BNL-71341-2003-JA

ATMOSPHERIC SCIENCE

Climate Forcing by Aerosols— a Hazy Picture

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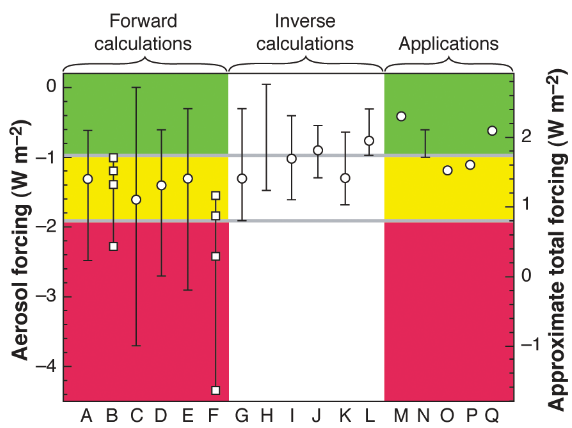
The global average surface temperature has risen by 0.6 K since the late 19th century. Ocean heat content has increased, and other climate indices also point to a warming world. Many studies have attributed this warming largely to top-of-atmosphere radiative forcing—a change in planetary heat balance between incoming solar radiation and outgoing infrared radiation—by anthropogenic greenhouse gases (GHGs) (*1*, *2*).

Such attribution studies compare temperature observations to climate model simulations forced by various industrial-era agents. Among these agents, GHGs have well-constrained positive forcings (creating a warming influence) (*3*). In contrast, the mostly negative forcings (cooling) associated with anthropogenic aerosols are highly uncertain (*3*, *4*).



Uncertainties in aerosol forcings. Global-mean anthropogenic aerosol forcing over the industrial era (left axis) as estimated by forward (A to F) and inverse (G to L) calculations and as used in applications (M to Q) (*20*). Circles with error bars are central values and 95% confidence limits. Bare error bars are stated range. Squares represent specific forcing calculations using alternative formulations within the same study. Right axis: Total forcing over the industrial era using the approximation that nonaerosol forcings are 2.7 W m^{-2} (*3*, *4*).

Different forcings have different spatiotemporal patterns; however, model studies indicate that climate sensitivity (the ratio of global mean equilibrium temperature response to global mean forcing) is approximately equal for almost all of the major forcing agents (*3*). Thus, total forcing (the global mean sum of all industrial-era forcings) is a widely used diagnostic parameter.

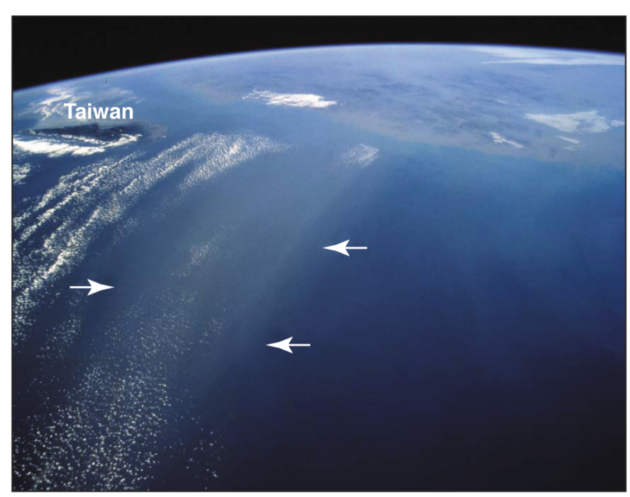
Here we argue that the magnitude and uncertainty of aerosol forcing may affect the magnitude and uncertainty of total forcing to a degree that has not been adequately considered in climate studies to date. Inferences about the causes of surface warming over the industrial period and about climate sensitivity may therefore be in error.

Anthropogenic aerosol forcings arise from multiple aerosol components and various forcing mechanisms. The sum of these forcings has been calculated by two independent methods. First, forward calculations are based on knowledge of the pertinent aerosol physics and chemistry. Second, inverse calculations infer aerosol forcing from the total forcing required to match climate model simulations with observed temperature changes.

Inverse calculations are based on the premise that the observed warming is caused by a positive total forcing over the industrial era (rather than by natural variability and/or unrecognized forcings). They constrain aerosol forcing to around –1 W m^{-2}, with uncertainties that extend no farther than –1 to –1.9 W m^{-2}, depending on the study (see the figure). Aerosol forcing determined by the forward calculations is considerably greater, centered around –1.5 W m^{-2}, with an uncertainty range that extends beyond –3 W m^{-2}. The larger magnitude aerosol forcings from the forward calculations greatly exceed the largest values allowed by the inverse calculations (see colored bands in the figure).

The substantial region of inconsistency shown in the figure (the red and, depending on the study, yellow bands) implies either that the large-magnitude aerosol forcings from the forward calculations are erroneously high or, alternatively, that the limits on aerosol-forcing magnitude inferred from the inverse calculations are erroneously low. We caution against simply assuming the former. The forward calculations are based on a substantial body of aerosol and cloud measurements, observation-based parameterizations of aerosol-cloud interactions, and well-understood physics of radiative transfer.

The inverse calculations are also based on sound physical principles. However, to the extent that climate models rely on the results of inverse calculations, the possibility of circular reasoning arises (*5*)—that is, using the temperature record to derive a key input to climate models that are then tested against the temperature record. Rather than rely exclusively on one ap-



Reflection of sunlight by aerosols. The southeast coast of China and the island of Taiwan viewed toward the southwest from the Space Shuttle at an altitude of 278 km above Okinawa, Japan. An aerosol plume (between arrows) is carried by northwest winds from China a distance of more than 600 km over the ocean; small clouds are embedded in the plume. Albedo enhancement is evident over the ocean, and indirect effects on clouds are possible.

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 Research by BNL investigators performed under Contract No. DE-AC02-98CH10886, U.S. DOE.

proach or the other, it is prudent to acknowledge the current inconsistency and seek to understand and resolve it.

Unfortunately, virtually all climate model studies that have included anthropogenic aerosol forcing as a driver of climate change (diagnosis, attribution, and projection studies; denoted "applications" in the figure) have used only aerosol forcing values that are consistent with the inverse approach. If such studies were conducted with the larger range of aerosol forcings determined from the forward calculations, the results would differ greatly.

The forward calculations raise the possibility that total forcing from preindustrial times to the present (right axis in the figure) has been small or even negative. If this is correct, it would imply that climate sensitivity and/or natural variability (that is, variability not forced by anthropogenic emissions) is much larger than climate models currently indicate.

Although even the sign of the current total forcing is in question, the sign of the forcing by the middle of the 21st century will certainly be positive. The reason is that GHGs accumulate in the atmosphere, whereas aerosols do not. Even if the most negative value of aerosol forcing shown in the figure turns out to be correct, the current range of plausible emissions scenarios (*6*) indicates that GHG forcing will exceed aerosol forcing somewhere between 2030 and 2050. Thus, despite current uncertainties, forward calculations lead to the unambiguous conclusion that anthropogenic activity will inevitably result in a strong, positive forcing of Earth's climate system.

In addressing the critical question of how the climate system will respond to this positive forcing, researchers must seek to resolve the present disparity between forward and inverse calculations. Until this is achieved, the possibility that most of the warming to date is due to natural variability, as well as the possibility of high climate sensitivity, must be kept open.

References and Notes

1. J. F. B. Mitchell *et al.*, in *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 695–738.
2. T. J. Crowley, *Science* **289**, 270 (2000).
3. V. Ramaswamy *et al.*, in *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 349–416.
4. O. Boucher, J. Haywood, *Climate Dyn.* **18**, 297 (2001).
5. H. Rodhe, R. J. Charlson, T. L. Anderson, *Climatic Change* **44**, 419 (2000).
6. U. Cubasch *et al.*, in *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 525–582.
7. J. T. Kiehl *et al.*, *J. Geophys. Res.* **105**, 1441 (2000).
8. J. E. Hansen, M. Sato, *Proc. Natl. Acad. Sci. U.S.A.* **98**, 14778 (2001).
9. J. E. Hansen *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **95**, 12753 (1998).
10. S. E. Schwartz, M. O. Andreae, *Science* **272**, 1121 (1996).
11. S. Menon, A. D. Del Genio, D. Koch, G. Tselioudis, *J. Atmos. Sci.* **59**, 692 (2002).
12. T. M. L. Wigley, S. C. B. Raper, *Science* **293**, 451 (2001).
13. L. D. D. Harvey, R. K. Kaufmann, *J. Climate* **15**, 2837 (2002).
14. J. M. Gregory *et al.*, *J. Climate* **15**, 3117 (2002).
15. N. G. Andronova, M. E. Schlesinger, *J. Geophys. Res.* **106**, 22605 (2001).
16. R. Knutti, T. F. Stocker, F. Joos, G.-K. Plattner, *Nature* **416**, 719 (2002).
17. C. E. Forest *et al.*, *Science* **295**, 113 (2002).
18. S. F. B. Tett *et al.*, *J. Geophys. Res.* **107**, 10.1029/2000JD000028 (2002).
19. G. A. Meehl *et al.*, *J. Climate* **16**, 426 (2003).
20. Forward calculations: (A) statistical sum by (*4*) of the radiative forcings given in (*3*); (B) sulfate-only forcings by (*7*); (C) (*8*); (D) (*9*); (E) (*10*); (F) indirect (that is, cloud-mediated) effects only by (*11*). Inverse calculations: (G) (*12*); (H) (*13*); (I) (*14*); (J) (*15*); (K) (*16*); (L): (*17*). Applications, anthropogenic aerosol forcing as used in (M) the detection/attribution study by (*2*); (N) detection/attribution review by (*1*); (O) climate projections by (*6*); (P) detection/attribution study by (*18*); (Q) forcing/response diagnostic study by (*19*).

21. We thank V. Ramaswamy, J. Haywood, and F. Joos for helpful discussions.