

Reply to comment by J. Feichter et al. on “Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming”

Mark Z. Jacobson

Department of Civil and Environmental Engineering, Stanford University, Stanford, California, USA

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INDEX TERMS: 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 1620 Global Change: Climate dynamics (3309); **KEYWORDS:** climate change, aerosol particles, black carbon, climate feedbacks, climate response, global warming

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1. Introduction

[1] This is a response to the commentary of *Feichter et al.* [2003] (hereinafter referred to as F2003), on the paper by *Jacobson* [2002] (hereinafter referred to as J2002). The commentary contains several factually inaccurate statements about the model used by J2002 and about results from the study, and I disagree with other comments. Controlling fossil-fuel black carbon plus organic matter (f.f. BC + OM) still appears to be the most effective method of slowing global warming for a specific period.

2. Factually Inaccurate Statements

[2] 1. “In the present paper, only lengthy tables of modeled and observed BC and sulfate concentrations at localized sites, mostly from few measurements, are provided.” This statement is inaccurate because the paper contains comparisons with many more parameters than just BC and sulfate. In the paper by J2002, Figure 4 compares modeled with satellite/climatological cloud water, precipitation, and cloud fraction; paragraph [73] compares regions of warming and cooling found in the paper with those from the temperature records of two published studies, paragraph [74] compares a calculated vertical temperature change with a radiosonde temperature record and with results from another model; paragraph [55] compares the CO₂ doubling equilibrium climate sensitivity with those from other studies; paragraph [62] compares the climate response found here with those from another study; paragraph [63] compares the ratio of sulfate to CO₂ climate response divided by direct forcing with that from *Intergovernmental Panel on Climate Change (IPCC)* [2001]; paragraph [70] discusses comparisons of predictions of direct forcing with those from other studies; and paragraph [70] compares the prediction

of direct forcing per unit mass of OC with that from another study.

[3] 2. “Neither in the present paper [*Jacobson*, 2002] nor in any other of the cited papers is a validation of the long-term behavior of the meteorology of M. Z. Jacobson’s GATOR-GCMM model presented.” This claim is inaccurate and misleading. It is inaccurate because, in the present paper (J2002), Figure 4 compares long-term yearly and zonally averaged modeled with satellite/climatological cloud water, precipitation, and cloud fraction. These parameters are components of meteorology, and the results would be impossible to obtain correctly if other aspects of the meteorology in the model were deficient. In addition, paragraphs [73], [74], [55], and [62] compare temperature responses of the model with those from the temperature record and from other models. Further, *Jacobson* [1999, p. 361] compares the modeled evolution of the ozone layer with near-present-day observations. Again, it would be impossible to generate the total ozone layer correctly with a coupled chemical-radiative-meteorological model that treats the troposphere and stratosphere together with inaccurate meteorology.

[4] The claim is misleading because it, along with other statements (“...we miss the standard tests...”), implies that other models have been tested more for accuracy than GATOR-GCMOM has. However, intercomparisons such as those described by F2003 are not evaluations of model error; they are evaluations of model bias (a comparison of monthly or yearly means, which is a measure of bias, not error). The standard error test in an atmospheric model is the paired-in-time-and-space comparison with data. No model in the field has had its gas, aerosol, meteorological, and radiative modules compared with paired-in-time-and-space data to the extent that those in GATOR-GCMOM have been compared. *Jacobson* [1997b] was the first and still only paper in which gas, size- and composition-resolved aerosol, radiative, and meteorological predictions have been compared simultaneously with paired-in-time-and-space data from a comprehensive field campaign. *Jacobson* [2001b] was the first

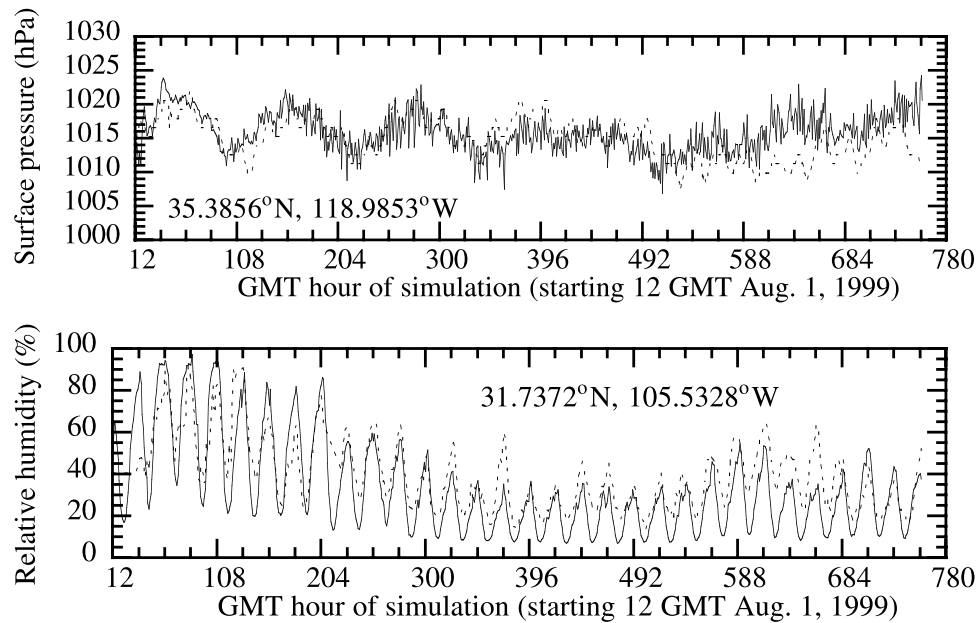


Figure 1. Comparison of hourly modeled (solid lines) with measured (dashed lines) near-surface pressure and relative humidity (U.S. Environmental Protection Agency (USEPA), Air data, 2003, available at <http://www.epa.gov/air/data>) at two air quality monitoring stations. The model set is described in the text. Model results were interpolated with bilinear interpolation from four surrounding grid cells of resolution $0.5^{\circ}\text{S-N} \times 0.75^{\circ}\text{W-E}$ to the location of interest. From *Jacobson et al.* [2003].

and still only paper in the field to compare meteorological and gas statistics for 20 gases simultaneously with paired-in-time-and-space data.

[5] *Jacobson et al.* [2003] compare gas, meteorological, and radiative parameters simultaneously with paired-in-time-and-space data for a month from that study. Figure 1 here shows one example of such a comparison of two meteorological parameters, pressure and relative humidity, from a global-regional nested simulation (inner-grid resolution of about 50×70 km), where the meteorological, gas, and aerosol boundary conditions for the regional model were obtained from the same global model used by J2002. The simulation involved no model spin-up or data assimilation. It was initialized with National Centers for Environmental Prediction (NCEP) meteorological fields on both scales. The relative accuracy of the error comparison with data (particularly relative humidity, which depends on both temperature and water vapor) for a month at relatively coarse resolution is encouraging. It is also a more rigorous evaluation of the model than the intercomparison of model biases described by F2003.

[6] In addition, GATOR-GCMOM contains over 110 numerical techniques and physical processes not treated in any other global model (<http://www.stanford.edu/group/efmh/GATOR/>). An intercomparison of a model containing dozens of processes with models not containing such processes is not useful. Some processes unique to GATOR-GCMOM include (1) physical treatment of cloud microphysics (e.g., condensation/deposition of water vapor on size-resolved aerosols to form size-resolved clouds, coagulation of size-resolved hydrometeors to form precipitation; coagulation of size-resolved hydrometeors with size-resolved aerosols; evaporative freezing); (2) physical treatment of aerosol/cloud interactions with radiation (e.g.,

shell/core treatment of size-resolved aerosols and size-resolved clouds for optical calculations; interaction of size-resolved hydrometeors and size-resolved aerosols with a >400 wavelength intervals of radiation; (3) basic aerosol processes (size-resolved coagulation among aerosols and their individual components; growth and nucleation treated simultaneously, as opposed to operator split, dissolutional growth solved simultaneously over multiple size bins, removal of size-resolved aerosols and their components by size-resolved coagulation with precipitation and by size-resolved nucleation scavenging followed by cloud evolution and size-resolved precipitation; and (4) surface processes (e.g., treatment of temperatures and energy fluxes over subgrid roads and rooftops; treatment of prognostic mixed-layer ocean transport with a potential-entropy-conserving scheme).

[7] 3. “*Jacobson* [2002] does not use the standard approach of “radiative forcing” (RF) and “climate response.” This statement is inaccurate because the definition of instantaneous direct forcing used in the paper (e.g., as in paragraph [63]) was the net downward irradiance change when a substance was present versus when it was absent, assuming the same meteorology and clouds in both cases, and this is the same definition given by F2003 (and also the same definition used by *Jacobson* [2001a]). Nowhere in the paper by J2002 does a definition of direct forcing appear, so it would be impossible for F2003 to know whether the definition given by J2002 was standard or not, although they claim they have such knowledge.

3. Responses to Numbered Points of F2003

[8] 1. F2003 claim sulfur dioxide and organic carbon cooling from fossil-fuel use should offset warming due to black carbon and cite studies of total BC + OM + sulfate

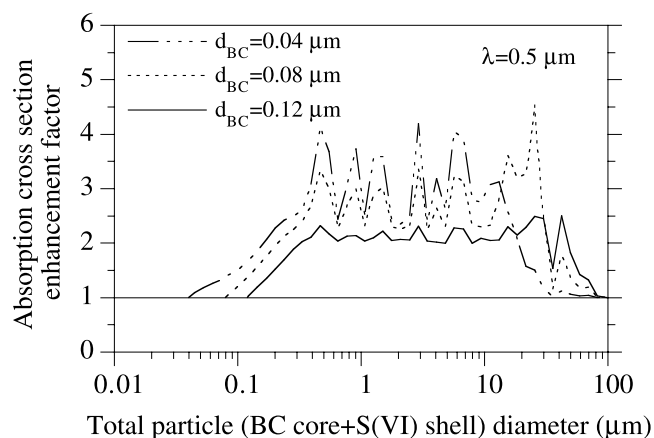


Figure 2. Mie-calculated absorption cross-section enhancement factors. The enhancement factor is the ratio of the absorption cross section of a total (coated) particle with a BC core (either 40-, 80-, or 120-nm diameter) and an S(VI) shell to the larger of the absorption cross section of BC alone (at either 40-, 80-, or 120-nm diameter) or of pure S(VI) at the same size as the total core + shell particle (which affects the factor only at large sizes). The leftmost values in the figure are the enhancement factor (1.0) corresponding to the pure core. The rightmost values (1.0) are those corresponding to a large pure S(VI) drop that absorbs since all particles with a nonzero imaginary refractive index become absorbing at some size. Absorption cross sections for the enhancement factor were calculated here with the Mie code originating from *Toon and Ackerman* [1981].

direct forcing to argue their point. However, the major sources of sulfur dioxide and many sources of organics differ from those of f.f. BC. What matters is not the total anthropogenic BC + OM + sulfate direct forcing, but that due to OM + sulfate associated with BC. In many countries, such as the United States and Switzerland, the greatest source of BC today is diesel combustion from agricultural machines and construction equipment. These sources emit relatively little SO₂, especially when low-sulfur diesel is used, and the primary organic matter emitted with BC in diesel is mostly insoluble lubricating oil [e.g., *Kittelson*, 1998]. Insoluble OC does not hydrate water or swell as other organic compounds would, so the magnitude of its direct forcing is small.

[9] In addition, when a condensable vapor is emitted together with soot, the vapor, upon condensation, enhances soot absorption, thereby enhancing warming of the total aerosol [e.g., *Jacobson*, 1997a, 1997b, 2000, 2001c]. Figure 2 here shows, from Mie theory, that the addition of a coating to a soot particle enhances its absorption. The theory has been tested experimentally by *Schnaiter et al.* [2003], who found that the addition of just a few monolayers of a condensed organic coating to a BC particle could increase its absorption coefficient by 35%. This increase would correspond to an enhancement factor of 1.35 and would appear in the region in Figure 2 just to the right of the size of pure cores (40, 80, or 120 nm).

[10] Finally, the sulfate direct forcing from *Jacobson* [2001a] (-0.32 W/m^2 , Table 8) is consistent with direct

forcings of sulfate from many other studies cited by J2002 as well as by *IPCC* [2001]. As stated in paragraph [70] of J2002, the direct forcing of OC was consistent with that from *Cooke et al.* [1999]. Given that the OC in f.f. BC + OM is mostly lubricating oil, which is insoluble and does not swell, it is unphysical to suggest that the magnitude of the direct forcing of such OC is large. Further, direct forcings of sulfate and OC [*Jacobson*, 2001a] were calculated with 17 aerosol sizes, 40 electrolyte and nonelectrolyte components per size bin, water uptake in each bin (accounting for current instantaneous relative humidities over the entire range), numerous electrolyte molalities, over 400 wave intervals of radiation, and radiative transfer through size-resolved liquid and ice hydrometeors, making it the most rigorous calculation of direct forcing to date.

[11] 2. Point 2 was addressed in section 2, above.

[12] 3. Since the publication of J2002, additional simulations of f.f. BC + OM have been run for 10 years. The conclusion after 10 years still holds. J2002 also stated that 11 additional simulations of the effect of BC + OM, under different conditions (including different emission rates, initial conditions, and different numerical techniques) were run. Since the paper, many more have been run. All cases have shown warming between +0.15 and +0.5 K, the range stated in the paper. The consistent direction of the results among multiple simulations under different conditions further supports the main conclusion of the study.

[13] The claim that the decrease in global mean surface pressure in J2002 shows the model did not conserve mass is incorrect. Mass (and total atmospheric pressure, integrated over the globe) in GATOR-GCMOM is exactly conserved (to machine precision). The pressure in the table was mistakenly labeled as surface pressure whereas, in fact, it was near-surface pressure (pressure in the middle of the bottom atmospheric layer).

[14] 4. Point 4 was addressed, in part, in section 2, above. Further, F2003's equation relating climate response linearly to instantaneous direct forcing through the constant λ may be reasonable for gases (as found by J2002 with respect to CO₂ and CH₄) but easily disprovable with respect to aerosols. For example, gases exhibit no "indirect effect" on clouds, but aerosols do, so simply considering this extra climate response (since the indirect effect is a response, not a forcing) gives a different λ for gases versus aerosols. Similarly, suppose two aerosol components exhibit the same direct forcing but have different cloud activating properties (e.g., one is soluble, the other is not). The climate response sensitivity, λ , will differ once again.

[15] Finally, F2002 state, "The '12 aerosol effects' found by *Jacobson* [2002] lack a clear distinction between forcing and response." There is nothing unclear since there was only one forcing considered: the change in emissions of f.f. BC + OM. All effects thereafter, including indirect effects, were climate responses (effects of aerosols on climate). Additional aerosol effects beyond those listed exist, but this does not diminish the novelty of several of the 12 listed that had not been identified previously.

[16] In sum, the main conclusions of J2002 still stand.

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M. Z. Jacobson, Department of Civil and Environmental Engineering, Stanford University, Terman Engineering Center, Room M-13, Stanford, CA 94305-4020, USA. (jacobson@ce.stanford.edu)