol direct forcing is not uniform spatially but exhibits substantial spatial (and temporal) variability because of high spatial and temporal variability in aerosol loading, composition, and microphysical and optical properties. A weakness of Eq (1) is that it does not take into account spatial and temporal correlations among the several variables, which can be addressed only by a three-dimensional model. Nonetheless Eq (1) serves to indicate the aerosol properties and geophysical quantities that determine the direct forcing and to illustrate the task that needs to be carried out in order to evaluate it. Equation (1) also serves as a basis for estimating uncertainties associated with forcing estimates (Penner *et al.*, 1994). Note finally that the magnitude of the forcing decreases with decreasing single scattering albedo and ultimately changes sign, that is, the aerosol exerts a warming influence, for low single scattering albedo together with high surface reflectance $\omega < 2R / [\beta(1-R)^2 + 2R]$.

A key quantity governing aerosol forcing is aerosol optical depth. How is this to be determined? In principle it could be determined by measurement. Satellites would seem ideally suited to this task. Imagine a satellite-borne instrument, or a sufficiently dense network of them, that could map out the aerosol optical depth (and its wavelength dependence), over land and sea, over snow and clouds, over the course of the day (during sunlit hours). However, no instrument is yet capable of this. Radiance instruments suffer the problem of subtraction of sea-leaving or surface-leaving radiance. Polarization instruments may help, as may instruments that look at the same location from multiple viewing angles. Still there remain issues associated with uncertainties in aerosol phase function.

Given the lack of suitable satellite-borne instruments, we might contemplate a network of land- (and sea-) based sunphotometers. The network would have to be fairly dense. Model calculations suggest that the spatial autocorrelation distance of aerosol optical depth is 1000 km or less (Benkovitz *et al*; 1994). Such a spacing could be achieved with a network of some 500 instruments, a density which is perhaps not out of the question. Such a network could obtain the requisite diurnal coverage and would also be capable of tracking response of aerosol optical depth to relative humidity, a key influence on size of hygroscopic particles and resulting aerosol extinction coefficient. Such a network would be incapable of measurements of aerosol optical depth above clouds.

How accurately must the aerosol optical depth be determined? If we desire an uncertainty in forcing of 0.3 W m^{-2}, roughly 10% of the global mean longwave forcing of the long-lived greenhouse gases, then for reasonable values of the several other quantities in Eq (1), the requisite accuracy of aerosol optical depth is about 0.01, a challenging requirement, but perhaps not out of the question.

In addition to optical depth, required aerosol properties are upscatter fraction and single scattering albedo. In the terminology of Ogren (1995) these are "intensive" aerosol properties that vary much less than the aerosol loading itself, an "extensive" property. Consequently it may be possible to develop a climatology of these aerosol properties that is sufficiently accurate for the purpose of radiative forcing calculations.

Let us suppose that through a measurement program we have characterized these aerosol properties including the spatial and temporal variation of all of these quantities, together with that of other pertinent variables sufficiently well to permit evaluation of aerosol direct forcing. At best we have enabled this evaluation only for the present time. We have not identified the responsible substances: sulfates and nitrates from fossil fuel combustion, anthropogenic organics from photochemical smog, organics from biomass burning, biogenic organics, mineral dust, sea salt. For this measurements of chemical composition are necessary, but, I argue, not sufficient. *In-situ* measurements would be necessary as well to determine the cloud nucleating properties of these aerosols, specifically the dependence of cloud droplet number concentration on supersaturation required to evaluate the indirect forcing.

Even if we were to succeed in all of the above, we would still fail in our major objective; that is, we would not have not determined the change in aerosol loading and properties over the industrial period that is necessary to represent aerosol forcing in climate models over this period that is necessary in turn to evaluate climate model performance. Nor would we have developed the ability to examine the dependence of forcing to prospective changes in emissions of aerosols and their precursors.

For this reason, it is essential, in conjunction with a measurement program such as this, to carry out a commensurate effort in modeling aerosol loading and properties. Such models would need to represent the key components of the aerosol life cycle: emissions of aerosols and precursors, chemical transformations responsible for gas-to-particle conversion, new particle formation, aerosol microphysical evolution, three-dimensional transport, and wet and dry removal processes of aerosols and precursors. The performance of these models also would need to be evaluated, by comparison with measurements, so the models certainly do not supplant the measurements. However once the models have been evaluated over a wide range of conditions, they can be used with known confidence to evaluate aerosol loading, and in turn forcing, at present, and for past times and for future emissions scenarios. We should further expect these models to yield the geographical distribution of aerosol loading and properties and correlations with cloudiness and other pertinent variables.

All of the above, both the measurement program and the modeling effort, places high demands on the aerosol research community. However the stakes are high and we must rise to the challenge.

References

Benkovitz C. M., Berkowitz C. M., Easter R. C., Nemesure S., Wagener R. and Schwartz S. E. Sulfate over the North Atlantic and adjacent continental regions: Evaluation for October and November 1986 using a three-dimensional model driven by observation-derived meteorology. *J. Geophys. Res.* **99** (1994) 20725-20756.

Charlson R. J., Schwartz S. E., Hales J. M., Cess R. D., Coakley J. A., Jr., Hansen J. E. and Hofmann D. J. Climate forcing by anthropogenic aerosols. *Science* **255** (1992) 423-430.

Cox S. J., Wang W.-C., and Schwartz S. E., Climate response to radiative forcings by aerosols and greenhouse gases. *Geophys. Res. Lett*. **22** (1995) 2509-2512.

Haywood, J. M., and K. P. Shine, The effect of anthropogenic sulfate and soot aerosol on the clear sky planetary radiation budget, *Geophys. Res. Lett*. **22** (1995) 603-606.

IPCC (Intergovernmental Panel on Climate Change). Climate Change 1995 - The Science of Climate Change. Contribution of WGI to the Second Assessment Report of the Intergovernmental Panel on Climate Change. J T Houghton, L G Meira Filho, B A Callander, N Harris, A Kattenberg and K Maskell (eds). Cambridge University Press, Cambridge U.K., 1996, 572 pp.

Ogren J. A. A Systematic Approach to *In Situ* Observations of Aerosol Properties. In Charlson R. J. and Heintzenberg J. (eds) *Aerosol Forcing of Climate*. Wiley, New York, 1995, pp. 215-226.

Penner J. E., Charlson R. J., Hales J. M., Laulainen N., Leifer R., Novakov T., Ogren J., Radke L. F., Schwartz S. E. and Travis L. Quantifying and minimizing uncertainty of climate forcing by anthropogenic aerosols. *Bull. Amer. Meteorol. Soc.* **75** (1994) 375-400.

Schwartz S. E. and Andreae M O. Uncertainty in climate change caused by anthropogenic aerosols. *Science* **272** (1996) 1121-1122.

Tegen, I., A. A. Lacis and I. Fung, The influence on climate forcing of mineral aerosols from disturbed soils. *Nature* **380** (1996) 419-422.

Wang W.-C., Dudek M. P., Liang X.-Z., and Kiehl J. T. Inadequacy of effective CO_2 as a proxy in simulating the greenhouse effect of other radiatively active gases. *Nature* **350** (1991) 573-577.