MODELING RADIATIVE FORCING BY AEROSOLS

HOW GOOD IS *GOOD ENOUGH?*

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Integrating Aerosol Measurements and Models

Fall Meeting

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http://www.ecd.bnl.gov/steve/schwartz.html

TOP-LEVEL QUESTION IN CLIMATE CHANGE SCIENCE

- ***How much will the global mean temperature change?***

$$\Delta T = \lambda F$$

where F is the ***forcing*** and λ is the ***climate sensitivity***.

- A ***forcing*** is a change in a radiative flux component, W m^{-2}.
- Forcings are thought to be ***additive*** and ***fungible***.

- ***What is Earth's climate sensitivity?***
  - ***National Academy Report (Charney, 1979):***

"We estimate the most probable global warming for a doubling of CO_2 to be ***near 3 degrees C***, with a probable error of ***plus or minus 1.5 degrees***.

- ***Intergovernmental Panel on Climate Change (IPCC, 2001):***

"Climate sensitivity [to CO_2 doubling] is likely to be in the range ***1.5 to 4.5˚C***.

HOW CAN CLIMATE SENSITIVITY BE DETERMINED?

Climate sensitivity $\lambda = \Delta T / F$

- ***Climate models*** evaluated by performance on prior climate change and/or
- ***Empirical determination*** from prior climate change
- Either way, ΔT and F must be determined with sufficiently small uncertainty to yield an uncertainty in λ that is useful for informed decision making.
- Present generally accepted uncertainty in λ (1.5 to 4.5˚C) — a factor of 3 — is not very useful for policy planning purposes.
- ***Uncertainty may be much greater!***

CONCLUSIONS

- ***Radiative forcing of climate change by anthropogenic aerosols is substantial in the context of other forcings of climate change over the industrial period.***

  Global annual mean aerosol forcing of -1 to -3 W m^{-2} is plausible given present understanding.

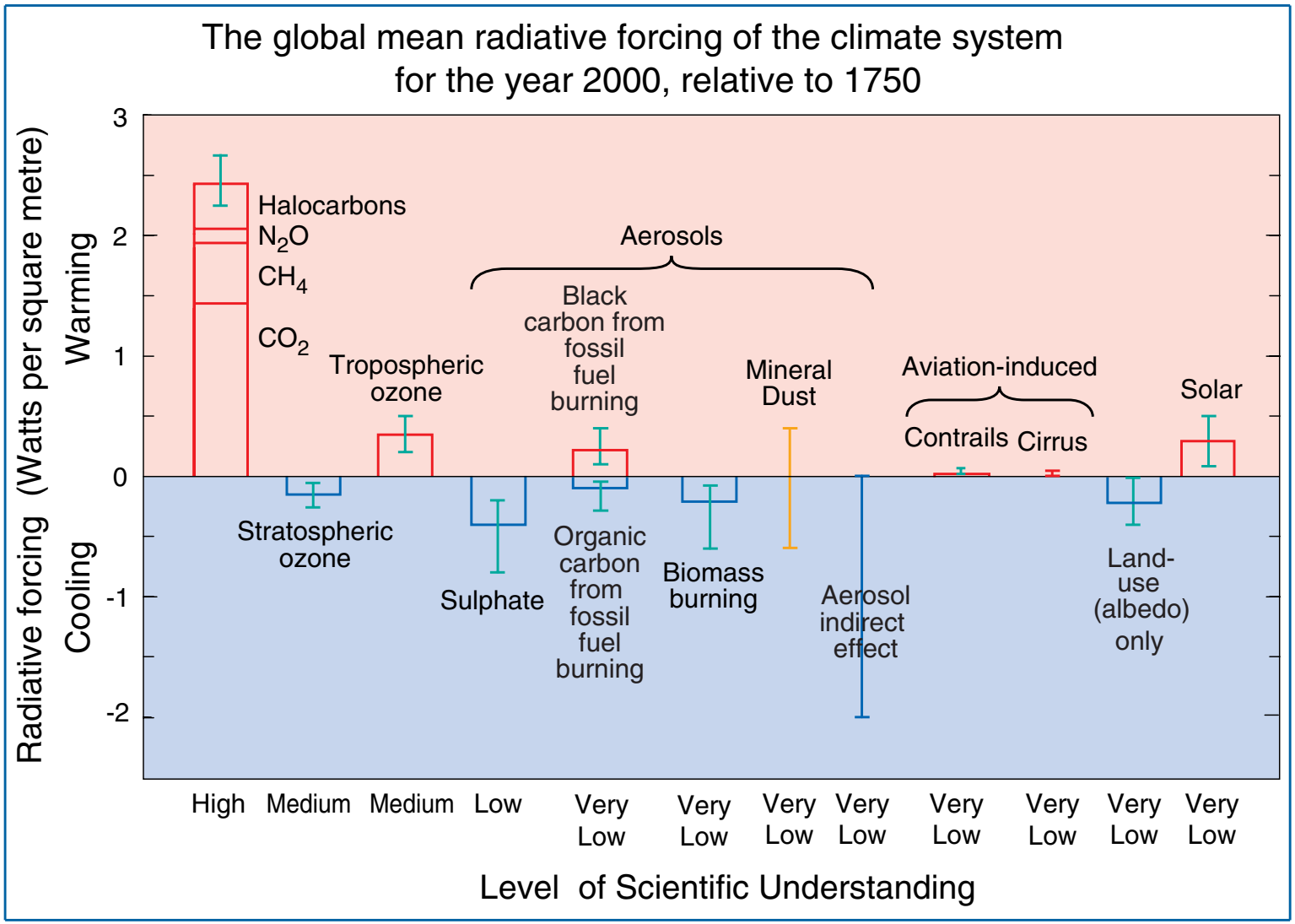
- ***Uncertainty in radiative forcing of climate change by anthropogenic aerosols is the greatest source of uncertainty in forcing of climate change.***

  This uncertainty precludes:

  - ***Evaluation of models*** of climate change.
  - ***Inference of climate sensitivity*** from temperature changes over the industrial period.
  - ***Informed policy making*** on greenhouse gases.

- ***Uncertainty in aerosol forcing must be reduced at least three-fold for uncertainty in climate sensitivity to be meaningfully reduced and bounded.***

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)

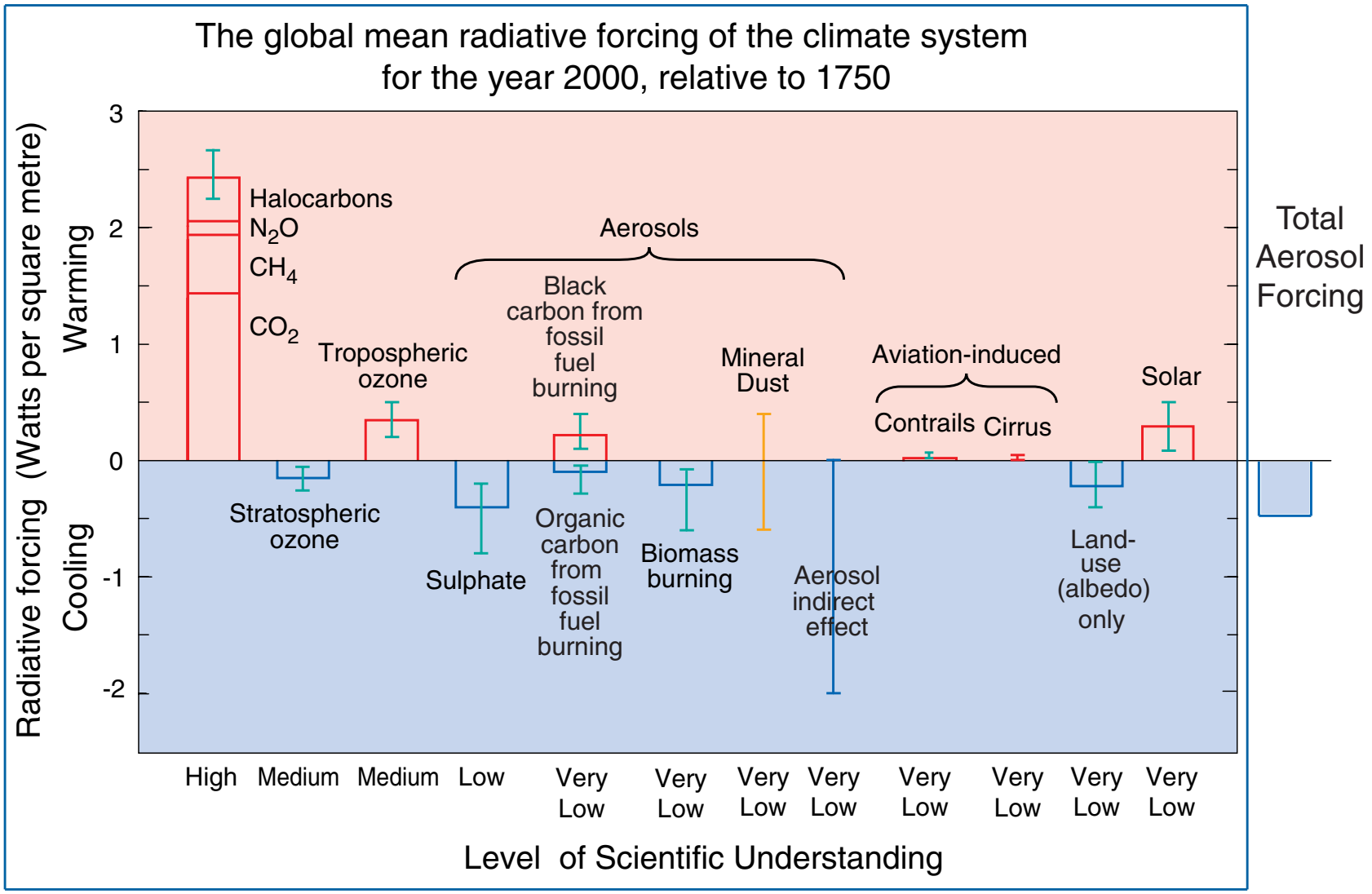


Summary for Policymakers

A Report of Working Group I of the Intergovernmental Panel on Climate Change

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)

With total aerosol forcing



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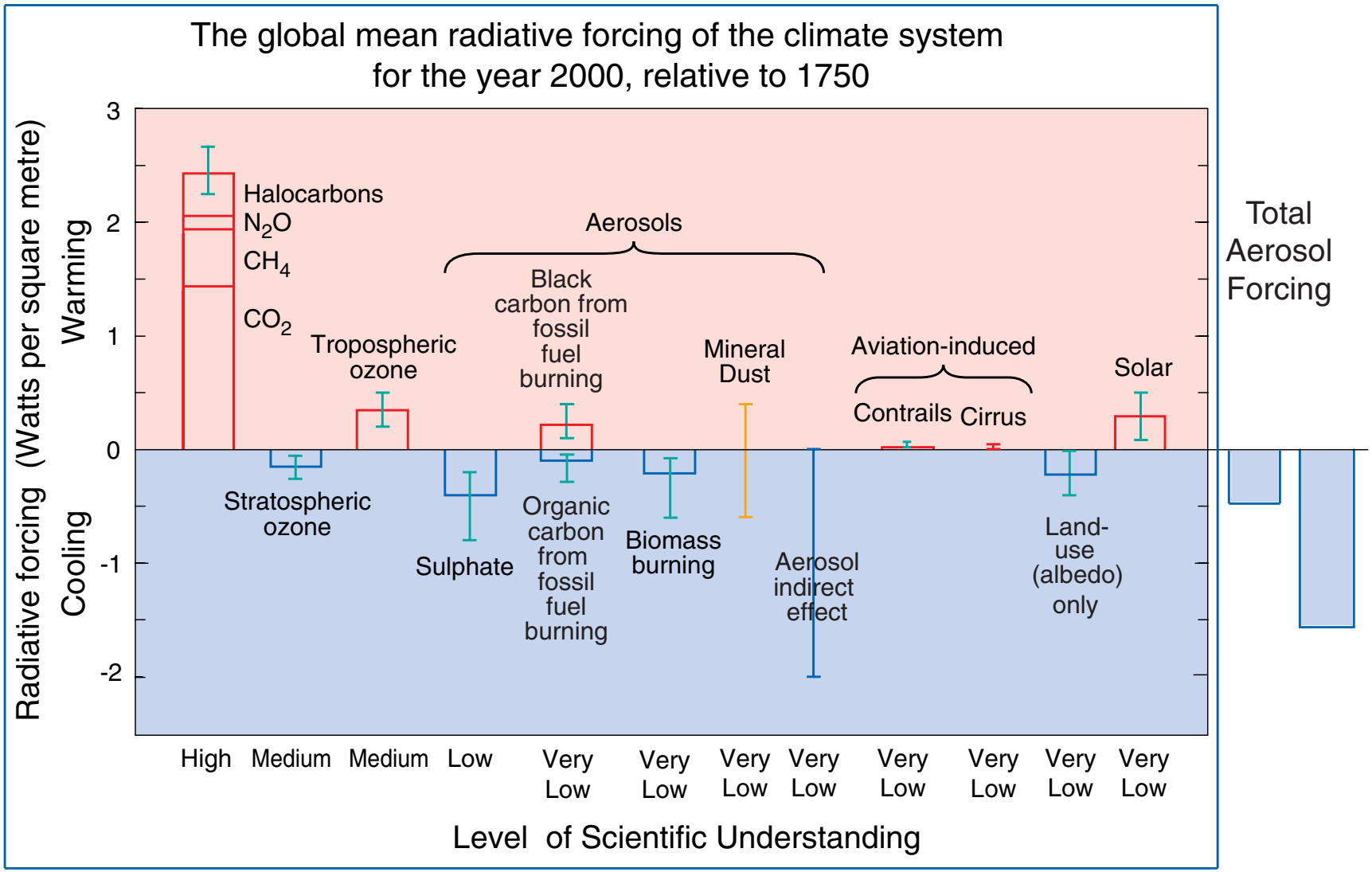
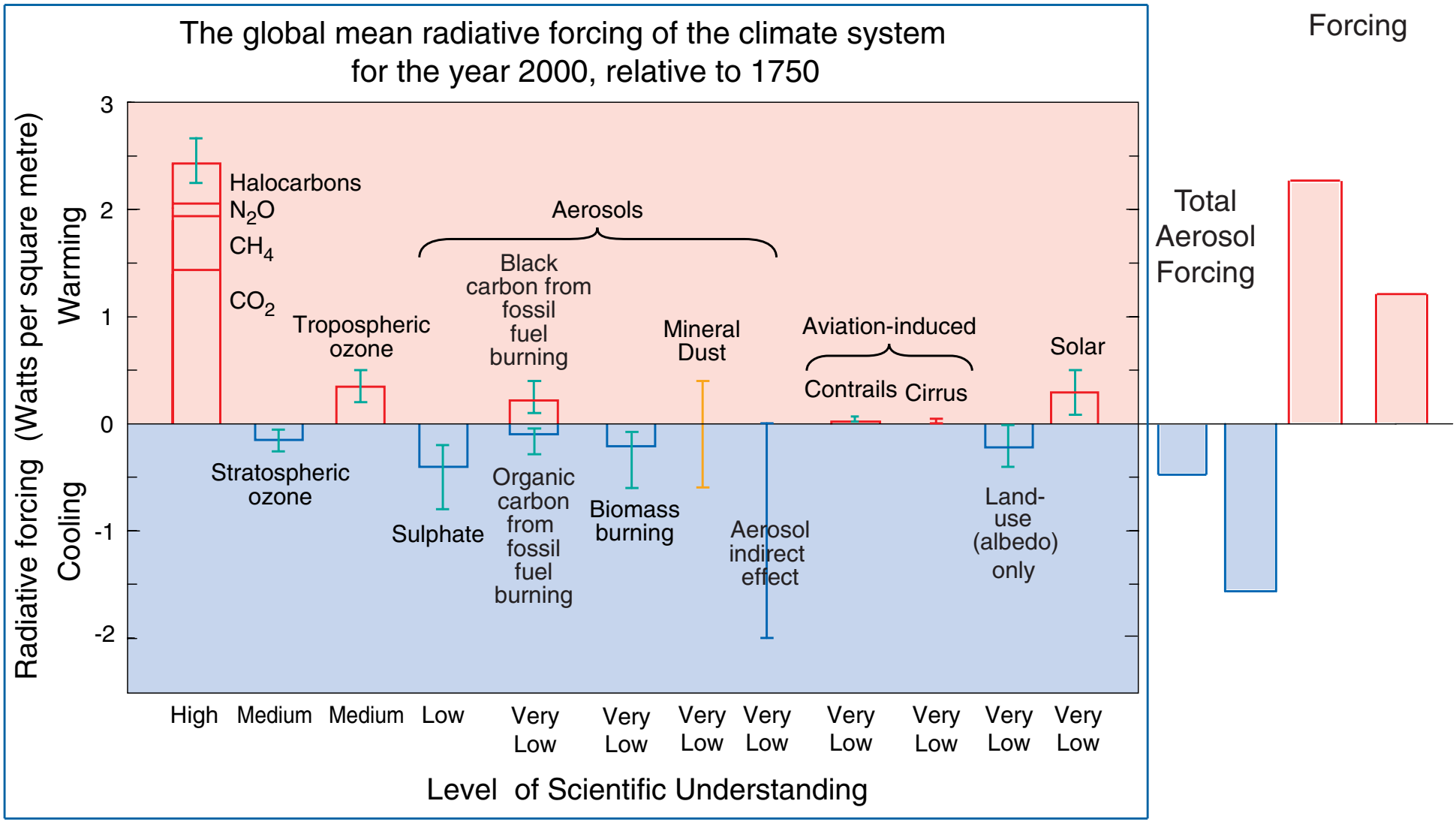


RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)
With total aerosol forcing and total forcing



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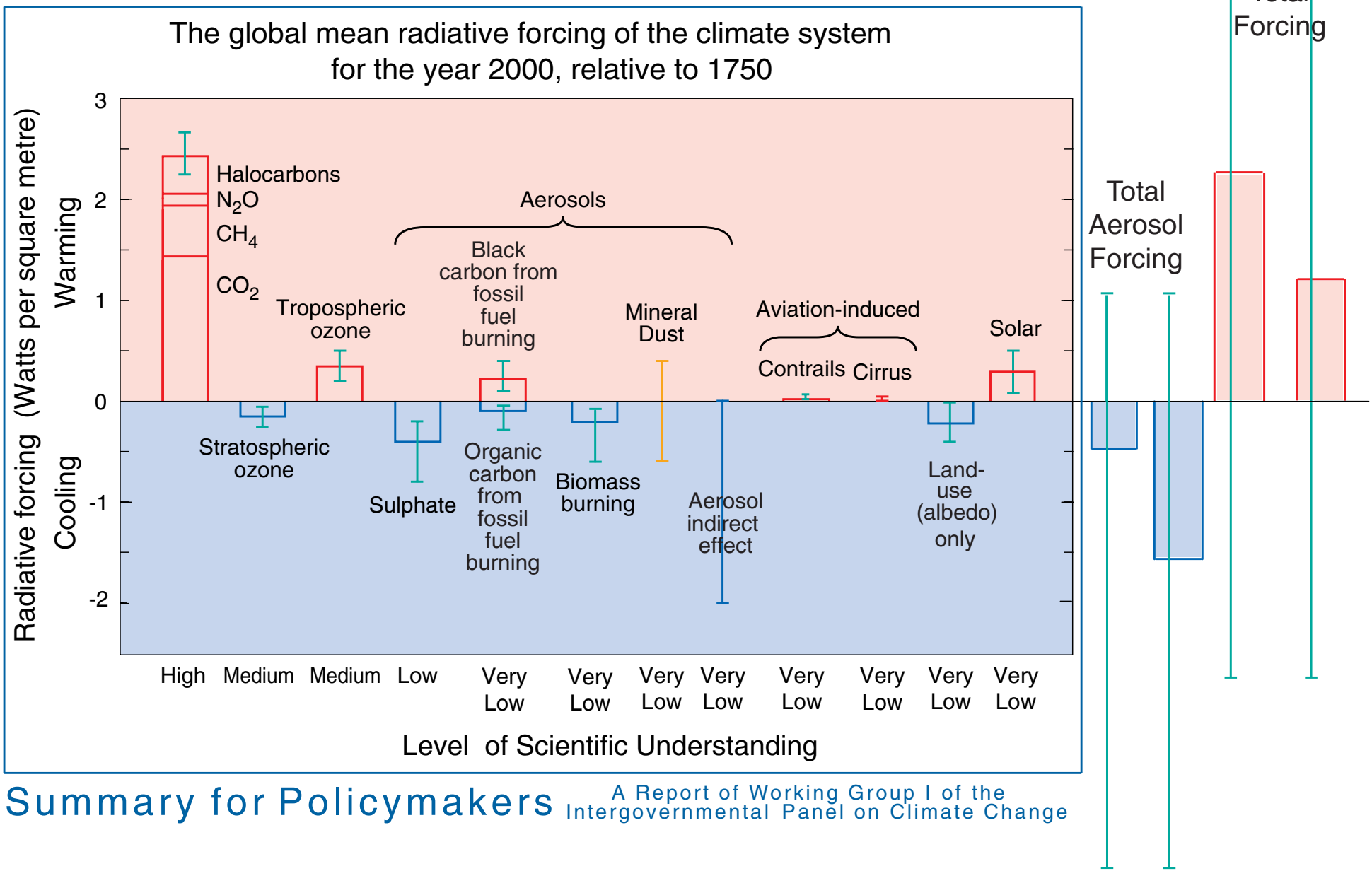

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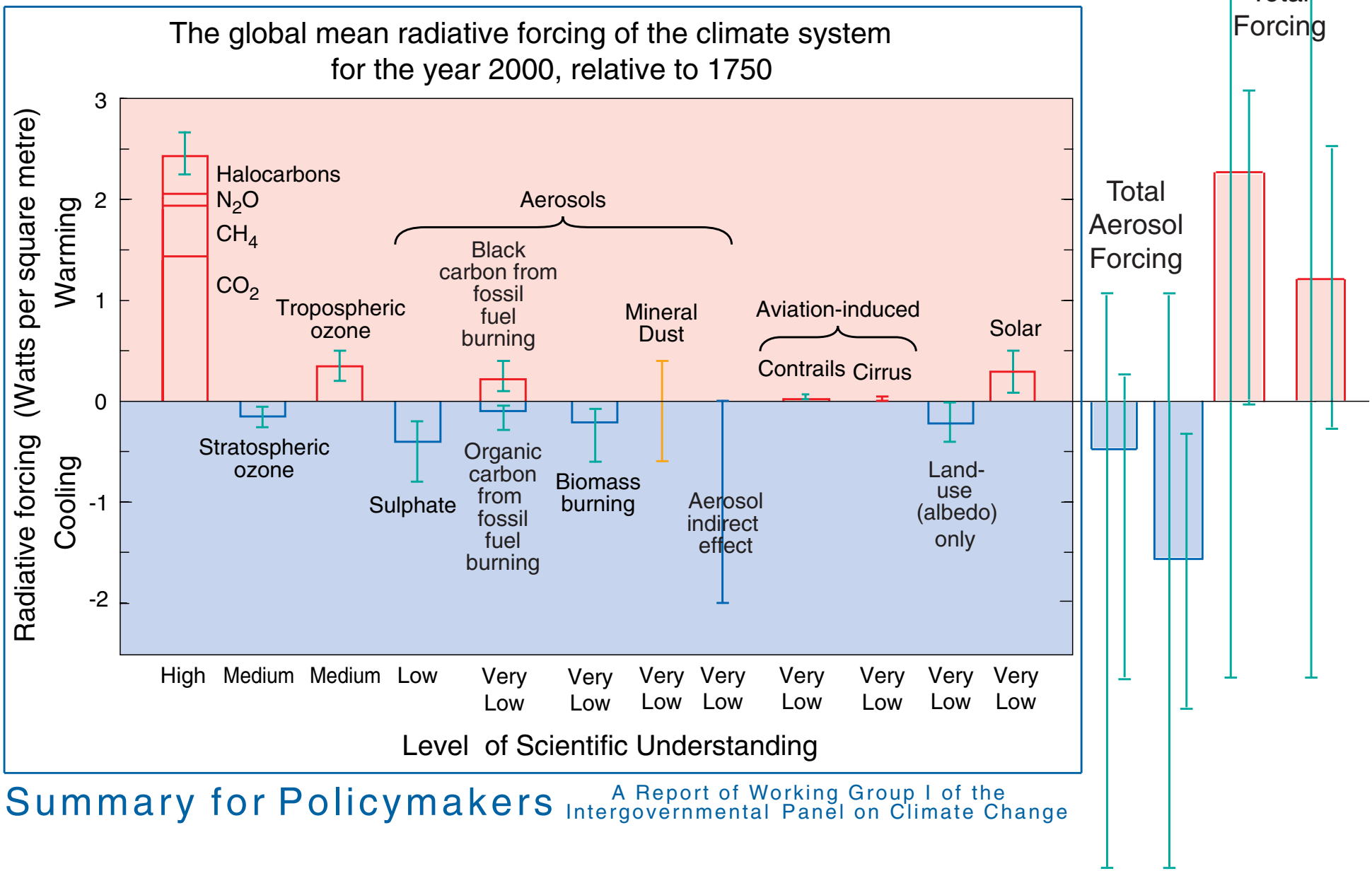

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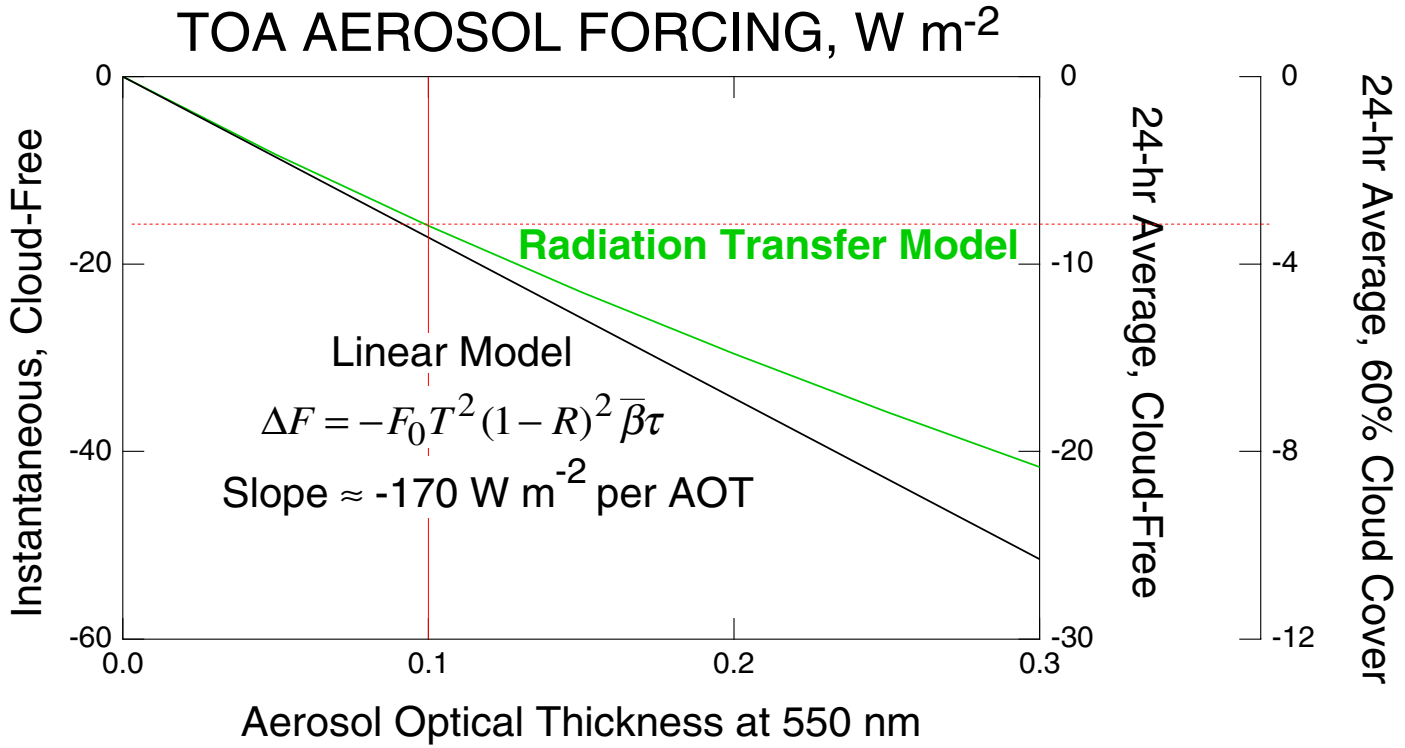
DIRECT AEROSOL FORCING

***Forcing* = (*Forcing per aerosol amount*) × (*Aerosol amount*)**

Comparison of linear formula and radiation transfer model

Particle radius r = 85 nm; surface reflectance R = 0.15; single scatter albedo ω_0 = 1.



Forcing is highly sensitive to modest aerosol loadings.

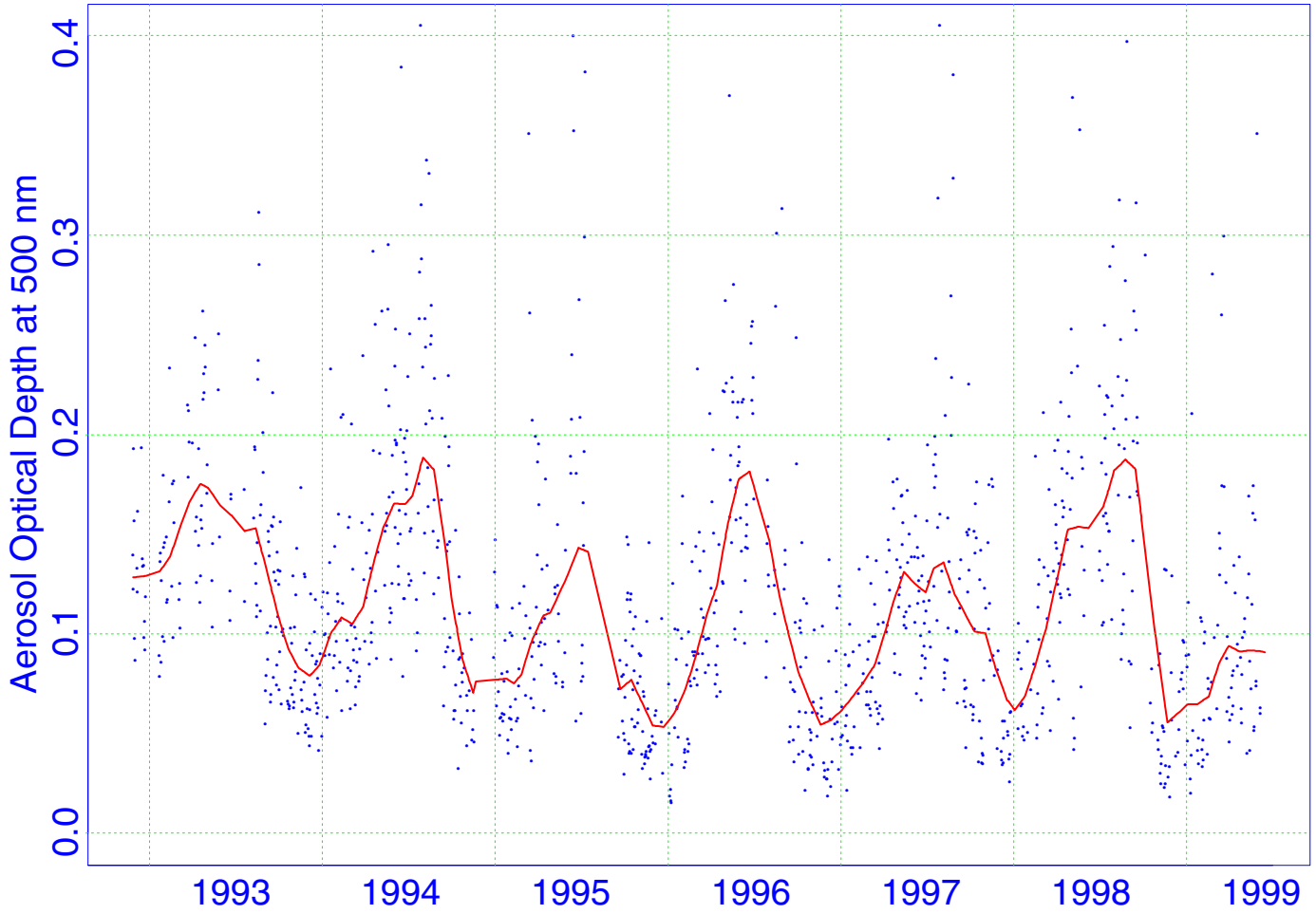
Global-average AOT 0.1 corresponds to global-average forcing -3.2 W m^{-2}.

Linear model is accurate and convenient, especially for error budgets.

AEROSOL OPTICAL DEPTH

Determined by Sunphotometry

North Central Oklahoma - Daily Average



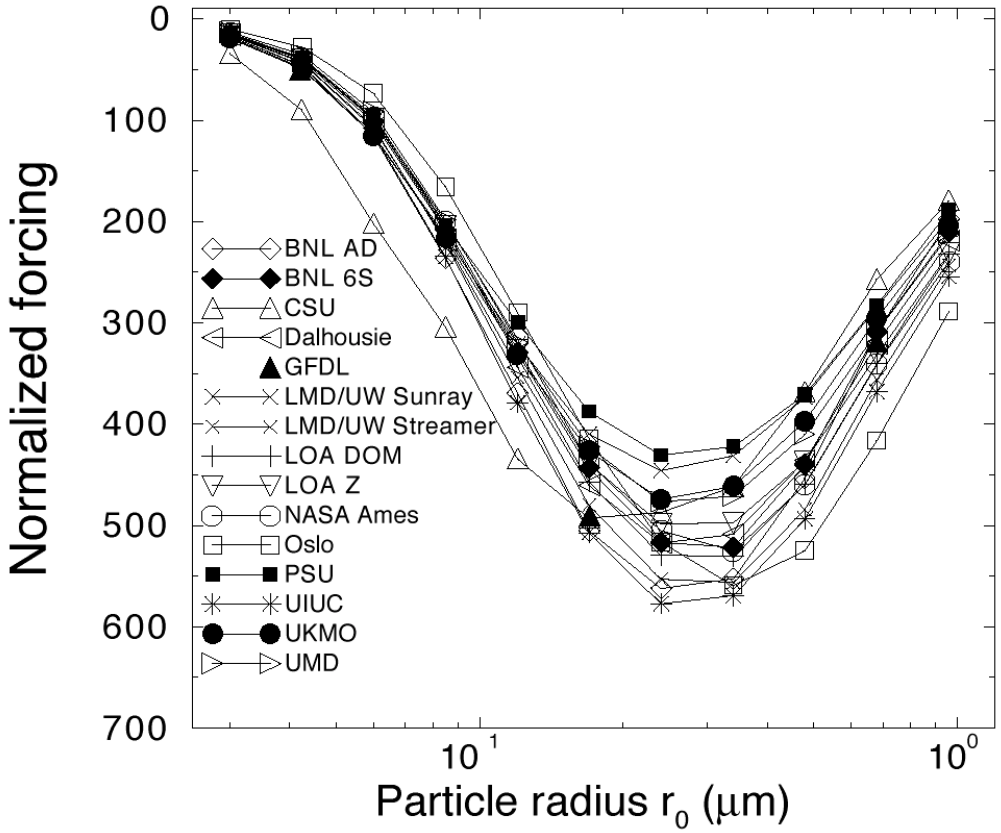
J. Michalsky et al., JGR, 2001

Variability is due to variability in tropospheric aerosols.
Optical depth variability of 0.1 is common even at a rural mid-continental site.

INTERCOMPARISON OF BROADBAND SHORTWAVE FORCING BY AMMONIUM SULFATE AEROSOL

Normalized global-average forcing: W m^{-2} / g(SO_4^{2-}) m^{-2} or W /g(SO_4^{2-})

Aerosol optical depth 0.2; surface albedo 0.15

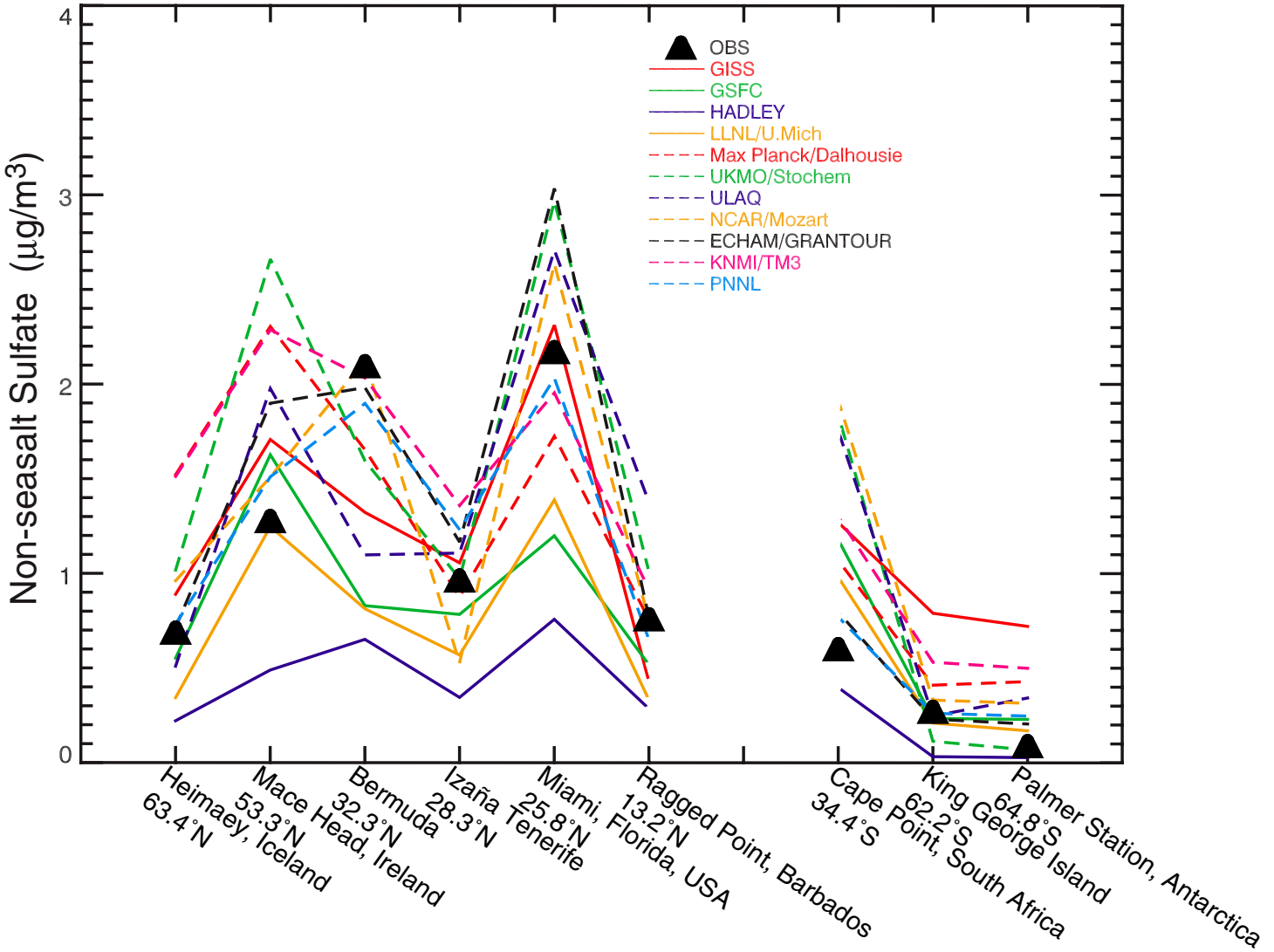


Standard deviation ~8% for 15 models at radius ~ 200 nm.

Boucher, Schwartz and 28 co-authors, JGR, 1998

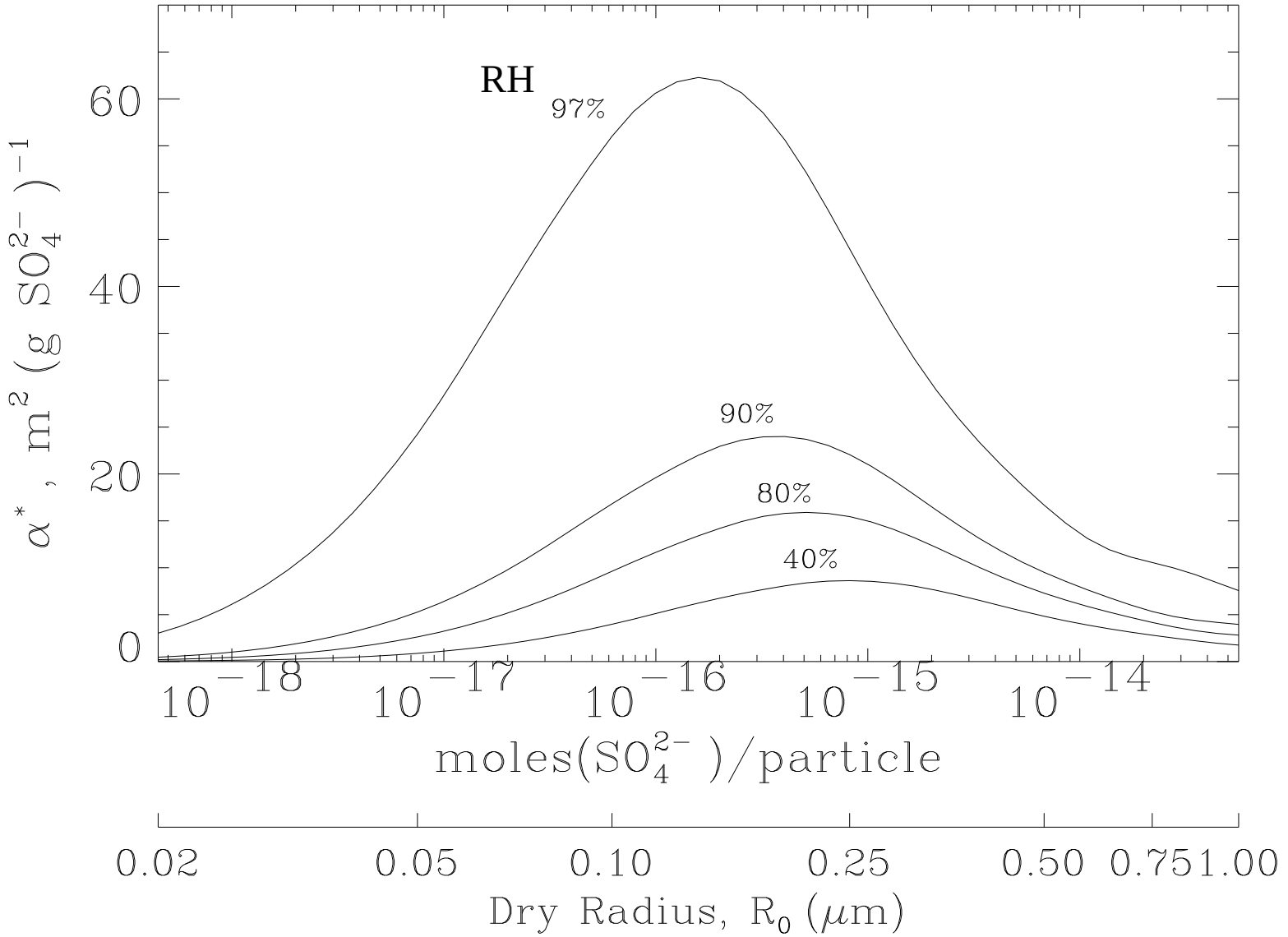
SULFATE MODEL INTERCOMPARISON

Annual average non-seasalt sulfate in 11 chemical transport models and comparison with observations at nine stations



Penner et al., IPCC, 2001

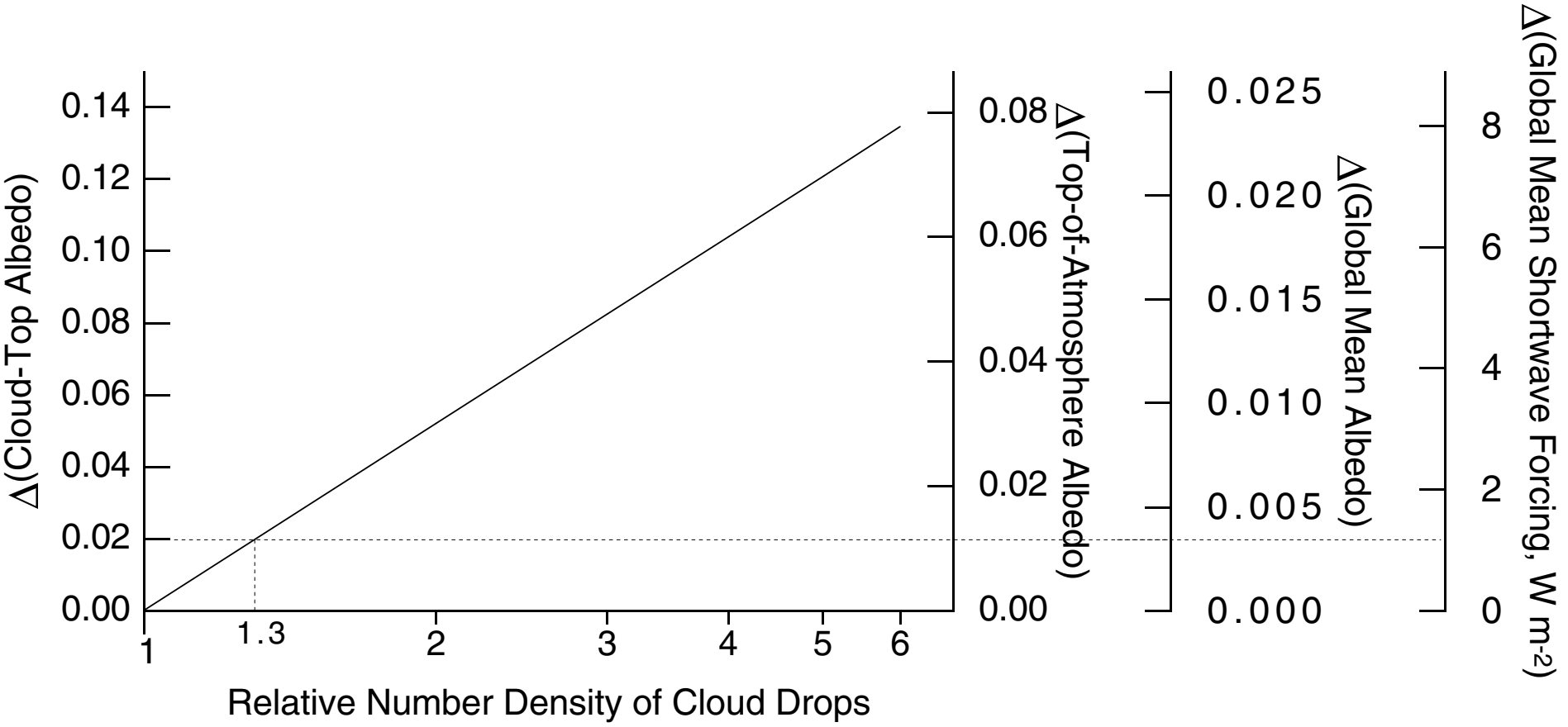
LIGHT SCATTERING EFFICIENCY OF $(NH_4)_2SO_4$ DEPENDENCE ON PARTICLE SIZE AND RH



Nemesure,Wagener & Schwartz, JGR, 1995

INDIRECT AEROSOL FORCING

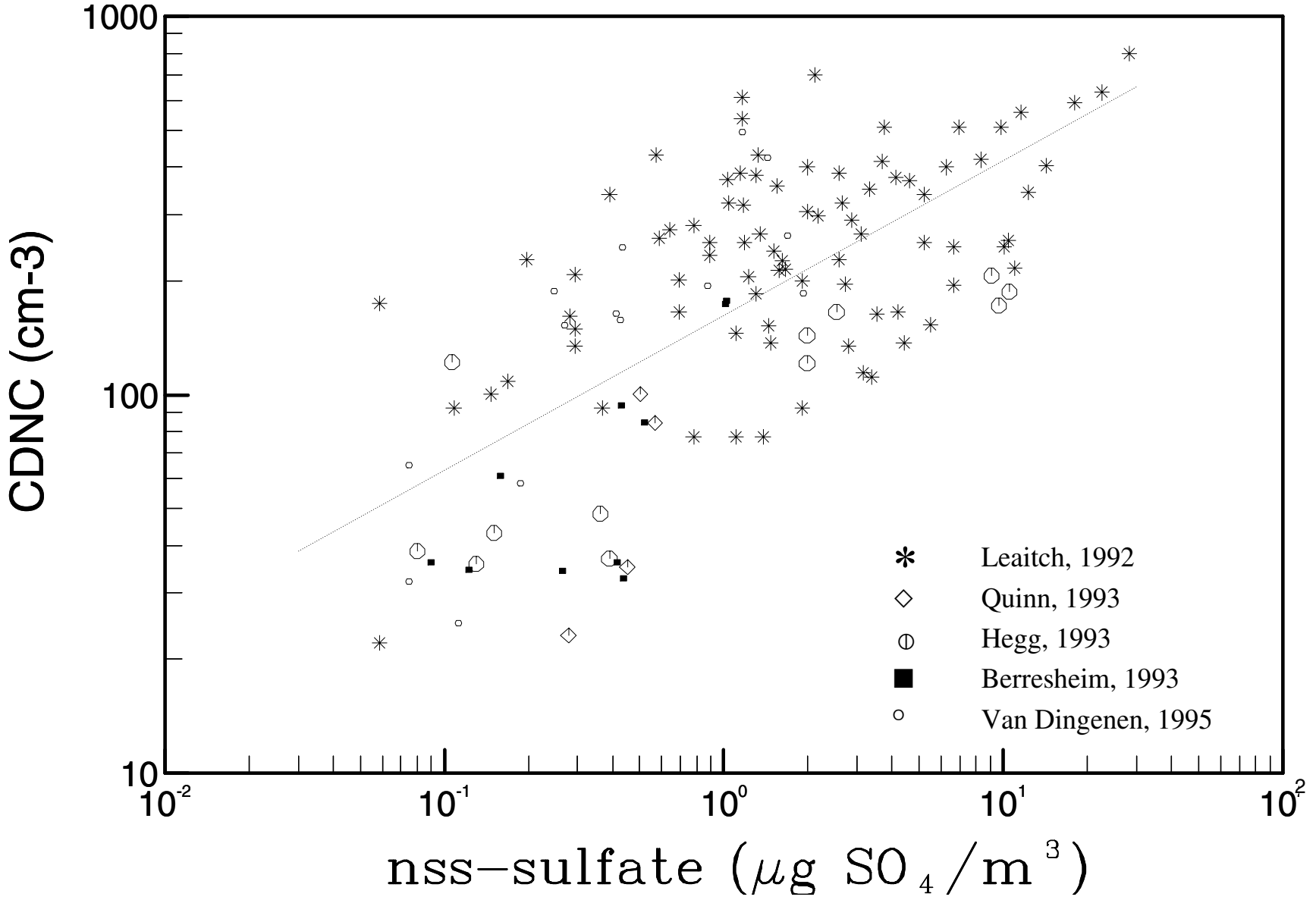
SENSITIVITY OF ALBEDO AND FORCING TO CLOUD DROP CONCENTRATION



Schwartz and Slingo (1996)

CLOUD DROPLET NUMBER CONCENTRATION

Dependence on Non-Seasalt Sulfate

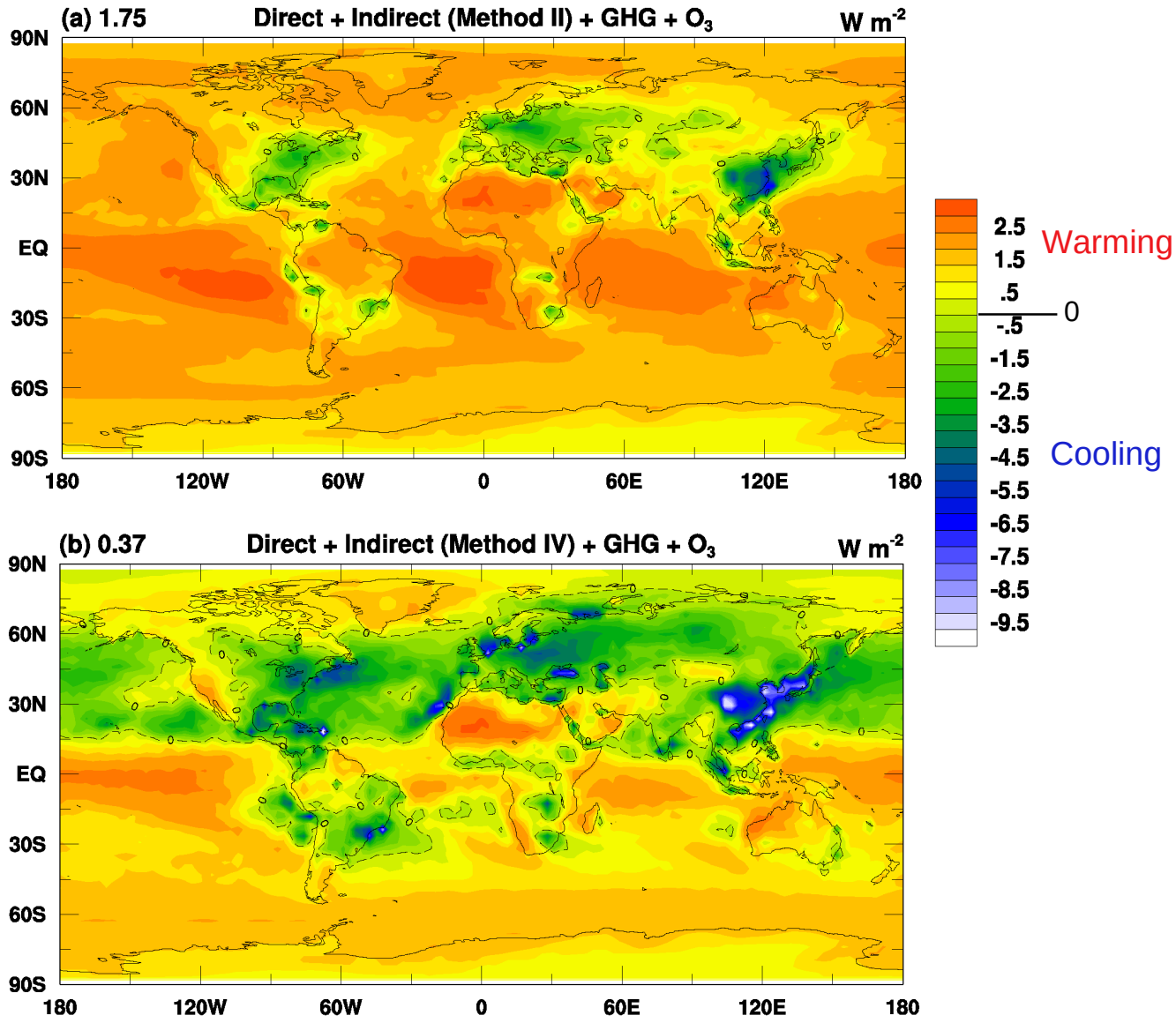


Boucher and Lohmann, 1995

SHORTWAVE FORCING, ANNUAL AVERAGE

GHG's + O_3 + Sulfate (Direct and Indirect)

Two Formulations of Cloud Droplet Concentration

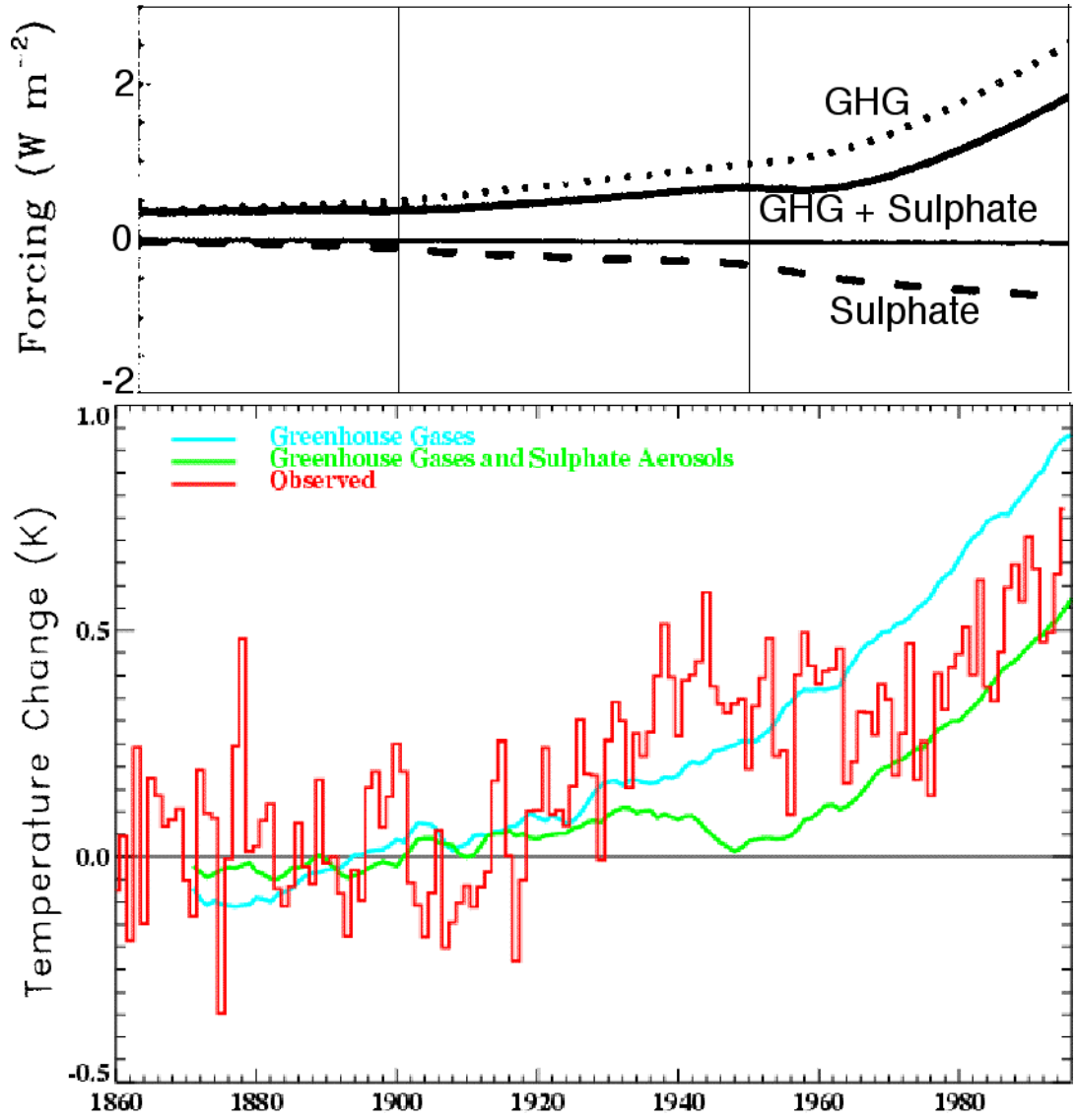


Kiehl et al., JGR, 2000

REPRESENTING AEROSOL INFLUENCES IN CLIMATE MODELS

FORCING AND RESPONSE IN THE UK MET OFFICE MODEL (1995)

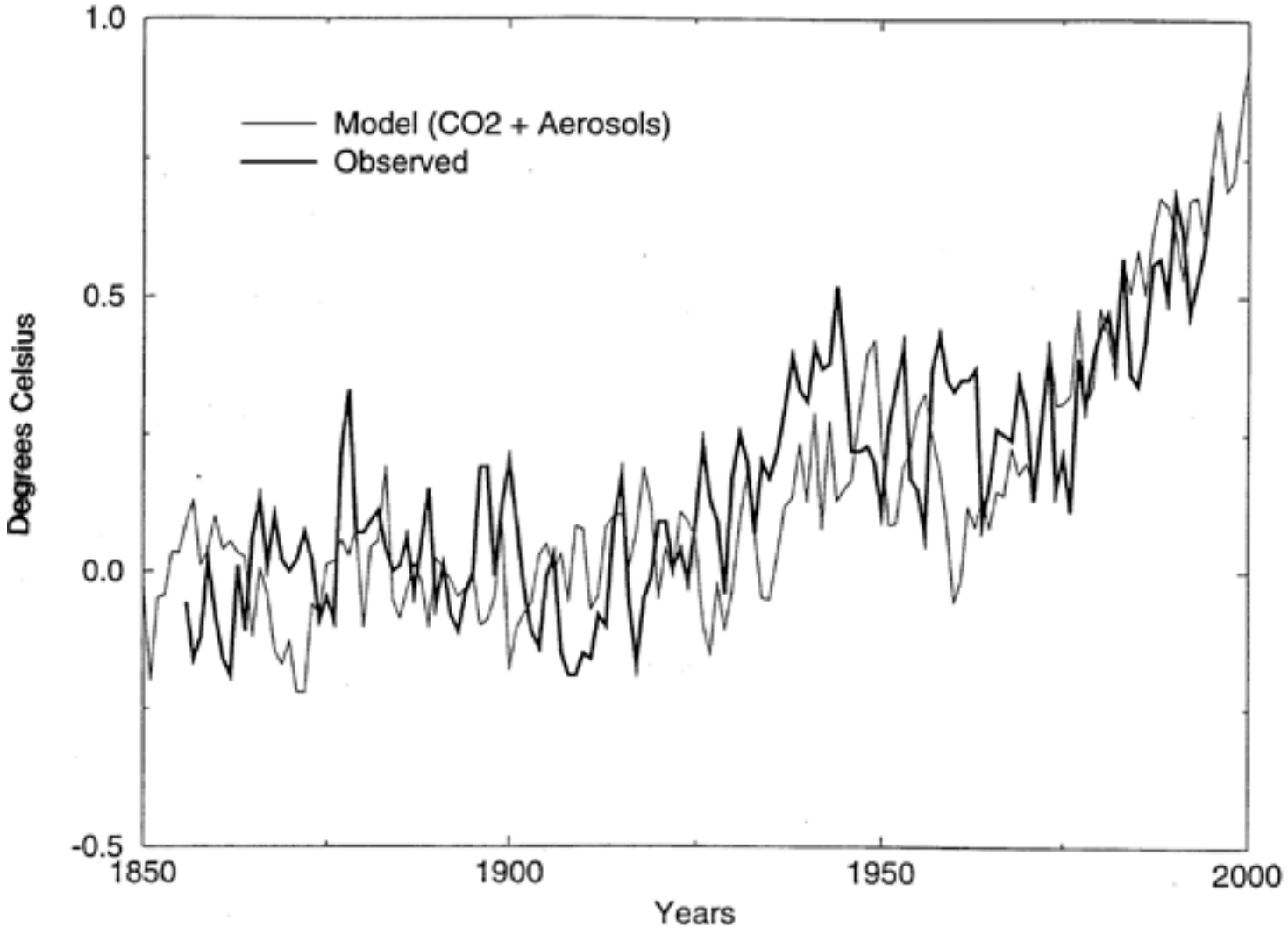
Model sensitivity = 2.5 K per CO_2 doubling; sulfate direct forcing only, -0.6 W m^{-2} (1990)



"Inclusion of sulphate aerosol forcing ***improves the simulation*** of global mean temperature over the last few decades." -- *Mitchell, Tett, et al., Nature, 1995*

CLIMATE RESPONSE IN THE GFDL MODEL (1997)

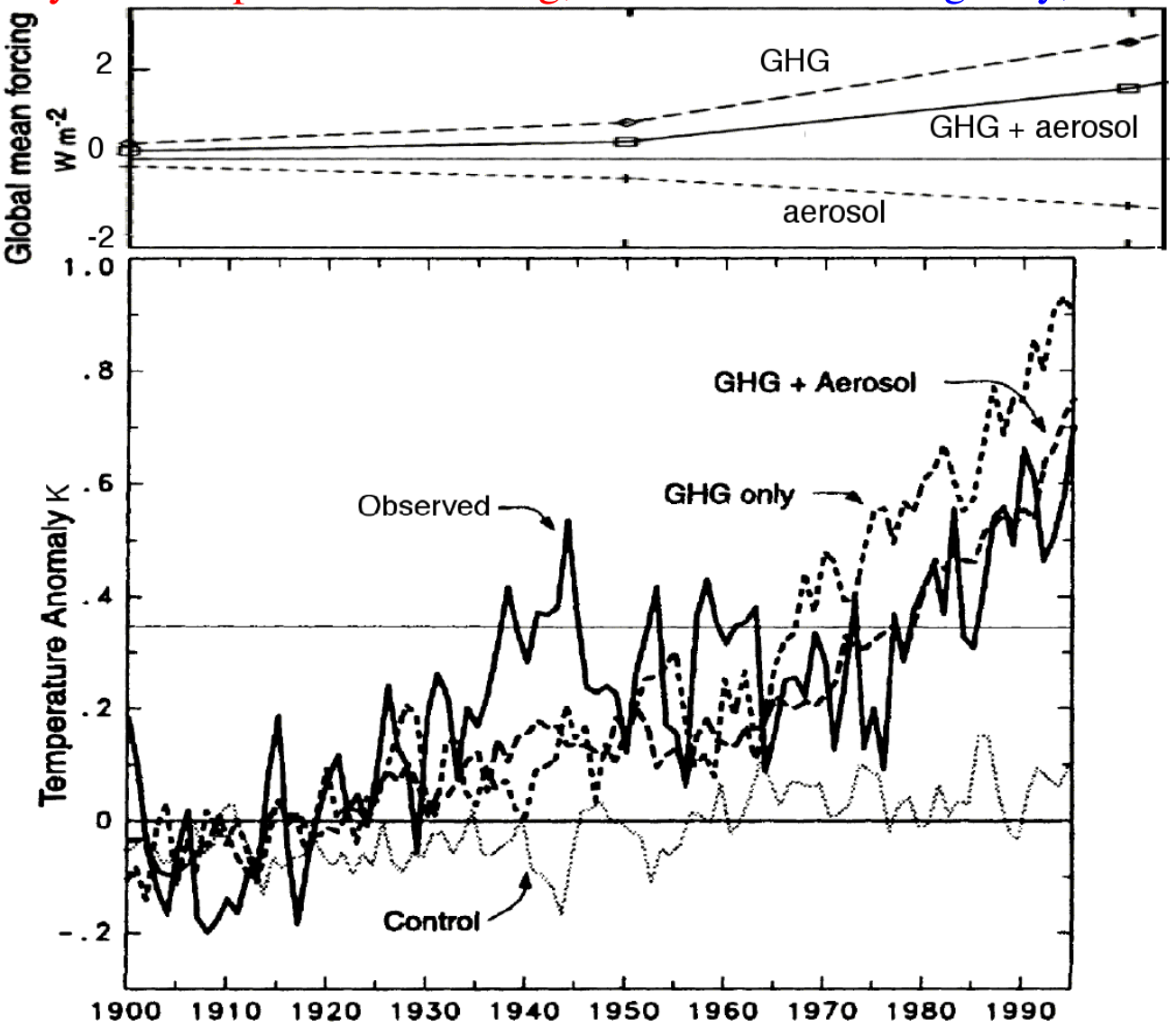
Model sensitivity = 3.7 K per CO_2 doubling; sulfate direct forcing only, -0.6 W m^{-2} (1990)



"The global average SAT trend from the model [is] in ***reasonable agreement*** with the observations." -- *Haywood, Ramaswamy et al., Geophys. Res. Lett, 1997*

FORCING AND RESPONSE IN THE CANADIAN CLIMATE MODEL (2000)

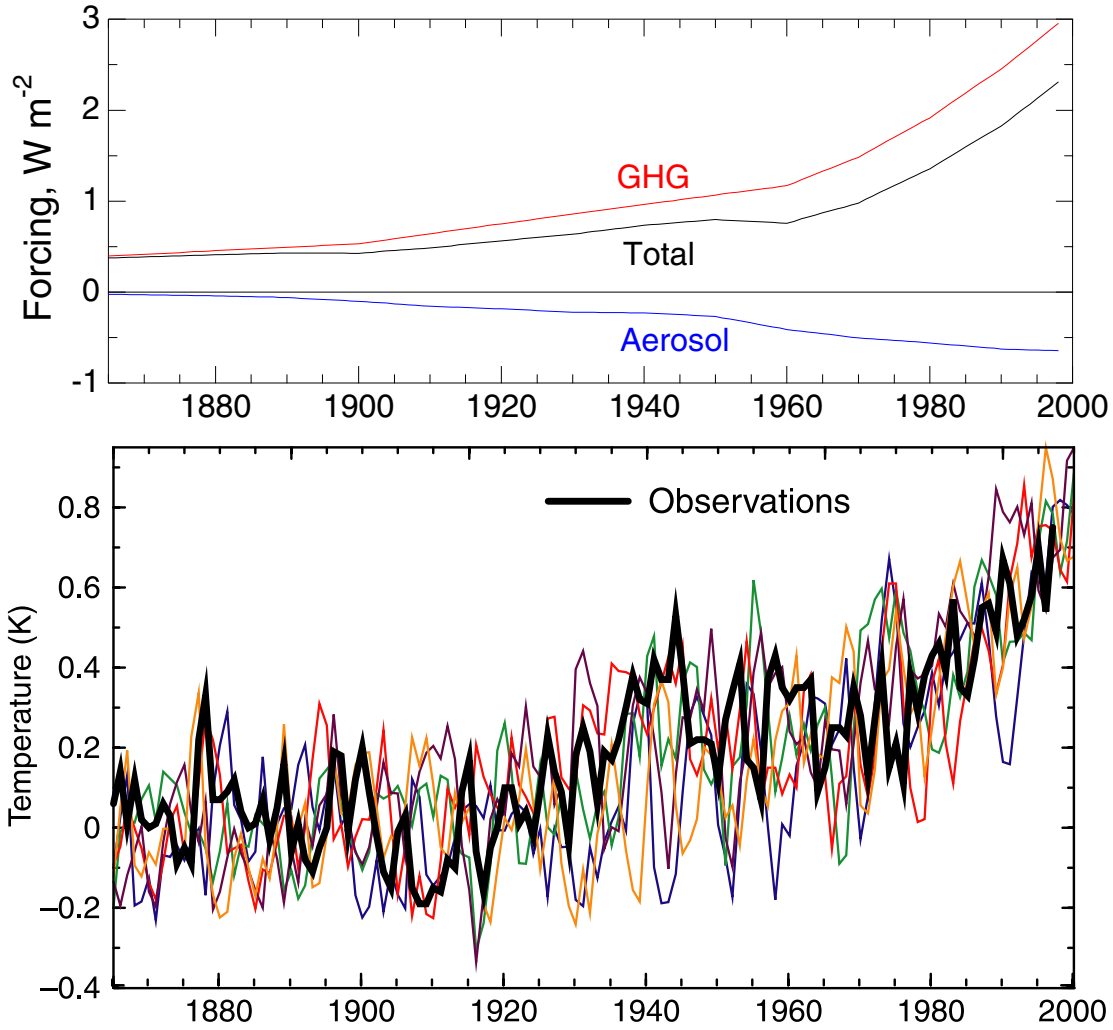
Model sensitivity = 3.5 K per CO_2 doubling; sulfate direct forcing only, -1.0 W m^{-2} (1990)



"Observed global mean temperature changes and those simulated for GHG + aerosol forcing show ***reasonable agreement***." -- *Boer, et al., Climate Dynamics, 2000*

FORCING AND RESPONSE IN THE GFDL MODEL (2000)

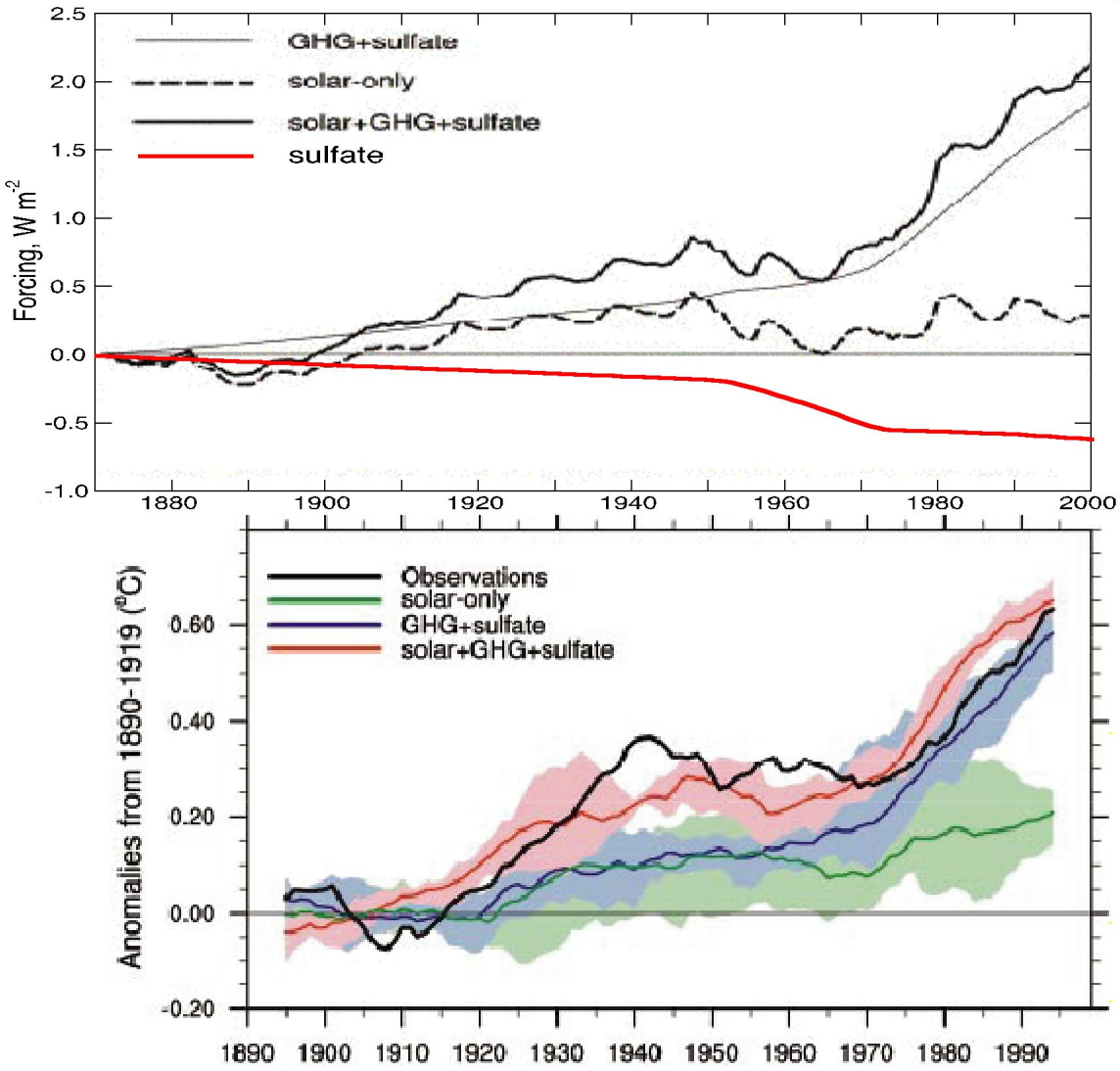
Model sensitivity = 3.4 K per CO_2 doubling; sulfate forcing, -0.62 W m^{-2} (1990)



"The surface temperature time series from the five GHG-plus-sulfate integrations show an increase over the last century, which is ***broadly consistent*** with the observations." -- *Delworth & Knutson, Science, 2000*

FORCING AND RESPONSE IN THE NCAR MODEL (2003)

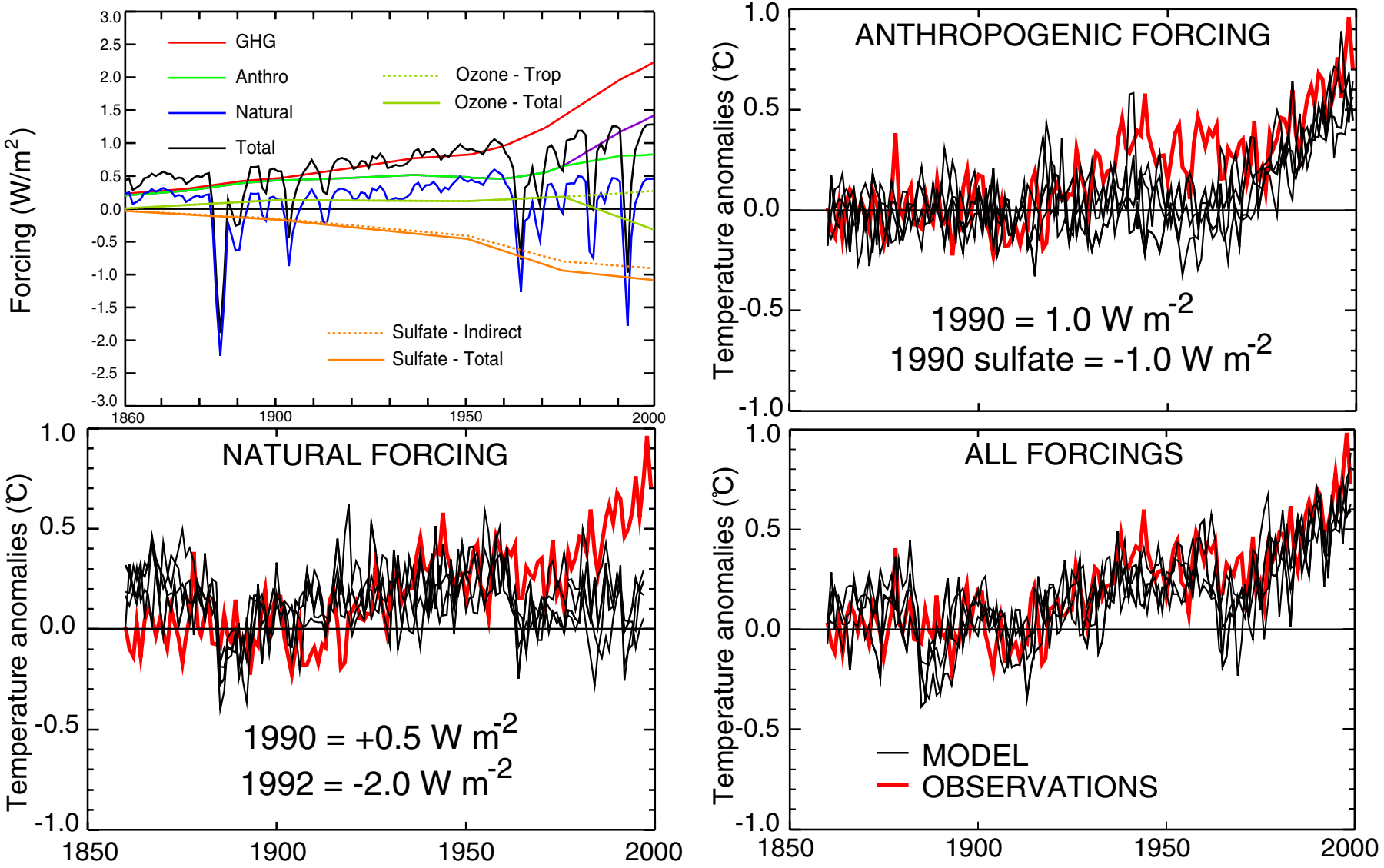
Model sensitivity = 2.18 K per CO_2 doubling; sulfate direct forcing only, -0.6 W m^{-2} (1990)



"The time series from GHG + sulfates + solar shows ***reasonable agreement*** with the observations." -- *Meehl, Washington, Wigley et al., J. Climate, 2003.*

FORCING AND RESPONSE IN THE UK MET OFFICE MODEL (2000)

Model sensitivity = 3.45 K per CO_2 doubling; sulfate + indirect forcing, -1.1 W m^{-2} (1990)

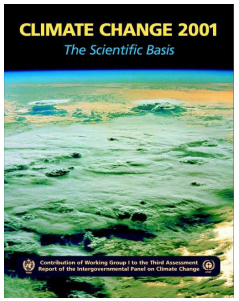


"The ALL ensemble ***captures the main features*** of global mean temperature changes observed since 1860." -- *Stott, Tett, Mitchell, et al., Science, 2000*

IPCC-2001 STATEMENTS ON DETECTION AND ATTRIBUTION OF CLIMATE CHANGE

“ ***Simulations that include estimates of natural and anthropogenic forcing reproduce the observed large-scale changes in surface temperature over the 20th century.***

“ ***Most model estimates that take into account both greenhouse gases and sulphate aerosols are consistent with observations over this period.***




OUR SIMULATIONS THAT INCLUDE ESTIMATES OF NATURAL AND ANTHROPOGENIC FORCING REPRODUCE THE OBSERVED LARGE-SCALE CHANGES IN SURFACE TEMPERATURE OVER THE 20TH CENTURY.
BUT MOM, DON'T THE GCM CALCULATIONS REQUIRE ACCURATE ESTIMATES OF FORCING?
SHHHH!! THE EMPEROR MIGHT HEAR YOU.
IPCC
GCM's
WMO
UNEP
The Emperor's New Clothes

UNCERTAINTY PRINCIPLES

Climate sensitivity $\lambda = \Delta T / F$

The fractional uncertainty in climate sensitivity λ is evaluated from fractional uncertainties in temperature change ΔT and forcing F as:

$$\frac{\delta\lambda}{\lambda} = \sqrt{\left(\frac{\delta\Delta T}{\Delta T}\right)^2 + \left(\frac{\delta F}{F}\right)^2}$$

A reasonable target uncertainty might be:

$$\frac{\delta\lambda}{\lambda} = 30\%, \textit{e.g.,}\ \Delta T_{2\times CO_2} = (3 \pm 1)\ \mathrm{K}$$

This would require uncertainties in temperature anomaly and forcing:

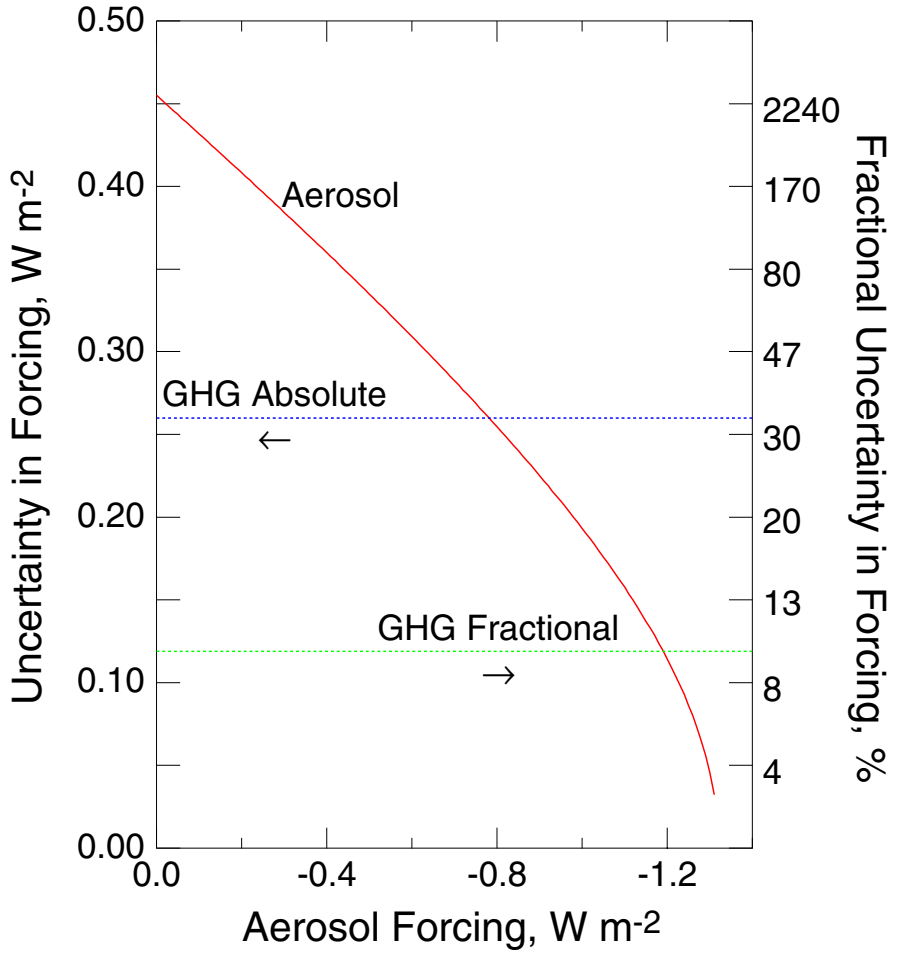
$$\frac{\delta\Delta T}{\Delta T} \approx \frac{\delta F}{F} \approx 20\%.$$

This imposes ***stringent requirements on uncertainty in aerosol forcing!***

REQUIRED UNCERTAINTY IN AEROSOL FORCING

Uncertainty in total forcing not to exceed 20%

GHG Forcing (well mixed gases + strat and trop O_3) = 2.6 W m^{-2} ± 10%



Uncertainty in aerosol forcing must be reduced by at least a factor of 3 to meet requirements for determining climate sensitivity.

CONCLUSIONS

- ***Radiative forcing of climate change by anthropogenic aerosols is substantial in the context of other forcings of climate change over the industrial period.***

  Global annual mean aerosol forcing of -1 to -3 W m^{-2} is plausible given present understanding.

- ***Uncertainty in radiative forcing of climate change by anthropogenic aerosols is the greatest source of uncertainty in forcing of climate change.***

  This uncertainty precludes:

  - ***Evaluation of models*** of climate change.
  - ***Inference of climate sensitivity*** from temperature changes over the industrial period.
  - ***Informed policy making*** on greenhouse gases.

- ***Uncertainty in aerosol forcing must be reduced at least three-fold for uncertainty in climate sensitivity to be meaningfully reduced and bounded.***