CONSTRAINING THE AEROSOL RADIATIVE FORCING AND CLIMATE SENSITIVITY

An Editorial Comment

In their editorial essay, Rodhe et al. (2000) imply that aerosol radiative forcing should be computed only from a bottom-up calculation using 3-D simulation models based on as detailed and complete an understanding of the physics and chemistry of the aerosol radiative forcing problem as possible. On the other hand, they argue against using observed temperature changes to estimate the aerosol radiative forcing, because the climate sensitivity (the ratio of equilibrium temperature change to the radiative forcing) is also unknown. To use the record of global mean temperature to deduce aerosol radiative forcings requires some assumption concerning climate sensitivity. If the resulting fit between modelled and observed temperature variation is used to confirm the climate sensitivity then, as Rodhe et al. (2000) point out, the entire argument involves circular reasoning. However, this simple-minded approach does not characterize what has been done so far (nor do Rodhe et al. imply that it has). If the number of independent equations or pieces of information matches the number of unknowns, then all the unknowns can (in principle) be determined without circular reasoning. Thus, given information on the change in global mean temperature *and* the interhemispheric difference in the temperature change, one might be able to deduce both the global mean temperature sensitivity and the global mean aerosol radiative forcing (as attempted by Wigley, 1989). I shall refer to this as the top-down approach.

In the remainder of my discussion of the comments by Rodhe et al. (2000), I would like to present the following arguments: (i) that there are still serious (and perhaps unresolvable) problems with both the bottom-up and top-down approaches to estimating aerosol radiative forcing, and (ii) that the most promising avenue for constraining the aerosol radiative forcing might be through a combination of bottom-up and top-down approaches. A similar evolution has occurred in economic assessments of the costs of reducing greenhouse gas emissions, which initially fell neatly into bottom-up or top-down assessments and gave diametrically opposed results (Hourcade et al., 1996).

First, it is clear that we are a very long way from being able to accurately calculate the aerosol radiative forcing based on first principles. This requires at least three distinct steps: (i) computing the 3-D distribution of aerosol loading in the atmosphere; (ii) computing the optical properties of the aerosol particles in the atmosphere; and (iii) computing the resulting direct and indirect radiative forcings. The direct radiative forcing pertains to the effect of aerosol particles in absorbing

Climatic Change **44:** 413–418, 2000.

or scattering solar radiation, while the indirect effect pertains to the likely effect of aerosols in altering the optical properties and/or lifespan of clouds. There are major uncertainties concerning emissions of some aerosol types, concerning the atmospheric loading for a given distribution of emissions, and concerning the optical properties of the aerosols. The uncertainties concerning indirect effects are even more daunting and difficult. The accompanying table is one of several tables from the recently published book, *Global Warming: The Hard Science* (Harvey, 1999), that illustrates these uncertainties with regard to pure sulphate aerosols. The uncertainty in the direct radiative forcing is comparatively small (a factor of 2), but the estimated indirect forcing spans an order of magnitude. Satellite observations can be used to estimate the total radiative forcing by aerosols for clear skies over the oceans (Haywood et al., 1999), but cannot distinguish natural from anthropogenic forcing and cannot be used to assess the direct or indirect forcing in cloudy regions or over land. In light of these uncertainties and limitations, it is hard to believe that direct observations of temperature changes cannot provide at least *some* constraint on the aerosol radiative forcing.

One difficulty in using the observed difference in NH and SH warming (along with the global mean warming) to estimate both the aerosol forcing and the climate sensitivity, is that there is a third unknown: the ratio of SH:NH aerosol radiative forcing. Wigley (1989) had assumed this ratio to be zero (i.e., no aerosol radiative forcing in the SH). According to the results shown in the accompanying table, published since Wigley's (1989) work, this ratio ranges from as low as 0.1 to as high as 0.9. The higher this ratio, the larger the aerosol forcing that is permitted without overly suppressing the NH warming relative to the SH warming, and so the larger the permitted mean aerosol forcing and the larger the permitted climate sensitivity while still simulating the observed overall global mean warming during the past century. However, if the bottom-up approach can be used to constrain the *ratio* of SH:NH forcing while leaving the absolute forcing uncertain, then a combination of the bottom-up and top-down approaches could very well yield useful information that could not be obtained from either approach alone, and without involving circular reasoning. Useful information could also be obtained if, based on the bottom-up approach, a *correlation* can be developed between the computed but uncertain radiative forcing and the equally uncertain SH:NH forcing ratio (in effect, adding a third equation). The basis for expecting some correlation is the following: Those models that remove aerosols relatively quickly from the atmosphere will simulate a lower aerosol loading (for a given emission) and thus will tend to simulate a smaller radiative forcing. At the same time, rapid removal of aerosols allows less time for geographical dispersion of the aerosols. Since most of the emissions are in the NH, this would result in a smaller SH:NH forcing ratio. At present, some of the difference in the computed SH:NH forcing ratio is due to differences in the assumed emissions and in cloud cover. If some of these other causes of different SH:NH forcing ratios can be greatly reduced, it might be possible to develop relationships that can be used as part of a top-down approach.

Apart from data uncertainties, there are a number of other problems in using hemispheric and global mean temperature changes to estimate climate sensitivity and the total aerosol radiative forcing. First, as discussed in *Global Warming: The Hard Science* (Chapter 11.2), it is possible that the effective climate sensitivity during the transient is different (and much smaller) than the equilibrium sensitivity (the effective sensitivity is the sensitivity that would result if the various feedback strengths that occurred during the transient were to persist until equilibrium is achieved). This is because the net cloud feedback depends critically on the geographical *patterns* of climatic change, and these are different for transient and equilibrium climatic change. Murphy and Mitchell (1995) provide an example of such behavior in a coupled atmosphere-ocean general circulation model. What this means is that the observed temperature variation can, at most, tell us the effective climate sensitivity during the transient, not the equilibrium climate sensitivity. Second, and related to the first point, is that the equilibrium climate sensitivity itself might be quite different in the NH and SH, due to differences in the cloud feedback (as well as due to differences in the land-sea fraction). This introduces yet another parameter in the simulation of the interhemispheric difference in climate warming (even if not explicitly included). Third, the delay in warming due to mixing of heat into the deep ocean could be quite different in the two hemispheres, thereby introducing interhemispheric differences in the warming that are unrelated to differences in the aerosol forcing or in the radiative feedbacks. Finally, and as pointed out by Rodhe et al. (2000), in order to quantify the aerosol forcing from temperature observations, all other important forcings must have been accurately estimated. Apart from aerosols, the other major unknown forcing is that due to the buildup of tropospheric ozone. This forcing is estimated to be about 0.28–0.70 W m^{-2} in the global mean, with a SH:NH ratio of 0.5 to 0.73 (Harvey, 1999, Chapter 7.3). Since the ozone forcing is opposite in sign to the aerosol forcing, a large, hemispherically asymmetric ozone forcing allows a larger aerosol forcing.

There are other ways in which temperature observations can be used to constrain the aerosol forcing. For example, a very large aerosol forcing tends to cause a sharp decrease in global mean temperature between 1940–1960, when aerosol emissions rose rapidly while greenhouse gas concentrations continued their gradual climb. Choosing a small climate sensitivity to avoid this temperature decline then results in too small a warming from 1860–present, particularly since the net (GHG + aerosol) anthropogenic forcing is also small in this case. Differences in the warming between night and day provide yet another piece of information, and have been used by Hansen et al. (1995) to estimate that the global mean aerosol cooling is about half the greenhouse gas heating.

In short, there is not enough information to meaningfully constrain the aerosol forcing using either a bottom-up or top down approach. Both approaches are subject to significant and difficult uncertainties that might take a long time to resolve. However, there are reasons to believe that a combination of the bottom-up and top-

TABLE I

Summary of mean global, NH, and SH present-day radiative forcings (W m^{-2}) due to pure anthropogenic sulphate aerosols as computed by different researchers. Also given are the corresponding anthropogenic emissions. AGCM = atmospheric general circulation model, CCN = cloud condensation nuclei, LWC = liquid water content, LMD = Laboratoire de Météorologie Dynamique, ECHAM pertains to a cross between the European Centre for Medium Range Forecasting and the University of Hamburg modelling groups

Reference	Global	NH	SH	SH:NH	Anthropogenic emission (TgS/yr)
A. Direct radiative forcing					
Boucher and Anderson (1995)	–0.28	–0.47	–0.11	0.23	72.3
Myhre et al. (1998)	–0.32	–0.55	–0.08	0.15	67.0
Fiechter et al. (1997)	–0.35	–0.55	–0.13	0.24	72.5
van Dorland et al. (1997)	–0.36	–0.59	–0.13	0.22	67.4
Haywood et al. (1997)	–0.38	–0.60	–0.15	0.25	72.3
Chuang et al. (1997)	–0.43	–0.71	–0.15	0.21	77.9
Kiehl et al. (1999)	–0.56	–0.81	–0.30	0.37	67.0
Charlson et al. (1991)	–0.59	–1.07	–0.11	0.10	72.3
Schult et al. (1997)[a]	–0.66	–0.95	–0.37	0.39	72.5
B. Indirect radiative forcing					
Using the Hadley Centre AGCM but different S-CCN relationships[b]					
Hegg (1994)	–0.5	–0.7	–0.3	0.4	
Boucher and Lohmann (1995)	–0.6	–0.8	–0.4	0.5	72.3
Jones et al. (1994)	–1.5	–2.0	–1.8	0.9	
Using the Boucher and Lohmann (1995) S-CCN relationship but different AGCMs[b]					
Hadley Centre AGCM	–0.6	–0.8	–0.4	0.5	
LMD AGCM	–1.1	–1.7	–0.4	0.2	72.3
ECHAM AGCM	–1.1	–1.6	–0.6	0.4	
With alternative assumptions concerning cloud microphysics[d]					
Standard Case[e]	–1.0	–1.3	–0.7	0.5	
Allow change in LWC	–1.4	–2.0	–0.8	0.4	
+ Alternative parameterization of cloud fraction	–4.8	–6.5	–3.1	0.5	69.0
+ Alternative parameterization of conversion from cloud droplets to rainfall	–2.2	–2.9	–1.5	0.5	
Other estimates					
Kiehl et al. (1999)	–0.40	–0.65	–0.16	0.25	67.0
Fiechter et al. (1997)	–0.86	–1.12	–0.60	0.53	69.0
Chaung et al. (1997)[f]	–0.62	–0.91	–0.34	0.37	77.9
	–1.24	–1.74	–0.75	0.43	77.9

[a] Results are for a cloud-free atmosphere. Multiply by (1.0 – the cloud fraction (about 0.6)) for comparison with the other results shown here.
[b] Results given below were computed by Jones and Slingo (1996) using the S-CCN relationship given in the reference listed in the first column.
[c] Forcings were computed by Boucher and Lohmann (1995).
[d] As computed by Lohmann and Feichter (1997) using the ECHAM AGCM.
[e] S aerosols affect the number of CCN and hence the droplet radius but not the cloud water content. This is the same as in all the other cases shown above.
[f] The lower of the two forcing estimates assumes that 85% of SO_2 is converted to SO_4^{2-} inside cloud droplets, while the higher forcing estimate assumes that 65% is oxidized in this way.

down approaches can yield useful constraints, but even this approach will require greatly reducing some current sources of uncertainty.

References

Boucher, O. and Anderson, T. L.: 1995, 'General Circulation Model Assessment of the Sensitivity of Direct Climate Forcing by Anthropogenic Sulfate Aerosols to Aerosol Size and Chemistry', *J. Geophys. Res.* **100**, 26117–26134.

Boucher, O. and Lohmann, U.: 1995, 'The Sulfate-CCN-Cloud Albedo Effect. A Sensitivity Study with Two General Circulation Models', *Tellus* **47B**, 281–300.

Charlson, R. J., Langner, J., Rodhe, H., Leovy, C. B., and Warren, S. G.: 1991, 'Perturbation of the Northern Hemisphere Radiative Balance by Backscattering from Anthropogenic Sulfate Aerosols', *Tellus* **43AB**, 152–163.

Chuang, C. C., Penner, J. E., Taylor, K. E., Grossman, A. S., and Walton, J. J.: 1997, 'An Assessment of the Radiative Effects of Anthropogenic Sulfate', *J. Geophys. Res.* **102**, 3761–3778.

Feichter, J., Lohmann, U., and Schult, I.: 1997, 'The Atmospheric Sulfur Cycle in ECHAM-4 and Its Impact on the Shortwave Radiative', *Clim. Dyn.* **13**, 235–246.

Hansen, J., Sato, M., and Ruedy, R.: 1995, 'Long-Term Changes in the Diurnal Temperature Cycle: Implications about Mechanisms of Global Climate Change', *Atmos. Res.* **37**, 175–209.

Hourcade, J. C. et al.: 1996, 'A Review of Mitigation Cost Studies', in Bruce, J. P., Lee, H., and Haites, E. F. (eds.), *Climate Change 1995: Economic and Social Dimensions of Climate Change*, Cambridge University Press, Cambridge, pp. 297–367.

Harvey, L. D. D.: 1999, *Global Warming: The Hard Science*, Addison Wesley-Longman (forthcoming).

Haywood, J. M., Ramaswamy, V., and Soden, B. J.: 1999, 'Tropospheric Aerosol Climate Forcing in Clear-Sky Satellite Observations over Oceans', *Science* **283**, 1299–1303.

Haywood, J. M., Roberts, D. L., Slingo, A., Edwards, J. M., and Shine, K. P.: 1997, 'General Circulation Model Calculations of the Direct Radiative Forcing by Anthropogenic Sulfate and Fossil-Fuel Soot Aerosol', *J. Climate* **10**, 1562–1577.

Hegg, D. A.: 1994, 'Cloud Condensation Nucleus-Sulphate Mass Relationship and Cloud Albedo', *J. Geophys. Res.* **99**, 25903–25907.

Jones, A., Roberts, D. L., and Slingo, A.: 1994, 'A Climate Model Study of Indirect Radiative Forcing by Anthropogenic Sulphate Aerosols', *Nature* **370**, 450–453.

Jones, A. and Slingo, A.: 1996, 'Predicting Cloud-Droplet Effective Radius and Indirect Sulphate Aerosol Forcing Using a General Circulation Model', *Quart. J. Roy. Meteorol. Soc.* **122**, 1573–1595.

Kiehl, J. T., Schneider, T. L., Rasch, P. J., Barth, M. C., and Wong, J.: 1999, 'Radiative Forcing Due To Sulfate Aerosols from Simulations with the NCAR Community Climate Model (CCM3)', *J. Geophys. Res.* (submitted).

Lohmann, U. and Feichter, J.: 1997, 'Impact of Sulfate Aerosols on Albedo and Lifetime of Clouds: A Sensitivity Study with the ECHAM4 GCM', *J. Geophys. Res.* **102**, 13685–13700.

Murphy, J. M. and Mitchell, J. F. B.: 1995, 'Transient Response of the Hadley Centre Coupled Ocean-Atmosphere Model to Increasing Carbon Dioxide. Part II: Spatial and Temporal Structure of Response', *J. Climate* **8**, 57–80.

Myhre, G., Stordal, F., Restad, K., and Isaksen, I. S. A.: 1998, 'Estimation of the Direct Radiative Forcing Due to Sulfate and Soot Aerosols', *Tellus* **50B**, 463–477.

Rodhe, H., Charlson, R. J., and Anderson, T. L.: 2000, 'Avoiding Circular Logic in Climate Modelling. An Editorial Essay', *Clim. Change* (this issue).

Schult, I., Feichter, J., and Cooke, W. F.: 1997, 'Effect of Black Carbon and Sulfate Aerosols on the Global Radiation Budget', *J. Geophys. Res.* **102**, 30107–30117.
Van Dorland, R., Dentener, F. J., and Lelieveld, J.: 1997, 'Radiative Forcing Due To Tropospheric Ozone and Sulfate Aerosols', *J. Geophys. Res.* **102**, 28079–28100.
Wigley, T. M. L.: 1989, 'Possible Climate Change Due To SO_2-Derived Cloud Condensation Nuclei', *Nature* **339**, 365–367.

Department of Geography,
University of Toronto,
100 St. George Street,
Ontario M5S 3G3,
Canada

L. D. DANNY HARVEY