Uncertainties in Climate Projections Caused By Aerosol Effects

Do We Know Enough To Proceed With Control Of Greenhouse Gas Emissions?

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Photo credit: “The Blue Marble”
http://visibleearth.nasa.gov/view_rec.php?id=2429
Outline

1. Climate forcing by aerosols: the largest uncertainty in total climate forcing and a leading cause of uncertainty in climate sensitivity ("Forcing" is an imposed change in energy balance, Wm⁻²)

2. How did we arrive at this situation? A history of the research on climate forcing by aerosols

3. The shift from using an observational to a modelling basis for quantifying climate forcing

4. Conclusions: Needed research; alternates to ΔT as indices of climate change;

5. Climate forcing projection to AD 2100
Global average radiative forcing (RF) estimates and uncertainty ranges in 2005, relative to the preindustrial climate, for anthropogenic carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale of the forcing and the assessed level of scientific understanding (LOSU). The total anthropogenic radiative forcing and its associated uncertainty (5-95% confidence interval) are also shown.

**IPCC (2007), Figure SPM.2**
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).

Published estimates of the aerosol indirect effect

Anthropogenic changes in net radiation at the TOA

Isaksen et al., (2009), Atmos. Environ., 43, 5138-5192
IPCC (2007) Figure 9.5 (adapted)
Blue and rose colored bands: 5-95% range for models, see IPCC (2007)
Red bar: Range of increase of modelled surface T from IPCC (2007)
Green bar: expected range of modelled T from IPCC range of uncertainty of forcings also given by IPCC (2007)
Correlation of Aerosol Forcing, Total Forcing, and Sensitivity in Climate Model

Nine coupled ocean-atmosphere models; Two energy balance models

\[ S = \Delta T / F \]
\[ F = \Delta T S^{-1} \]

Total forcing is linearly correlated with inverse sensitivities of the models. Climate models with lower sensitivity (higher inverse sensitivity) employed a greater total forcing.

- Greater total forcing is due to smaller (less negative) aerosol forcing.
- All models accurately reproduce known temperature change over 20th century.
- Similar results appear to exist for AR-4.

*Modified from Kiehl, GRL, 2007*
How did we arrive at this situation?
Old History:

- Light scattering as a cause of optical extinction: Boguer’s Law (Beer-Lambert law), 1729
- Light scattering theory: Rayleigh, 1870; Mie, 1908
- Theory of haze droplet growth and cloud droplet activation: Koehler, 1921
- Visible hazes and fogs; visual range: Koschmieder, 1924:
  \[ L_V = \frac{-\ln \varepsilon}{\sigma_{\text{ext}}} \cong \frac{3.9}{\sigma_{\text{ext}}} \]
  for a black object seen against the horizon sky
- Military applications: WWI and WWII
- Telephotometer, A. W. Brewer’s optical instruments. Problem: \( I/I_0 \) approximately equals 1 because of small values of extinction coefficient
Old History, continued:

- The polar nephelometers of Waldram
- The integrating nephelometer of R. G. Beuttell:
  Beuttell and Brewer, 1949

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Fig. 2. Scattering at $a$, $b$ and $c$. (The black body $B$ appears to have brightness due to light scattered at points such as $a$, $b$ and $c$. The brightness is a measure of the visibility)

Fig. 9.26. Diagram of the “polar nephelometer” of Waldram.
Memorable experiences:

- Across the Atlantic Ocean on the SS United States and RMS Queen Elizabeth (1964-5)
- Experiences as a mountain climber in the 1960s
- Life in London (1964-5)

- Observed very extensive areas of low visibility caused by scattering; \( L_v \) much less than one to a few km;
- Also observed exceptionally good visibility;
- Raised the questions of what the scatterers were composed of; what was their concentration; what was their thermodynamic state; and what was the role of RH;
- Recognition that the scattering component of extinction was often dominant and varied over a large range; \( 10^{-5} < \sigma_{\text{scat}} < 10^{-2} \text{ m}^{-1} \);
- Clean air at high altitude on down to visual ranges as small as a few meters in a London “pea soup” fog
- Recognition of a need to make measurements of scattering coefficient as f(RH)
Scientific situation of the 1960s:

- Lack of any suitable theory for relating the key variables of optical effect (scattering coefficient), amount and composition of aerosol and the RH. Mie theory was believed to be adequate but particle size and composition were unknown and RH effect was complex and non-linear (Koehler).

- Extant belief that particle size was highly variable from place to place and time to time. Junge’s size distribution was very crude. Friedlander’s “Self-preserving” size distribution was still hypothetical. Whitby was just starting to make measurements.
Scientific situation of the 1960s, continued:

- Recognition of increasing problem of urban smog; Los Angeles visibility; killer smogs of London, New York, Donora PA, etc.
- Lack of any instrument for measuring the low values of scattering coefficient.
- Strictly from T records, inference of regional to global scale cooling by aerosols: Bryson, Mitchell
- 1969 forecast of a pending ice age by Rasool and Schneider (Science)
The Beuttell-Brewer integrating nephelometer geometry might be used with a closed chamber to allow (i) control of RH and (ii) calibration with Rayleigh scattering of pure gases.

\[ \mathcal{B} = \left( \frac{I_0}{y} \right) \int_0^\pi \beta'(\phi) \sin \phi \, d\phi = I_0 b_{\text{scat}}/2\pi y \quad (9.51) \]

The definitions of photometric quantities and this derivation follow from Middleton (1952), who concluded his analysis with the remark, “This happy result depends entirely on the cosine distribution of the radiation from the light source.”
Correlation of $\sigma_{\text{scat}}$ with filterable mass:

- New York City experiment, December 1967

- General result: Preoccupation with particle volume concentrations rather than mass; slope ca. $3m^2/g$

$\rho \sim 1$
The “Great Smog Caper” of 1969 at Cal Tech:

- Goal: characterize L. A. smog aerosols
- Ken Whitby and U. of Minnesota team measured size distribution

Whitby

Hidy Liu Friedlander (?)
The “Great Smog Caper,” continued

- We from the U. of Washington measured light scattering with the new multi-wavelength nephelometer.
- Result was a closure exercise comparing measured light scattering that calculated from the measured size distribution.
- Good correlation ($r \approx 0.9$); calculated $\sigma_{\text{scat}}$ was a factor of about 2 too low.

*N.B.:* In 1997, Anderson et al. refined that comparison and achieved uncertainties of less than 10% for accumulation sized aerosols, using laboratory generated aerosols.
RH dependence of $\sigma_{\text{scat}}$

*N.B.*: Detection of NaCl and NH$_4$SO$_4$ via RH of inflection point of $\sigma_{\text{scat}}$ versus RH curve; extensive experiments in the St. Louis, MO, region showed regional haze, not urban smog.

It is well known that the visibility of a given sample of air depends upon the relative humidity, so that the scattering coefficient as measured in this way does not necessarily give the free-air visibility. It does, however, give the scattering coefficient under standard conditions of low relative humidity and so measures the haze and the extent to which dust, etc., is present.

Beuttel & Brewer (1949)
RH dependence of $\sigma_{\text{scat}}$, continued

- Molecular form in St. Louis varied from $\text{H}_2\text{SO}_4$ to $(\text{NH}_4)_2\text{SO}_4$. Refractive index and particle size role in wavelength dependence and angular scattering function.
Scientific situation of the 1970s:

- Growing recognition of the possibility of anthropogenic climate change;
- Separate interest in and focus on rainwater acidification by sulfuric acid from coal burning;
- Recognition of soot as a cause of light absorption;
- Development of measurement methods for light absorption by particles on filters;
- Development of hemispheric backscatter nephelometer for a simple parameterization of aerosol effect on albedo;
- 1969 paper by Charlson and Pilat calling attention to the dual role of aerosol particles as both scatterers and absorbers of sunlight (J. Appl. Meteorol.)
Correlation of $\sigma_{\text{scat}}$ with mass concentration of sulfate aerosol: Swedish aircraft data

Slope ca. 5 m$^2$/g; high uncertainty. N.B.: $\text{SO}_4^{2-}$ data from colorimetric titration analysis, predating the much more accurate ion chromatography in use today.

Beginnings of the notion that sulfates might dominate $\sigma_{\text{scat}}$ and therefore local optical depth.

Bolin/Charlson missed the extension from local to global scale via a simple box model for atmospheric sulfate.
Late 1970s and 1980s:

- The rise of global thinking about biogeochemical cycles and the SCOPE books and increased attention to enhanced greenhouse effect (major role of Bert Bolin);

- Increased the awareness of anthropogenic perturbation of S and N cycles in the global atmosphere;

- Extensive measurement programs aimed at quantifying S and N fluxes in rainwater; provided empirical basis for global models;

- Recognition of large anthropogenic perturbation of C cycle;

- Refinement of thinking about climate change: notion of quantifying forcing ($W/m^2$) as being more certain than $\Delta T$. Dickinson and Cicerone, 1986, Ramanathan, 1985.

- Theoretical model by Grassl (1988) provided a 2-dimensional estimate of sulfate forcing as a function of latitude in the N.H.
Late 1980s continued:

**Grassl (1988)**
Existence of a large negative forcing by anthropogenic aerosols (e.g., SO$_4$)

*What Are the Radiative and Climatic Consequences of the Changing Concentration of Atmospheric Aerosol Particles?*

H. Grassl

Anthropogenic aerosol particle influence outside clouds on solar radiation, for particles without soot (thick line) and with 20% soot (thin line).
Recognition of aerosol indirect effect:

- **Bolin and others (mid-1970s)**, Beginnings of large international research projects (GARP; SCOPE)

<table>
<thead>
<tr>
<th>Step</th>
<th>I</th>
<th>II</th>
<th>III</th>
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<tr>
<td><strong>CO₂</strong></td>
<td>Ia</td>
<td>Ha</td>
<td>IIIa</td>
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<tr>
<td>Understanding of the behaviour of the CO₂ system atmosphere — ocean — biosphere with respect to natural and anthropogenic fluctuations of injection rates, etc. into the atmosphere. Problem partially solved for anthropogenic injections but fairly open for long-term natural fluctuations.</td>
<td>Understanding of the <em>direct</em> influence on the long-wave radiation budget in a <em>static</em> atmosphere disregarding any dynamically induced feed-back processes as by the hydrological cycle, etc. Problem practically solved due to the homogeneous distribution of CO₂ in the troposphere, etc.</td>
<td>Understanding of the complete, realistic effects on the three-dimensional circulation and climate, including all dynamical feedback processes by the hydrological cycle, etc. Problem entirely open.</td>
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<tr>
<td><strong>Aerosols</strong></td>
<td>Ib</td>
<td>IIb</td>
<td>IIIb</td>
</tr>
<tr>
<td>Understanding of the non-uniform quasi-steady state distribution within the troposphere and its changes as a function of production, modification and removal processes and their variations. Problem not yet attacked; can possibly be best approached by approximation with a two- or three-dimensional steady state circulation model of the troposphere with parameterized mixing and cloud formation processes.</td>
<td>Understanding of the <em>direct</em> influence on the short- and long-wave radiation budget in a <em>static</em> atmosphere and its change with source variations, etc. Problem is solved to some extent and can be completed in the near future if further data and the input from Ib are available.</td>
<td>Understanding of the complete realistic effects of the three-dimensional circulation and climate, including all feedback processes by the hydrological cycle, etc. For both the <em>direct</em> and the <em>indirect</em> influences on the radiation budget. Problem similar to that of CO₂ but more complex and entirely open.</td>
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<td><strong>IIc</strong></td>
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<td>Understanding of the <em>indirect</em> influence on the short- and long-wave radiation budget by modification of cloud micro- and macro-structure, i.e., albedo, cloud cover, etc. Problem practically open. Can possibly be approached by approximation with a static model.</td>
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Twomey (1971, 1977) Sensitivity of cloud albedo to droplet population

**The Aerosol and the Solar Energy Input**

**Twomey**

Commonwealth Scientific and Industrial Research Organization
Division of Cloud Physics, Sydney, N.S.W., Australia

and

Institute of Atmospheric Physics,
University of Arizona, Tucson, Ariz., U.S.A.
Late 1980s:

- **Coakley, Bernstein and Durkee, *Science* (1987)**
  Observations of the influence of droplet size on cloud reflectance

  Hypothetical feedback involving marine phytoplankton, dimethylsulfide, cloud albedo

Jacobson et al. (2000)
Figure 17-9, page 454
Connection of Bolin/Charlson ideas to modelled global distribution of aerosol:

Refined regression of measured sulfate mass versus measured light scattering provided an empirical basis for estimating the optical depth caused by anthropogenic sulfate. White (1990) arrived at 6.6 m²/g, using ion chromatography data.

Dominance of $\sigma_{sp}$ by sulfates and organics (White, 1990)

$$\sigma_{sp\cdot \text{fine\cdot dry}} (525 \text{ nm}) (\text{Mm})^{-1} =$$

$$1.8 + (6.6 \pm 0.4) [\text{SO}_4^{2-}]_{\text{fine}} (\mu\text{g m}^{-3})$$

$$+ (5.5 \pm 0.3) [\text{C}_{\text{org}}]_{\text{fine}} (\mu\text{g m}^{-3})$$

$$r^2 = 0.948$$
SCIENTIFIC CORRESPONDENCE

Sulphate aerosol and climate

Sir—Wigley has suggested in Scientific Correspondence that the Northern Hemisphere may be warming more slowly than the Southern Hemisphere, possibly due to an anthropogenic increase of cloud condensation nuclei of about 20% in the Northern Hemisphere. We wish to propose an alternative yet complementary explanation for the suggested difference—that backscatter of solar radiation by non-cloud, anthropogenic SO₄ aerosol particles in cloud-free air significantly reduces the incoming solar radiation over much of the Northern Hemisphere. A simple box-model calculation illustrates the expected magnitude of the mean column burden of anthropogenic sulphate, \(\text{SO}_4\):

\[
\text{SO}_4 = \frac{F_{SO_4}}{\sigma_{SO_4}} \times 10^{-6} \text{ g m}^{-2}
\]

where \(F_{SO_4}\) is the average flux of this SO₄ through the atmosphere in the Northern Hemisphere (assumed to be half of 70 Tg yr⁻¹ of sulphur emitted as SO₂), \(\sigma_{SO_4}\) is the mean sulphate aerosol particle lifetime (about 6 days) and \(A\) is the area of the Northern Hemisphere. We assume that all anthropogenic SO₄ originates and stays in the Northern Hemisphere. An empirical optical scattering efficiency, \(\sigma(10 \mu m, \text{g}^{-1})\) ref. 2, then yields an estimate of optical depth, \(\delta_{SO_4}\), for solar wavelengths due to anthropogenic SO₄:

\[
\delta_{SO_4} = \frac{F_{SO_4}}{\sigma_{SO_4}} \times 10^{-6} = 0.066
\]

Finally, an empirical backscatter fraction, \(\beta\) (0.15, ref. 3), and estimated cloud fraction, \(f\) (~0.6), allow for estimation of the energy lost from the Earth's surface, \(L\) (we disregarded the effect of aerosols above cloud level):

\[
L = (1 - \beta)(1 - 2f)\delta_{SO_4} \sim 0.08
\]

where the factor of two is the season of solstice, and the factor of two is the season of winter.

If the solar irradiance incident on this low-altitude aerosol is about 240 W m⁻², the irradiance (direct plus diffuse solar radiation) is lost at a rate of about 2 W m⁻²—due to the aerosol (reflectivity) of the underlying surface. This radiation is comparable in magnitude but opposite in sign to the current forcing by anthropogenic CO₂ of about 1.5 W m⁻² (ref. 4). Hence, backscatter of solar radiation by SO₄ aerosol cannot be ignored and could account for some or all of the difference in temperature trends between the two hemispheres.

The shorter cycles of hair loss in mice discussed by Bowden, which occur as waves across the body, and the mosaic replacement in man (and guinea pigs) are highly speculative. The lack of a seasonal link in the guinea pig can be interpreted as due to evolution near the equator, where forcing may cause shifts in meteorological parameters unlike those due to the geographically uniform forcing by greenhouse gases. It does seem unlikely, however, that the magnitude of irradiance loss estimated above would change radically in a refined model calculation. Thus, the effect of anthropogenic aerosol has to be taken into account in any assessment of climate change.

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N.B. Wigley suggestion (Ref. 1) that the N.H. may be warming more slowly than the S.H. because of anthropogenic CCN.

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Department of Atmospheric Sciences, University of Washington, Seattle

J. Langner, H. Rodhe  
Department of Meteorology, Stockholm University, Sweden

... A simple box-model calculation illustrates the expected magnitude of the mean column burden of anthropogenic sulphate,

\[
B_{SO_4^{2-}} = \frac{F_{SO_4^{2-}} \tau_{SO_4^{2-}}}{A} \approx \frac{(3.3 \times 10^6 \text{ g s}^{-1}) (5 \times 10^5 \text{ s})}{2.5 \times 10^{14} \text{ m}^2} \\
\approx 6.6 \times 10^{-3} \text{ g m}^{-2}
\]

where \(F_{SO_4^{2-}}\) is the average flux of this \(SO_4^{2-}\) through the atmosphere in the Northern Hemisphere (equivalent to about half of 70 Tg yr \(^{-1}\) of sulphur emitted as SO\(_2\)); \(\tau_{SO_4^{2-}}\) is the mean sulphate aerosol particle lifetime (about 6 days) and \(A\) is the area of the northern Hemisphere. We assume that all anthropogenic \(SO_4^{2-}\) originates and stays in the Northern Hemisphere.
An empirical optical scattering efficiency, $\alpha$ (10 m$^2$ g$^{-1}$, at RH=80%), then yields an estimate of optical depth $\delta_{SO_4^{2-}}$, for solar wavelengths due to anthropogenic $SO_4^{2-}$:

$$\delta_{SO_4^{2-}} = \alpha B_{SO_4^{2-}} \sim 0.066 \quad (N.H.)$$

Finally, an empirical backscatter fraction, $\beta$ (0.15) and estimated cloud fraction, $f$ ($\sim$0.6), allow for estimation of the energy lost from the Earth’s surface, $L$ (we disregard the effect of aerosols above cloudy areas):

$$L \sim (1-f) \beta_{SO_4^{2-}} (2\delta_{SO_4^{2-}}) \sim 0.8\%$$

where the factor of two is the secant of solar zenith angle averaged over the sunlit hemisphere.
Subsequent papers:

- Charlson, Langner, Rodhe, Leovy and Warren (1991), *Tellus*
- Charlson et al. (1992), *Science*
- Kiehl and Briegleb (1993), *Science*, sulfate forcing map via a coupled CTM RTM
- IPCC (1994) first inclusion of forcing by sulfates
Thus far, the global result was inferred from a combination of:

- Measured properties of sulfate-dominated aerosol in industrial regions ($m^2/g$, $f(RH)$, etc.)
- Simple mass-balance chemical model calculation of sulfate burden ($g/m^2$)
Early to mid-1990s:

Transition to “pure” modelling approach with sulfate optical properties being calculated from assumed size distribution etc. with the Mie formalism.

Average heat gain, July 1993 (watts per square meter)

Figure used in:
*Charlson and Wigley, Scientific American, 270 (1994)*
Conclusions:

- Climate forcing by anthropogenic sulfates was originally at via an empirical/observational pathway with a CTM.
- Recognize that characterizing atmospheric aerosols and clouds with *in-situ* observations is itself difficult and still a matter of experiment. Doing these sorts of observations by remote sensing is even harder!
- New tools for observational approach: CVI; lidar nephelometer
Conclusions, continued:

- New tools for observational approach, continued: satellite observations (CALIOP lidar on CALIPSO); new chemical tools; multiple, simultaneous satellite observations; L-1 and DSCOVR.

- A continued need for comparison and closure between observational and modelling approaches; integrated measurement/modelling efforts; a need for demonstration of coherence between *in-situ* and satellite data.

- A useful strategy might employ intensive, multivariate *in-situ* observations in a few typical impacted regions to “anchor” satellite retrievals.
A-Train

DSCOVR at L-1
1.5 x 10^6 km

3.8 x 10^5 km

The A-Train

PARASOL 60 sec 13 min
CALIPSO 15 sec
CloudSat 30 sec
Aqua

Aura

OCO 15 min
Key regions:

- Eastern U.S.
- China / Japan / Korea
- Europe
- Biomass burning area
### Multiple indices of climate change

<table>
<thead>
<tr>
<th>Index of change</th>
<th>Symbol, unit</th>
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<tbody>
<tr>
<td>Global mean surface temperature</td>
<td>$\Delta T$</td>
</tr>
<tr>
<td>Ocean heat content</td>
<td>Joules</td>
</tr>
<tr>
<td>Change in regional-scale surface temperature</td>
<td>$\Delta T$</td>
</tr>
<tr>
<td>Change in global- or regional-scale atmospheric water content</td>
<td>$B_{H2O}$, g m$^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$B_{H2O, region}$</td>
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<tr>
<td>Total greenhouse absorption</td>
<td>$LW_{abs}$, W m$^{-2}$</td>
</tr>
<tr>
<td>Global or regional mean radiative forcing</td>
<td>$\Delta F$, W m$^{-2}$</td>
</tr>
<tr>
<td>Global or regional mean precipitation</td>
<td>mm</td>
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<tr>
<td>Atmospheric GHG concentration or concentration change</td>
<td>e.g., $\Delta CO_2$</td>
</tr>
<tr>
<td>Ocean pH</td>
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<tr>
<td>Global or regional mean albedo</td>
<td>$\Delta A$</td>
</tr>
<tr>
<td>Sea level change</td>
<td>meters</td>
</tr>
<tr>
<td>Global or regional change in solar irradiance at the surface</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>Change in cloud cover, type of cloud, height of cloud, etc.</td>
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Conclusion: do we know enough to proceed with control of greenhouse gases (GHG)?

Conclusion (continued):

YES!

...Because by the year 2100, if the world continues to produce GHG as predicted by the IPCC emission scenarios, the forcing will be positive and very large (ca. +4-9 W/m$^{-2}$) and the aerosol forcing will not be much larger than at present, thus too small to be important to the total forcing.

This figure ... 4 to 9 W/m$^{-2}$ ... is a significant fraction of the amount of solar radiation incident upon the planet Earth.
Conclusion (continued):

YES!

... BUT, we *also* need to reduce the uncertainty in climate forcing by aerosols, in order to:

...better understand the temperature record of the 20th century

...better constrain the climate sensitivity

...provide a more accurate projection of climate change for the 21st century
Four types of uncertainties in “direct” and “indirect” forcing:

I. Parametric
II. Structural
III. Correlative
IV. Mechanistic
Example of a correlative uncertainty in direct forcing:

Let the forcing due to a vertical column of aerosol be $\Delta F$:

$$\Delta F = E \cdot \delta$$

where: $E$ contains information on solar flux, scattering angle, etc.

$\delta = \text{aerosol optical depth}$

$$= E \cdot \alpha \cdot m \cdot f(\text{RH})$$

$\alpha = \text{scattering efficiency of dry aerosol, m}^2/\text{g}$

$m = \text{column burden of aerosol, g/m}^2$

$f(\text{RH}) = \text{increase in } \delta \text{ due to RH, above that of a “dry” column}$

$$= E \cdot \alpha \cdot \frac{(\bar{m} + m') (f(\text{RH}) + f'(\text{RH}))}{(\bar{m} + m') (f(\text{RH}) + f'(\text{RH}))}$$

(by Reynold’s averaging)

$$= E \cdot \alpha \cdot \left[ \bar{m} f(\text{RH}) + \bar{m} f'(\text{RH}) + m' f(\text{RH}) + m' f'(\text{RH}) \right]$$

what models give

unknown change in forcing

caused by correlation of $m'$ and $f'(\text{RH})$
BUT!

We are getting too serious ...
Wizard of Id / By Brant Parker and Johnny Hart

I believe we are entering another ice age!

Based on what?

My calculations.

For a minute you had me worried.
It says, "Global warming will be canceled out by global cooling. So don't sweat it."
“If we were clever enough to balance these two effects -- the reflectivity of particulate matter and the concentration of carbon dioxide -- the Earth’s temperature might stay constant.”

Dr. Lee Dubridge
Science Advisor to President Nixon
US News and World Report
January, 1970
CAVEAT:

Aerosol effects and greenhouse gas effects cannot simply cancel each other out.

WHY?

Because they occur at different places and times in the atmosphere.
Acknowledgements

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Georg Witt

Henning Rodhe

A long list of graduate students and collaborators
Thank you very much.