Aerosol Forcing and Causal Attribution of 20th Century Warming

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March 2, 2004
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* aerosol research
climate modeling
mathematics/inverse modeling
Demonstration

• generation of particles from gases

• scattering of visible light by particles
Energy Balance Theory of Climate Change

Equilibrium (stable global-mean temperature)...

\[ E_{IN} = E_{OUT} \]

- \( E_{IN} \): shortwave, solar energy absorbed by Earth
- \( E_{OUT} \): longwave, infrared energy emitted by Earth

Forced change ...

\[ \Delta T_s = \lambda \Delta F \]

- \( \Delta F \): forcing, change in energy balance (W/m\(^2\))
- \( \Delta T_s \): response, change in surface temperature (K)
- \( \lambda \): feedbacks, climate sensitivity \( \{K/(W/m^2)\} \)
Greenhouse Effect versus Aerosol Effects

- Trapping of infrared radiation by greenhouse gases
- Direct effect
- Sulfate haze
- Indirect effect
- Clouds
- Cloud condensation nuclei
- SO₂ (gas)
- DMS

Industry

Marine phytoplankton
Aerosol forcings are extremely uncertain, but . . .


... dramatic progress is coming over the next few years.

A-Train satellite constellation (2005-2008)
Current global-warming paradigm

Warming of the Earth’s surface…
- Is predicted by climate models forced with GHG’s
- Has in fact been detected
- Match between prediction and observation is sufficiently good that attribution has been claimed

Conceptual framework for this paradigm:

$$\Delta T = \lambda \Delta F$$  \hspace{1cm} (Eq. 6.1 of IPCC, 2001)

$\Delta F$: externally imposed change in TOA energy balance ($W/m^2$)
$\Delta T$: resulting change in surface temperature (K)
$\lambda$: climate sensitivity
Current GW paradigm rests on three, interconnected premises:

**Premise 1: Positive Forcing**  
\( \Delta F \) is positive and of substantial magnitude

**Premise 2: "Detection"**  
\( \Delta T \) is outside the range of natural variability.

**Premise 3: "Attribution" to human causes**  
\( \Delta T \) is consistent with current knowledge of \( \Delta F \) and of the forcing/response relationship as embodied in climate models.
Premise 1: Initially self-evident

1a. Unequivocal, **positive** forcing from greenhouse gases.

1b. **Substantial** enough to cause significant warming (according to climate models)
Premise 2: Detection

Global Warming?

Global Cooling?

FIGURE 2-4
The globally averaged temperature history from 1850 to 1996, showing the 0.5°C (1°F) cooling associated with the eruption of Mt. Pinatubo in 1991. Anomalies are defined as deviations from the 1951–1980 mean. (From R.W. Christopherson, Geosystems: An Introduction to Physical Geography, 3/e, 1997. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)
Premise 2: Detection

Data from thermometers (red) and from tree rings, corals, ice cores and historical records (blue).
Premise 3: Attribution (to human causes)

Figure 4: Simulating the Earth’s temperature variations, and comparing the results to measured changes, can provide insight into the underlying causes of the major changes.
Global warming forecast in context of temperature record

1000 to 1861, N.Hemisphere, proxy data; 1861 to 2000 Global, instrumental; 2000 to 2100, SRES projections

Proxy

Instrumental

Theory/prediction

Bars show the range in 2100 produced by several models
Premise 1: Re-examined

\[ \Delta T_s = \lambda \Delta F \]

Premise 1:
Climate forcing over the industrial era, \( \Delta F \), has been positive and substantial in magnitude.
Premise 1: Re-examined

Knowledge of forcings as of 2001.  What is missing from this graph?

Figure 3: Many external factors force climate change.
Statistical summation of IPCC bar graph


Easy question: What causes this breadth???
Aerosol forcing dominates the uncertainty in total forcing.

To evaluate Premise 1, we need to grapple with aerosol forcing.
We propose a new method of examining Premise 1:
• more sensitive and robust than simply summing the forcings
• based on a comparison of the two, independent approaches to calculating aerosol forcings

1. **Forward calculations (study the aerosol)**
   • aerosol mass from chemical transport model
   • mass-dependent optical and cloud-nucleating properties from measurements (* our group * )
   • rapidly advancing satellite data as constraint

2. **Inverse calculations (fit the T-record)**
Forward calculation

Model-estimated direct aerosol forcings


Models: Penner et al., 1998; Grant et al., 1999; Tegen et al., 1996
Aerosol forcing is visible from space

Photo credit: NASA Earth Sciences & Image Analysis Laboratory, Johnson Space Center
Testing Premise 1

compare two, independent ways of calculating aerosol forcing

1. *Forward calculations (study the aerosol)*

2. *Inverse calculations (fit the T-record)*
   - assume Premise 1 (i.e. observed warming is the response to a substantial, positive forcing)
   - multiple runs of simple climate models with varying values for the poorly known input parameters (aerosol forcing, climate sensitivity, ocean heat diffusivity)
   - assign probabilities based on fit to simplified versions of the temperature record
Aerosol forcing estimates

Forward calculations (aerosol-based):

A. Boucher and Haywood, Clim. Dyn. 18, 297 (2001)
B. Kiehl et al., JGR, 105, 1441 (2000) (sulfate only)

Inverse calculations (T-record and climate-model-based):

J. Andronova and Schlesinger, JGR 106, 22605 (2001)
The comparison is robust method of testing Premise 1*
* Premise 1: Industrial-era forcing is positive and substantial

Case A: Boucher and Haywood

Aerosol Forcing (Wm$^{-2}$)

Forward calcs

Inverse calcs

Approximate Total Forcing (Wm$^{-2}$)

77%

19%
Aerosol forcing applications

Applications in climate studies:

N. Mitchell et al., 2001 (IPCC Chap 12) (attribution)
O. Cubasch et al., 2001 (IPCC Chap 9) (projection)
P. Tett et al., 2002, J. Geophys. Res. (attribution)
Q. Meehl et al., 2003, J. Climate (diagnosis)

M. - fits paleo temperature record with solar and volcanic forcings
- shows recent warming is anomalous and is explained by the
  known anthropogenic forcings
N. - review of detection/attribution studies for industrial era
- shows that pattern of 100-year warming is very well explained
  by the known anthropogenic and natural forcings
O. - IPCC climate change projections for various emission scenarios
P. - new detection/attribution study for industrial era
Q. - climate diagnostic study; exploring natural variability, climate
  sensitivity, etc.
IPCC (2001) Attribution summary

The graph shows temperature anomalies in °C over time, with a comparison between model predictions and observations. The graph indicates a clear trend of increasing temperature anomalies from 1850 to 2000.
By the way... fitting the T-record is not a new result


Note: very different set of forcings!

Fig. 5. Global temperature trend obtained from climate model with sensitivity 2.8°C for doubled CO₂. The results in (a) are based on a 100-m mixed-layer ocean for heat capacity; those in (b) include diffusion of heat into the thermocline to 1000 m. The forcings by CO₂, volcanoes, and the sun are based on Broecker (25), Lamb (27), and Hoyt (48). Mean ΔT is zero for observations and model.
IPCC, 2001: Forcing projection... 

*with uncertainty in current forcing*

*with uncertainty in 2100 forcing*

**Figure 19:** Simple model results: estimated historical anthropogenic radiative forcing up to the year 2000 followed by radiative forcing for the six illustrative SRES scenarios. The shading shows the envelope of forcing that encompasses the full set of thirty five SRES scenarios. The method of calculation closely follows that explained in the chapters. The values are based on the radiative forcing for a doubling of CO$_2$ from seven AOGCMs. The IS92a, IS92c, and IS92e forcing is also shown following the same method of calculation. [Based on Figure 9.13a]
Current paradigm: a firm foundation?
Discussion

Questions raised by the "red" and "yellow" zones:

1. Is the climate more sensitive than currently thought?

2. Is the surface temperature record wrong?

3. Does the observed warming represent internal climate variability?

4. Are there other radiative forcings (natural or anthropogenic) that were missed?
Conclusions and recommendations

Implications for Attribution:

• Attribution studies to date have failed to consider the full range of aerosol forcing magnitude that derives from the forward calculations.

• Thus, one must question whether the agreement found in these studies
  a. should be used to bolster confidence in the attribution of 20th century warming to GHGs (as claimed), or
  b. is fortuitously due to the choice of a small negative aerosol forcing
     (One can get agreement for the wrong reasons.)

Bottom line…
Unless and until the magnitude of negative aerosol forcing is shown to be sufficiently small, the possibility of alternative causes for the observed warming, and the possibility of high climate sensitivity, must be kept open.
Epilogue

Graph showing global temperature changes from 1860 to 2020. The graph compares observed data to predicted models by Hansen in 1987 (A, B, C), with a detection limit indicated by a dashed line.

- **Observed to 1987**
- **Hansen 88 - A**
- **Hansen 88 - B**
- **Hansen 88 - C**
- **Detection Limit**
Epilogue
Epilogue