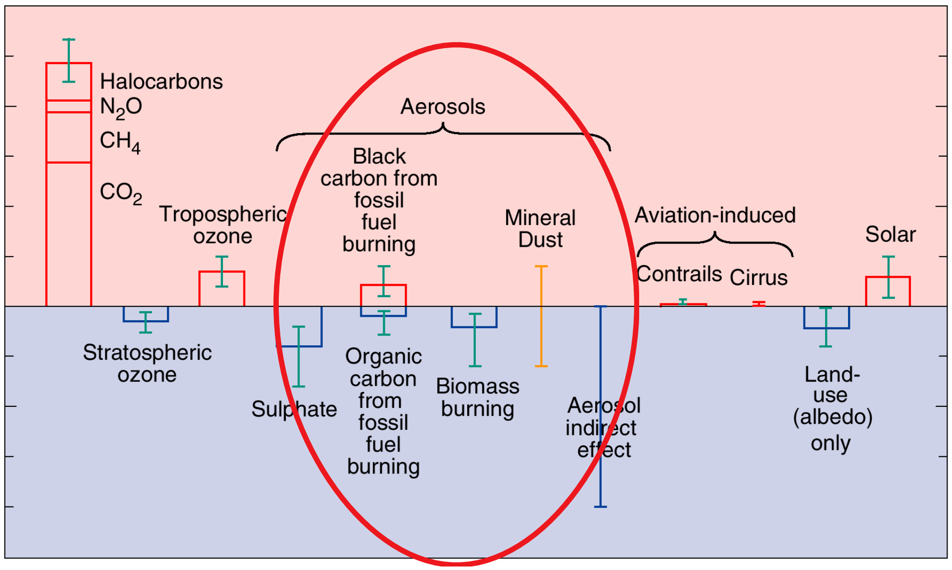
AEROSOL RADIATIVE FORCING

WHY IT IS ESSENTIAL THAT THIS BE QUANTIFIED AND HOW WELL IT NEEDS TO BE KNOWN



Stephen E. Schwartz

BROOKHAVEN NATIONAL LABORATORY

Upton, New York, USA

Workshop on Interactions

Of Climate Change and Regional Air Quality

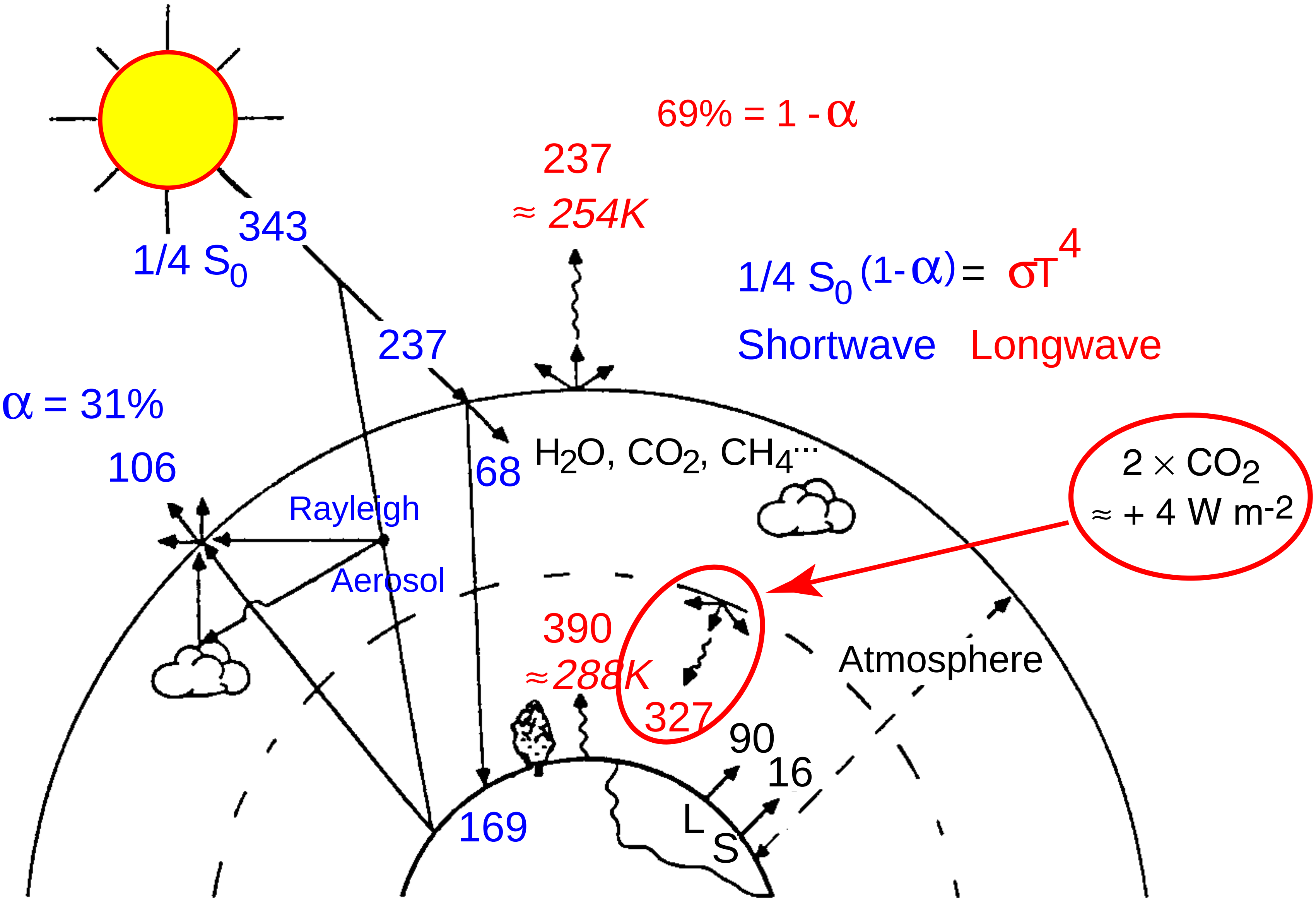
Washington DC

April 26-27, 2005

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

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

RADIATIVE FORCING OF CLIMATE CHANGE

A ***change*** in a radiative flux term in Earth's radiation budget, *F*, W m^{-2}.

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?***

- ***U.S. National Academy Report (Charney, 1979):*** F = 4 W m^{-2}

"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***.

This level of uncertainty is not very useful for policy planning.

CLIMATE RESPONSE

The ***change*** in global and annual mean temperature, ΔT, K, resulting from a given radiative forcing.

Working hypothesis:

The change in global mean temperature depends on the magnitude of the forcing, not its nature or its spatial distribution.

$$\Delta T = \lambda F$$

CLIMATE SENSITIVITY

The ***change*** in global and annual mean temperature per unit forcing, λ, K/(W m^{-2}).

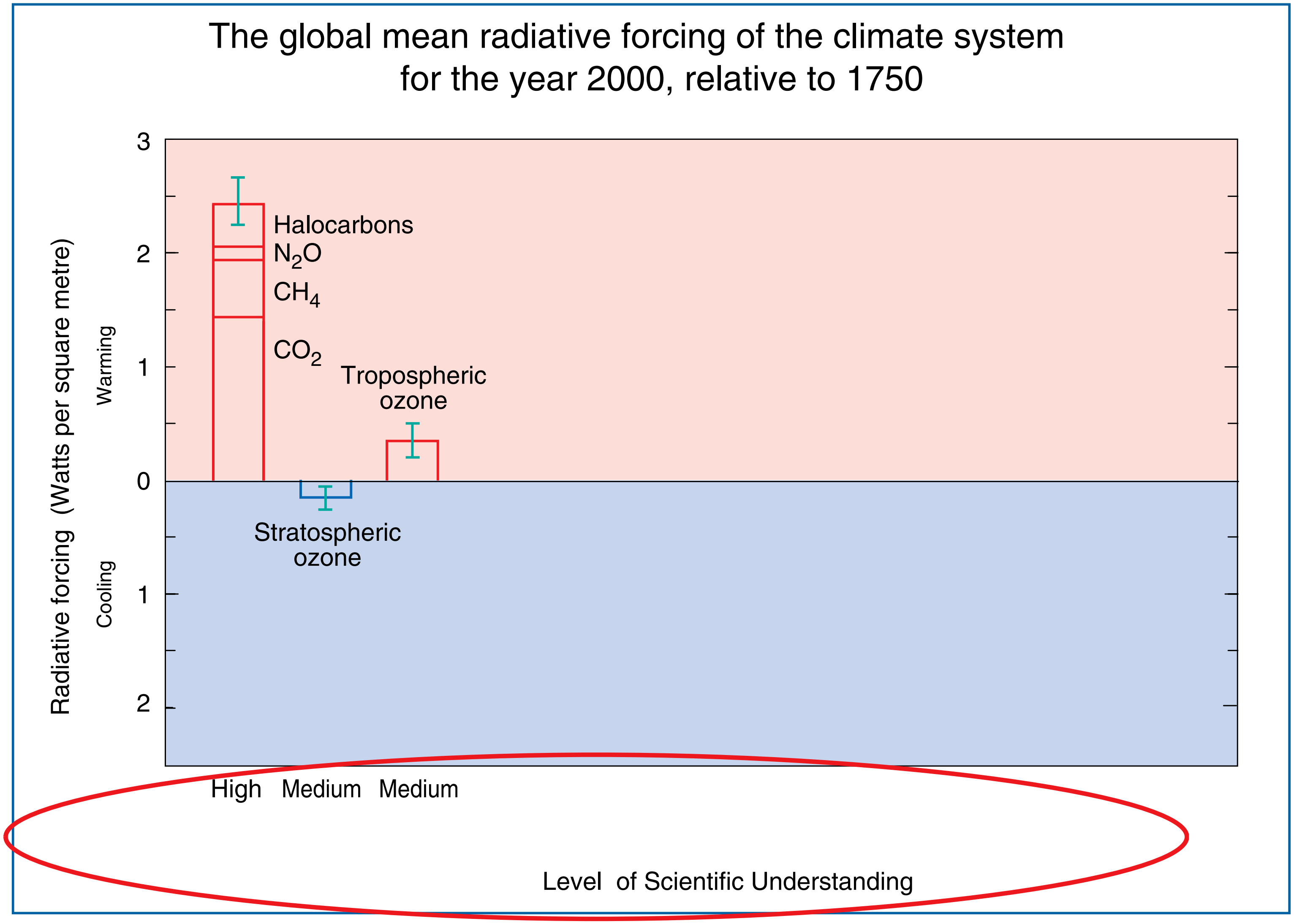
HOW CAN CLIMATE SENSITIVITY BE DETERMINED?

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.

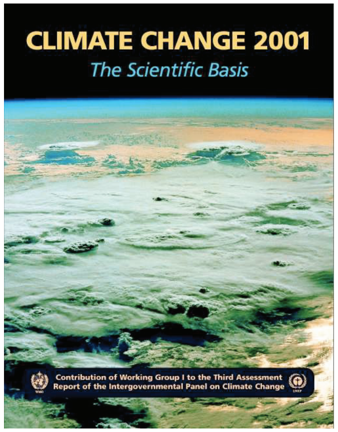
RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD IPCC (2001)

Greenhouse gases only



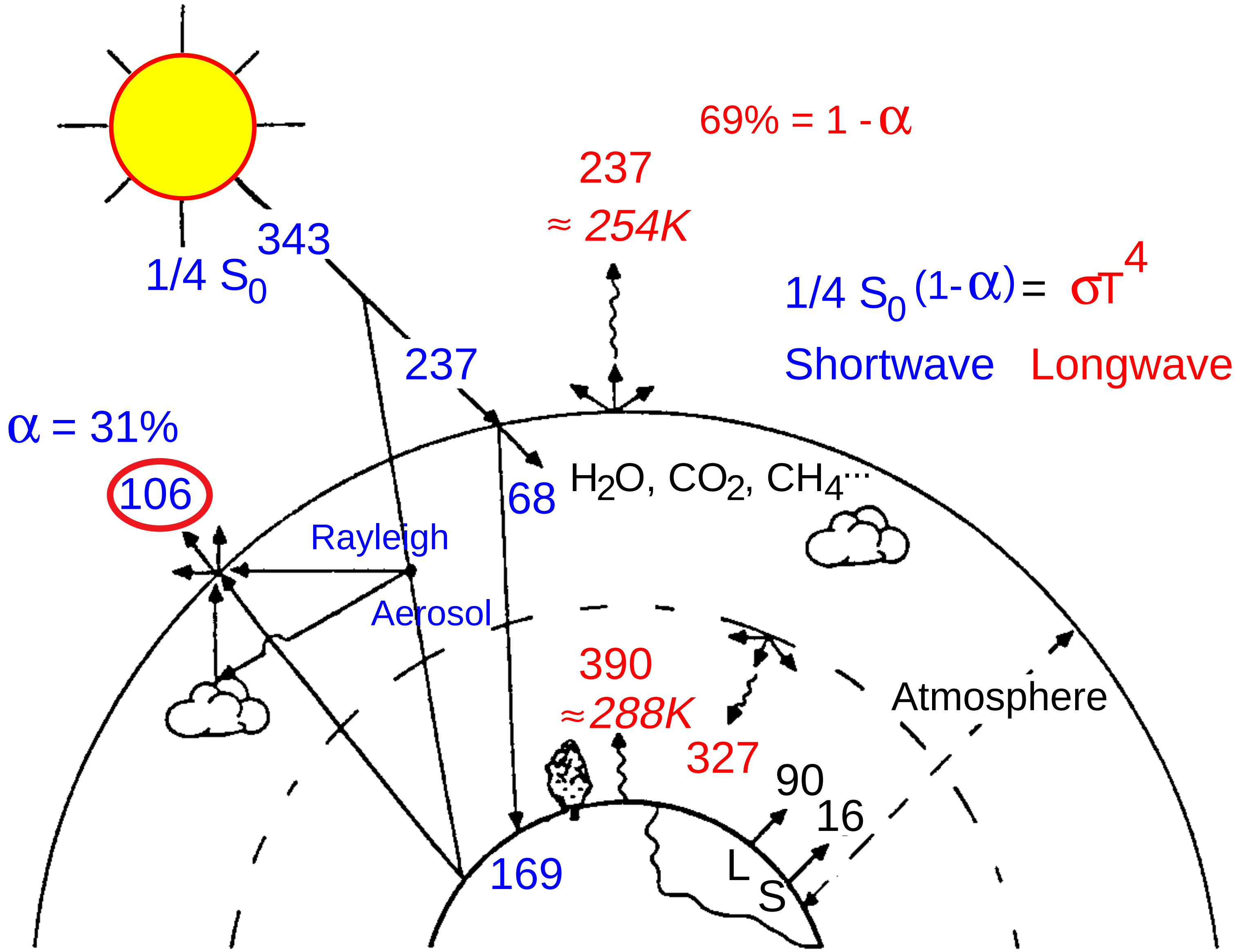
Summary for Policymakers

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



GLOBAL ENERGY BALANCE

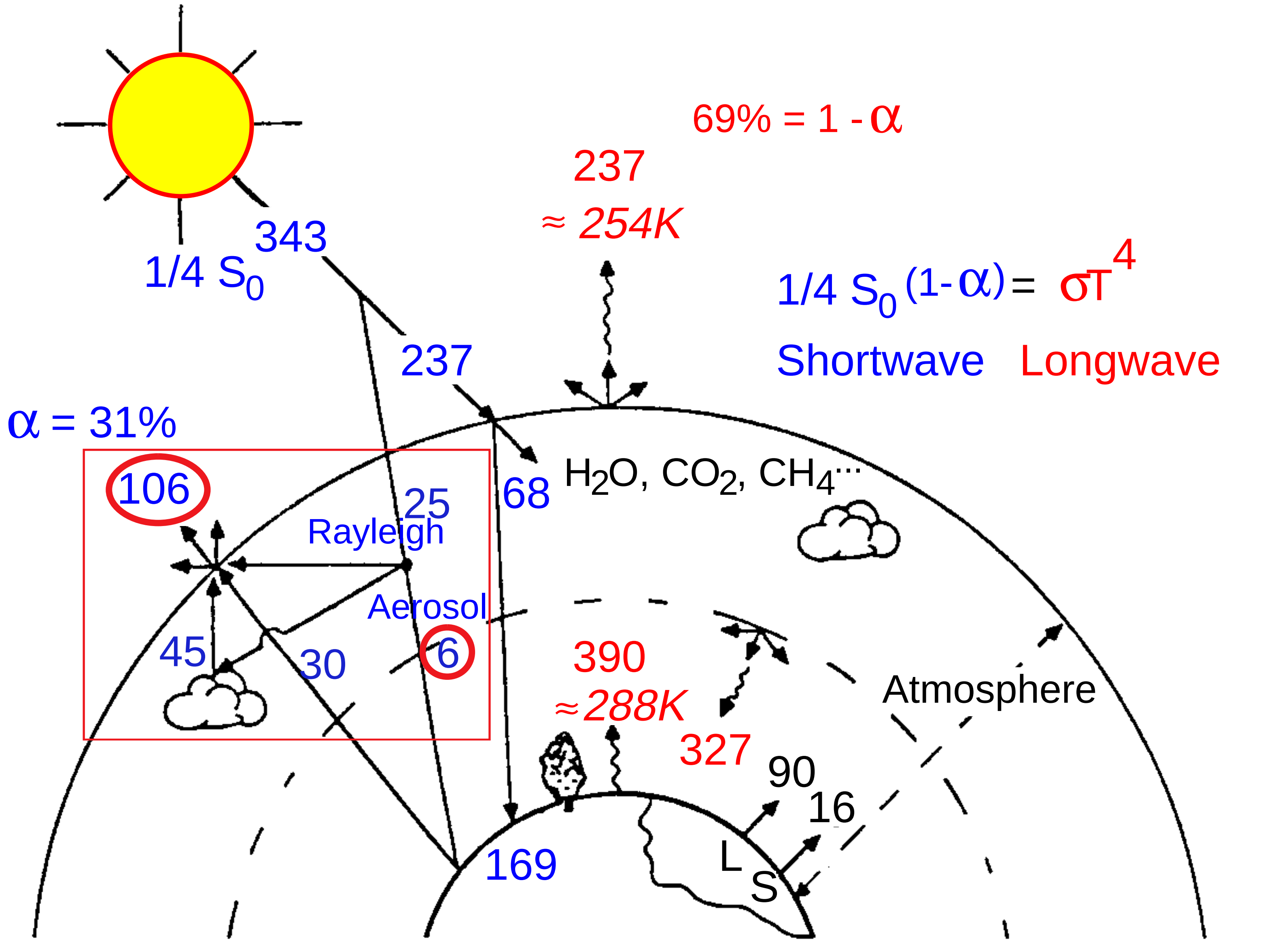
Global and annual average energy fluxes in watts per square meter



Modified from Ramanathan, 1987

GLOBAL ENERGY BALANCE

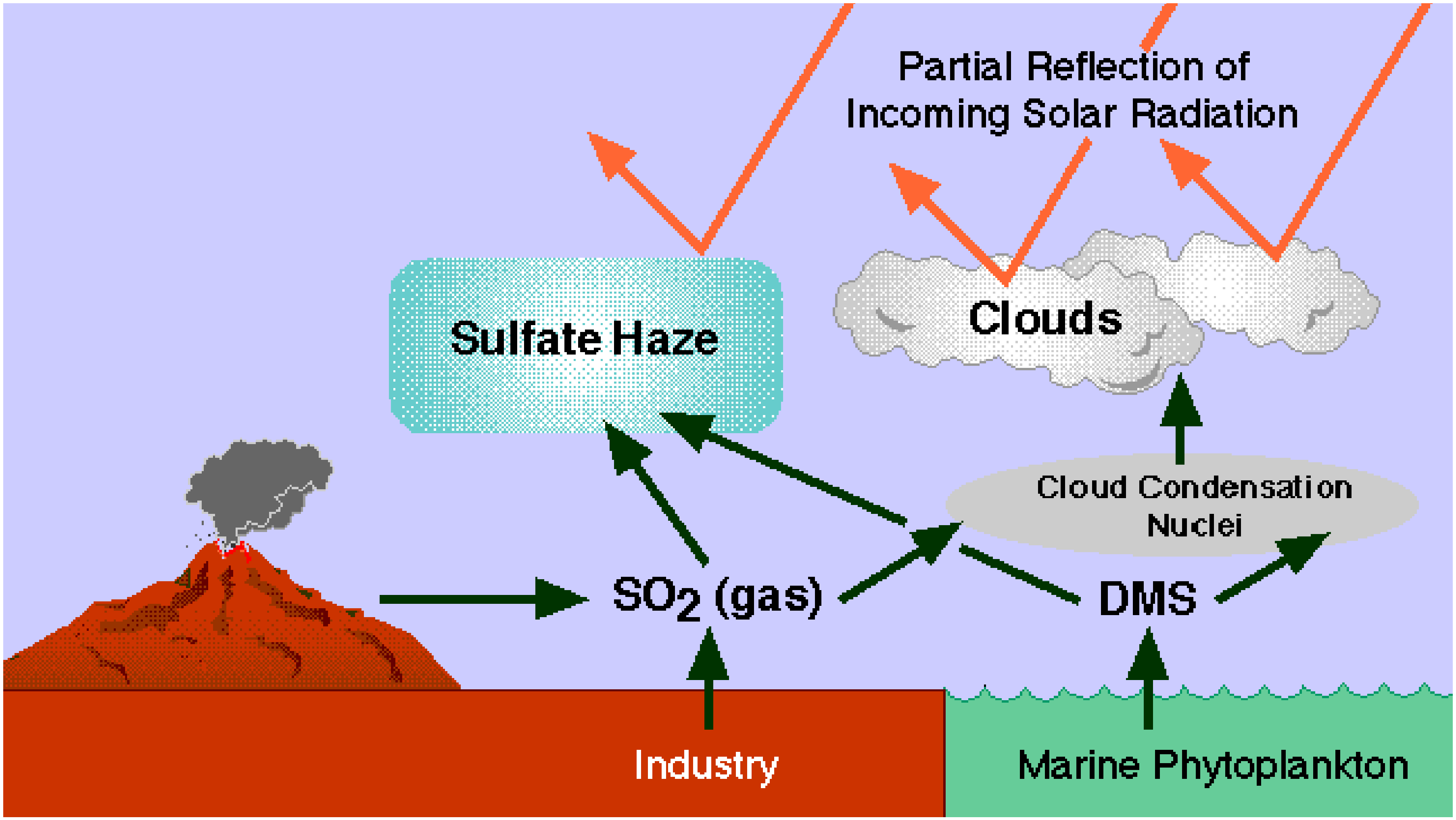
Global and annual average energy fluxes in watts per square meter



Modified from Ramanathan, 1987

THE "WHITEHOUSE EFFECT"

RADIATIVE FORCING OF CLIMATE CHANGE BY AEROSOLS



AEROSOL INFLUENCES ON RADIATION AND CLIMATE

Direct Shortwave Radiative Effects (Clear sky)

Light scattering → Cooling influence

Light absorption → Warming influence, depending on surface

Indirect Shortwave Radiative Effects–Aerosols influence cloud properties

More droplets → Brighter clouds (Twomey)

More droplets → Enhanced cloud lifetime (Albrecht)

More droplets → Narrowing of drop distribution -- warming (Liu)

Semi-Direct Shortwave Radiative Effect

Absorbing aerosol heats air and evaporates clouds (Hansen)

Longwave Radiative Effect (Clear sky)

Greenhouse effect of aerosol particles (Vogelmann)

Hydrological Effects

Suppressed surface evaporation -- Spinning down the water cycle

Displaced precipitation -- Clouds last longer or evaporate (Rosenfeld)

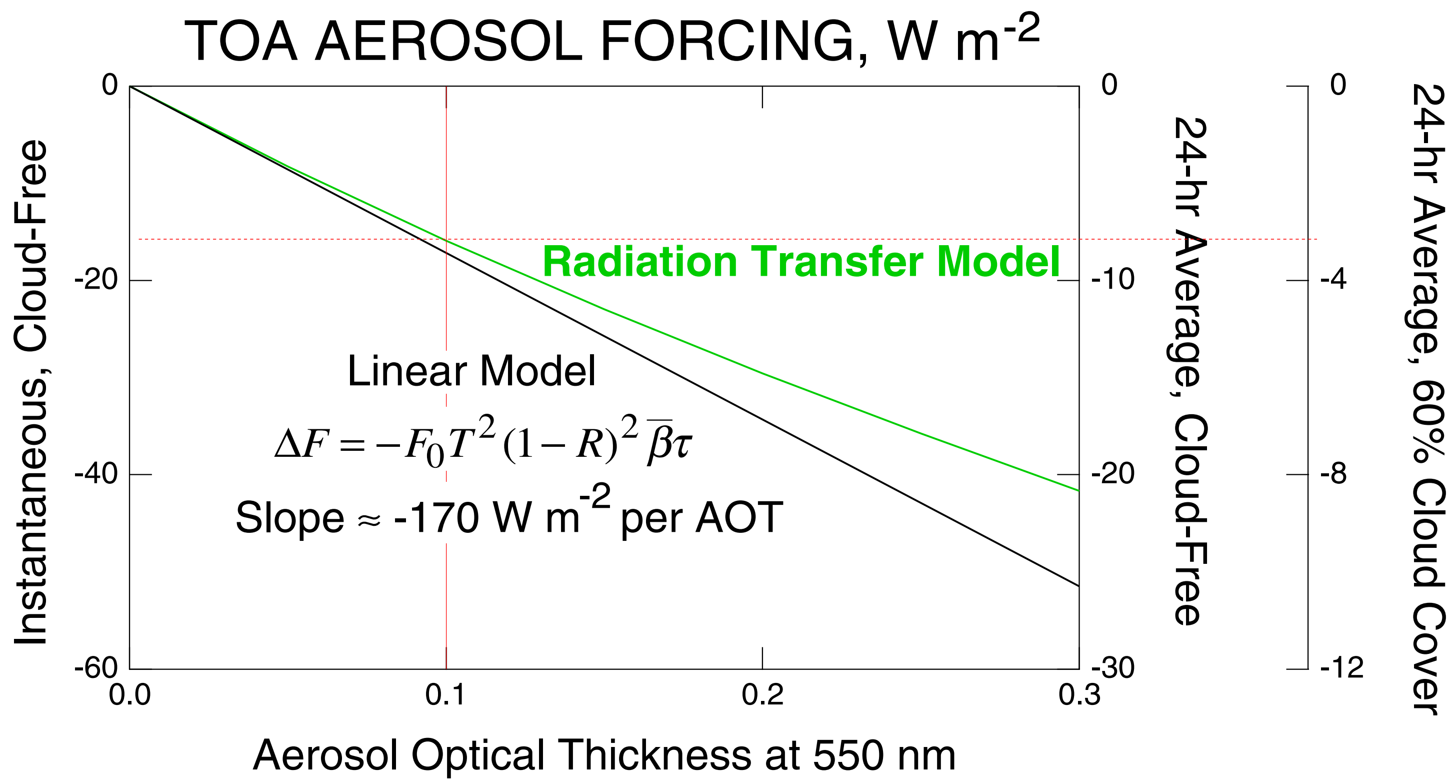
DIRECT EFFECT

DIRECT AEROSOL FORCING AT TOP OF ATMOSPHERE

Dependence on Aerosol Optical Thickness

Comparison of Linear Formula and Radiation Transfer Model

Particle radius r = 85 nm; surface reflectance $R = 0.15$; single scatter albedo $\omega_0 = 1$.



Forcing is highly sensitive to modest aerosol loadings.

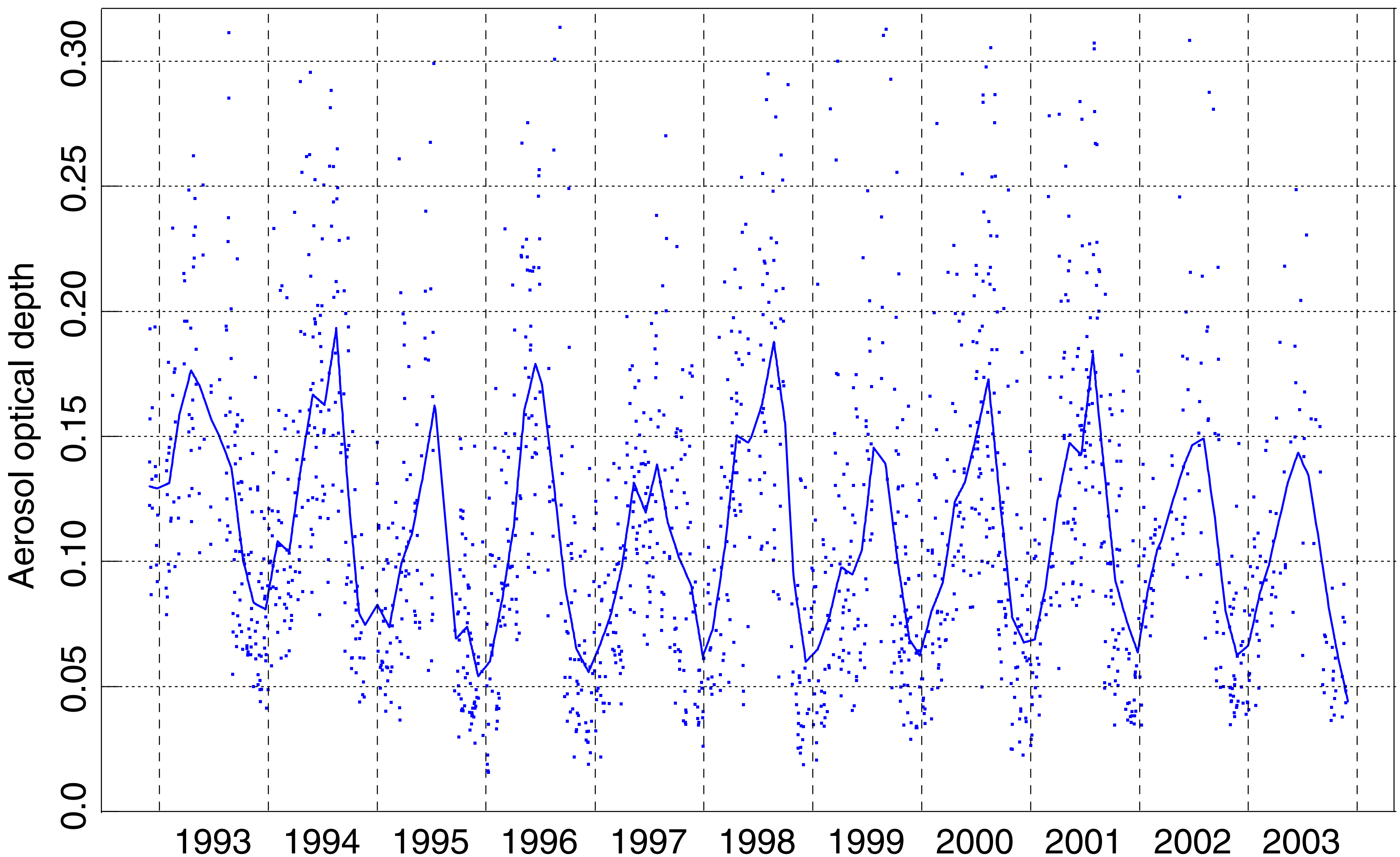
Global-average AOT 0.1 corresponds to global-average forcing -3.2 W m^{-2}.

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

AEROSOL OPTICAL DEPTH

Determined by sunphotometry

North central Oklahoma - Daily average at 500 nm



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.

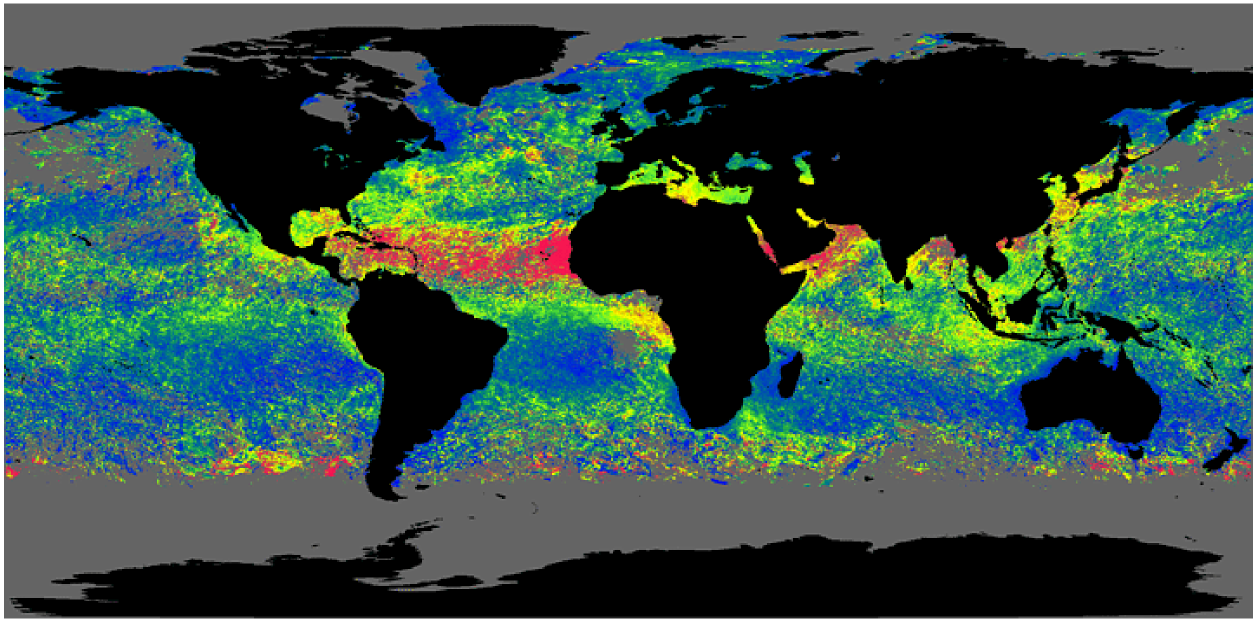
MONTHLY AVERAGE AEROSOL JUNE 1997

Polder radiometer on Adeos satellite

Optical Thickness τ

$\lambda = 865$ nm

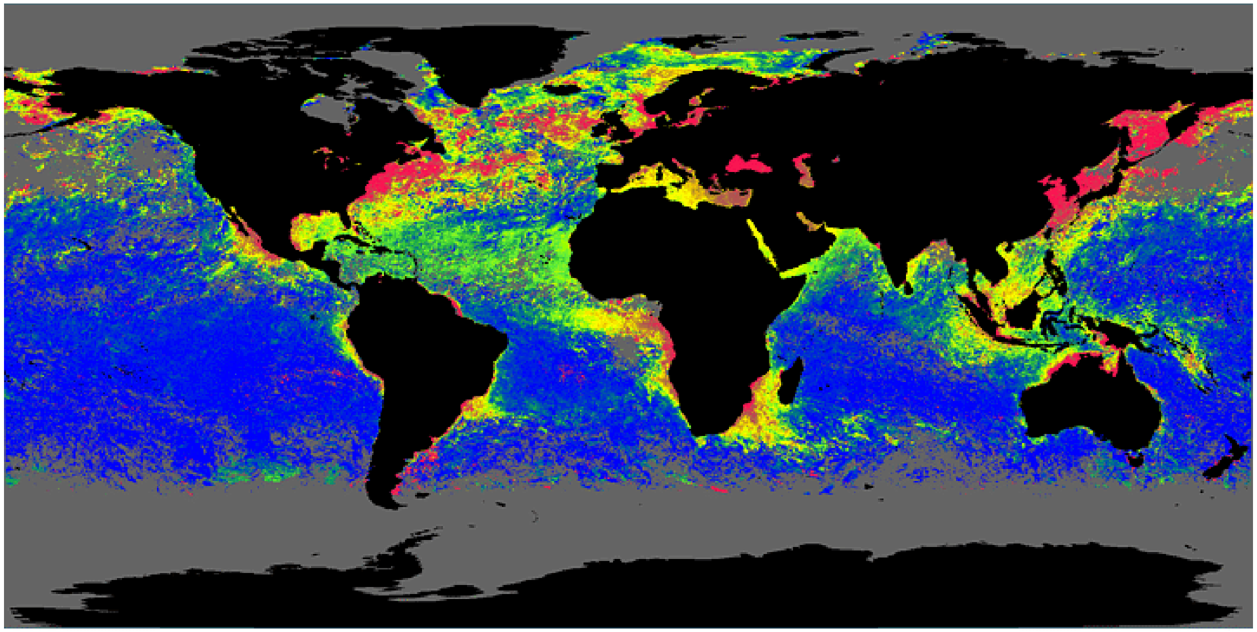
0 — 0.5



Ångström Exponent α

$$\alpha = -d \ln \tau / d \ln \lambda$$

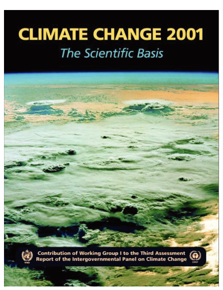
-0.2 — 1.2



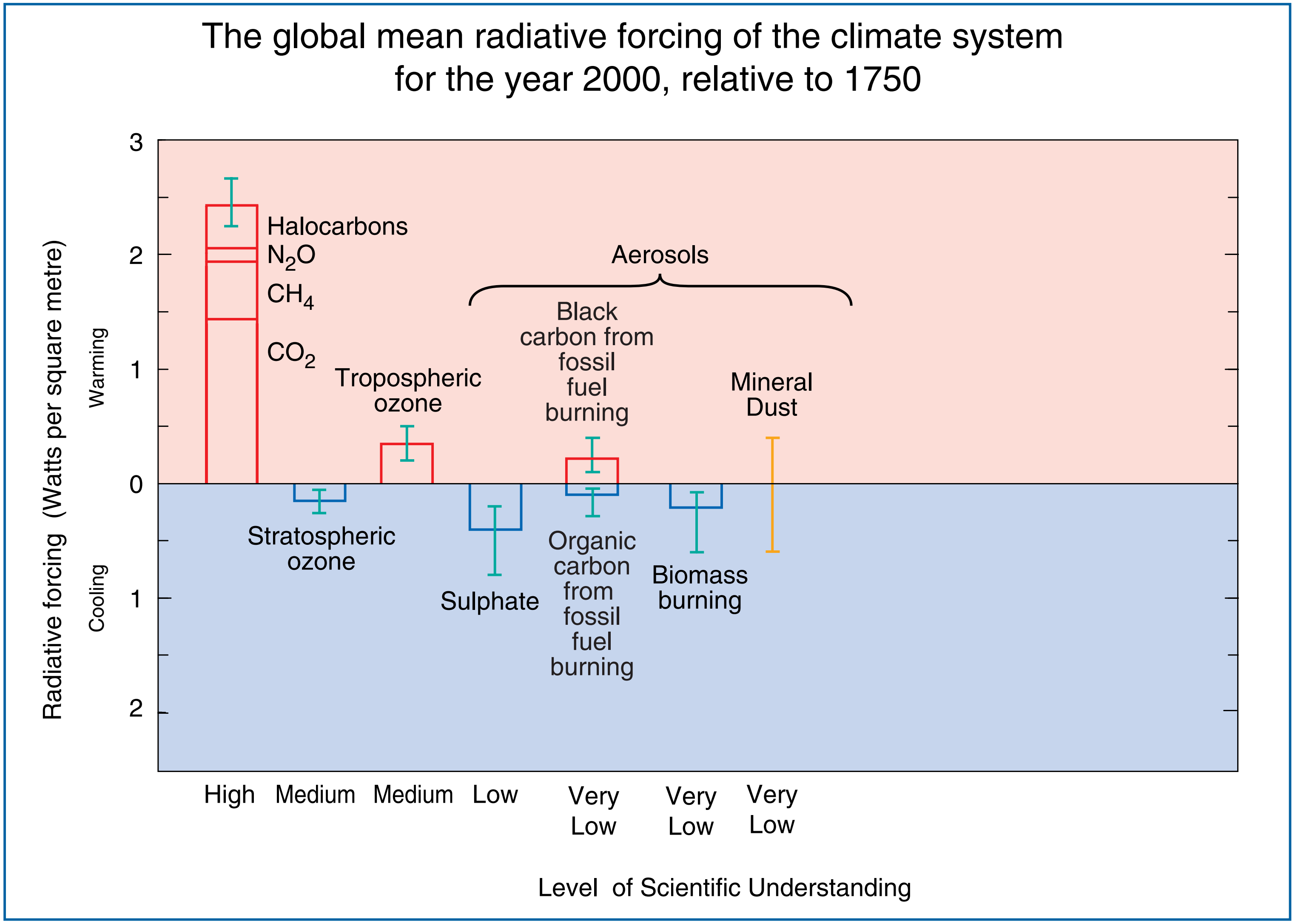
UNCERTAINTY BUDGET FOR *DIRECT* FORCING BY ANTHROPOGENIC SULFATE AEROSOL

Quantity	Central Value	2/3 Uncertainty Range
Total emission of anthropogenic sulfate from fossil fuel burning (Tg/yr)	69	57.5 to 82.8
Atmospheric burden of sulfate from fossil fuel burning (Tg S)	0.525	0.35 to 0.79
Fraction of light scattered into upward hemisphere, $\bar{\beta}$	0.23	0.17 to 0.29
Aerosol mass scattering efficiency ($m^2 g^{-1}$), α_s	3.5	2.3 to 4.7
Aerosol single scattering albedo, co-albedo (dry), ω_0 , 1- ω_0	1	
T_a, atmospheric transmittance above aerosol layer	0.87	0.72 to 1.00
Fractional increase in aerosol scattering efficiency due to hygroscopic growth at RH=80%	2.0	1.7 to 2.3
Fraction of Earth not covered by cloud	0.39	0.35 to 0.43
Mean surface albedo, co-albedo	0.15	0.08 to 0.22
Result: Central value of forcing is –0.5 Wm^{-2}, the uncertainty range is from -0.25 to -1.0 Wm^{-2}		

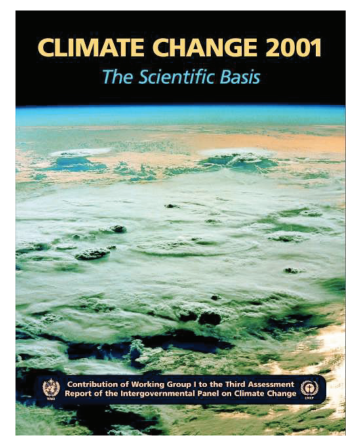
Modified from Penner et al., IPCC, 2001



RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)
GHG's and aerosol direct effects

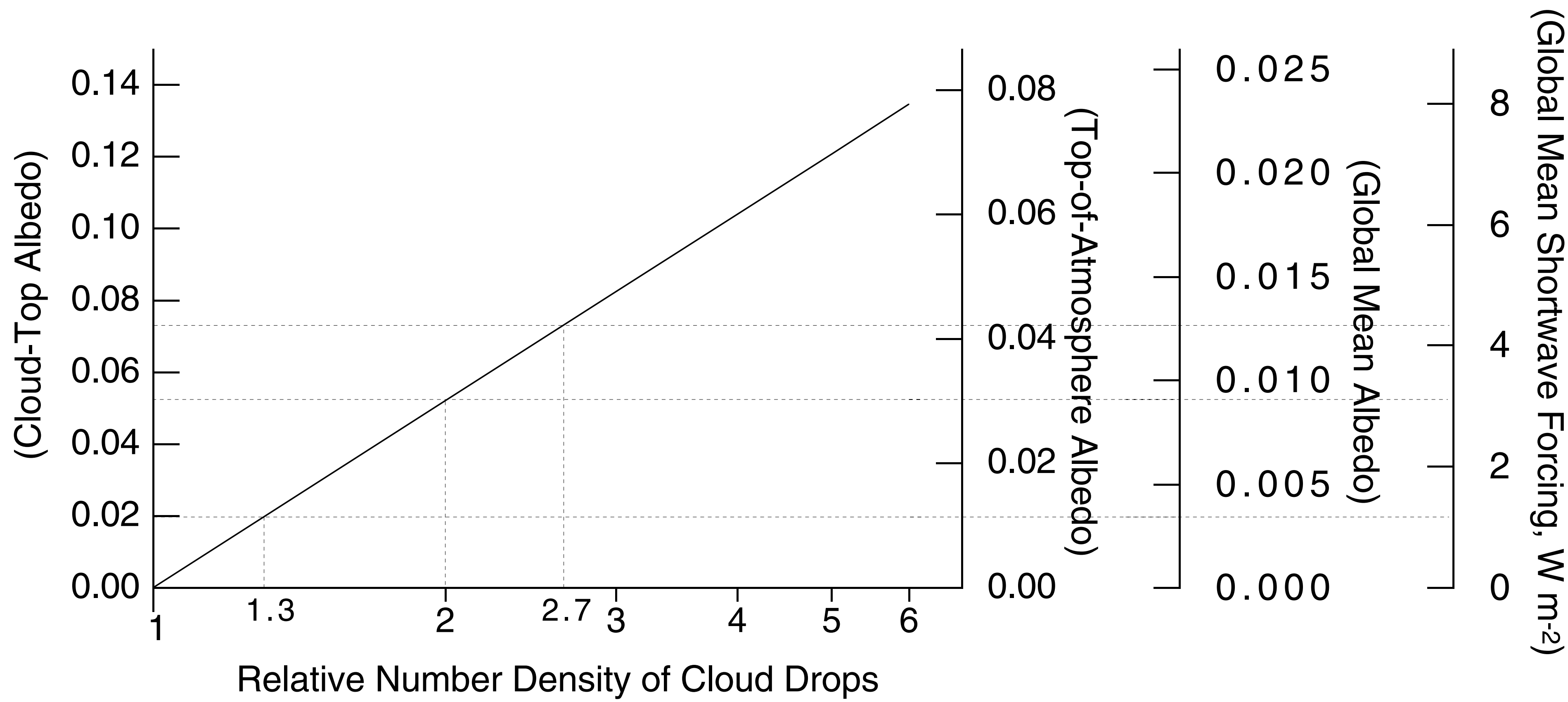


Summary for Policymakers
A Report of Working Group I of the Intergovernmental Panel on Climate Change



INDIRECT EFFECT

SENSITIVITY OF ALBEDO AND FORCING TO CLOUD DROP CONCENTRATION



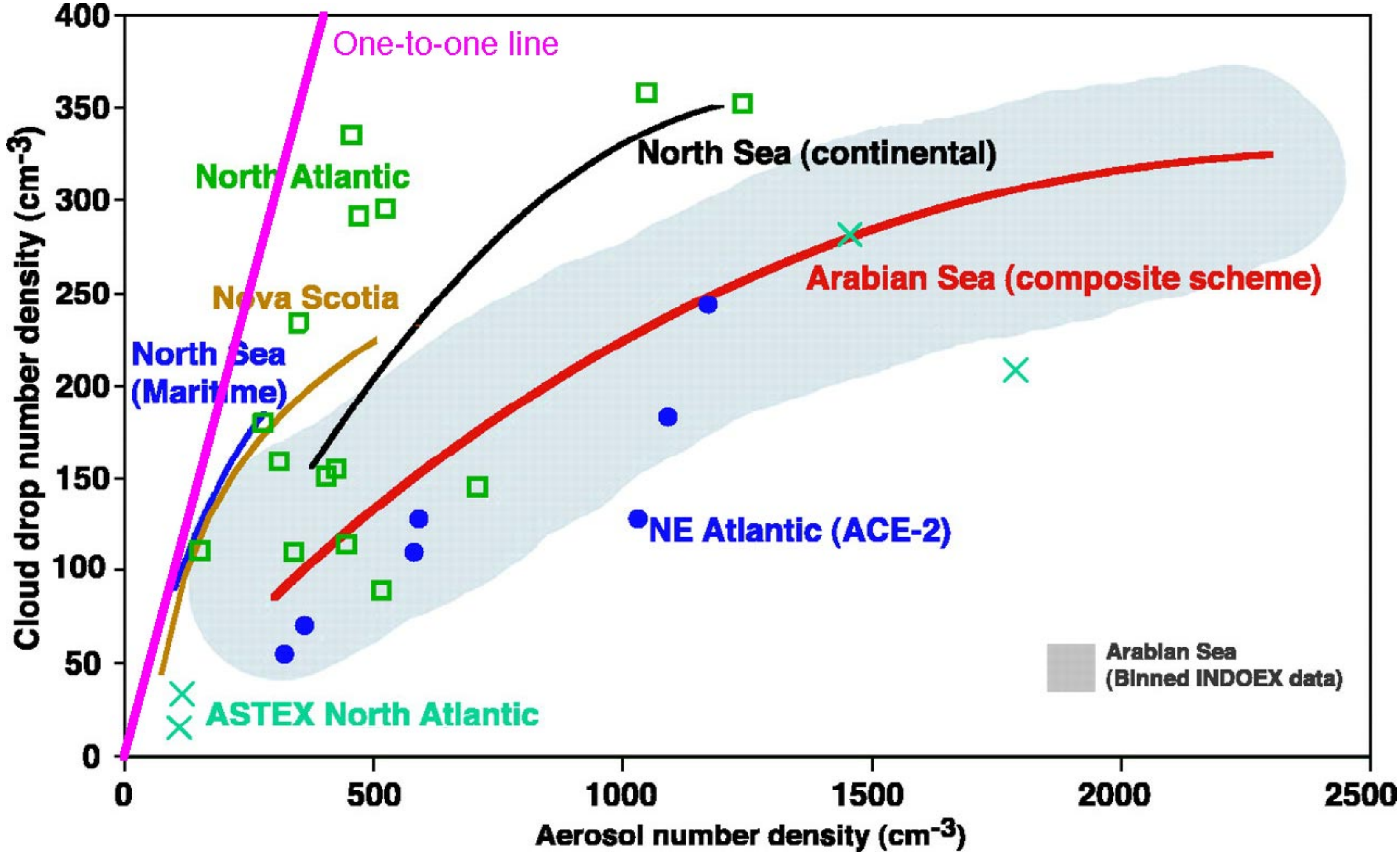
Schwartz and Slingo (1996)

Indirect forcing is highly sensitive to small perturbations in cloud drop concentration.

A 30% increase in cloud drop concentration results in a forcing of ~1 W m^{-2}.

CLOUD DROP NUMBER CONCENTRATION

Dependence on aerosol particle concentration



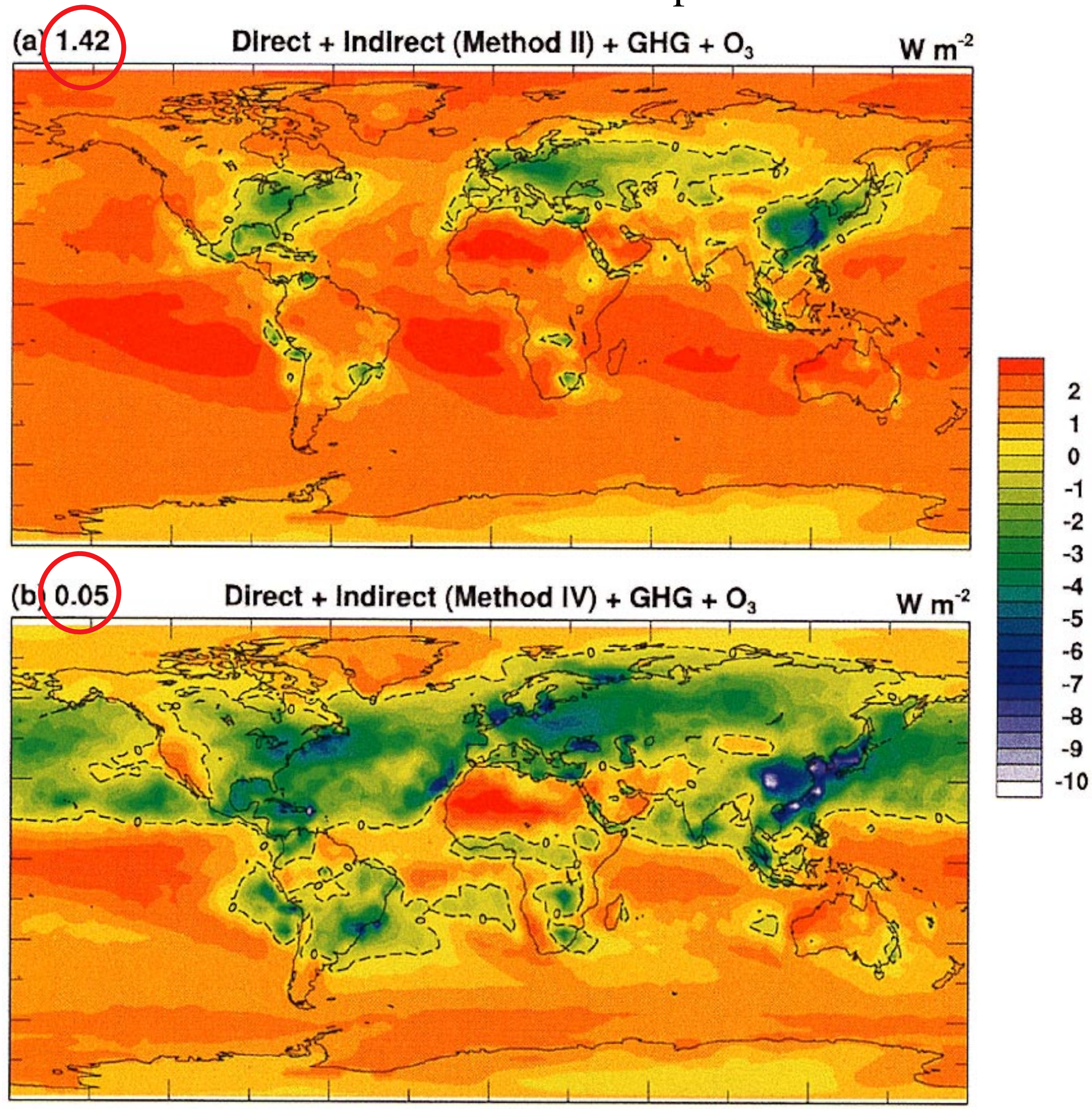
Modified from Ramanathan et al., Science, 2000

The large spread in the relation between aerosol particle and cloud drop number concentration leads to great uncertainty in modeled CDNC.

SHORTWAVE FORCING, ANNUAL AVERAGE

GHG's + O3 + Sulfate (Direct and Indirect)

Two Formulations of Cloud Droplet Concentration

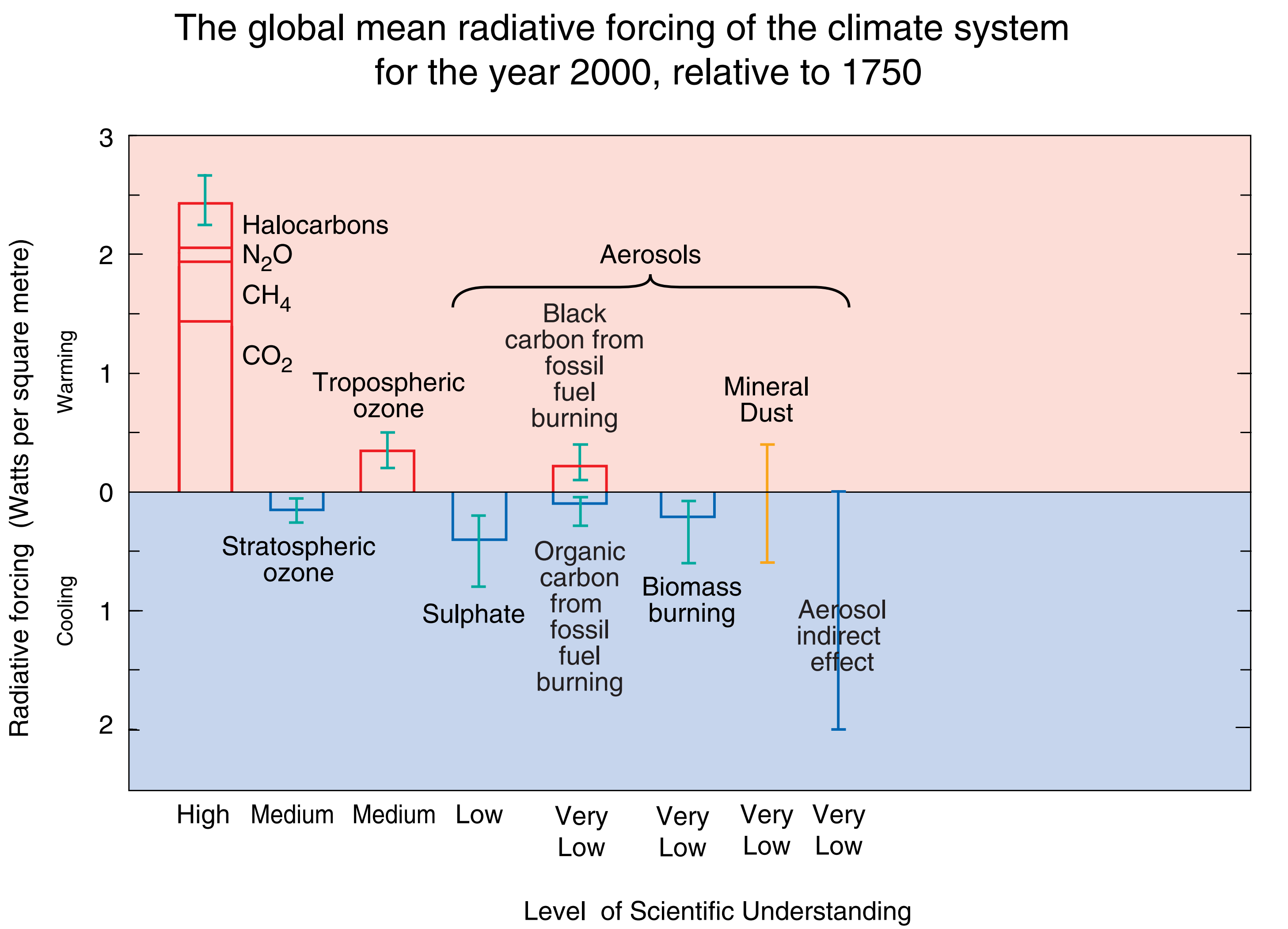


Kiehl et al., JGR, 2000

Indirect forcing is highly sensitive to the assumed relation between sulfate concentration and cloud droplet number concentration.

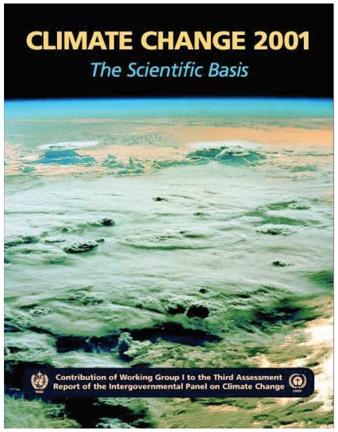
RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD IPCC (2001)

GHG's and aerosol direct and indirect effects



Summary for Policymakers

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



WHY SO LARGE UNCERTAINTY IN AEROSOL FORCING?

- ***Uncertainties in knowledge of atmospheric composition***

Mass loading and chemical and microphysical properties and cloud nucleating properties of anthropogenic aerosols, and geographical distribution.

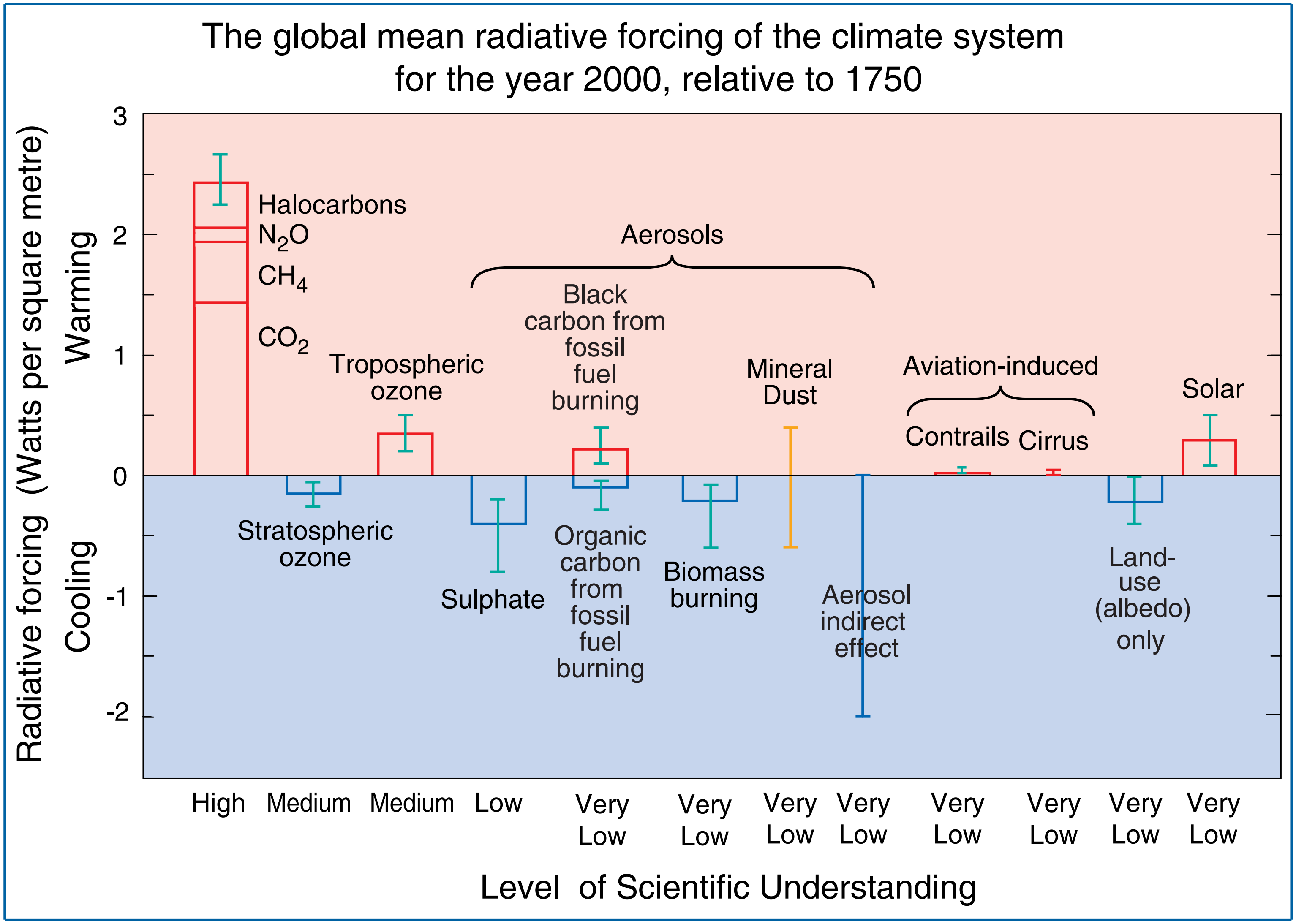
At present and as a function of secular time.

- ***Uncertainties in knowledge of atmospheric physics of aerosols***

Relating direct radiative forcing and cloud modification by aerosols to their loading and their chemical and microphysical properties.

The U.S. Department of Energy has initiated a new research program examining aerosol chemistry and physics pertinent to radiative forcing of climate change.

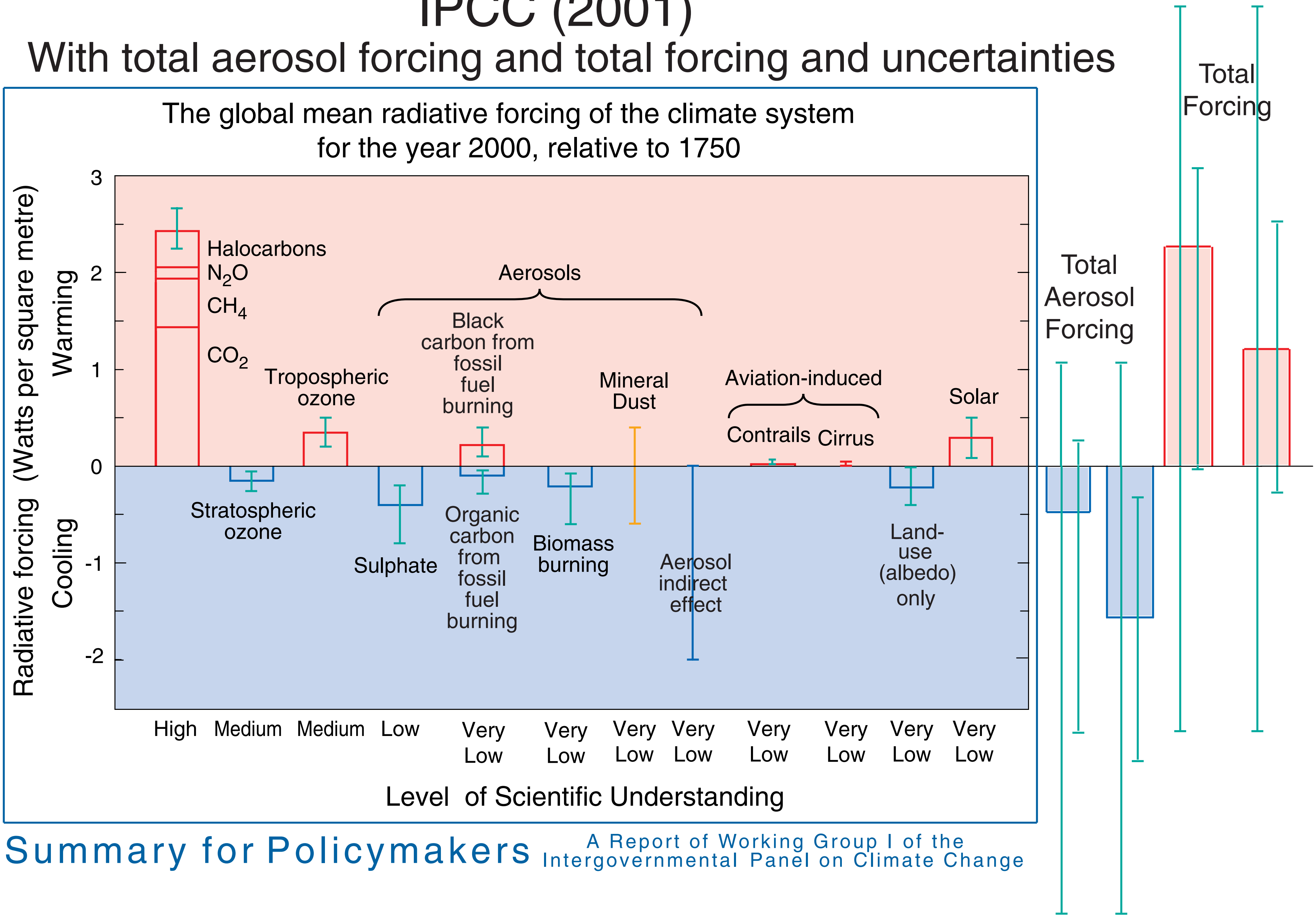
RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)



ADDING UP THE FORCINGS

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)

With total aerosol forcing and total forcing and uncertainties



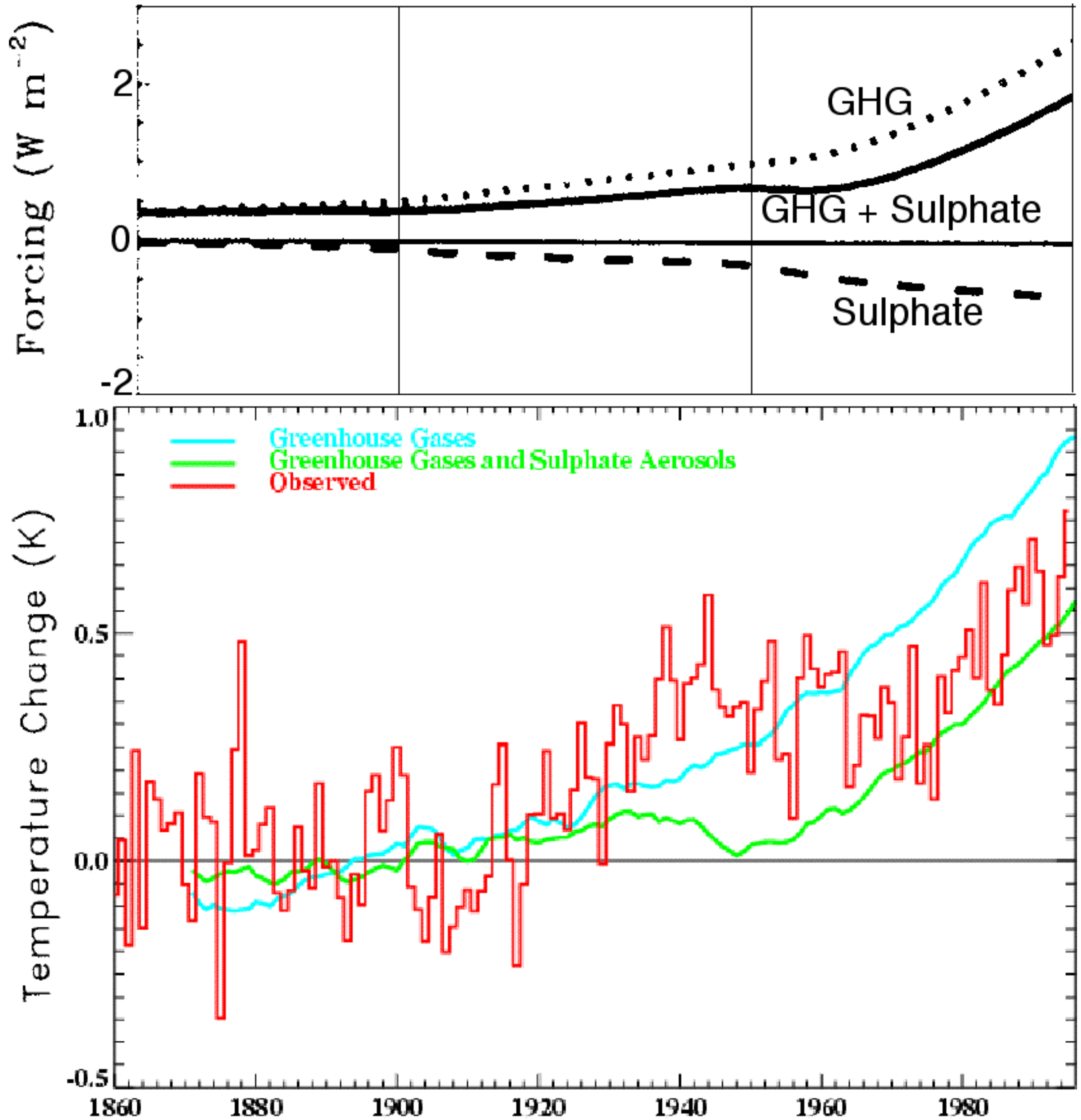
Summary for Policymakers
A Report of Working Group I of the Intergovernmental Panel on Climate Change

Schwartz, JAWMA, 2005

REPRESENTING AEROSOL INFLUENCES IN CLIMATE MODELS

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

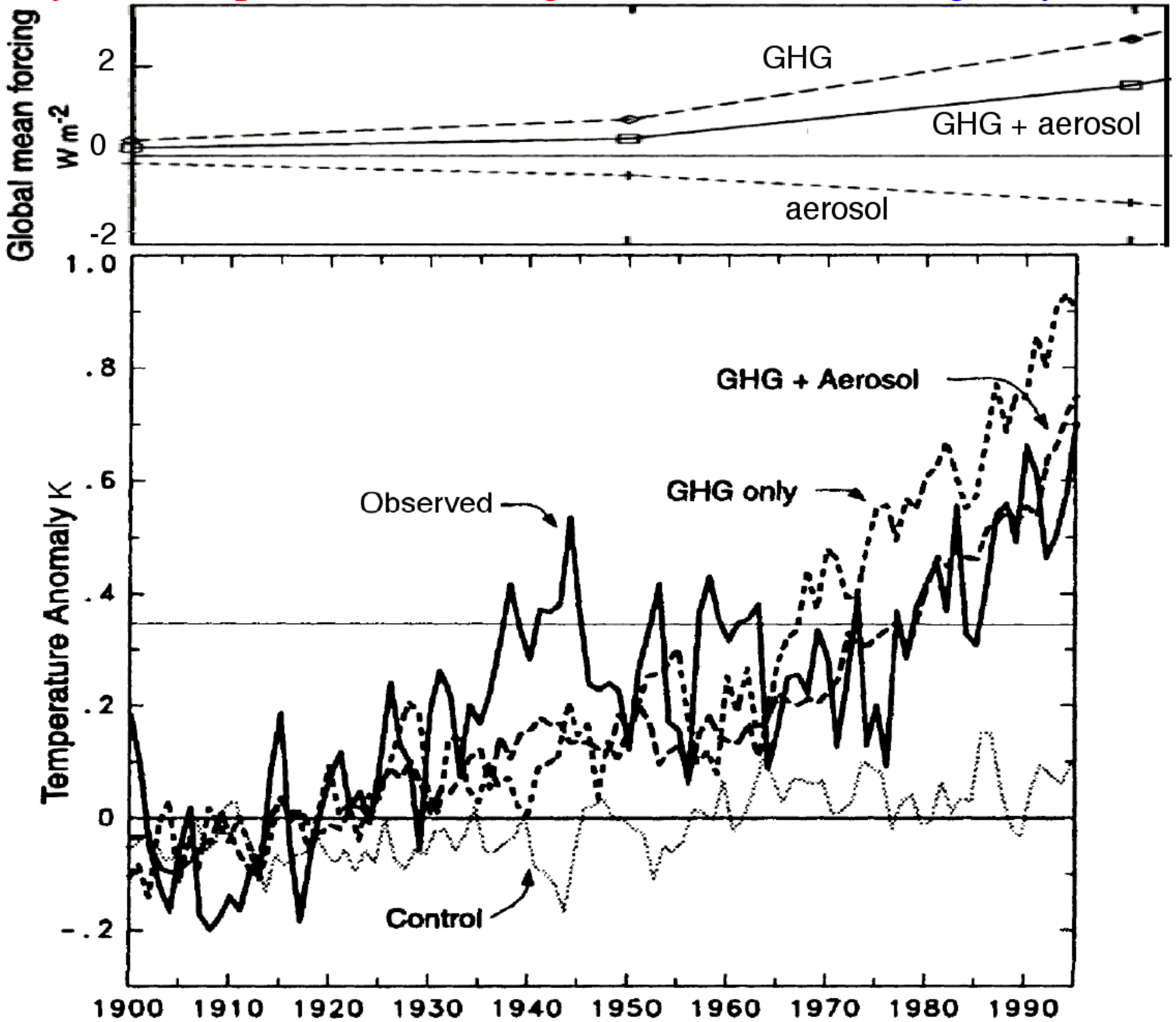
Model sensitivity = 2.5 K per CO_2 doubling; sulfate direct forcing only, -0.6 W m^{-2} (1990)



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

FORCING AND RESPONSE IN THE CANADIAN CLIMATE MODEL (2000)

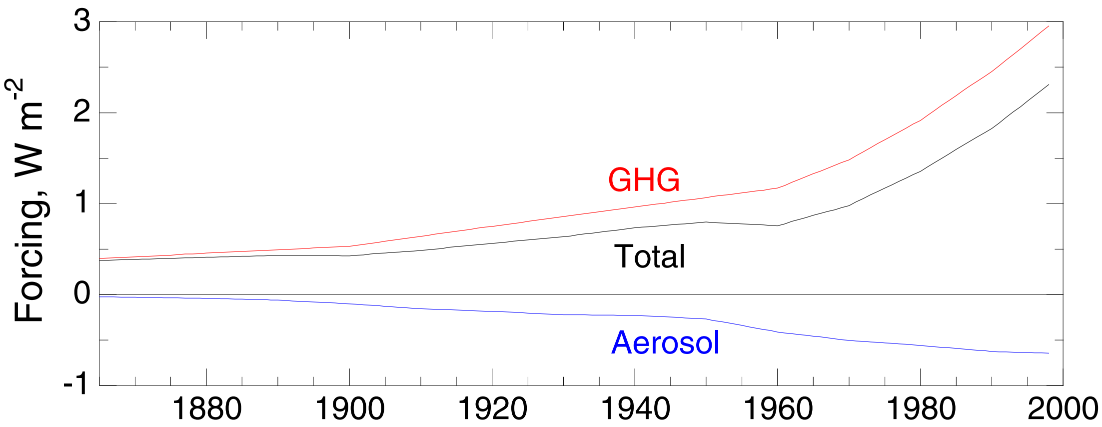
Model sensitivity = 3.5 K per CO_2 doubling; sulfate direct forcing only, -1.0 W m^{-2} (1990)

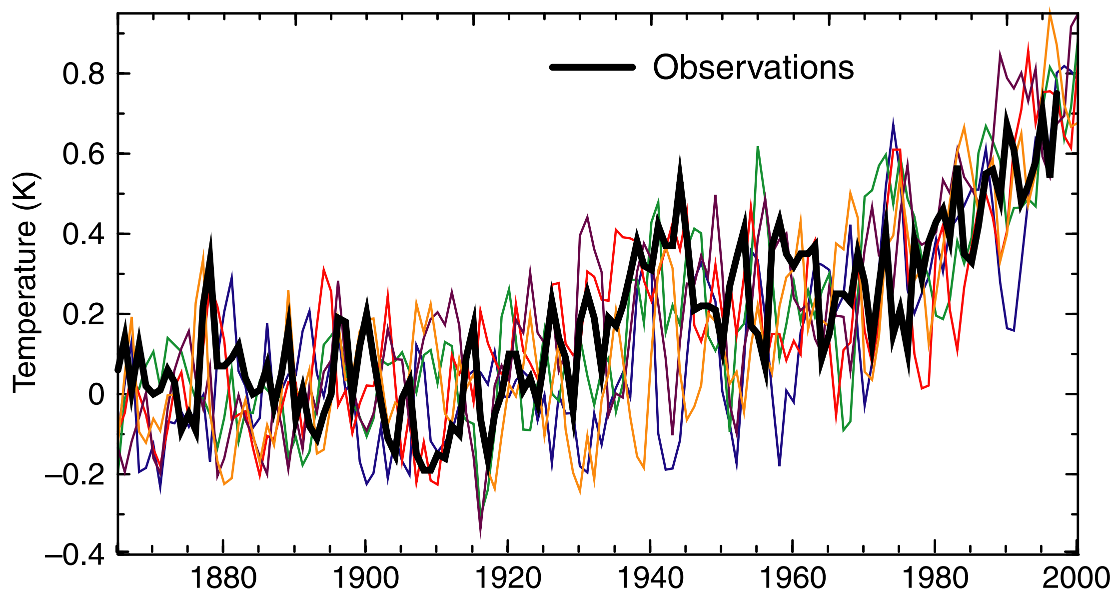


"Observed global mean temperature changes and those simulated for GHG + aerosol forcing show ***reasonable agreement***." -- *Boer, et al., Climate Dynamics, 2000*

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)

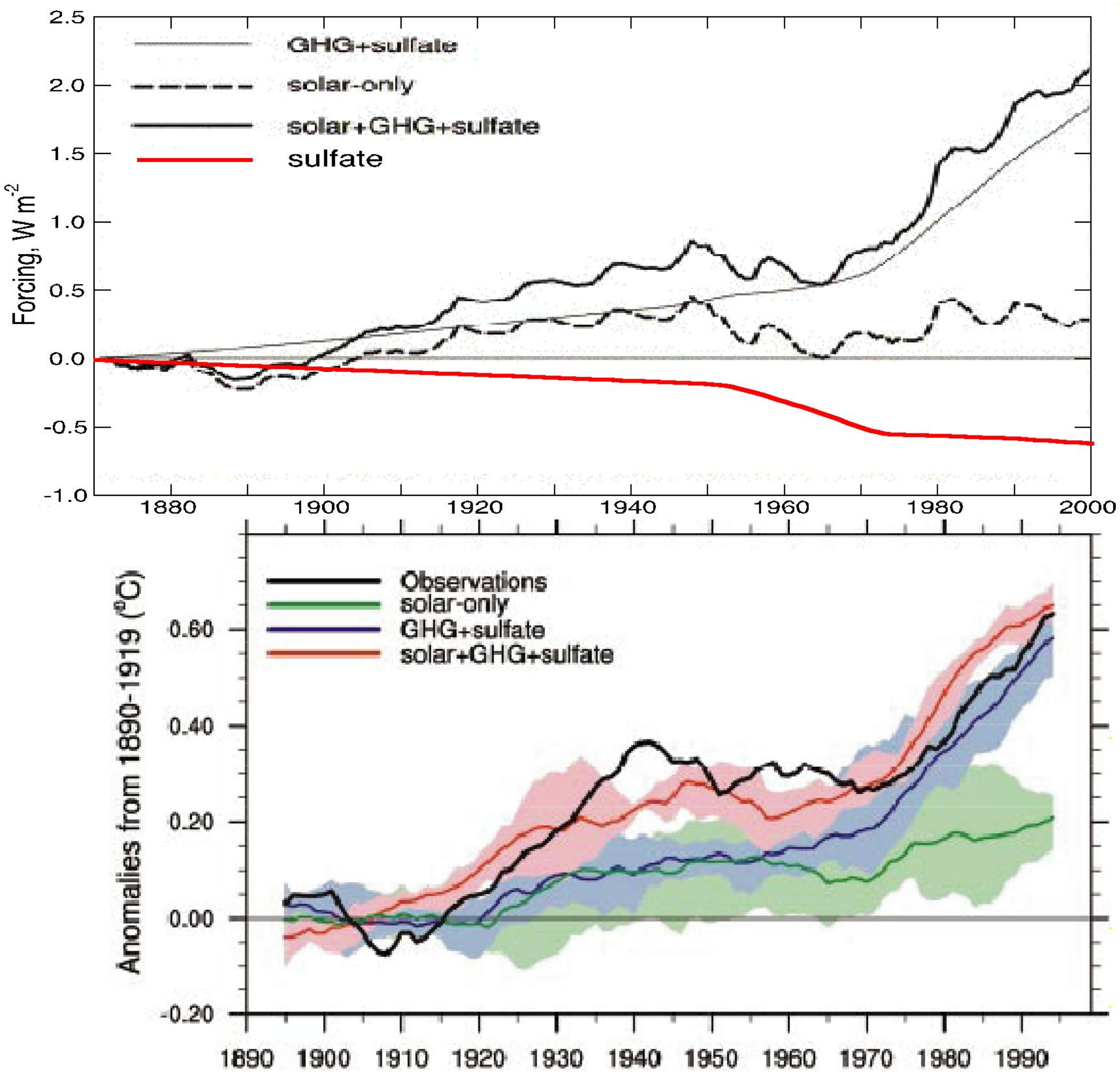




"The surface temperature time series from the five GHG-plus-sulfate integrations show an increase over the last century, which is ***broadly consistent*** with the observations." -- *Delworth & Knutson, Science, 2000*

FORCING AND RESPONSE IN THE NCAR MODEL (2003)

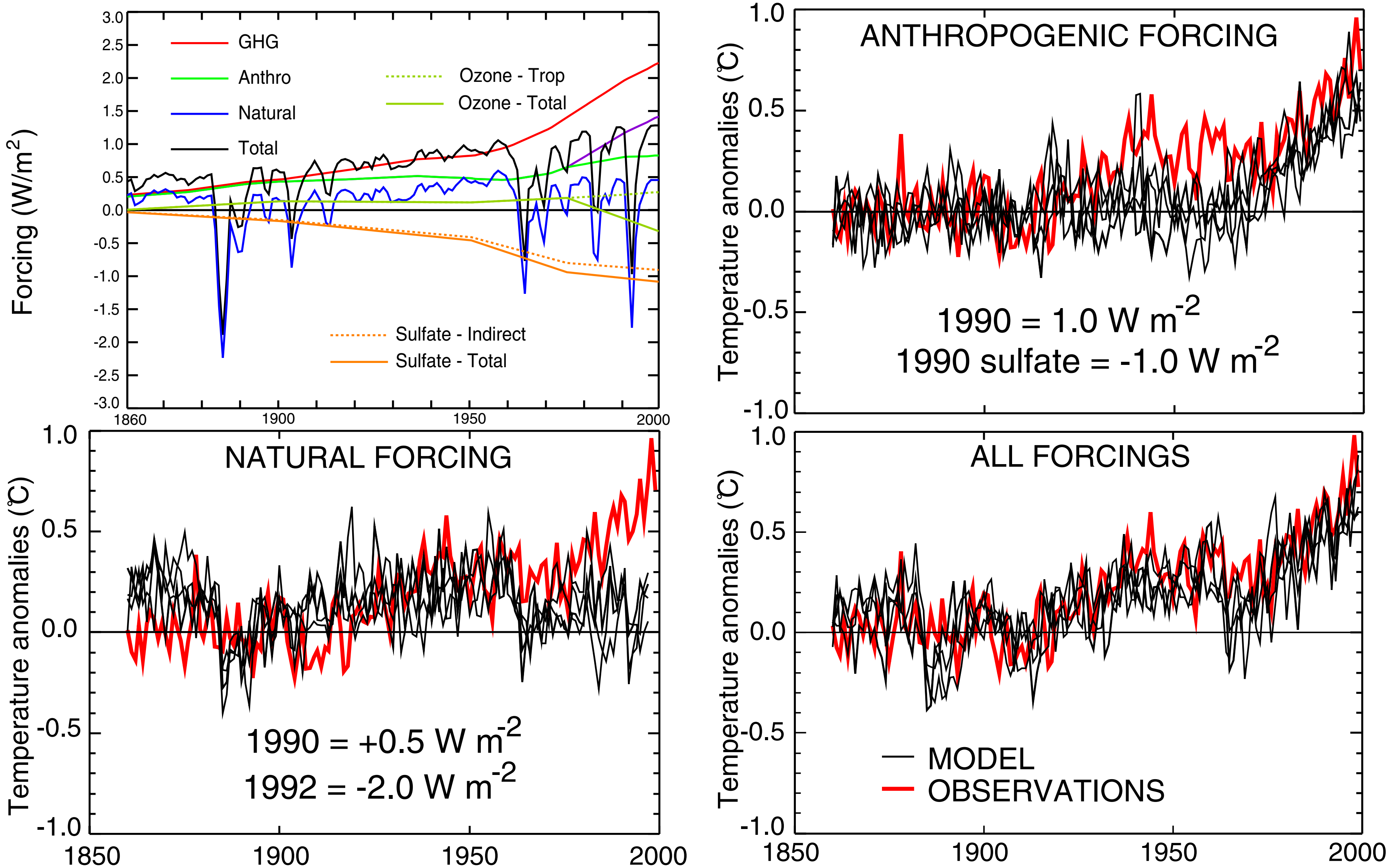
Model sensitivity = 2.18 K per CO_2 doubling; sulfate direct forcing only, -0.6 W m^{-2} (1990)



"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)



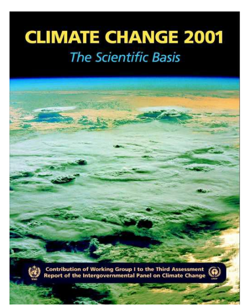
"The ALL ensemble ***captures the main features*** of global mean temperature changes observed since 1860." -- *Stott, Tett, Mitchell, et al., Science, 2000*

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.***

UNEP



WMO

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:

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

This would require uncertainties in temperature anomaly and forcing:

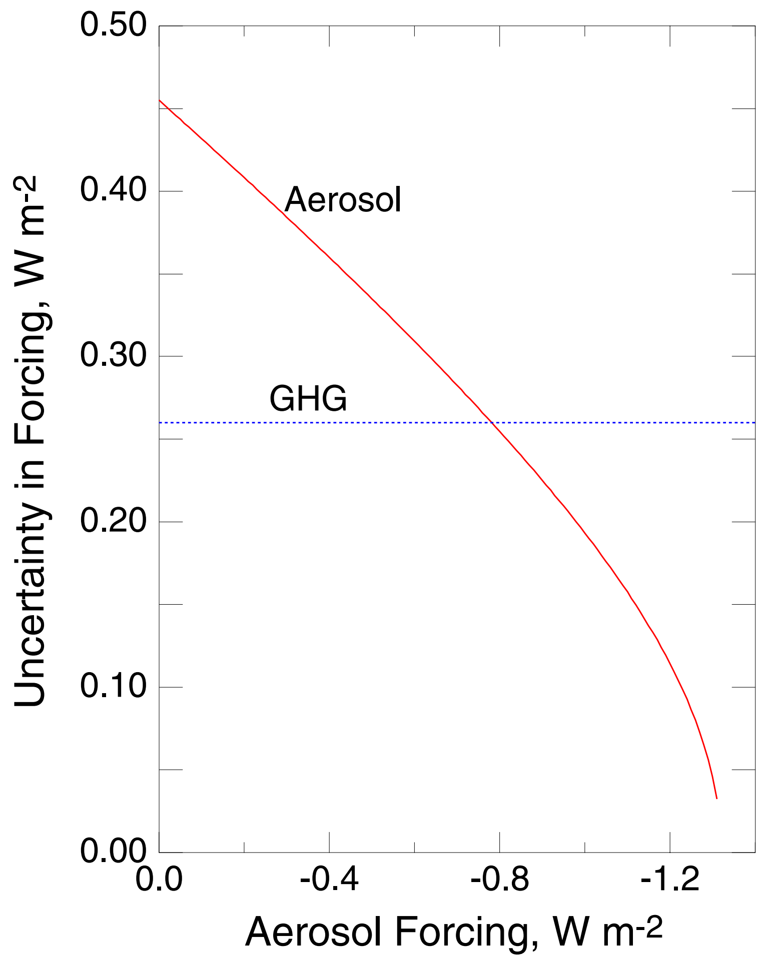
$$\frac{\delta\Delta T}{\Delta T} \approx \frac{\delta F}{F} \approx 20\%.$$

This imposes ***stringent requirements on accuracy of aerosol forcing!***

REQUIRED ACCURACY 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.***

SOME CONCLUDING OBSERVATIONS

- GHG concentrations and forcing are increasing. GHGs persist in the atmosphere for decades to centuries.
- Aerosol forcing is comparable to greenhouse gas forcing but much more uncertain.
- Hence total forcing over the industrial period is highly uncertain.
- Hence the sensitivity of the climate system remains highly uncertain.
- Climate sensitivity will remain uncertain unless and until aerosol uncertainty is substantially decreased.
- Decisions must be made in an uncertain world. (Lack of controls on GHG emissions is also a decision).

SPECIFIC RESEARCH NEEDS THAT COULD HELP GUIDE FUTURE INVESTMENTS

AEROSOL INFORMATION REQUIRED TO DETERMINE DIRECT FORCING

Time-dependent 3-D map of size-dependent particle concentration, composition, and morphology.

Needed for computation of optical properties, cloud-nucleating properties, and radiative and hydrological influences.

This can be obtained only by chemical transport modeling of aerosols . . .

Based on ***understanding*** of the controlling processes.

Evaluated by comparison with observations.

Concentrations
Rates

ISSUES IN DETERMINING AEROSOL INDIRECT FORCING

1. Change in aerosol particle concentration, size, composition, etc. between preindustrial and present, as function of location.
2. Relation between aerosol particle concentration (and size, composition, etc.) and cloud droplet concentration.
3. Relation between cloud drop concentration and cloud reflectance.
4. Aerosol influences on LWP, cloud lifetime, etc., in addition to reflectance.

SPECIFIC RESEARCH NEEDS THAT COULD HELP GUIDE FUTURE INVESTMENTS

Goal: Accurate Chemical Transport Models (CTMs) that can be used with confidence to assess aerosol direct and indirect forcing at present, over the industrial period, and for various future emission scenarios.

Requirements: Development of these models and evaluation of their accuracy require:

Emissions

Aerosol precursor gases, by compound, as f(x, y, z, t).

Primary aerosols, by size and composition, as f(x, y, z, t).

Dependence on activity and conditions.

Atmospheric chemistry and aerosol microphysics

Gas-to-particle conversion mechanisms and rates.

Aerosol microphysical evolution.

Predictive capability for size dependent composition

cont'd

Requirements, *cont'd*:

Aerosol-cloud interactions

Activation

Aqueous chemistry

Precipitation development, precipitation scavenging

Aerosol optics

Dependence on composition and size distribution

Aerosol radiative effects

Clear sky

Uniform clouds

Broken clouds, high RH near clouds

UNCERTAINTY

UNCERTAINTY
UNCERTAINTY

UNCERTAINTY

UNCERTAINTY

UNCERTAINTY