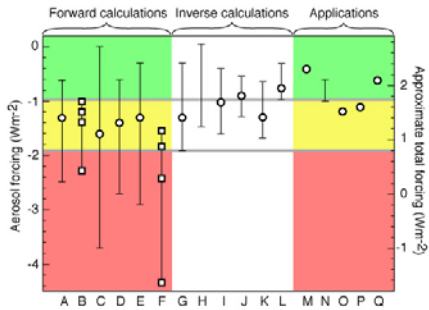


Aerosol Forcing and Causal Attribution of 20th Century Warming

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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)...

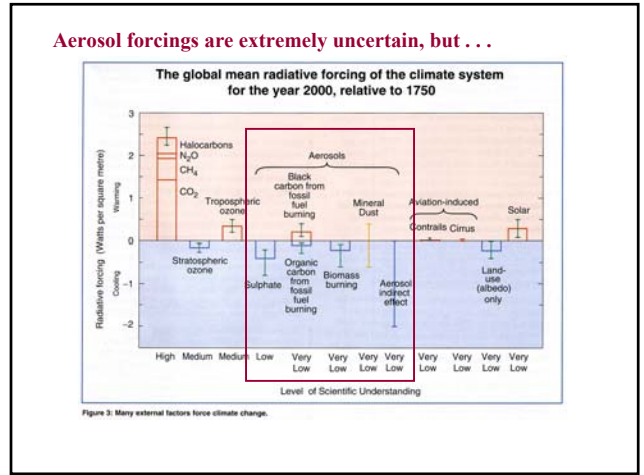
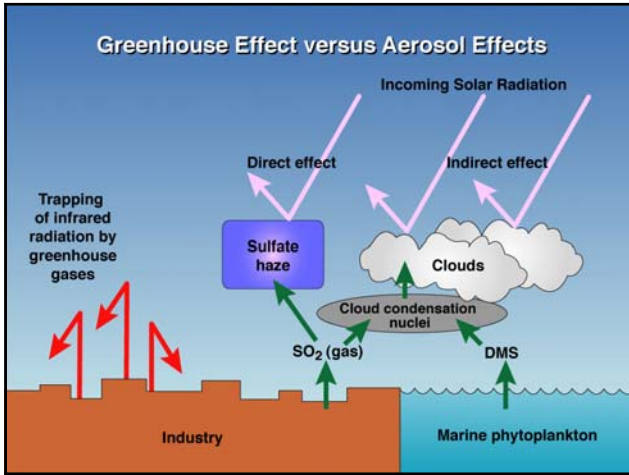
$$E_{IN} = E_{OUT}$$

shortwave, solar energy absorbed by Earth = longwave, infrared energy emitted by Earth

Forced change ...

$$\Delta T_s = \lambda \Delta F$$

ΔF : forcing, change in energy balance (W/m²)
 ΔT_s : response, change in surface temperature (K)
 λ : feedbacks, climate sensitivity {K/(W/m²)}



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:

$$\Delta T = \lambda \Delta F \quad (\text{Eq. 6.1 of IPCC, 2001})$$

ΔF : externally imposed change in TOA energy balance (W/m²)
 ΔT : resulting change in surface temperature (K)
 λ : climate sensitivity

Current GW paradigm rests on three, interconnected premises:

Premise 1: Positive Forcing

ΔF is positive and of substantial magnitude

Premise 2: "Detection"

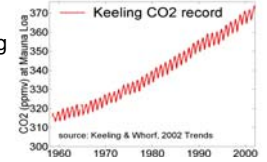
ΔT is outside the range of natural variability.

Premise 3: "Attribution" to human causes

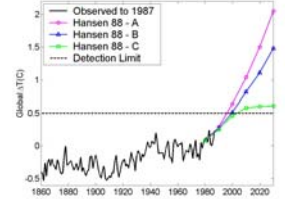
ΔT is consistent with current knowledge of ΔF and of the forcing/response relationship as embodied in climate models.

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

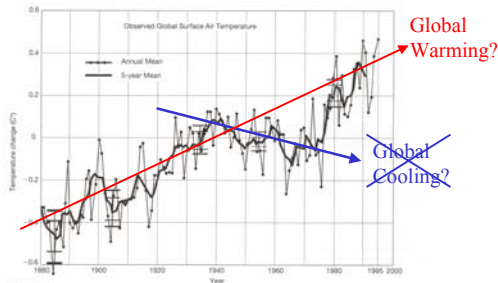
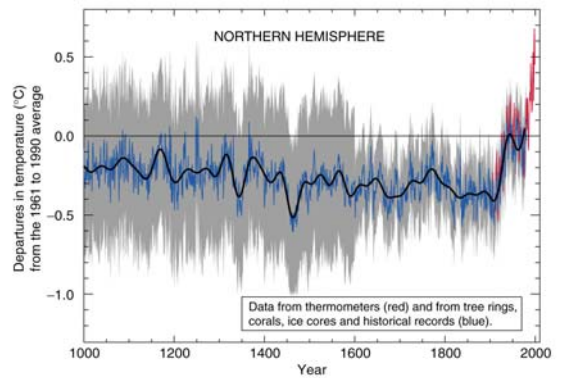


FIGURE 2-4 The globally averaged temperature history from 1950 to 1996, showing the 0.5°C (1°F) cooling associated with the eruption of Mt. Pinatubo in 1991. Anomalies are defined as deviations from the 1951–1980 mean. (From R. W. Christy et al., *Global Surface Temperature Anomalies*, in *Introduction to Physical Geography*, 3rd ed., 1997. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

Premise 2: Detection



Premise 3: Attribution (to human causes)

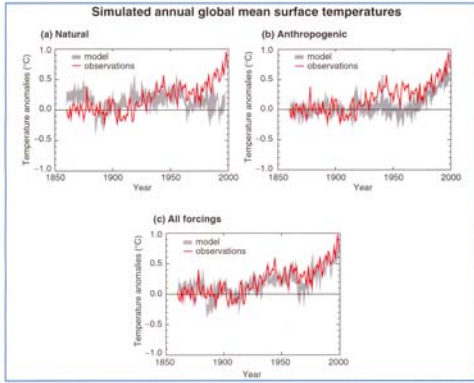
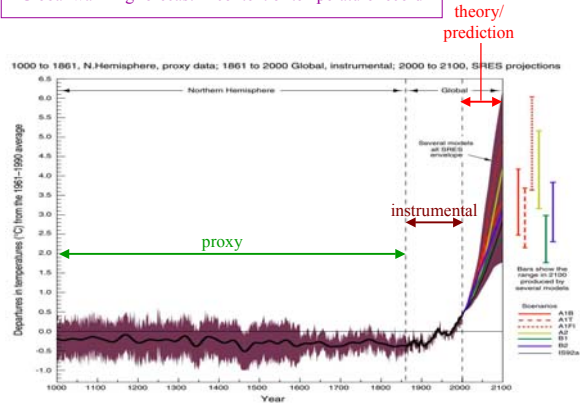


Figure 4: Simulating the Earth's temperature variations, and comparing the results to measured changes, can provide insight into the underlying causes of the major changes.

Global warming forecast in context of temperature record



Premise 1: Re-examined

$$\Delta T_s = \lambda \Delta F$$

Premise 1:

Climate forcing over the industrial era, ΔF , has been positive and substantial in magnitude.

Premise 1: Re-examined

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

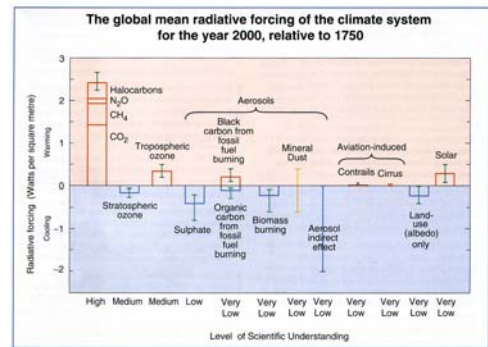
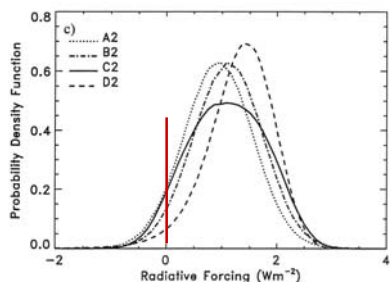


Figure 3: Many external factors force climate change.

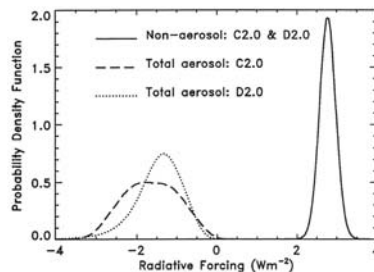
Statistical summation of IPCC bar graph



reference: Boucher and Haywood, 2001, *Clim. Dyn.* 18, 297.

Easy question: What causes this breadth???

Boucher and Haywood (cont)



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

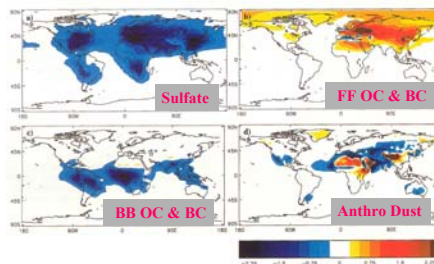
1. *Forward calculations (study the aerosol)*

- 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



Haywood, J and O Boucher, *Revs. Geophys.*, 38, 513-543, 2000

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):

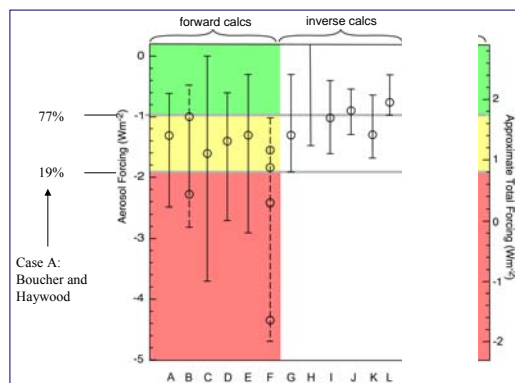
- Boucher and Haywood, *Clim. Dyn.* 18, 297 (2001)
- Kiehl et al., *JGR*, 105, 1441 (2000) (*sulfate only*)
- Hansen and Sato, *Proc. NAS* 98, 14778 (2001)
- Hansen et al., *Proc. NAS* 95, 12753 (1998)
- Schwartz and Andreae, *Science* 296, 2139 (1996)
- Menon et al., *J Atmos Sci* 59, 692 (1998) ; Lohmann and Feichter, *JGR* 102, 13685 (1997) (*indirect only*)

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

- Wigley and Raper, *Science* 293, 451 (2001)
- Harvey and Kaufmann, *J. Clim.* 15, 2837 (2002)
- Gregory et al., *J. Clim.* 15, 3117 (2002)
- Andronova and Schlesinger, *JGR* 106, 22605 (2001)
- Knutti et al., *Nature* 416, 719 (2002)
- Forest et al., *Science* 295, 113 (2002)

The comparison is robust method of testing Premise 1*

* Premise 1: Industrial-era forcing is positive and substantial



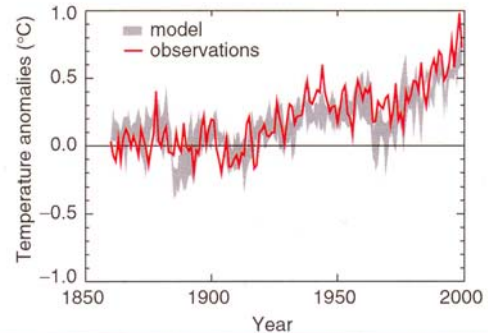
Aerosol forcing applications

Applications in climate studies:

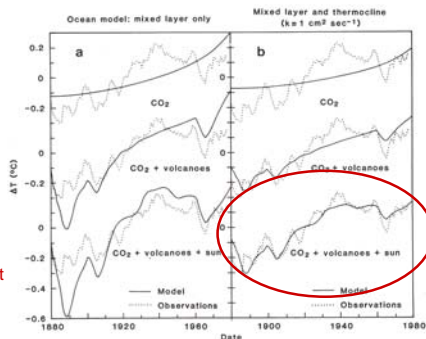
| | |
|---|---------------|
| M. Crowley, Science 289, 270 (2000) | (attribution) |
| N. Mitchell et al., 2001 (IPCC Chap 12) | (attribution) |
| O. Cubasch et al., 2001 (IPCC Chap 9) | (projection) |
| P. Tett et al., 2002, J. Geophys. Res. | (attribution) |
| Q. Meehl et al., 2003, J. Climate | (diagnosis) |

- 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



By the way... fitting the T-record is not a new result



Source:
Hansen et al.
1981, Science,
213, 957-966

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 (46). Mean ΔT is zero for observations and model.

IPCC, 2001: Forcing projection...

with uncertainty in current forcing

with uncertainty in 2100 forcing

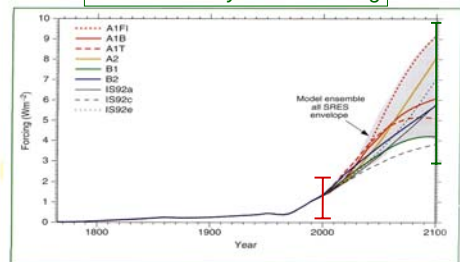
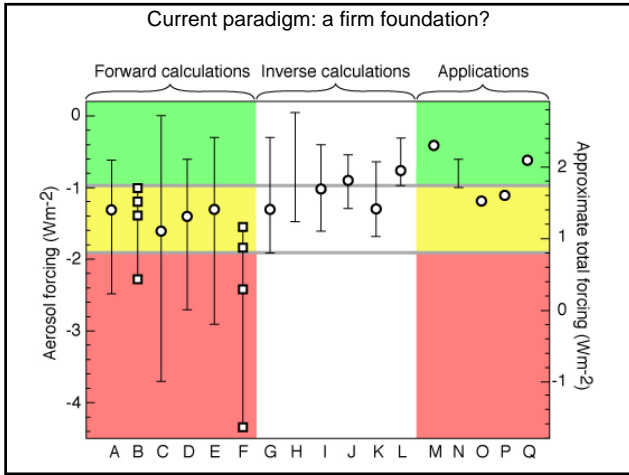


Figure 19: Simple model results: estimated historical anthropogenic radiative forcing up to the year 2000 followed by radiative forcing for the six illustrative SRES scenarios. The shading shows the envelope of forcing that encompasses the full set of thirty-five SRES scenarios. The method of calculation closely follows that explained in the chapters. The values are based on the radiative forcing for a doubling of CO₂ from seven AOGCMs. The IS92a, IS92c, and IS92e forcing is also shown following the same method of calculation. [Based on Figure 9.13a]



Discussion

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

$\Delta T \propto \lambda \Delta F$ 1. Is the climate **more sensitive** than currently thought?

$\Delta T = \lambda \Delta F$ 2. Is the **surface temperature record** wrong?

$\Delta T = \lambda \Delta F$ 3. Does the observed warming represent **internal climate variability**?

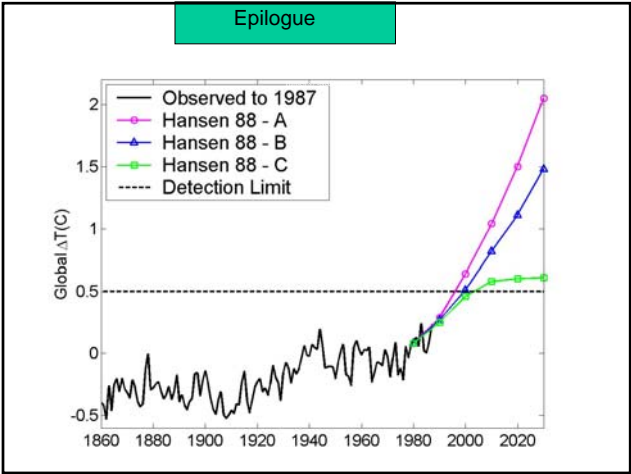
$\Delta T = \lambda \Delta F$ 4. Are there **other radiative forcings** (natural or anthropogenic) that were missed?

Conclusions and recommendations

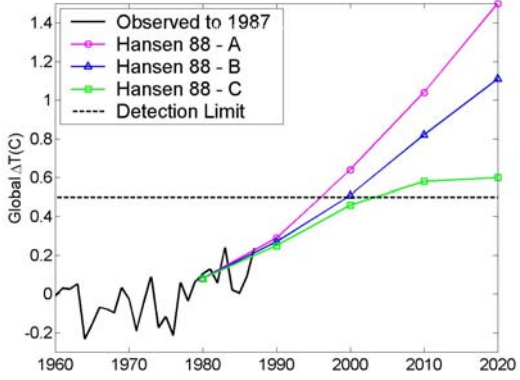
- Implications for Attribution:*
- Attribution studies to date have failed to consider the full range of aerosol forcing magnitude that derives from the forward calculations.
 - Thus, one must question whether the agreement found in these studies
 - a. should be used to bolster confidence in the attribution 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



Epilogue



Epilogue

