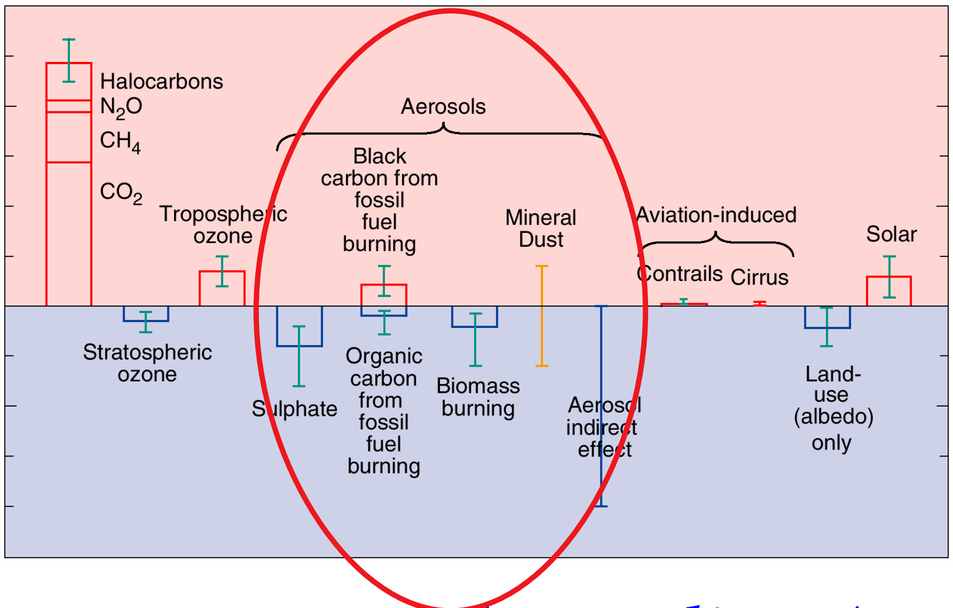
RADIATIVE FORCING OF CLIMATE CHANGE BY AEROSOLS

WHY THIS IS IMPORTANT
AND HOW WELL IT NEEDS TO BE KNOWN



Stephen E. Schwartz

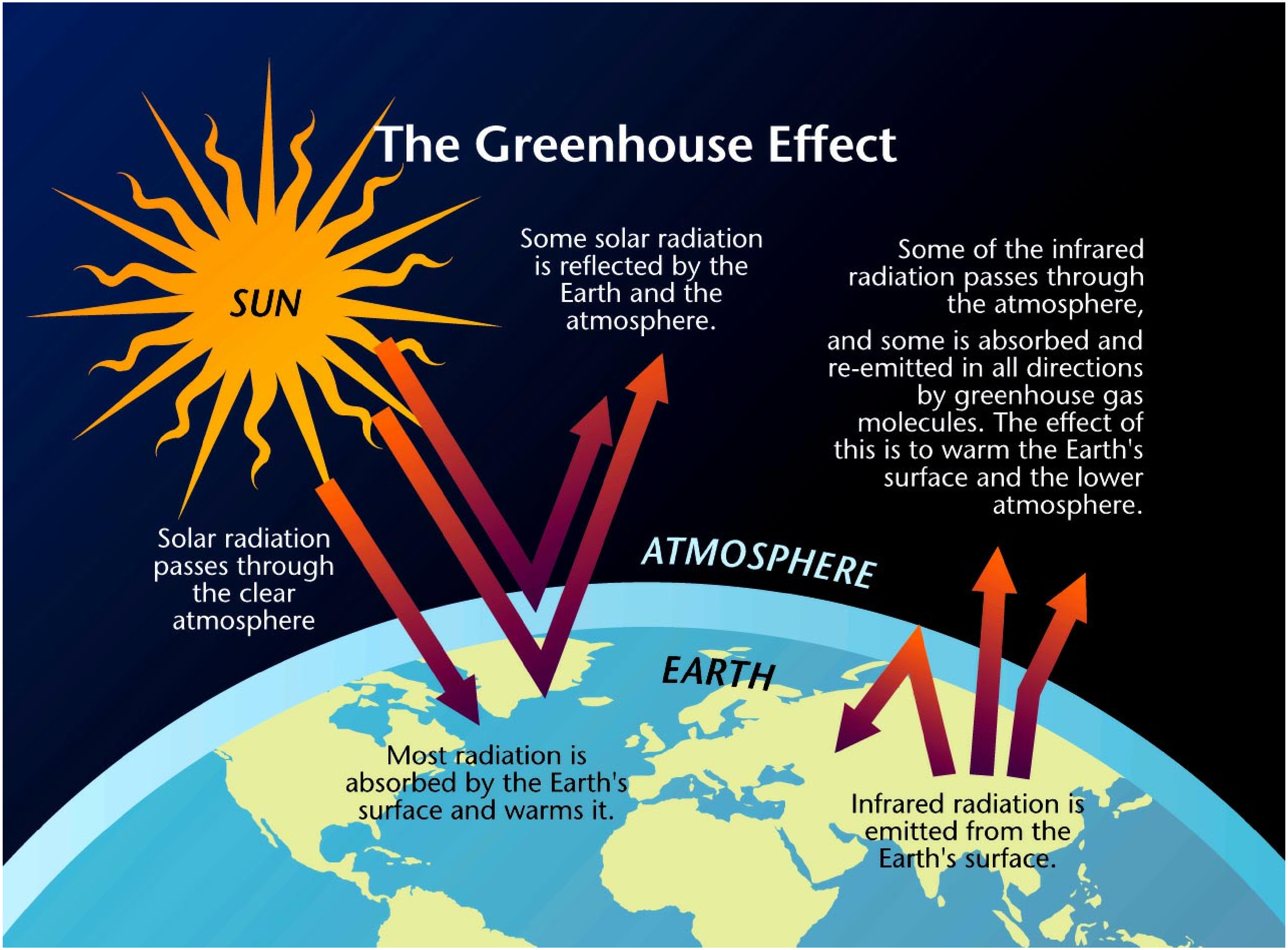
BROOKHAVEN NATIONAL LABORATORY

Upton, New York, USA

Australian Aerosol Workshop

University of New South Wales, Sydney, Australia
March 30 – April 1, 2005

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

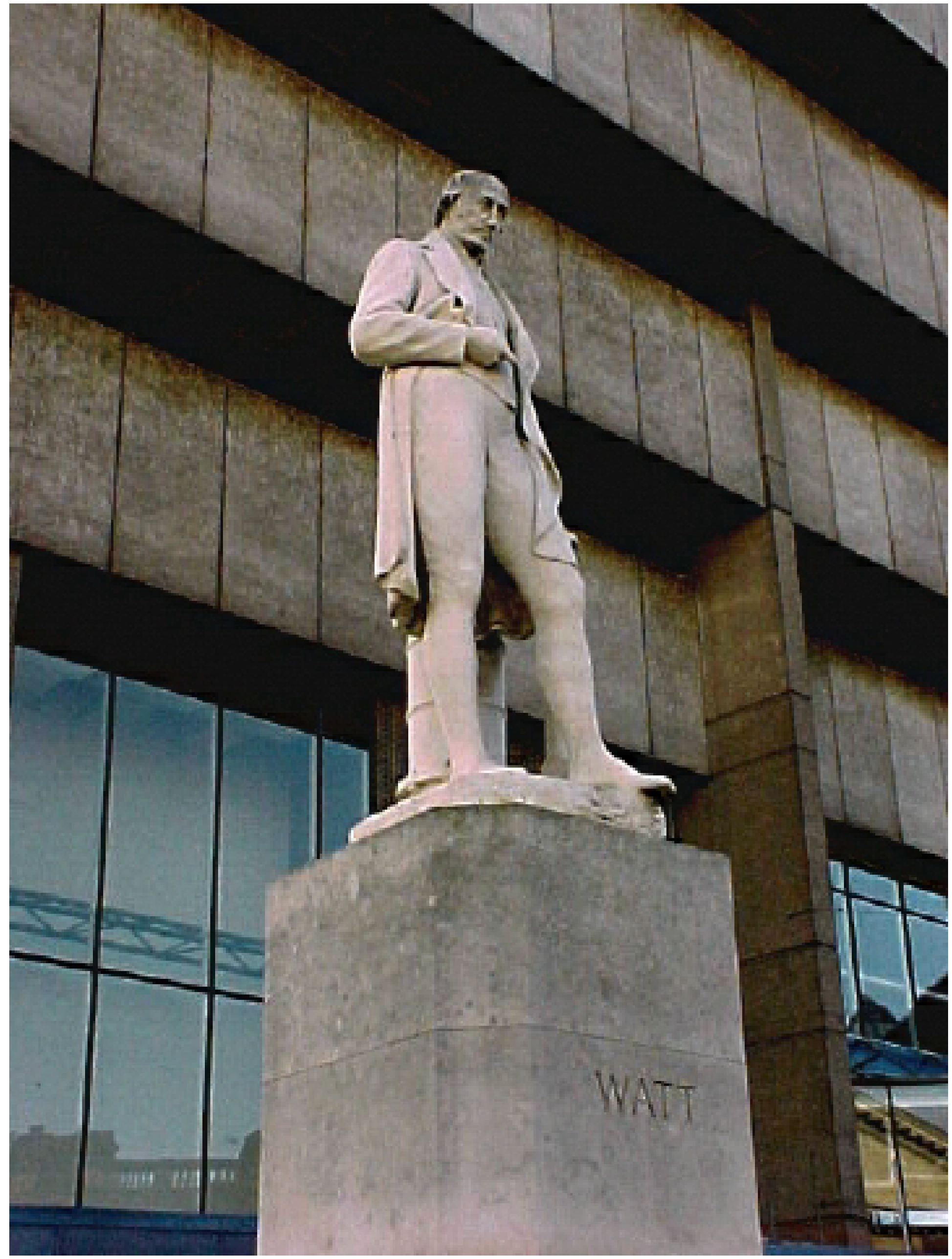

The Greenhouse Effect
SUN
Some solar radiation is reflected by the Earth and the atmosphere.
Some of the infrared radiation passes through the atmosphere,
and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the Earth's surface and the lower atmosphere.
Solar radiation passes through the clear atmosphere
ATMOSPHERE
EARTH
Most radiation is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.

ATMOSPHERIC RADIATION

Energy per area per time

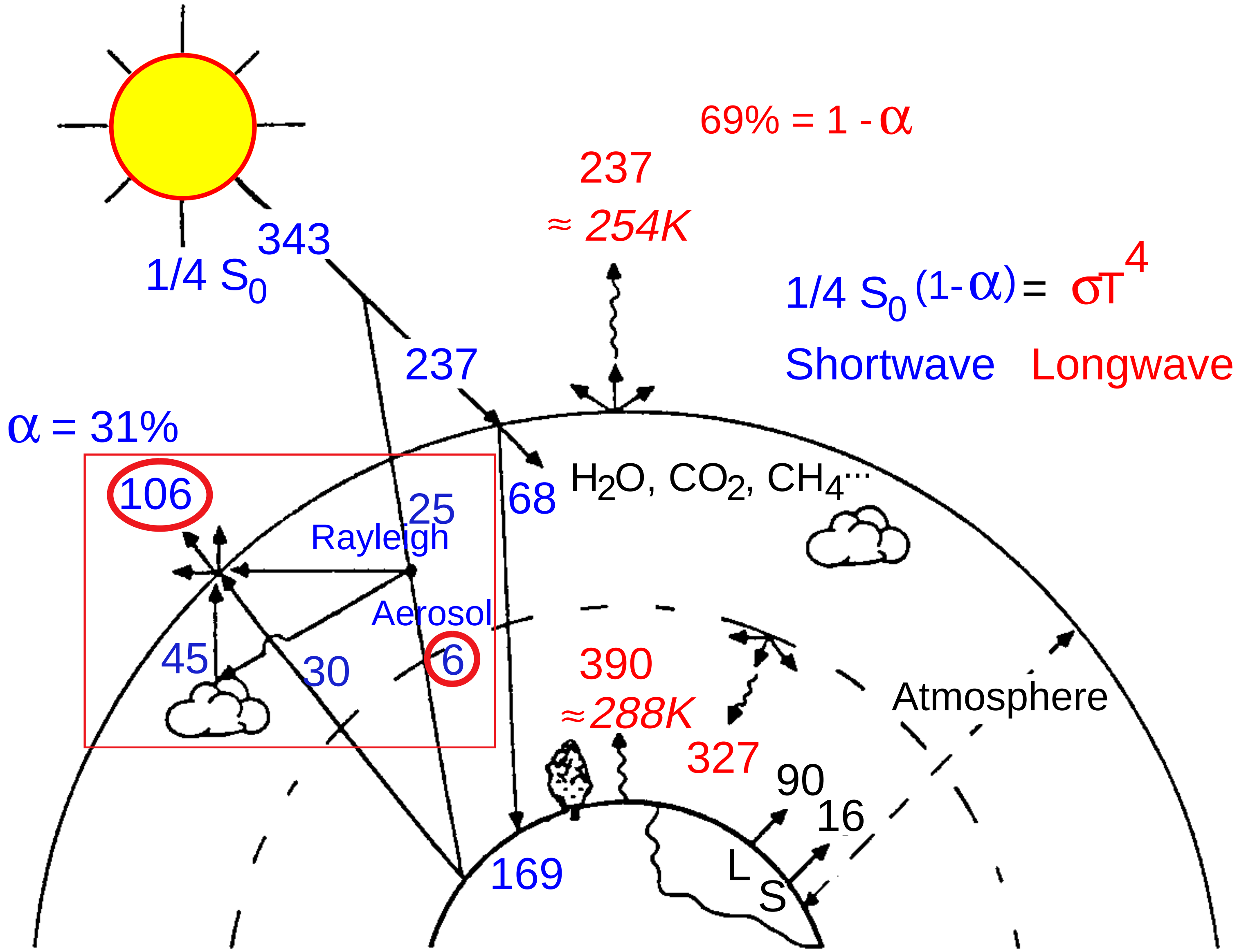
Power per area

Unit:
Watt per square meter
$W\ m^{-2}$



GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Modified from Ramanathan, 1987

RADIATIVE FORCING OF CLIMATE CHANGE

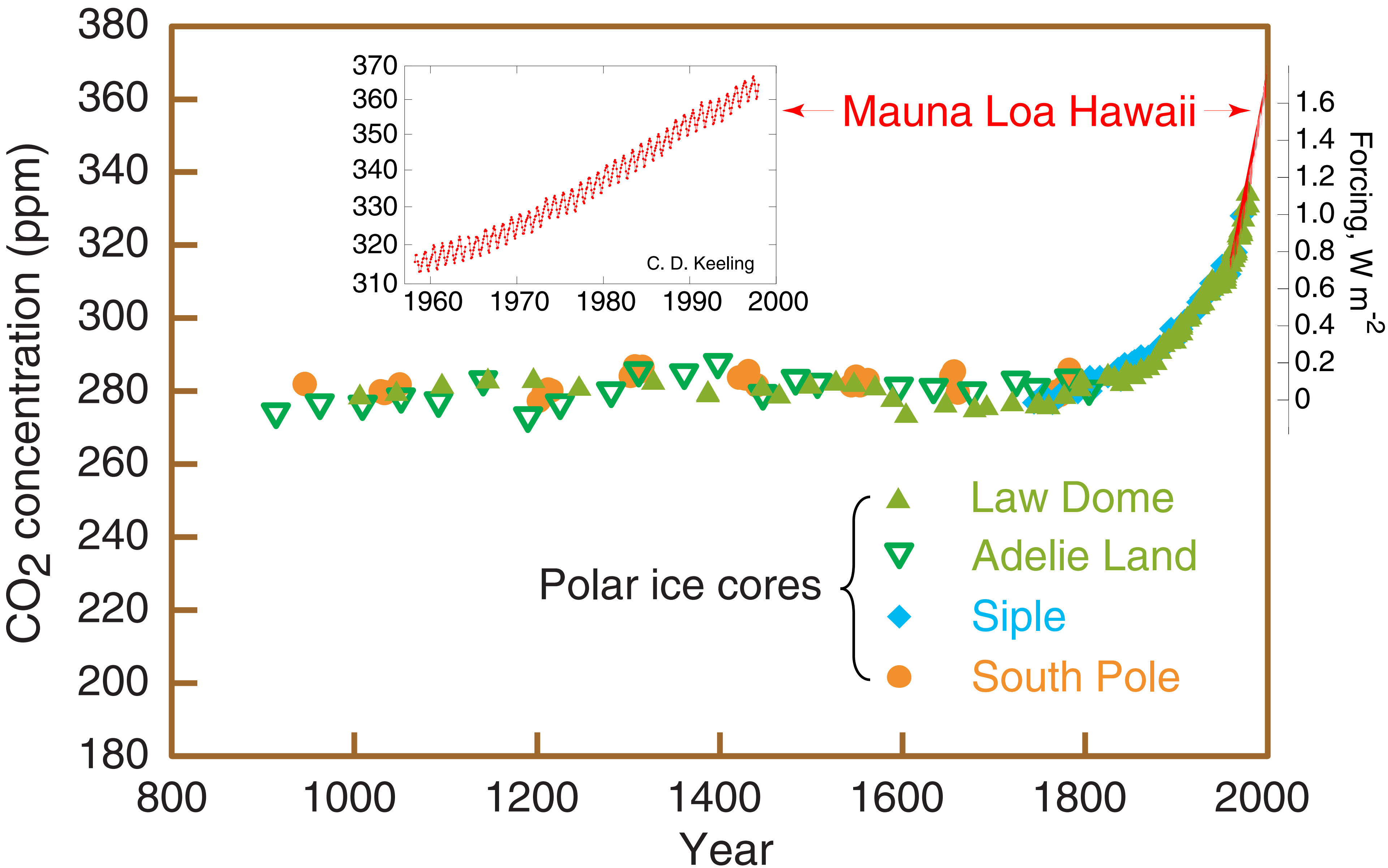
A ***change*** in a radiative flux term in Earth's radiation budget, F, W m^{-2}.

Working hypothesis:

On a global basis radiative forcings are additive and fungible.

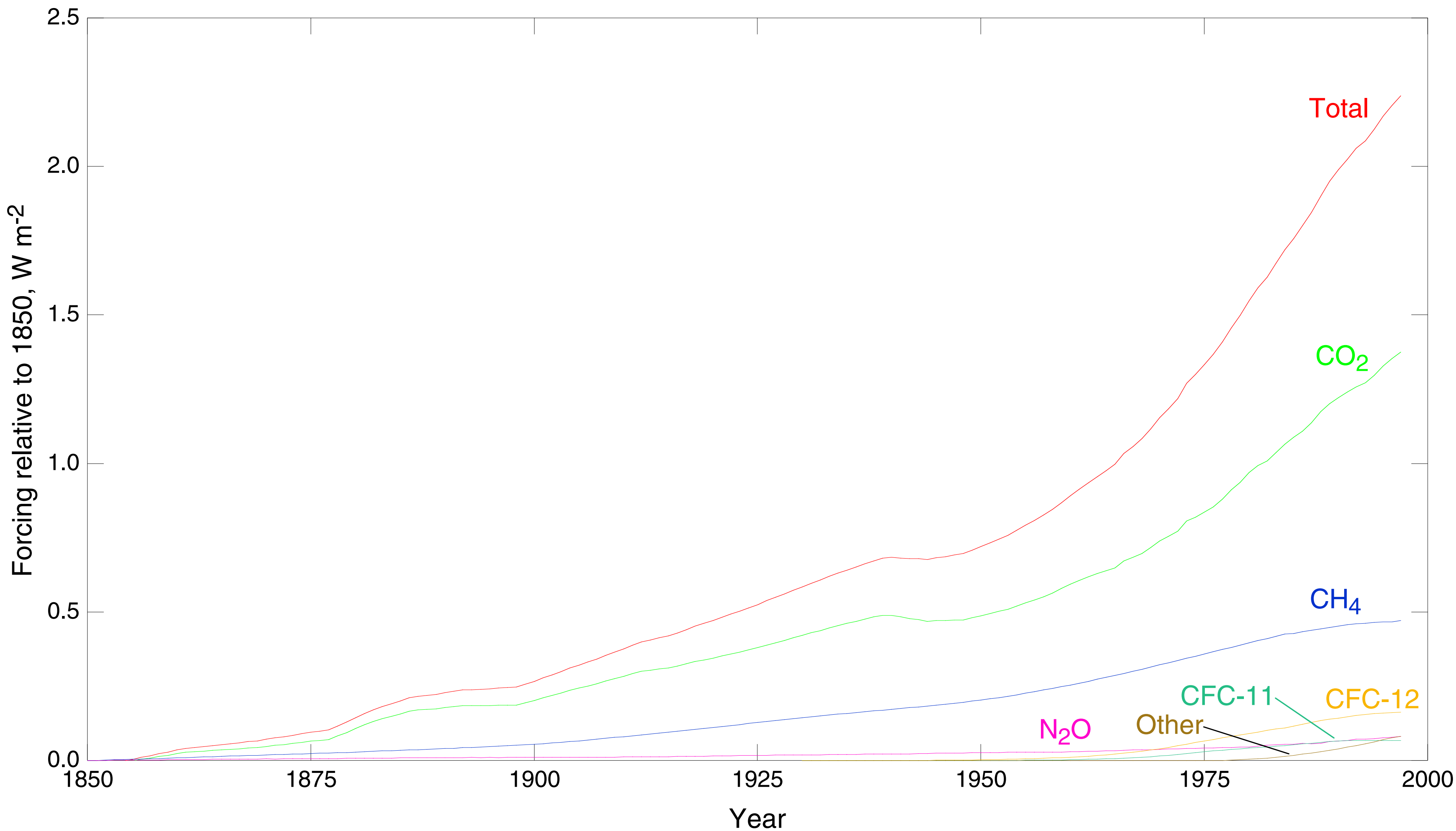
- This hypothesis is fundamental to the radiative forcing concept.
- This hypothesis underlies much of the assessment of climate change over the industrial period.

ATMOSPHERIC CARBON DIOXIDE IS INCREASING



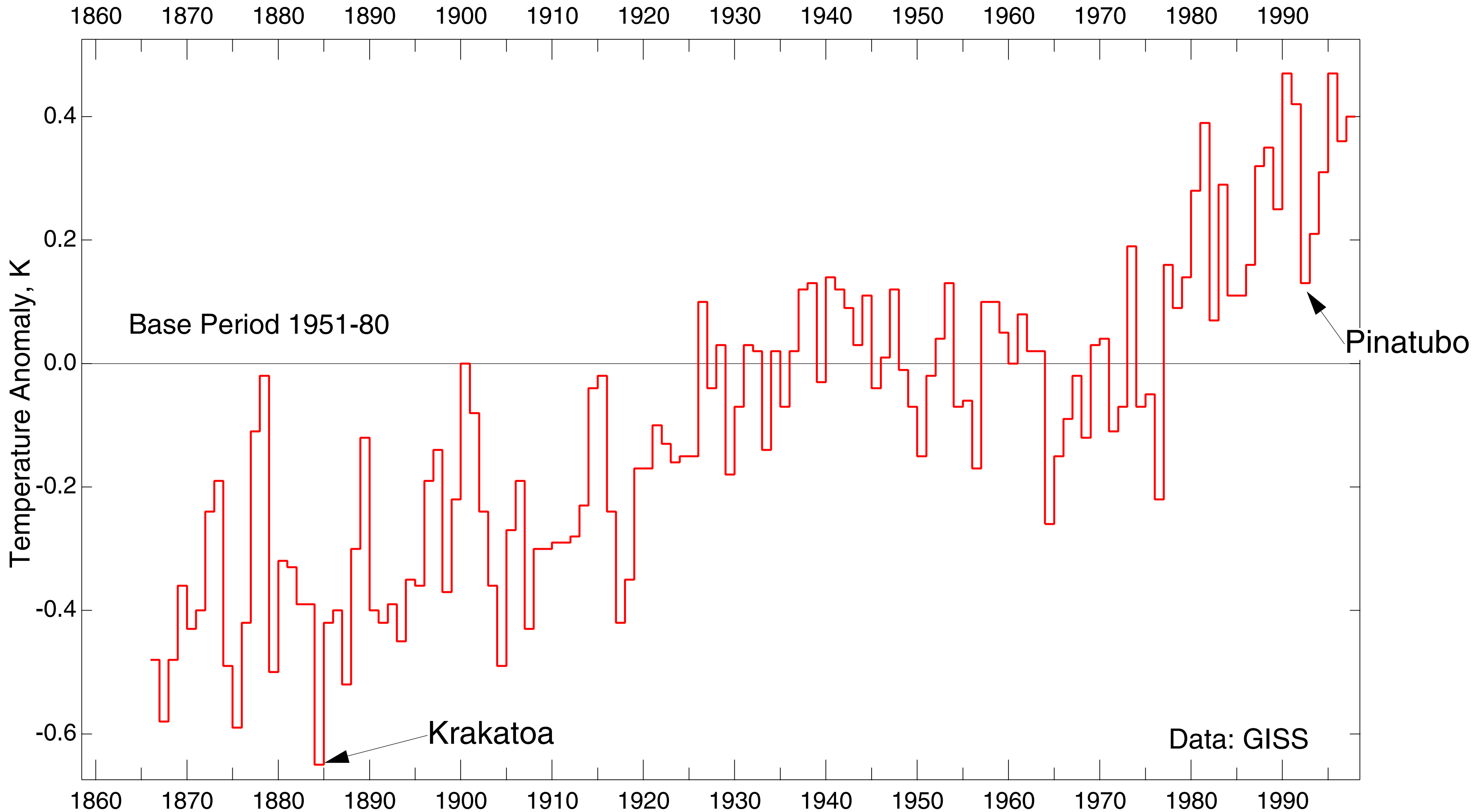
Global carbon dioxide concentration and infrared radiative forcing over the last thousand years

GREENHOUSE GAS FORCINGS OVER THE INDUSTRIAL PERIOD



Data: GISS

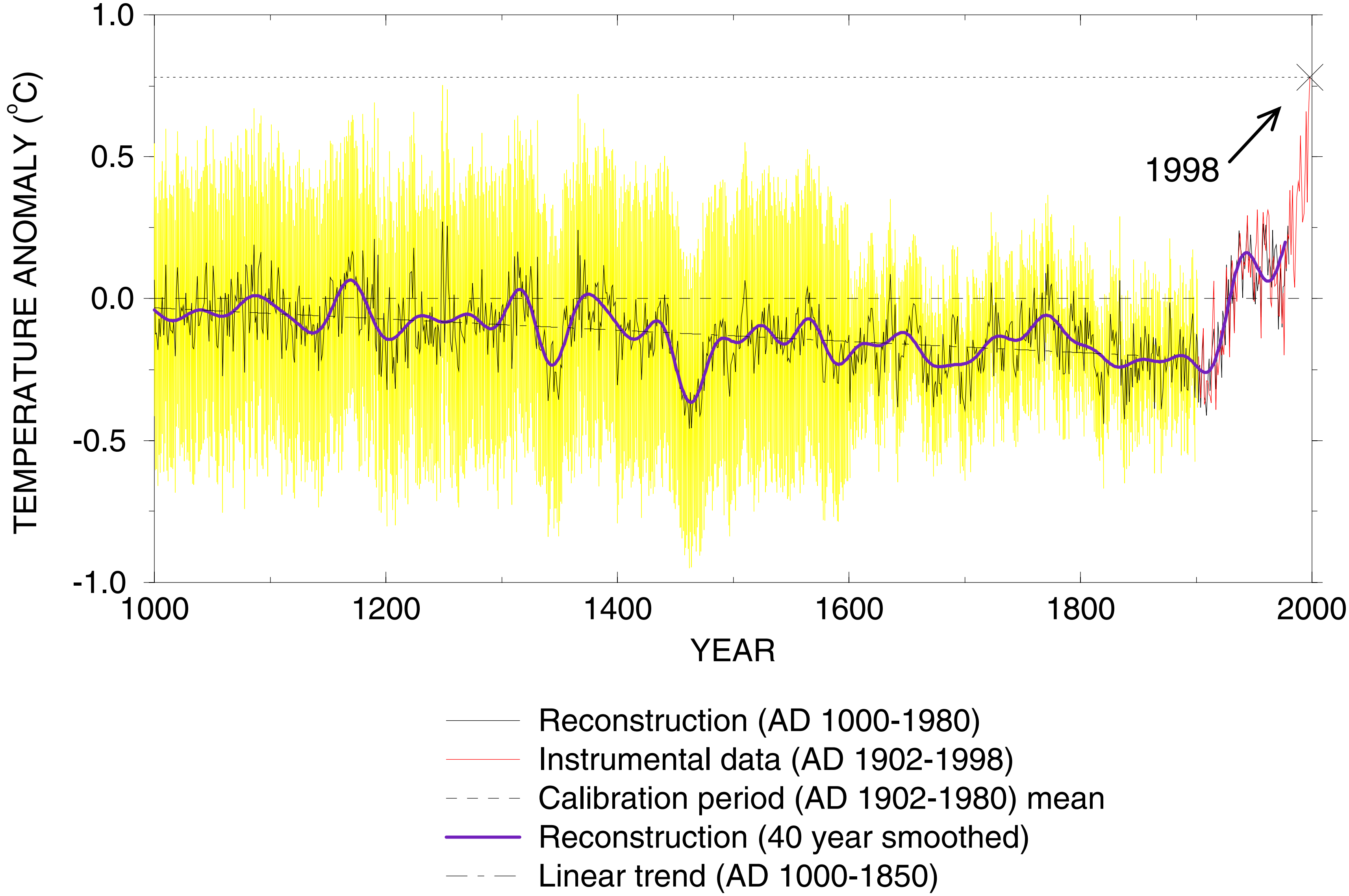
GLOBAL TEMPERATURE TREND OVER THE INDUSTRIAL PERIOD



NORTHERN HEMISPHERE TEMPERATURE TREND (1000-1998)

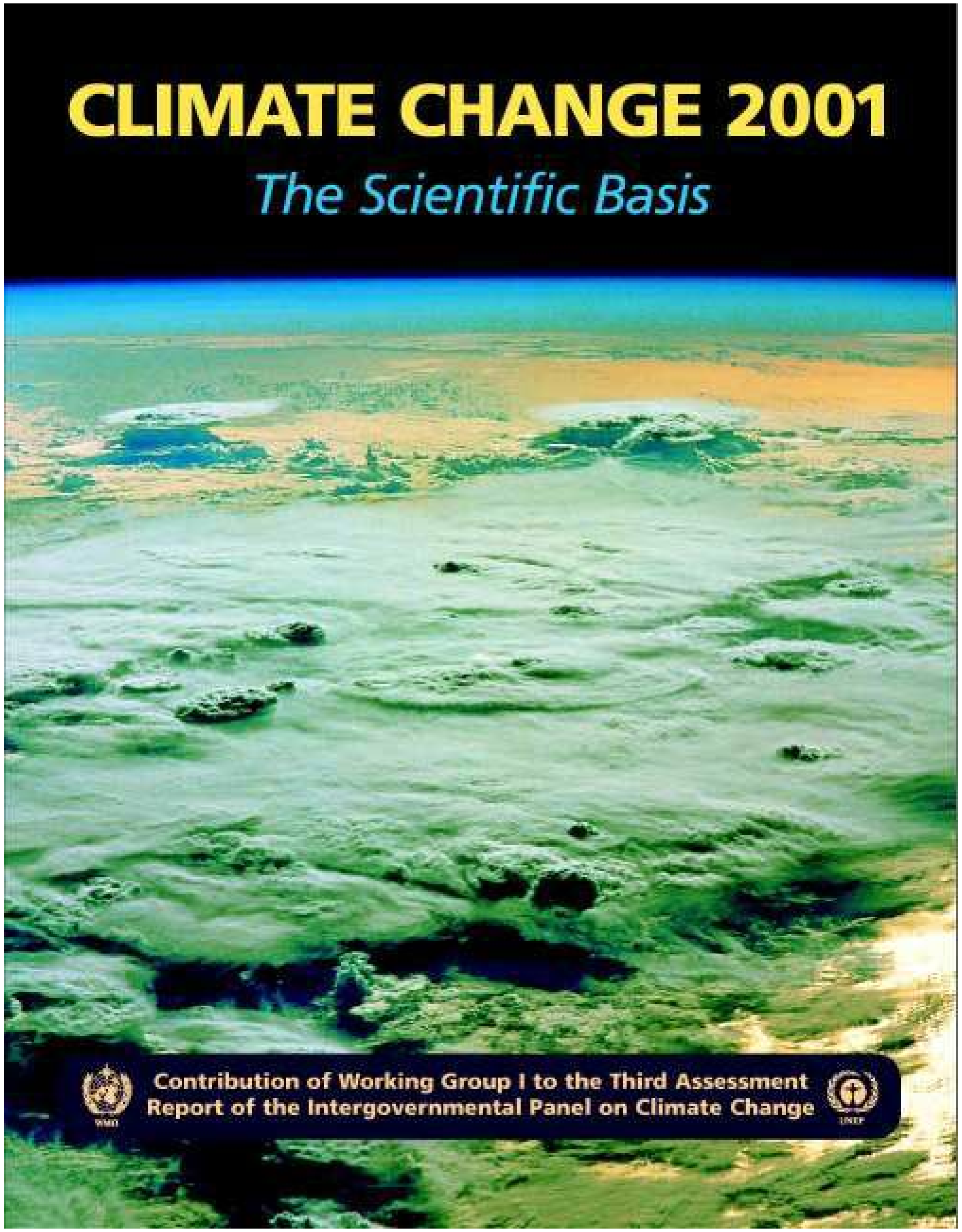
From tree-ring, coral, and ice-core proxy records

As calibrated by instrumental measurements



Mann et al., GRL, 1999

THE "BIBLE" OF CLIMATE CHANGE RESEARCH

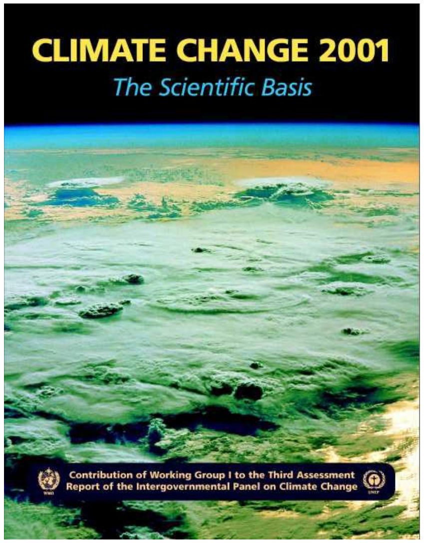


WMO

UNEP

Cambridge University Press, 2001

THE BIBLE OF CLIMATE CHANGE



It's big and thick.

Every household should have one.

No one reads it from cover to cover.

You can open it up on any page and find something interesting.

It was written by a committee.

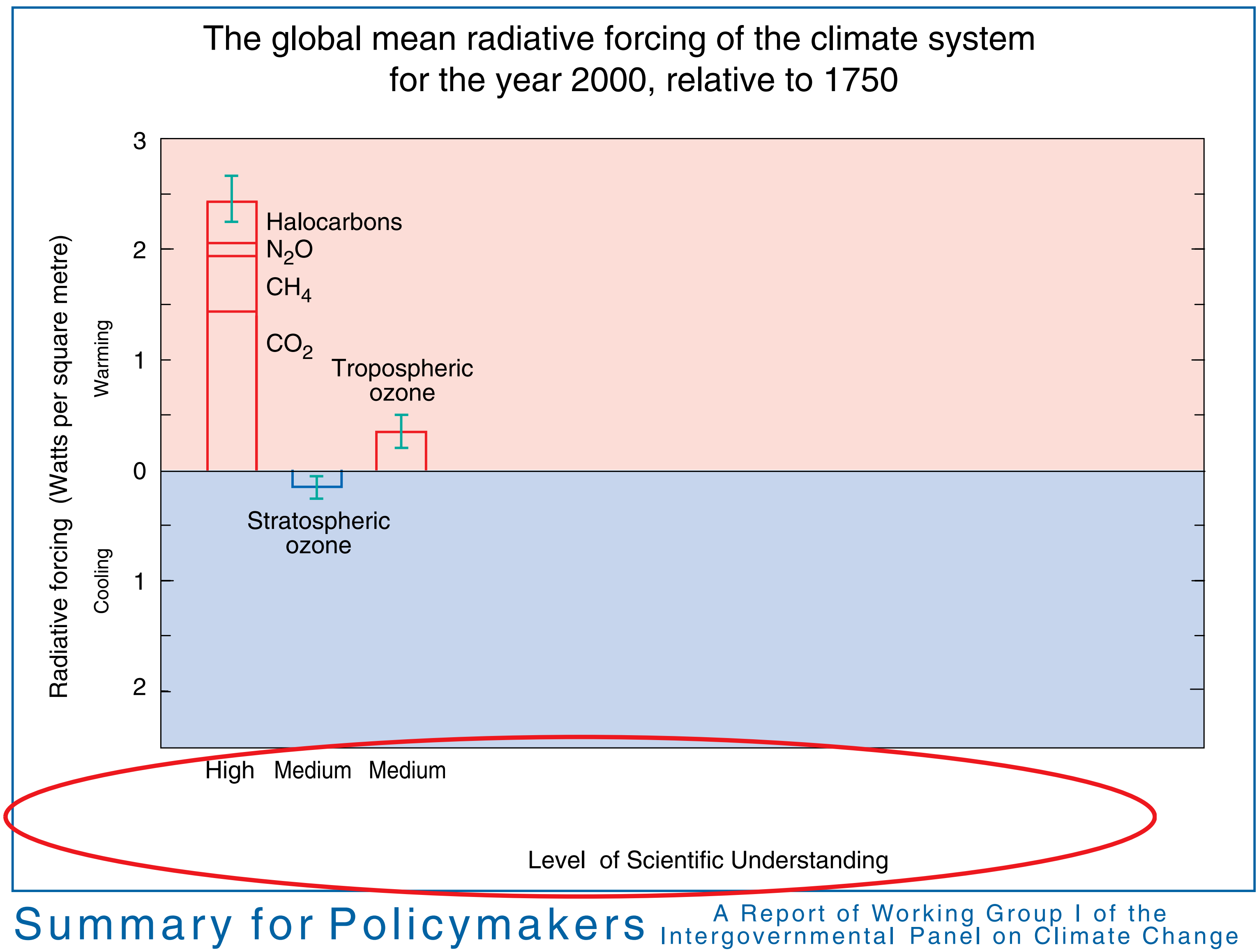
It is full of internal contradictions.

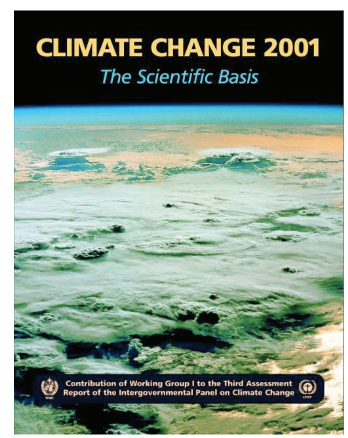
It deals with cataclysmic events such as floods and droughts.

It has its true believers and its nonbelievers.

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)

Greenhouse gases only





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}).

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.

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.

CLIMATE CHANGE SENSITIVITY
Summary of 15 Current Models

Quantity, Unit	Mean	Standard Deviation	Range
λ, K/(W m^{-2})	0.87	0.23	0.5 - 1.25
$\Delta T_{2\times}$, K	3.5	0.9	2 - 5

IPCC *Climate Change 2001*, Cambridge University Press, 2001

EMPIRICAL CLIMATE SENSITIVITY

Greenhouse forcing over the industrial period is 2.5 W m^{-2}

Temperature increase over the industrial period is 0.6 K.

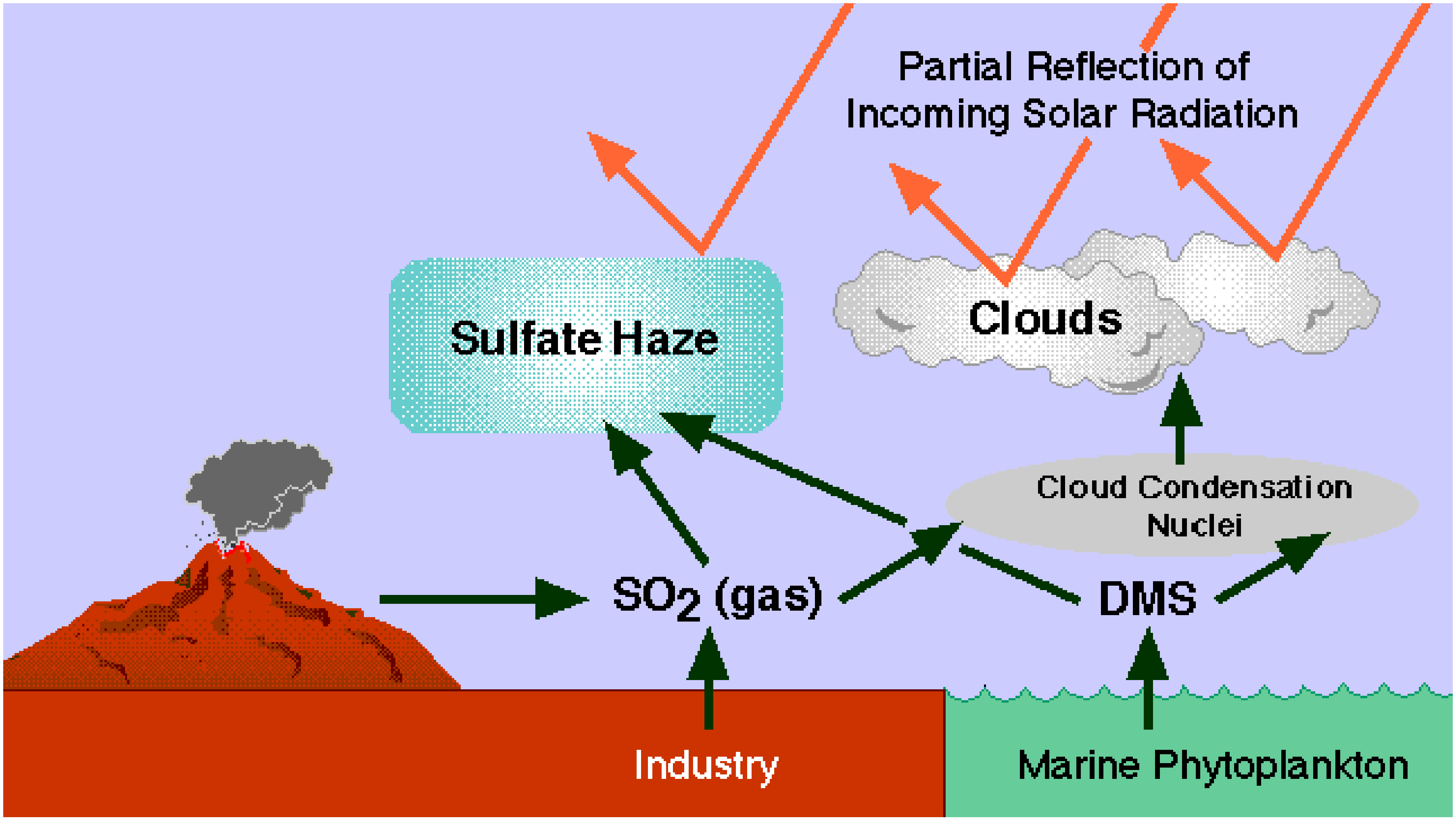
Empirical Sensitivity:

$$\lambda = \frac{dT}{dF} = \frac{0.6\ \text{K}}{2.5\ \text{W m}^{-2}} = 0.24\ \text{K} \ / \ (\text{W m}^{-2}) \qquad \textit{or} \qquad \Delta T_{2\times} = 1\ \text{K}$$

Why is the empirical sensitivity so much lower than model-based estimates?

THE "WHITEHOUSE EFFECT"

RADIATIVE FORCING OF CLIMATE CHANGE BY AEROSOLS



AEROSOL INFLUENCES ON RADIATION BUDGET AND CLIMATE

Direct Effect (Cloud-free sky)

Light scattering -- Cooling influence

Light absorption -- Warming influence, depending on surface

Indirect Effects (Aerosols influence cloud properties)

More droplets -- Brighter clouds (Twomey)

More droplets -- Enhanced cloud lifetime (Albrecht)

Semi-Direct Effect

Absorbing aerosol heats air and evaporates clouds

DIRECT EFFECT

AEROSOL: A suspension of particles in air

February 4, 2003

Atmospheric aerosols may result from primary emissions (dust, smoke) or from gas to particle conversion in the atmosphere (haze, smog).

DIRECT RADIATIVE FORCING DUE TO ANTHROPOGENIC SULFATE AEROSOL

Geophysics | Aerosol Optical Depth

$$\overline{\Delta F_{\mathrm{R}}} = -\frac{1}{2} F_{\mathrm{T}} T^2 (1 - A_{\mathrm{c}})(1 - R_{\mathrm{s}})^2 \cdot \bar{\beta}\,\alpha_{\mathrm{SO_4^{2-}}} f(\mathrm{RH}) \cdot Q_{\mathrm{SO_2}} Y_{\mathrm{SO_4^{2-}}} \left(\frac{\mathrm{MW}_{\mathrm{SO_4^{2-}}}}{\mathrm{MW_S}} \right) \tau_{\mathrm{SO_4^{2-}}} \Big/ A$$

Aerosol Microphysics | Column Burden Atmospheric Chemistry

$\overline{\Delta F_{\mathrm{R}}}$ is the area-average shortwave radiative forcing due to the aerosol, W m^{-2}

F_{T} is the solar constant, W m^{-2}

A_{c} is the fractional cloud cover

T is the fraction of incident light transmitted by the atmosphere above the aerosol

R_{s} is the albedo of the underlying surface

$\bar{\beta}$ is upward fraction of the radiation scattered by the aerosol,

$\alpha_{\mathrm{SO_4^{2-}}}$ is the scattering efficiency of **sulfate and associated cations** at a reference low relative humidity, m^2 (g SO_4^{2-})$^{-1}$

f(RH) accounts for the relative increase in scattering due to relative humidity

$Q_{\mathrm{SO_2}}$ is the source strength of anthropogenic SO_2 g S yr^{-1}

$Y_{\mathrm{SO_4^{2-}}}$ is the fractional yield of emitted SO_2 that reacts to produce sulfate aerosol

MW is the molecular weight

$\tau_{\mathrm{SO_4^{2-}}}$ is the sulfate lifetime in the atmosphere, yr

A is the area of the geographical region under consideration, m^2

Charlson, Schwartz, Hales, Cess, Coakley, Hansen & Hofmann, Science, 1992

EVALUATION OF GLOBAL MEAN DIRECT RADIATIVE FORCING DUE TO ANTHROPOGENIC SULFATE

Quantity	Central Value	Units	Uncertainty Factor
F_T	1370	W m^{-2}	—
1-A$_c$	0.4	——	1.1
T	0.76	——	1.15
1-R$_s$	0.85	——	1.1
$\overline{\beta}$	0.29	——	1.3
$\alpha_{SO_4^{2-}}$	5	m^2 (g SO_4^{2-})$^{-1}$	**1.5**
f(RH)	1.7	——	1.2
Q_{SO_2}	80	Tg S yr^{-1}	1.15
$Y_{SO_4^{2-}}$	0.4	——	**1.5**
$\tau_{SO_4^{2-}}$	0.02	yr	**1.5**
A	5×10^{14}	m^2	—
$\overline{\Delta F_R}$	-1.1	W m^{-2}	2.4

$\alpha^* = 8.5$ m^2 (g SO_4^{2-})$^{-1}$

Column Burden 4 mg SO_4^{2-} m^{-2}

Optical Depth = 0.03

Total uncertainty factor evaluated as $f_t = \exp\left[\sum\left(\log f_i\right)^2\right]^{1/2}$

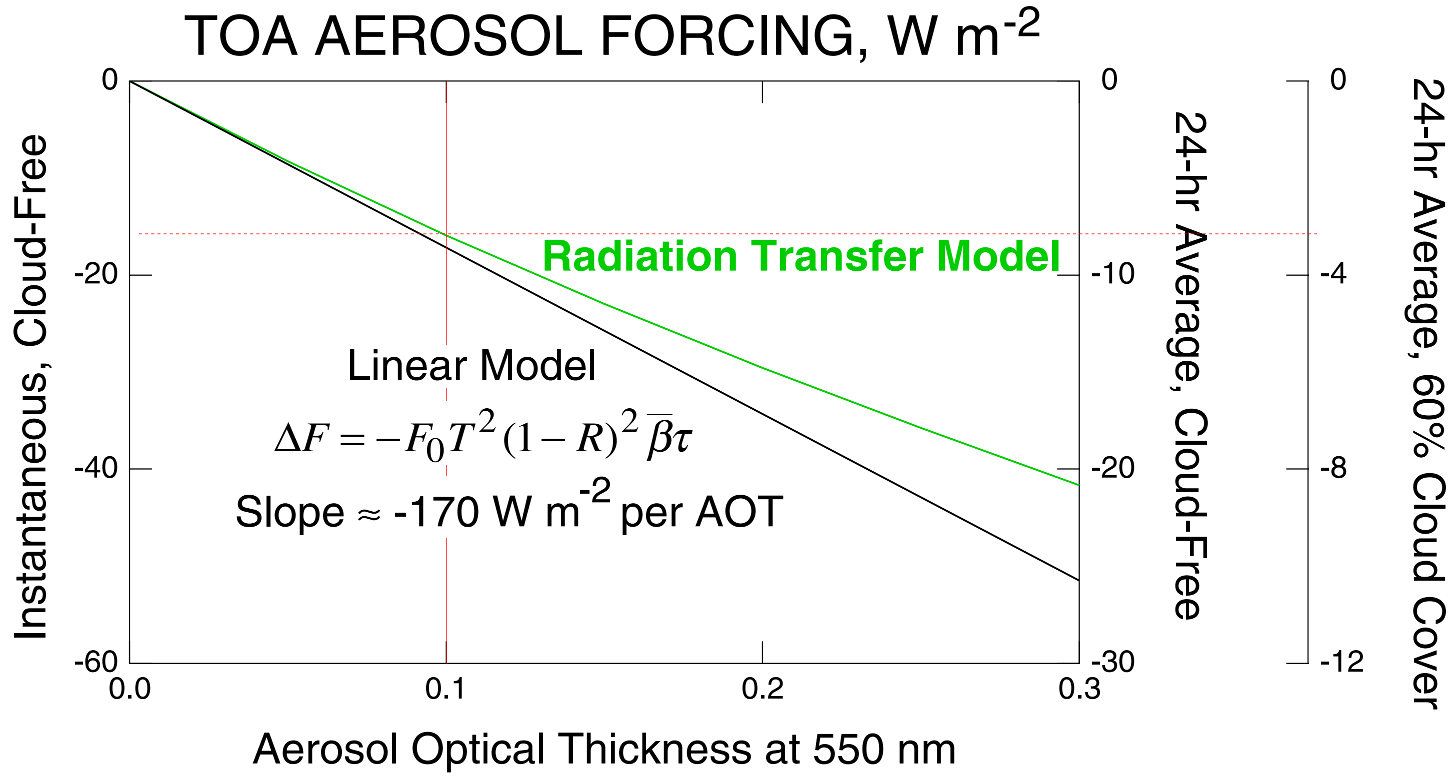
Penner, Charlson, Hales, Laulainen, Leifer, Novakov, Ogren, Radke, Schwartz & Travis, BAMS, 1994

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 ω_0 = 1.



Forcing is highly sensitive to modest aerosol loadings.

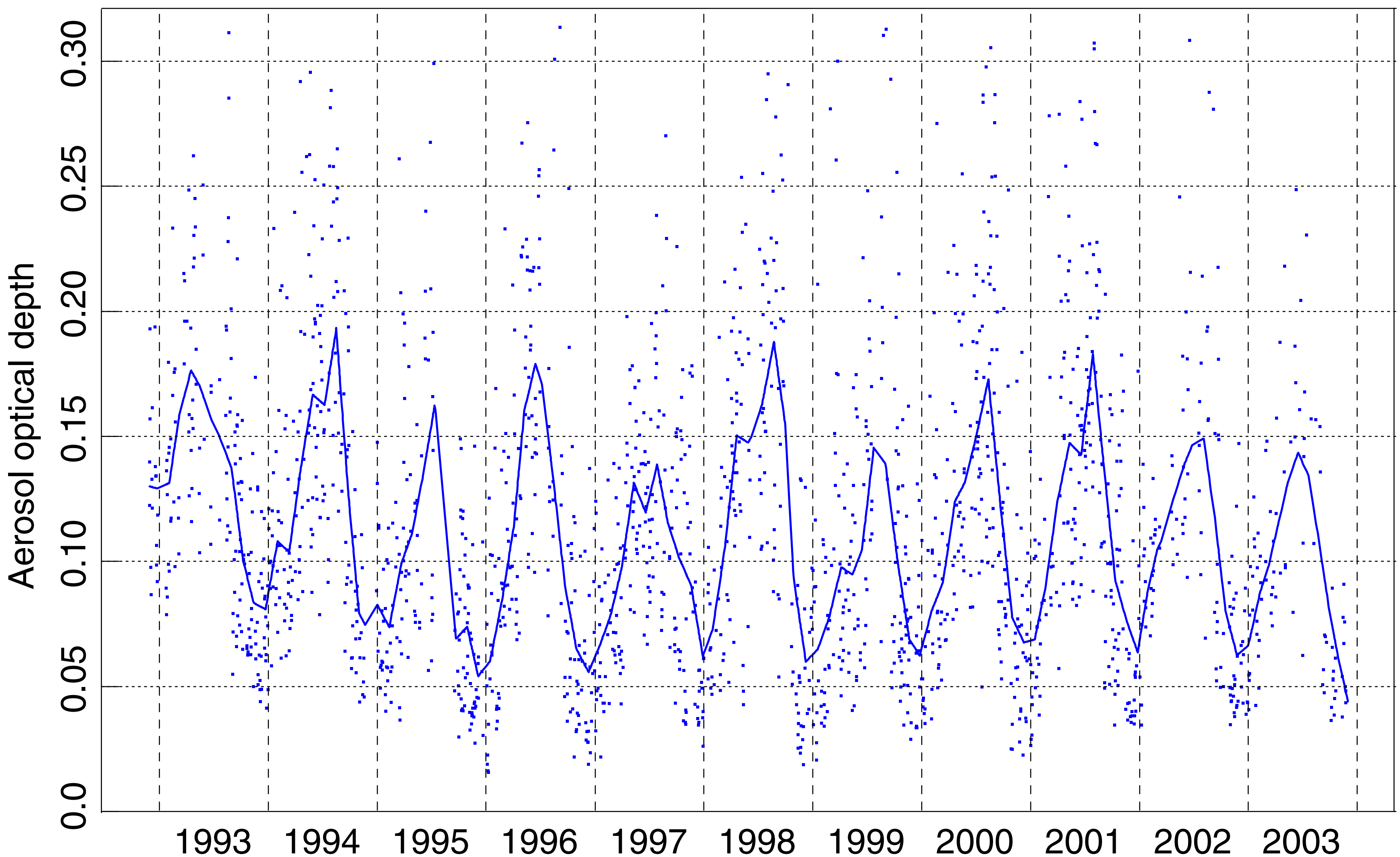
Global-average AOT 0.1 corresponds to global-average forcing -3.2 W m^{-2}.

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

AEROSOL OPTICAL DEPTH

Determined by sunphotometry

North central Oklahoma - Daily average 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.

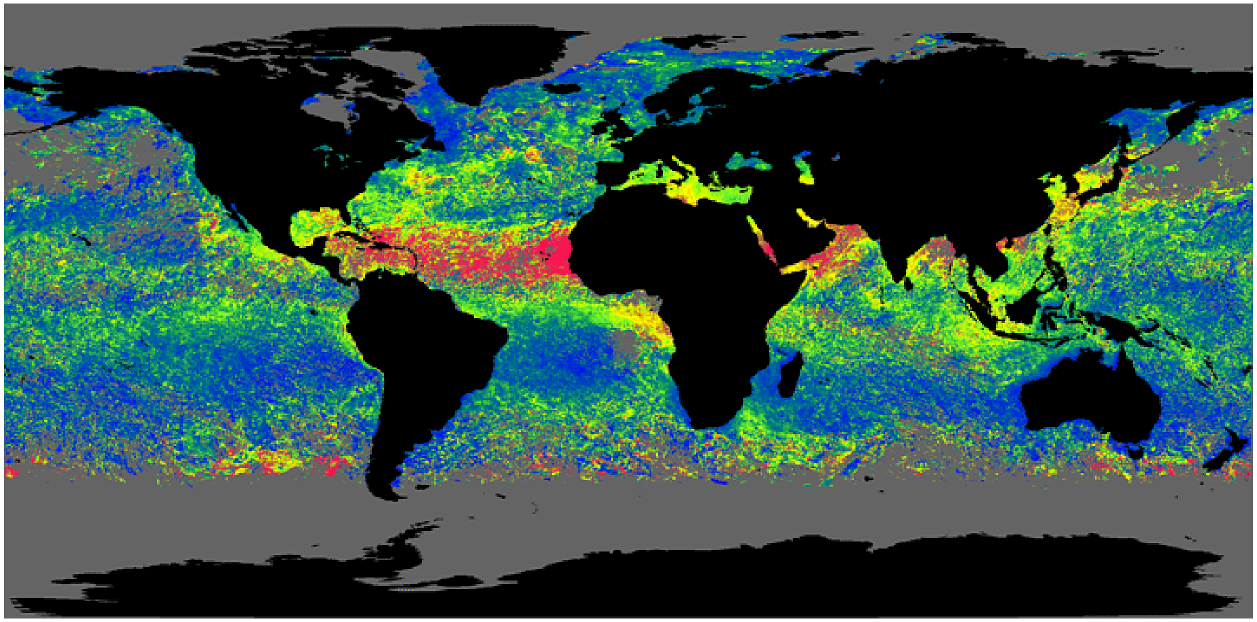
MONTHLY AVERAGE AEROSOL JUNE 1997

Polder radiometer on Adeos satellite

Optical Thickness τ

$\lambda = 865$ nm

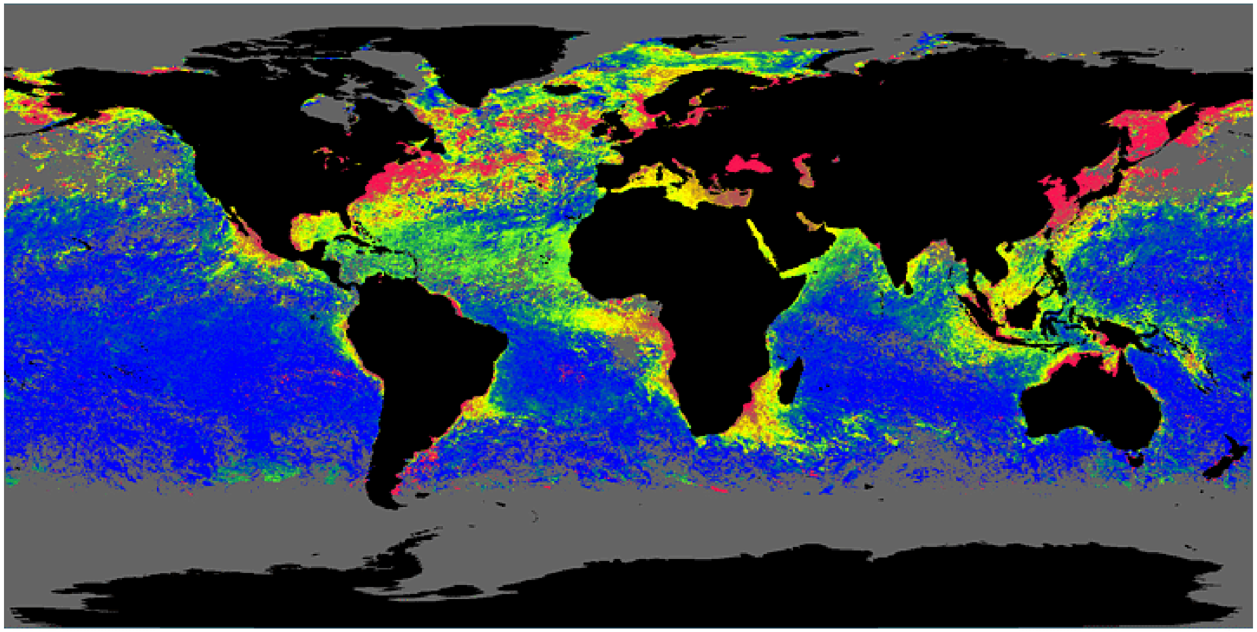
0 0.5



Ångström Exponent α

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

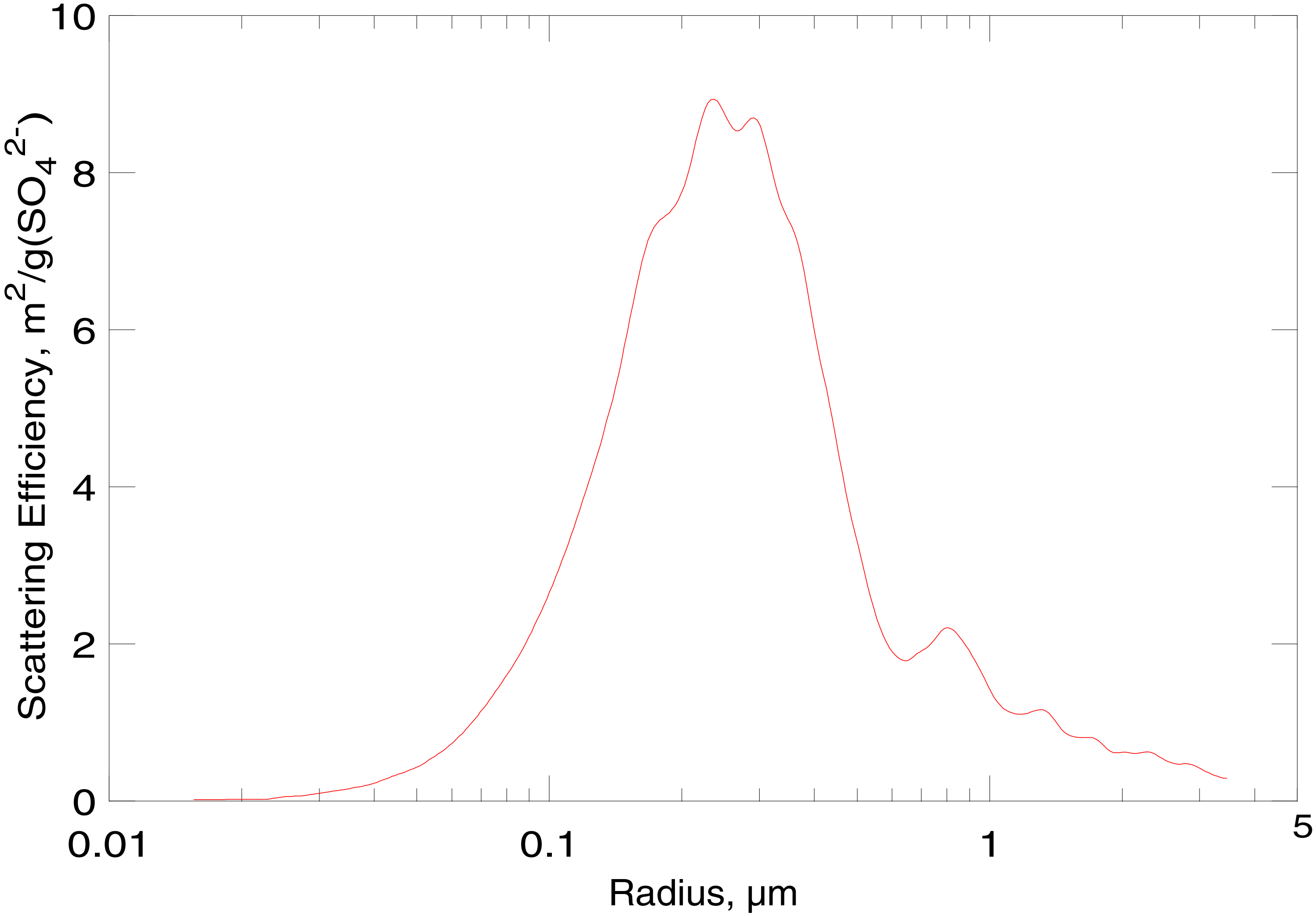
-0.2 1.2



LIGHT SCATTERING EFFICIENCY

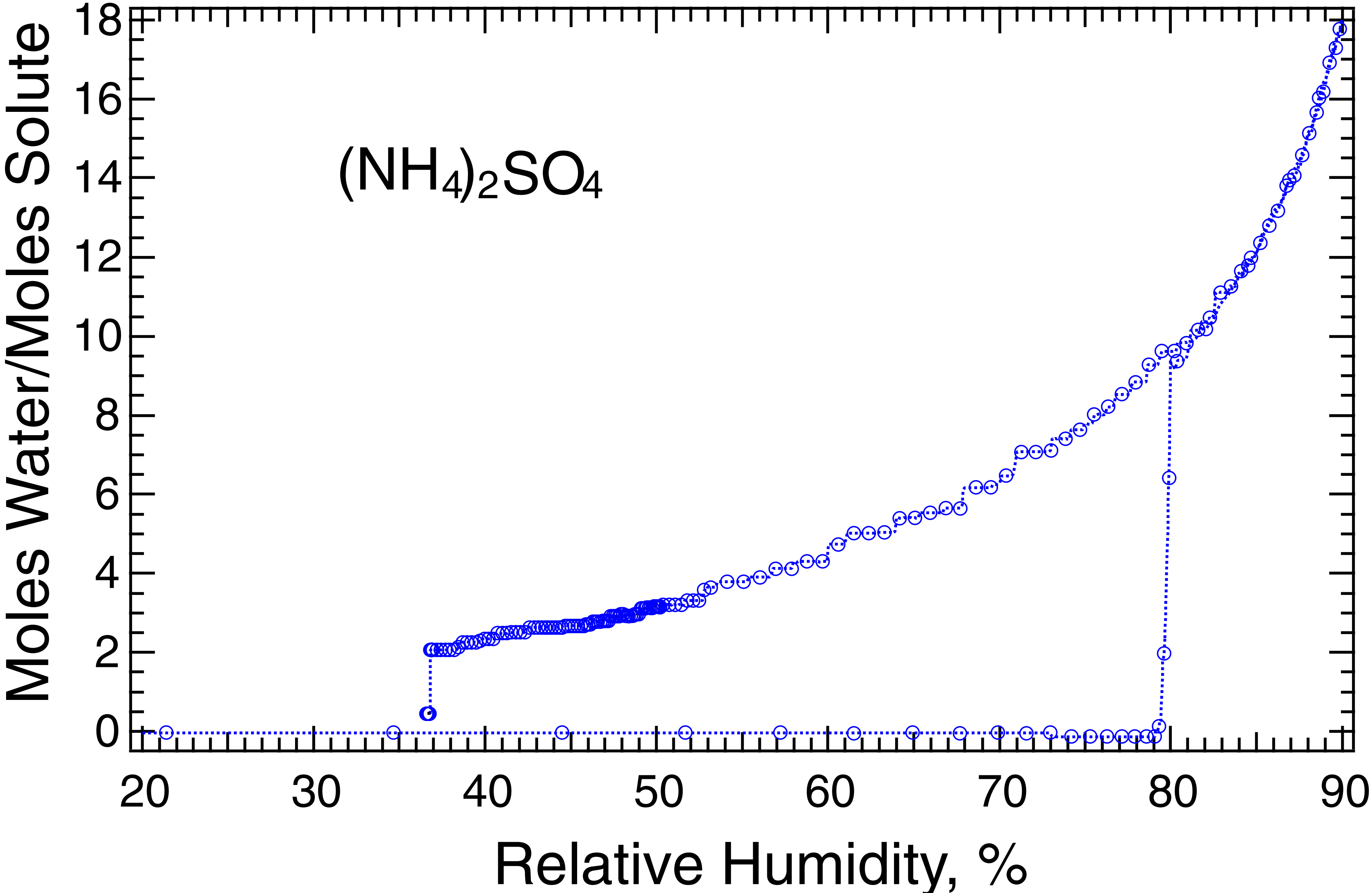
Dependence on particle radius -- Size matters!

Ammonium Sulfate, 530 nm



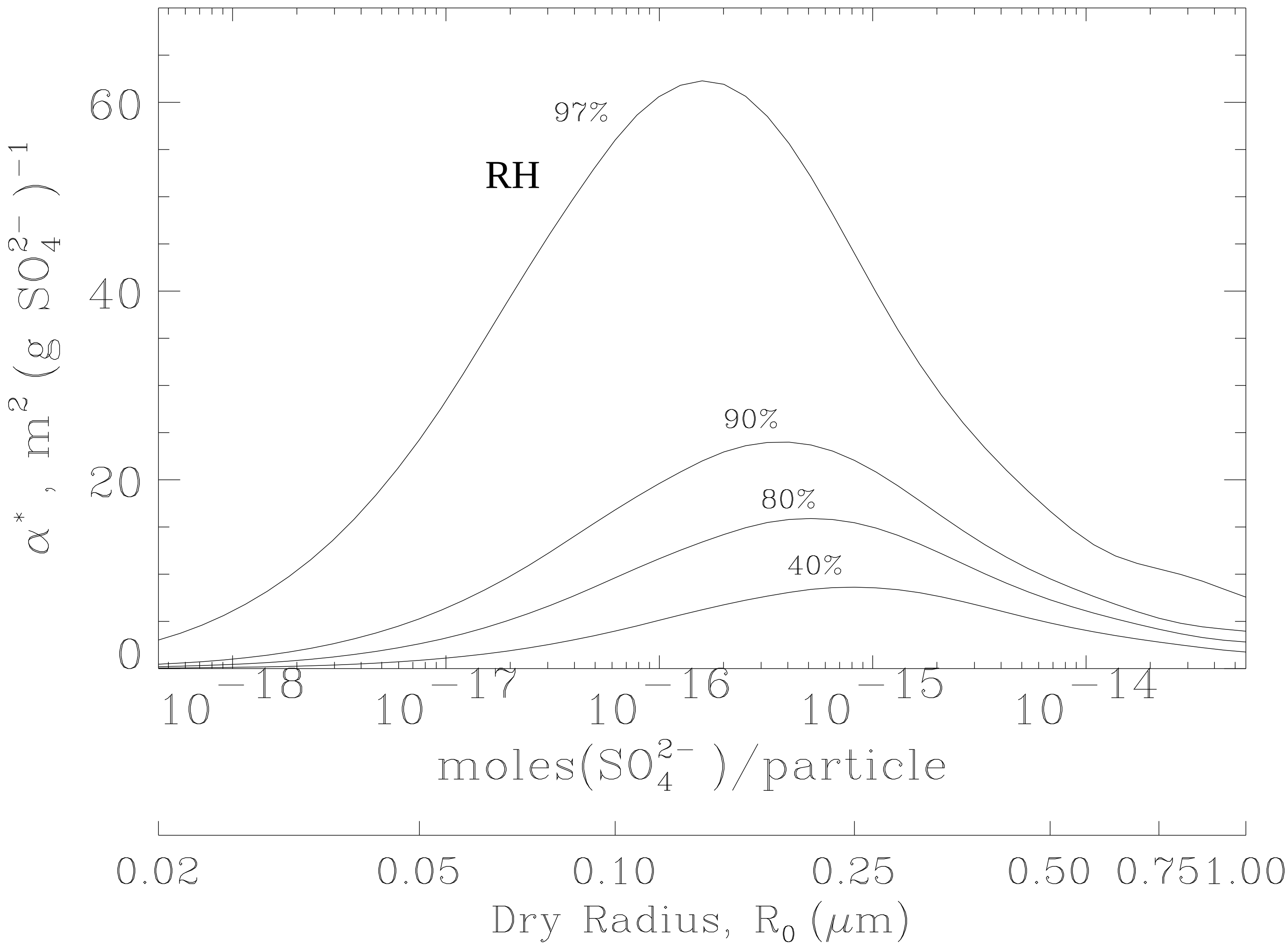
Data of Ouimette and Flagan, 1982

WATER UPTAKE BY HYGROSCOPIC PARTICLE
Dependence on relative humidity



D. Imre, T. Onasch, BNL

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



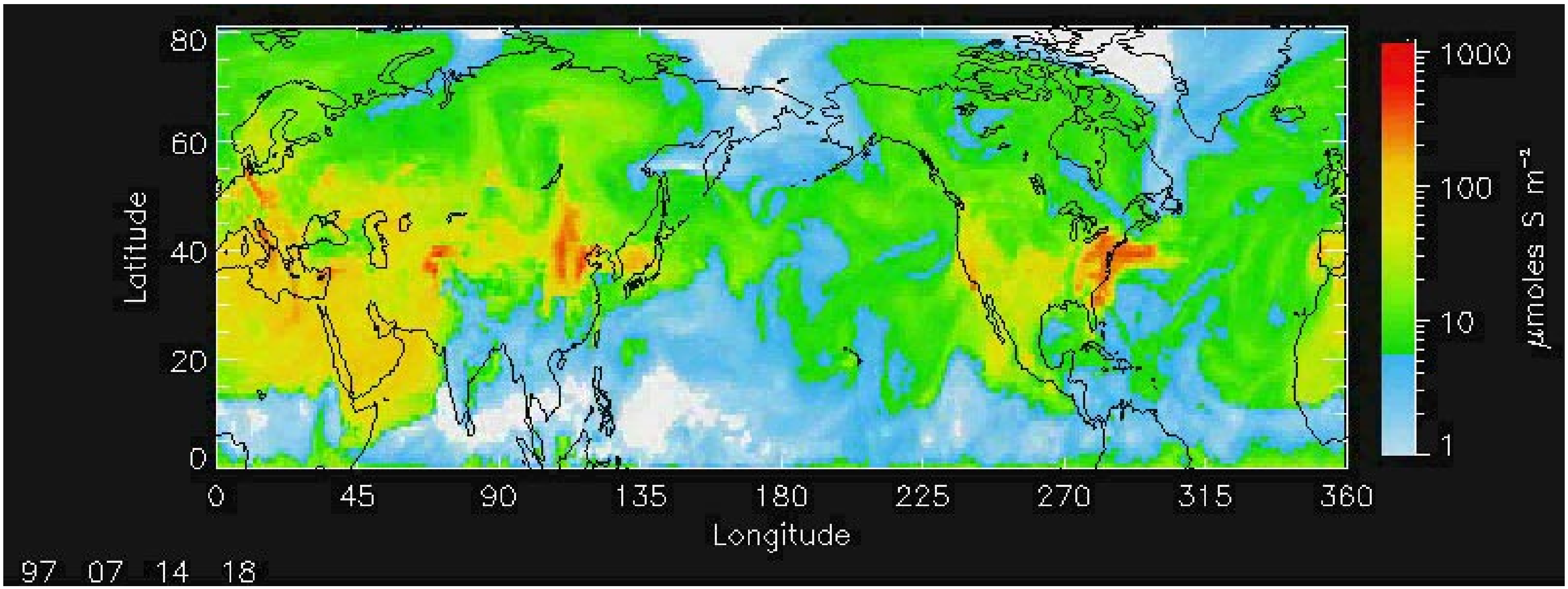
Nemesure,Wagener & Schwartz, JGR, 1995

Scattering, optical depth, and forcing are highly sensitive to particle size and to hygroscopic growth, which depends on composition.

HEMISPHERIC DISTRIBUTION OF SULFATE COLUMN BURDEN

Vertical integral of concentration

July 14, 1997, 1800 UTC

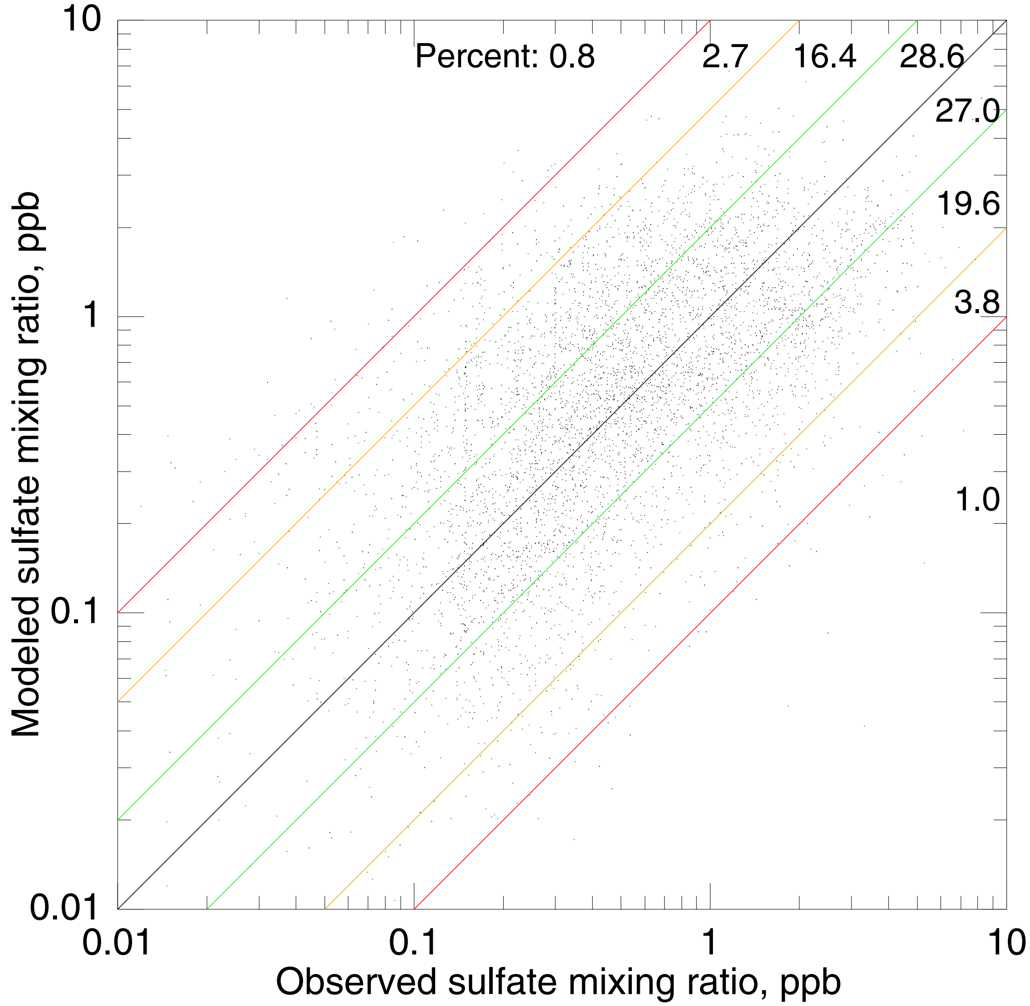


Brookhaven National Laboratory Chemical Transport Model

Benkovitz et al.,Geochem. Geophys. Geosyst., 2001

MODEL-OBSERVATION COMPARISONS

5083 24-Hour sulfate mixing ratio in BNL CTM driven by assimilated meteorological data - June-July 1997



56% of comparisons within factor of 2; 92% within factor of 5.

Benkovitz et al., JGR, In press, 2004

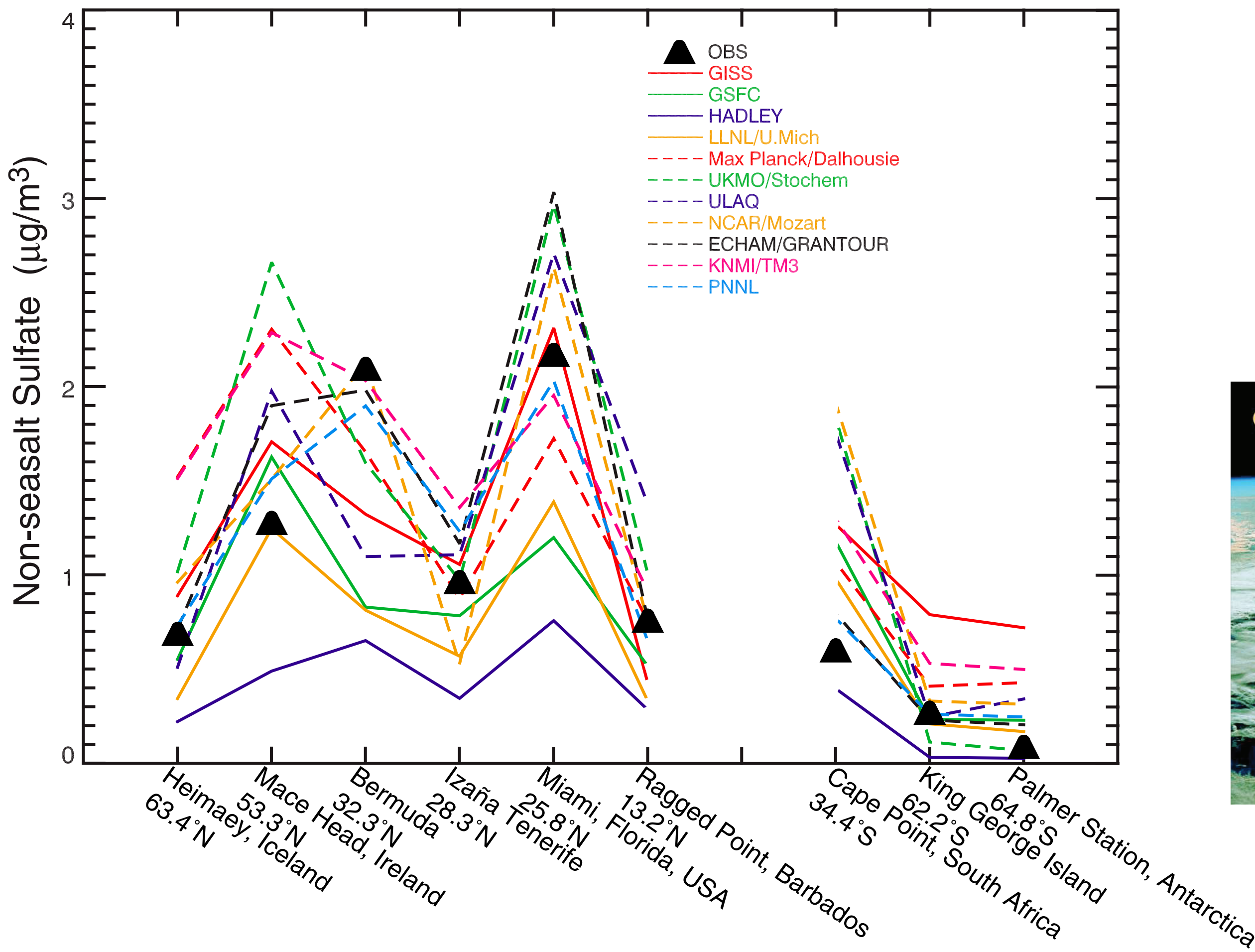
STATISTICS OF SEVERAL SULFATE CTMs

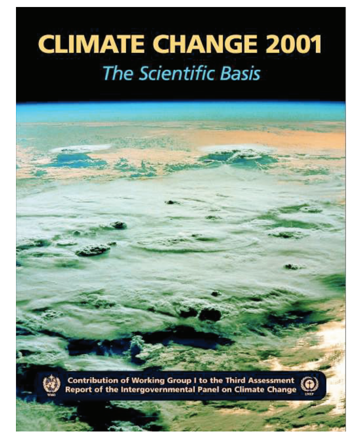
Model	F96	L97	R98	K99	R00	C00	B97	B04
SO_2 Sink Rate (%/day)								
Dry Deposition	26	10	8	17	16	26	12	24
Wet Deposition	5	0	0	0	1	7	0	4×10^{-4}
Gas Conversion	11	7	8	6	6	9	8	14
Aqueous Conversion to sulfate	22	26	27	15	29	15	16	30
Oxidation & immediate wet dep								21
Sulfate Sink Rate (%/day)								
Dry Deposition	3	5	5	4	2	2	3	2
Wet Deposition	20	14	17	14	23	15	18	13
Inverse Lifetime (%/day)								
SO_2	63	43	42	38	53	56	36	90
Sulfate	23	19	21	18	25	17	21	15
Sulfate yield, %								
	51	76	82	55	68	43	66	50
Burden (Tg S)								
SO_2	0.33	0.56	0.61	0.56	0.4	0.43		0.20
Sulfate	0.43	1.05	0.96	0.73	0.60	0.63		0.60
Sulfate Potential (days)								
	2.1	4.4	3.7	3.4	2.5	2.7		3.3

Benkovitz & Schwartz, 2004

SULFATE MODEL INTERCOMPARISON

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





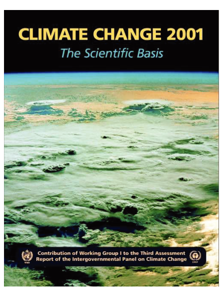
Penner et al., IPCC, 2001

"Most models predict surface-level seasonal mean sulphate aerosol mixing ratios to within 20%."

"We cannot be sure that these models achieve reasonable success for the right reasons."

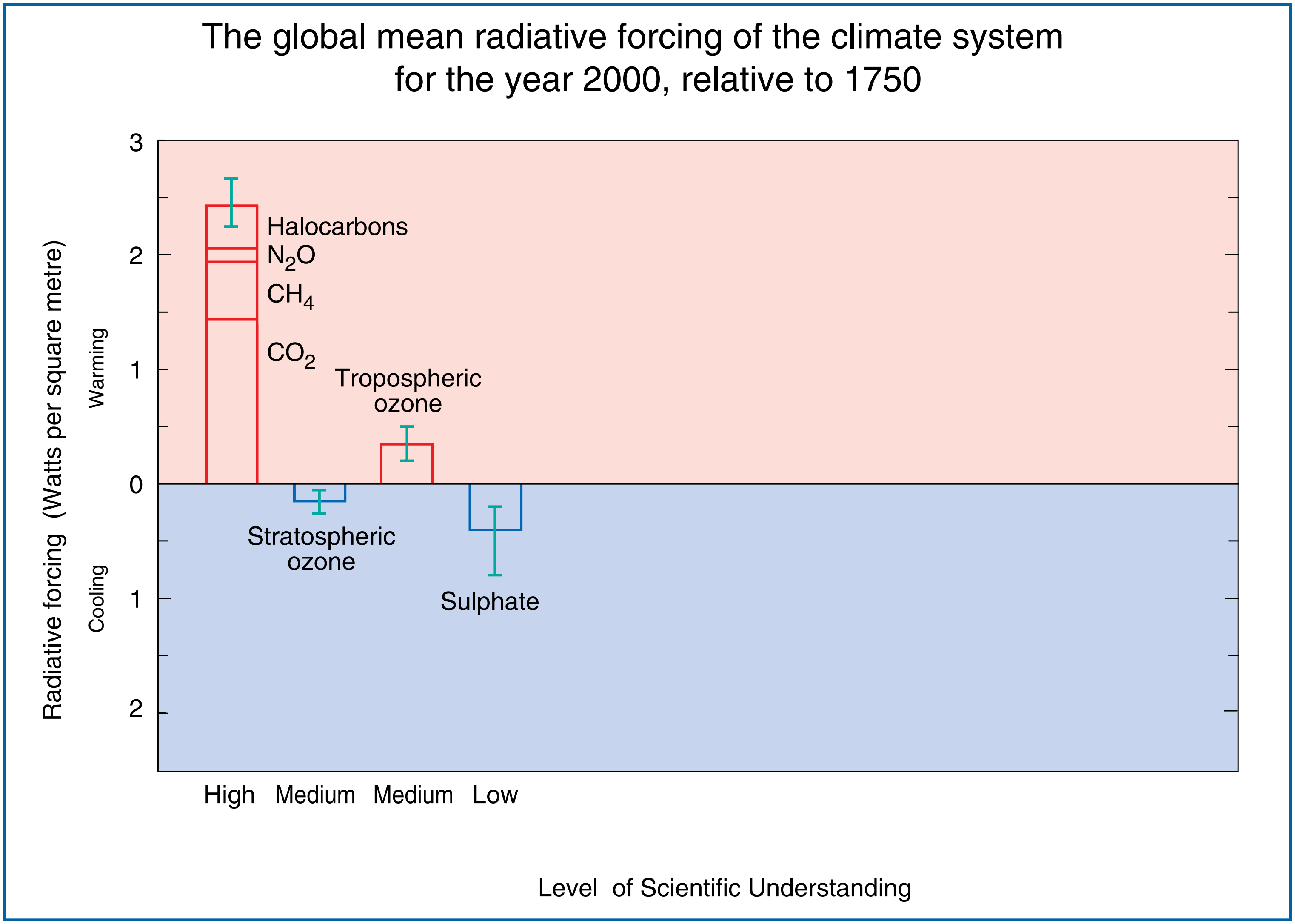
UNCERTAINTY BUDGET FOR *DIRECT* FORCING BY ANTHROPOGENIC SULFATE AEROSOL

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, $1-\omega_0$	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}.		



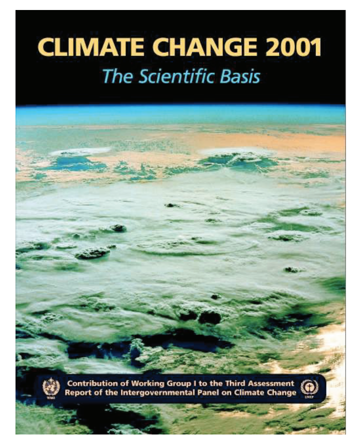
Modified from Penner et al., IPCC, 2001

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



Summary for Policymakers

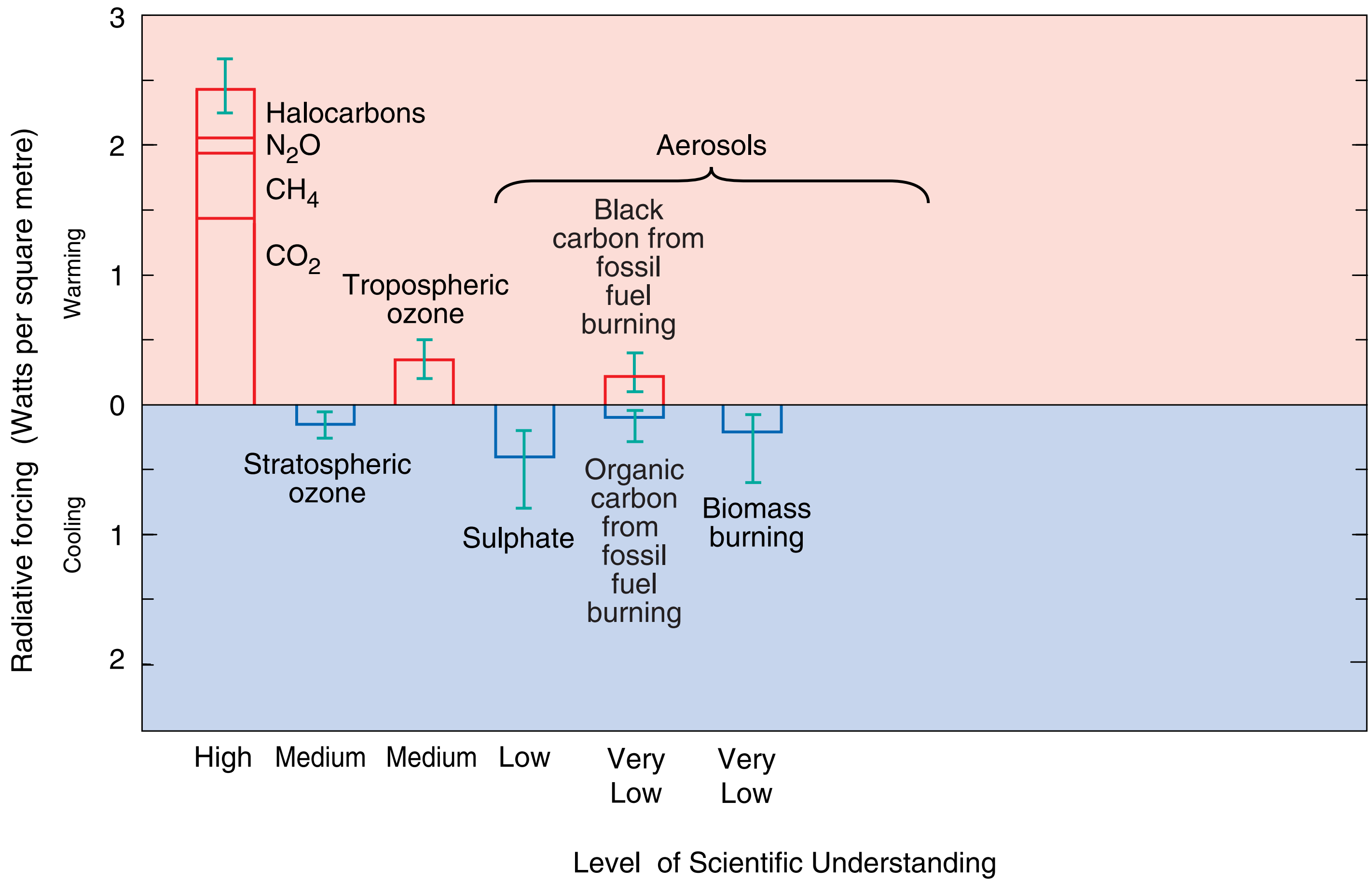
A Report of Working Group I of the Intergovernmental Panel on Climate Change



RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD IPCC (2001)

GHG's and aerosol direct effects

The global mean radiative forcing of the climate system for the year 2000, relative to 1750



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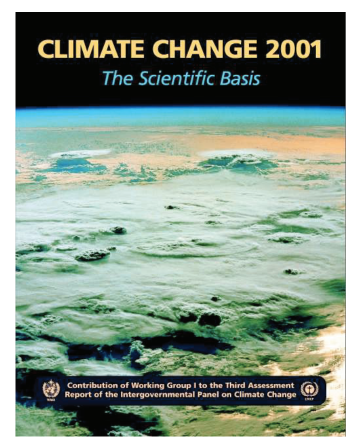
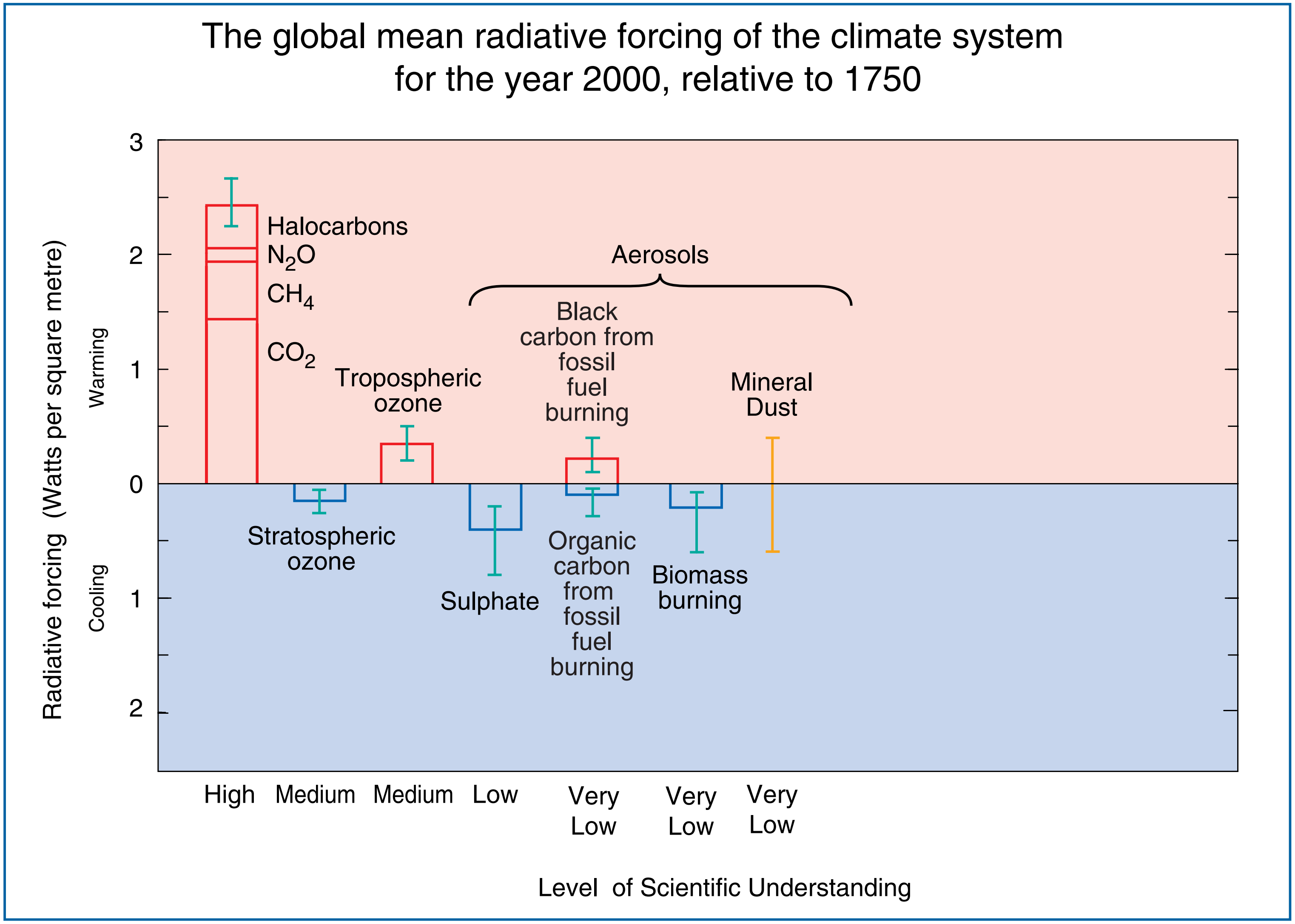


RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)
GHG's and aerosol direct effects



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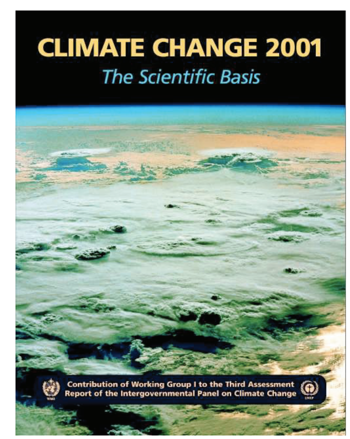
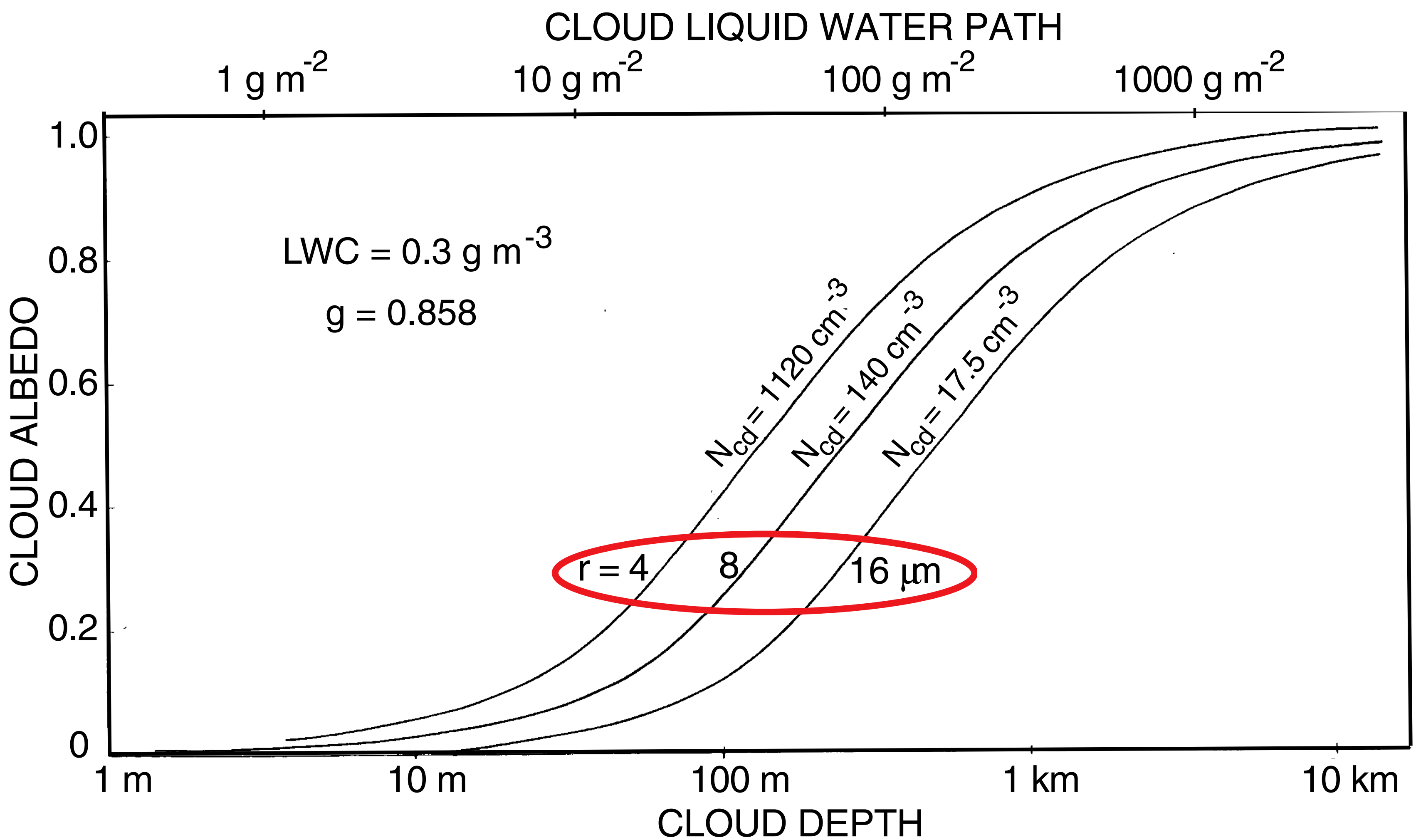


INDIRECT EFFECT

DEPENDENCE OF CLOUD ALBEDO ON CLOUD DEPTH

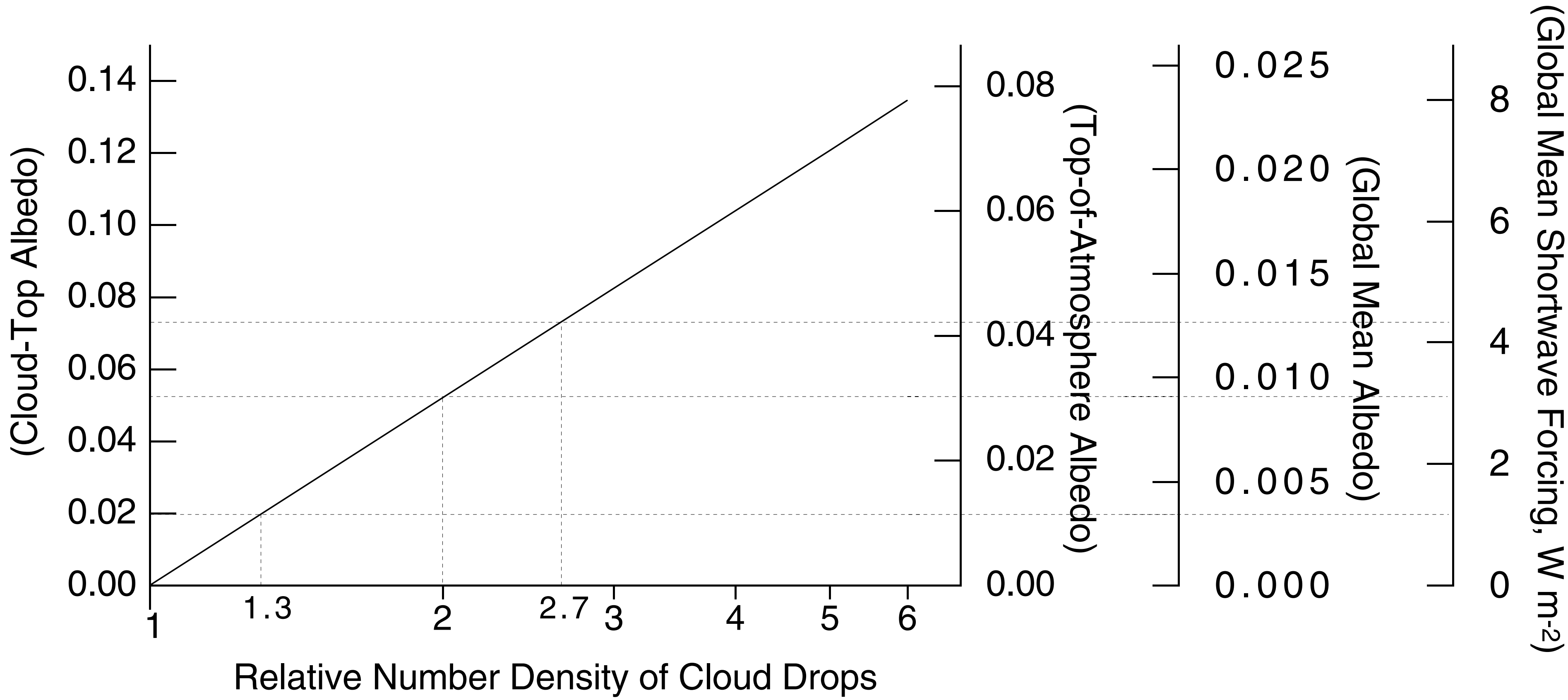
Influence of Cloud Drop Radius and Concentration



Twomey, *Atmospheric Aerosols*, 1977

For a given liquid water path, cloud albedo is highly sensitive to cloud drop number concentration or radius.

SENSITIVITY OF ALBEDO AND FORCING TO CLOUD DROP CONCENTRATION



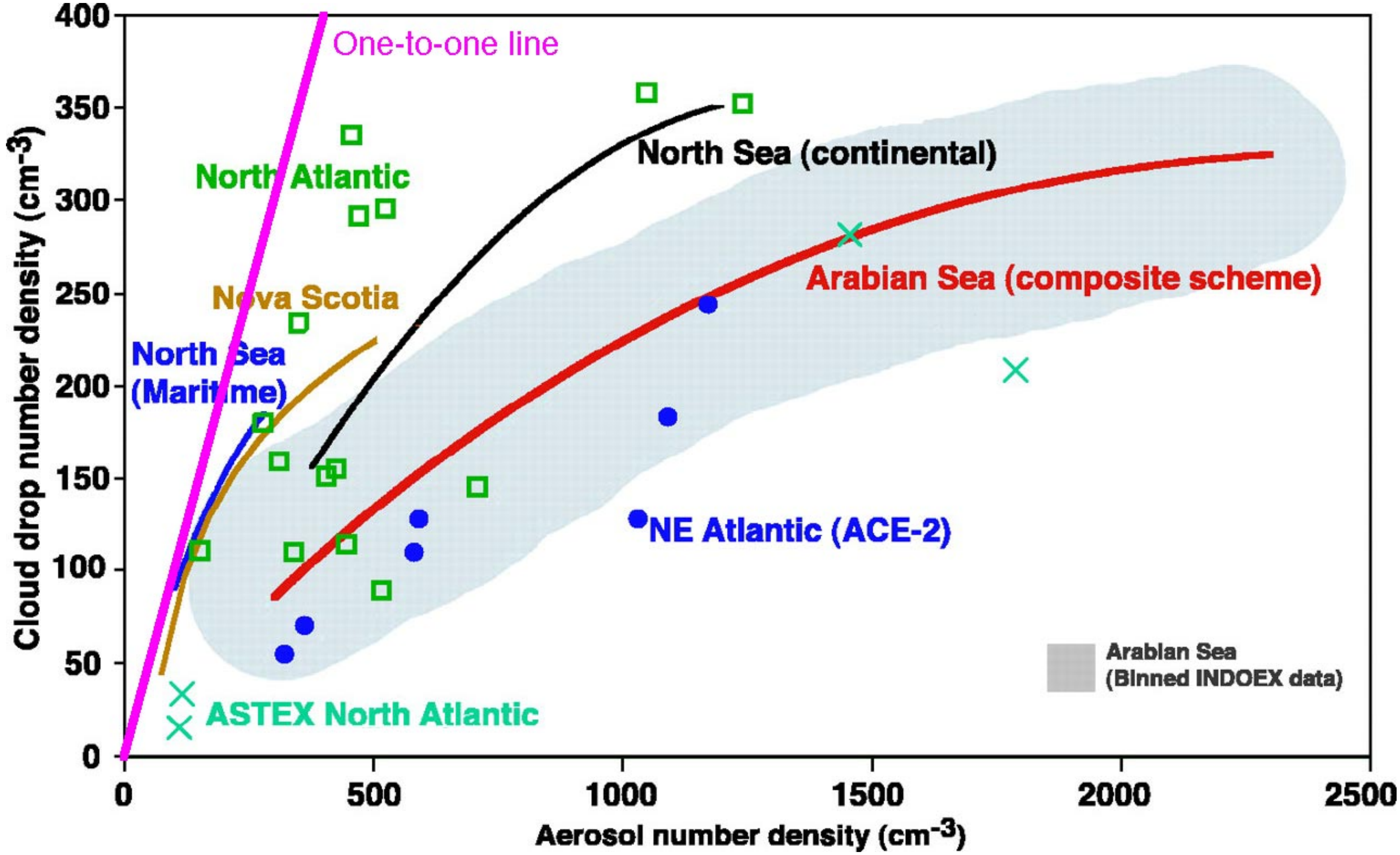
Schwartz and Slingo (1996)

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



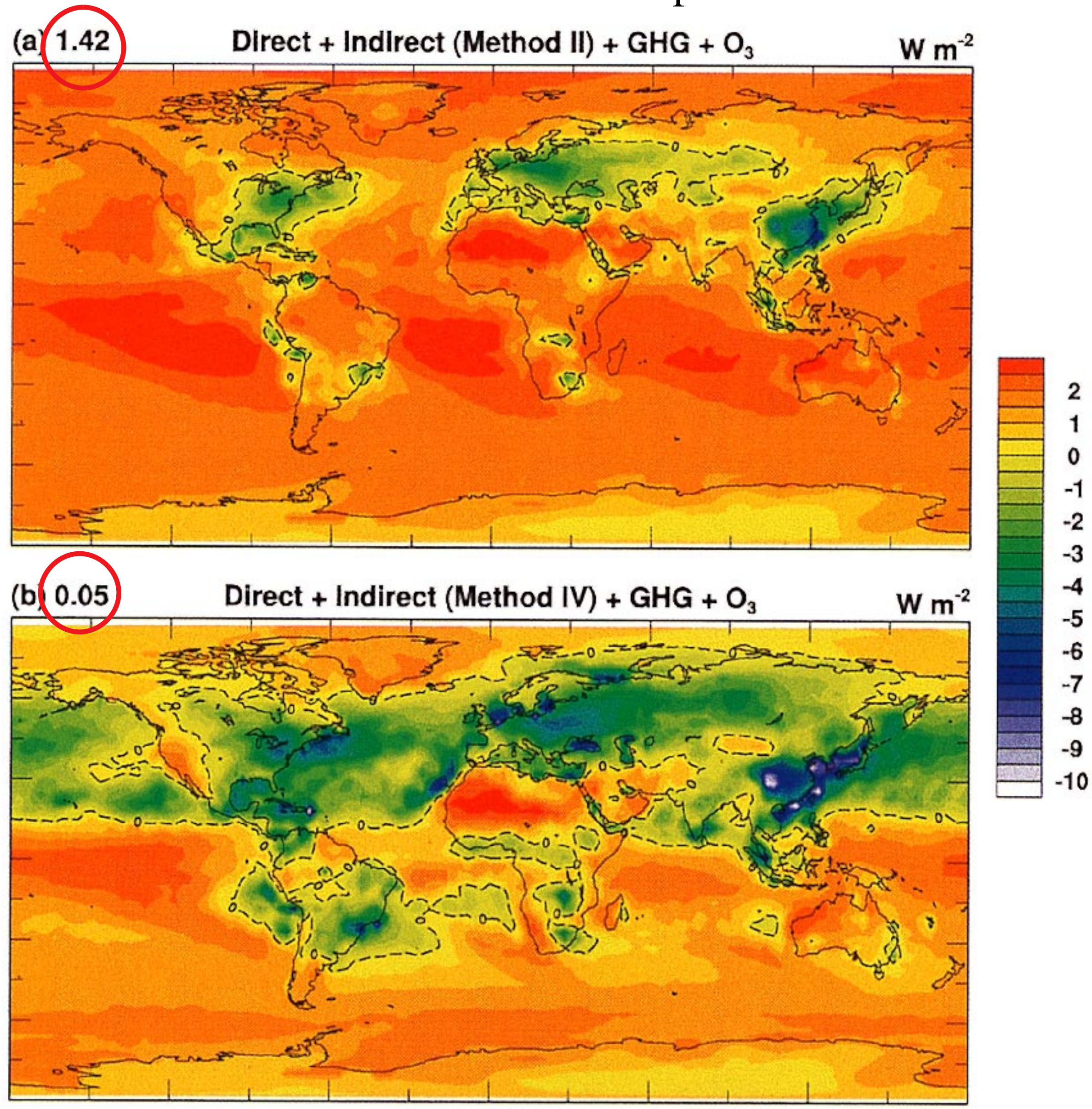
Modified from Ramanathan et al., Science, 2000

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 + O_3 + Sulfate (Direct and Indirect)

Two Formulations of Cloud Droplet Concentration



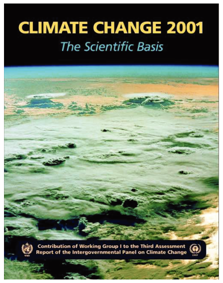
Kiehl et al., JGR, 2000

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

UNCERTAINTY BUDGET FOR *INDIRECT* FORCING BY INDUSTRIAL AEROSOLS

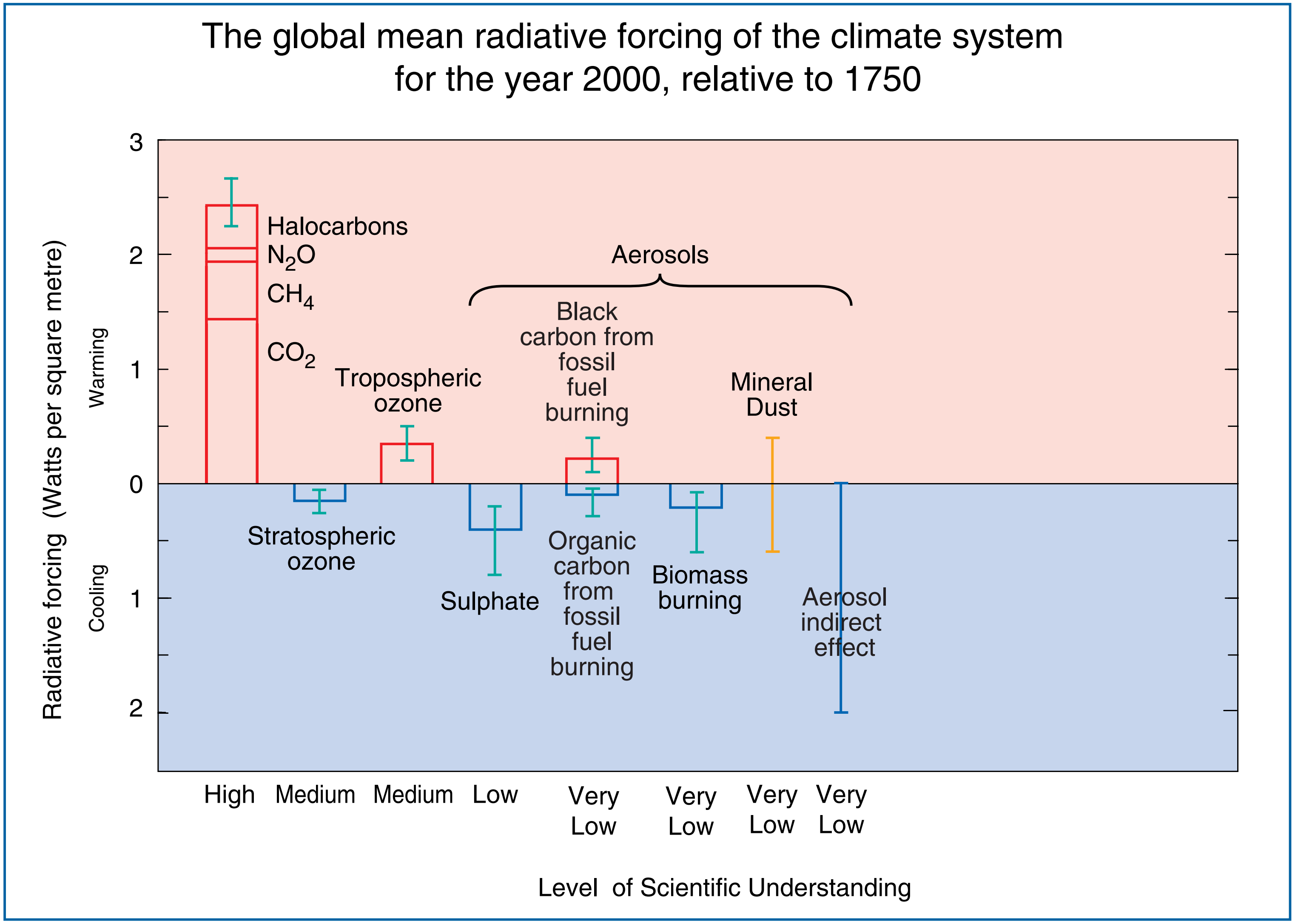
Quantity	Central Value	2/3 Uncertainty Range
Background N_d for Northern Hemisphere marine (cm^{-3})	140	66 to 214
Perturbed N_d for Northern Hemisphere marine (cm^{-3})	217	124 to 310
Cloud mean liquid water content (LWC) (g m^{3-})	0.225	0.125 to 0.325
Background sulfate concentration (g m^{3-})	1.5	0.85 to 2.15
Cloud layer thickness (m)	200	100 to 300
Perturbed sulfate concentration (g m^{3-})	3.6	2.4 to 4.8
Susceptible cloud fraction, f_c	0.24	0.19 to 0.29
Atmospheric transmission above cloud layer, T_a	0.92	0.78 to 1.00
Mean surface albedo	0.06	0.03 to 0.09
Result: If central value is -1.4 Wm^{-2} the 2/3 uncertainty range is from 0 to -2.8 Wm^{-2}.		

Modified from Penner et al., IPCC, 2001



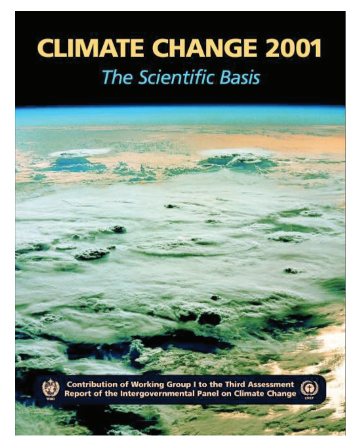
RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD IPCC (2001)

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.

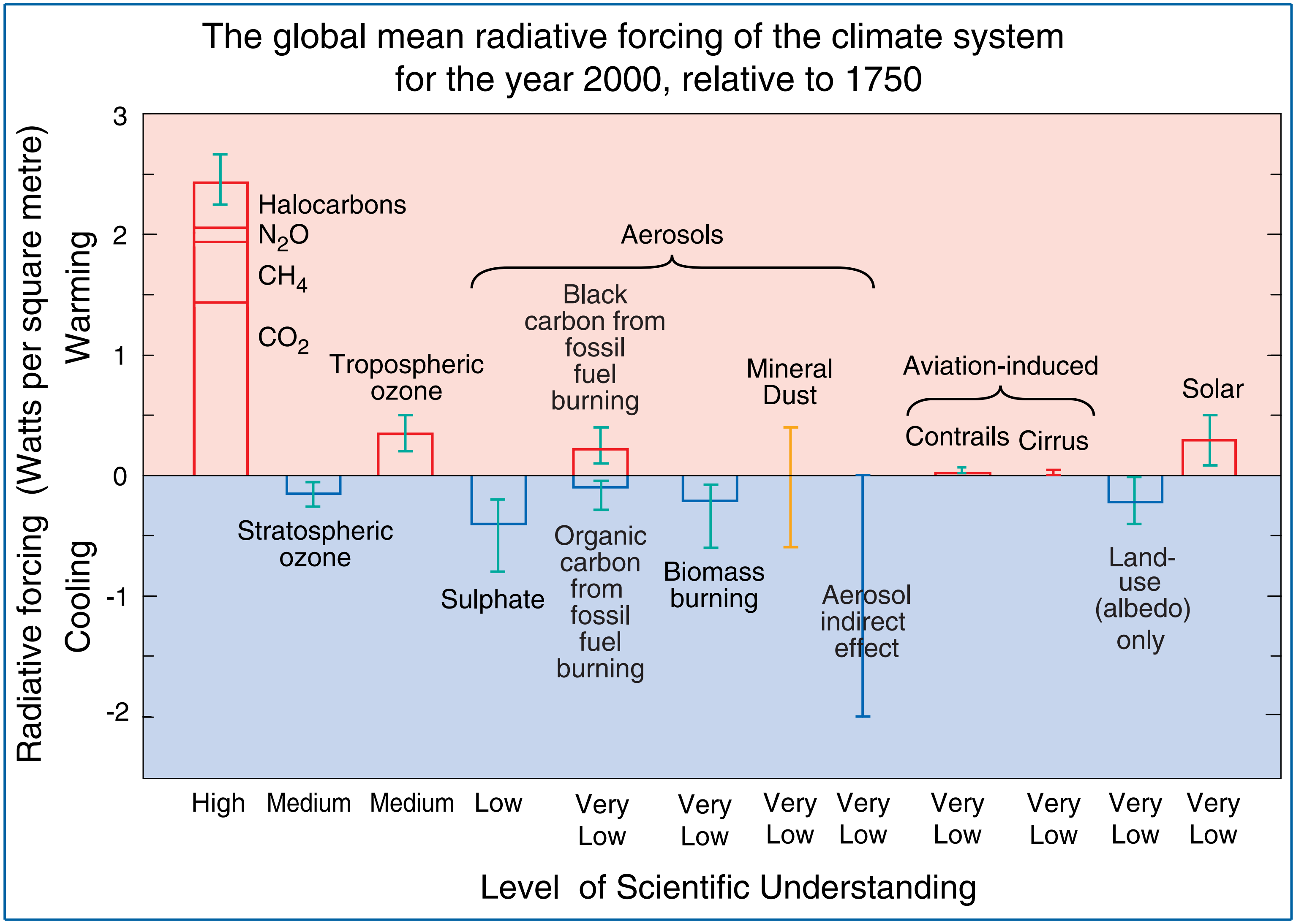
At present and as a function of secular time.

- ***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.

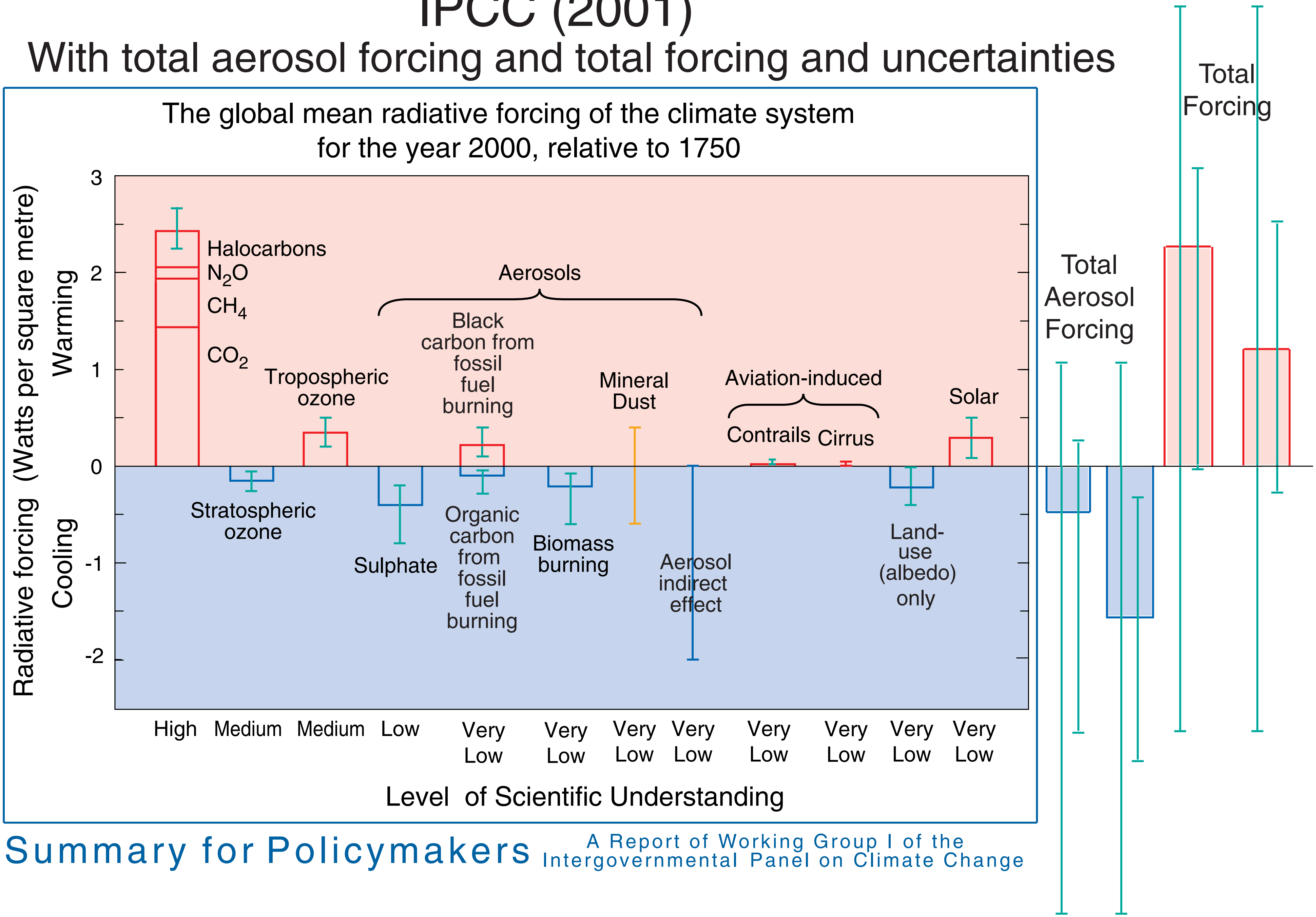
RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)



ADDING UP THE FORCINGS

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)

With total aerosol forcing and total forcing and uncertainties

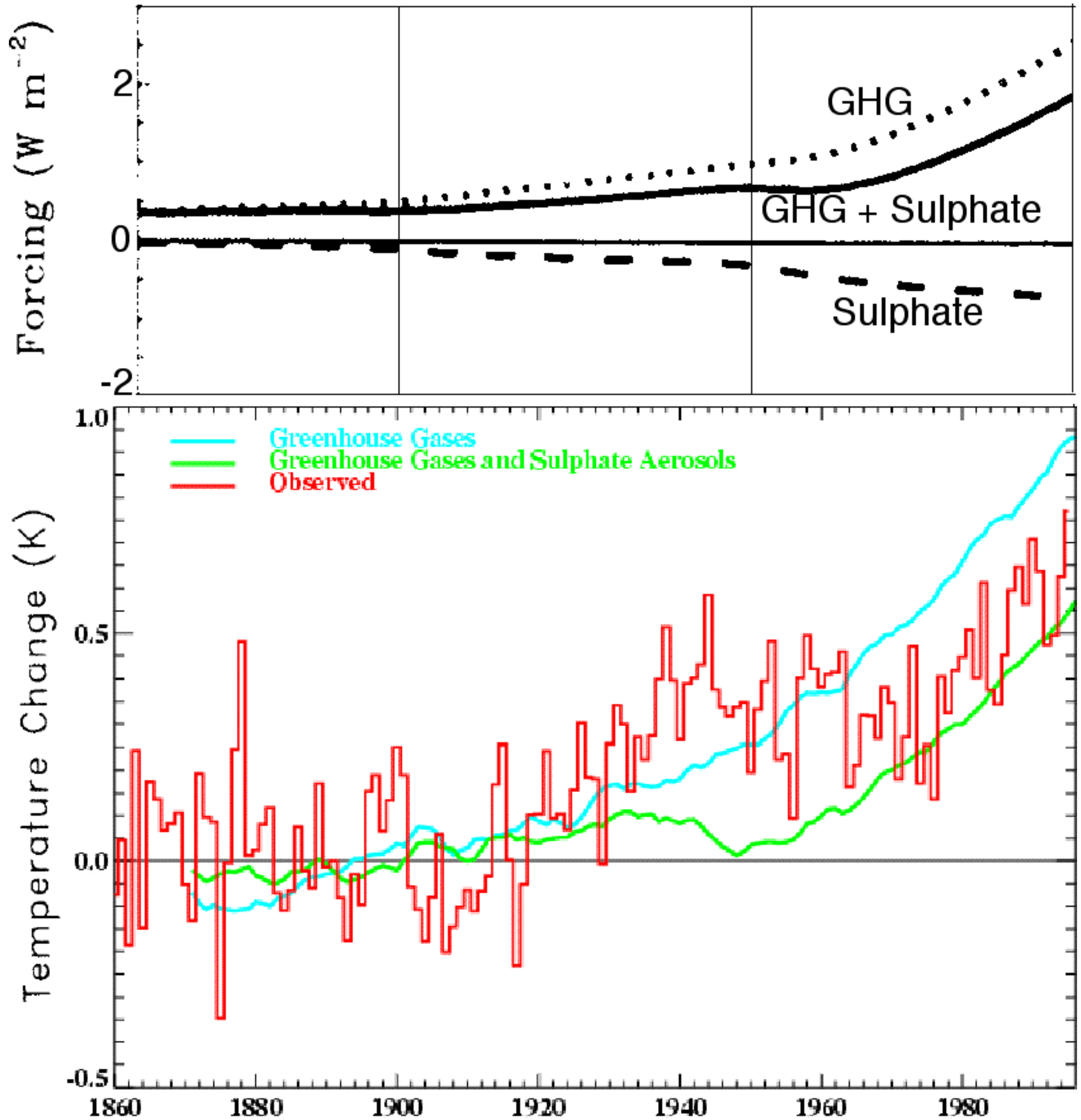


Schwartz, JAWMA, 2005

REPRESENTING AEROSOL INFLUENCES IN CLIMATE MODELS

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

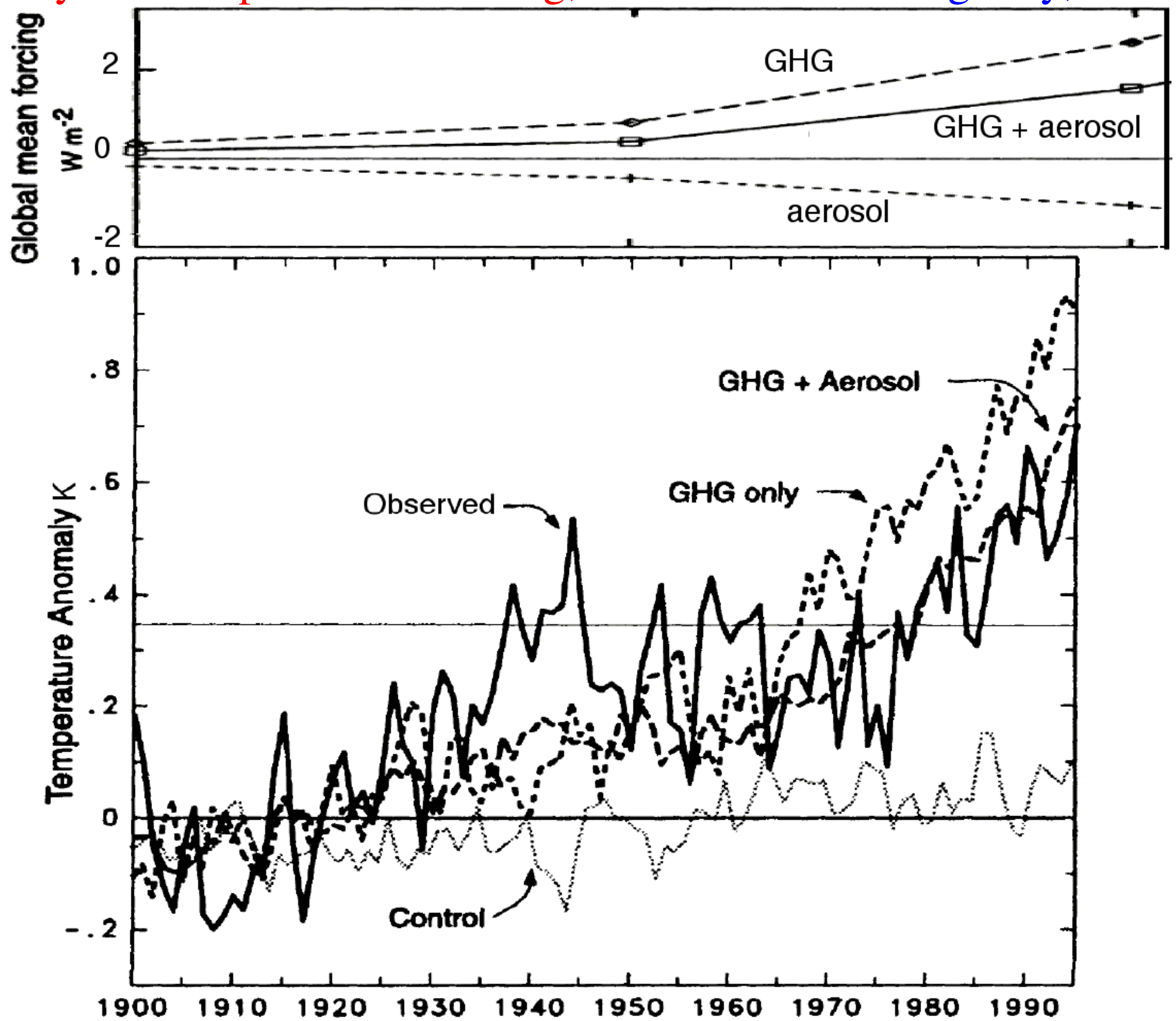
Model sensitivity = 2.5 K per CO_2 doubling; sulfate direct forcing only, -0.6 W m^{-2} (1990)



"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)

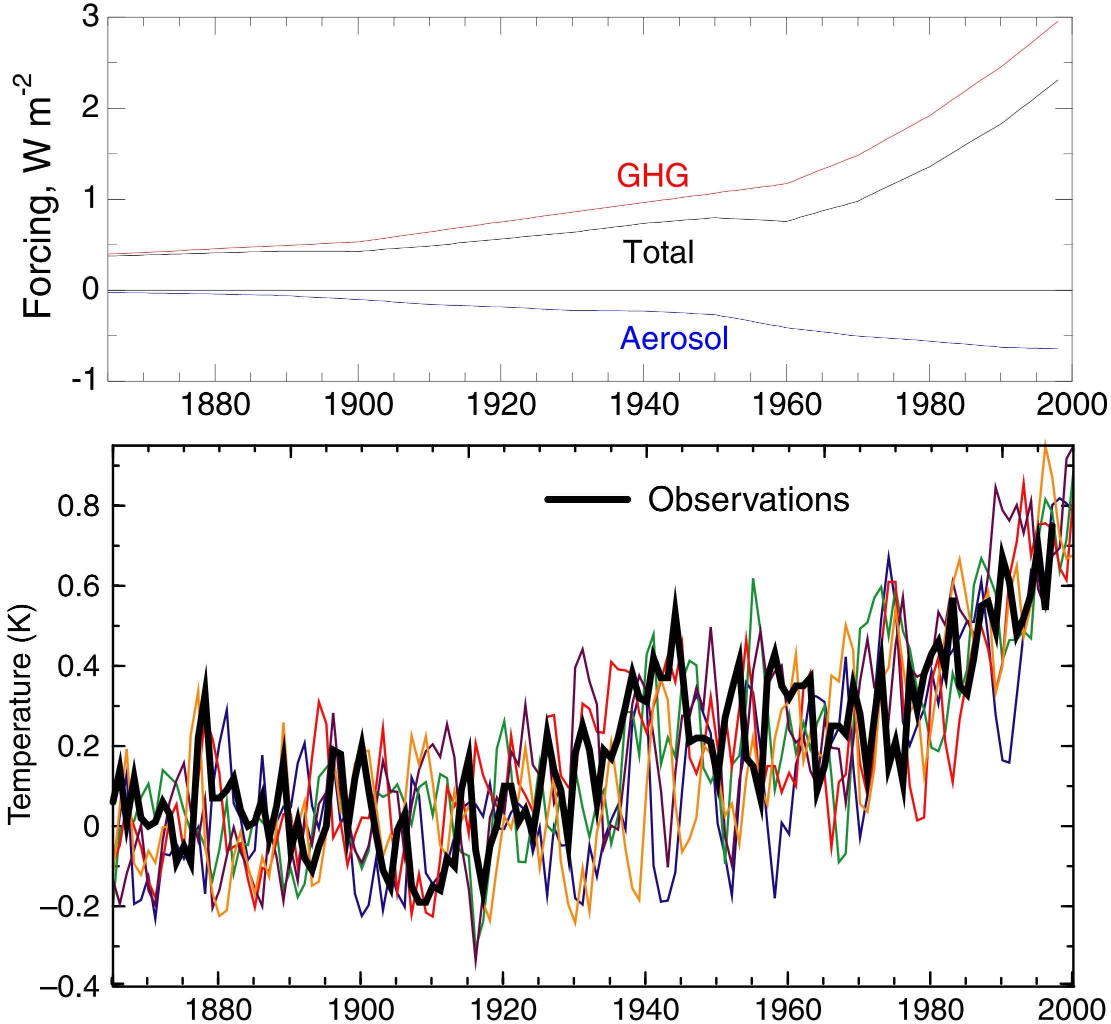
Model sensitivity = 3.5 K per CO_2 doubling; sulfate direct forcing only, -1.0 W m^{-2} (1990)



"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)

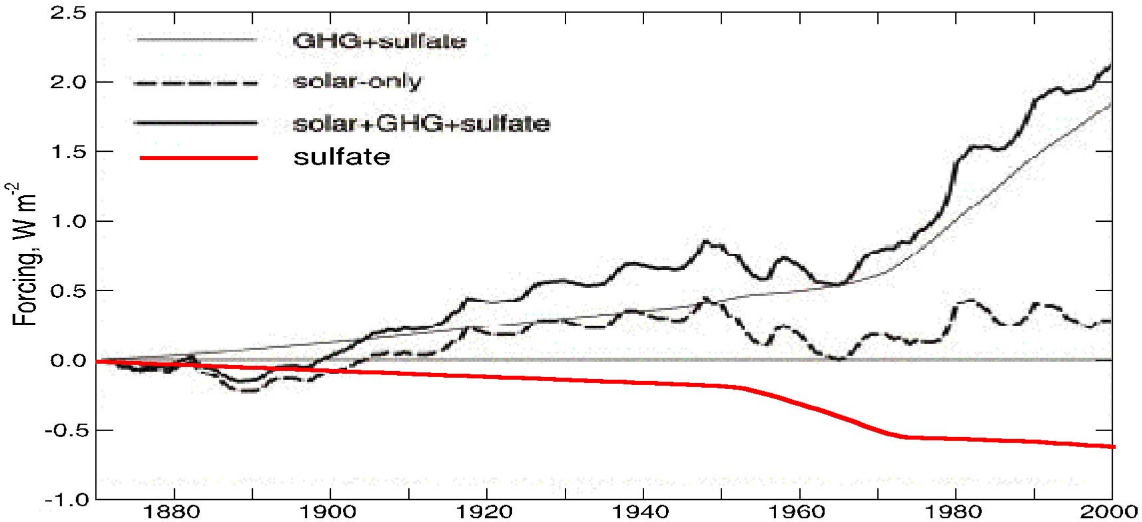
Model sensitivity = 3.4 K per CO_2 doubling; sulfate forcing, -0.62 W m^{-2} (1990)

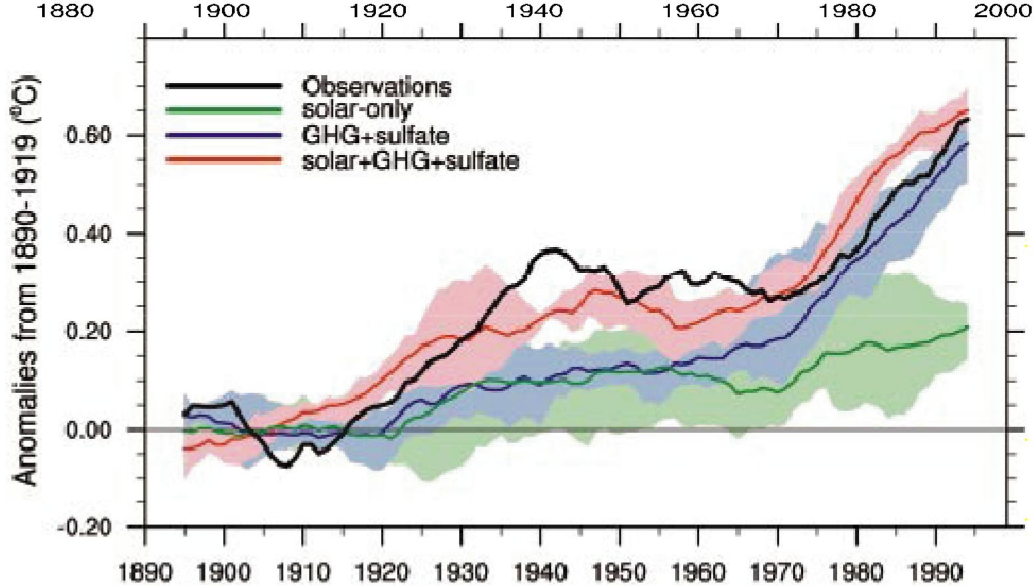


“The surface temperature time series from the five GHG-plus-sulfate integrations show an increase over the last century, which is ***broadly consistent*** with the observations.” -- *Delworth & Knutson, Science, 2000*

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)

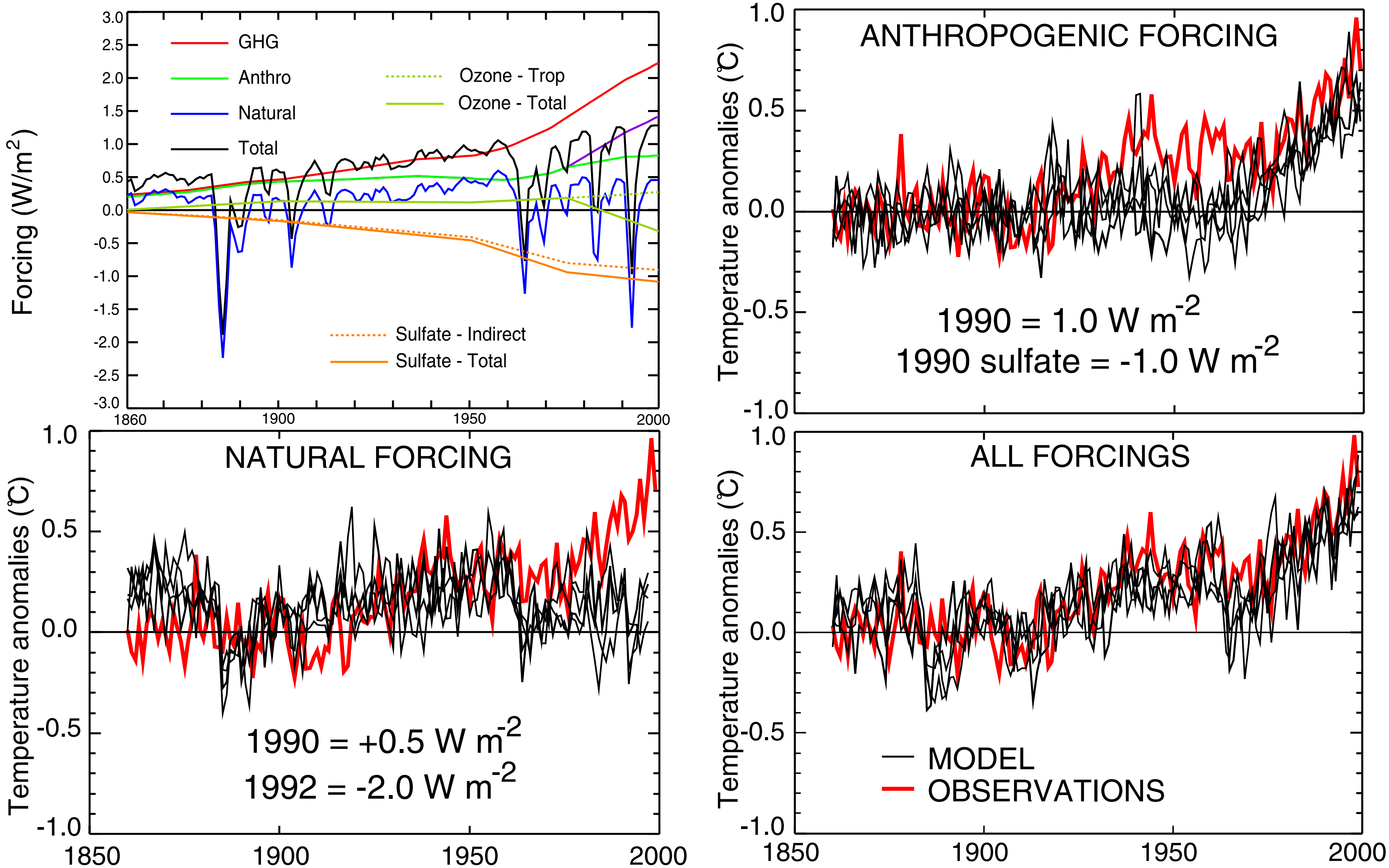




"The time series from GHG + sulfates + solar shows ***reasonable agreement*** with the observations." -- *Meehl, Washington, Wigley et al., J. Climate, 2003.*

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)



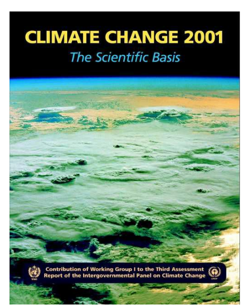
"The ALL ensemble ***captures the main features*** of global mean temperature changes observed since 1860." -- *Stott, Tett, Mitchell, et al., Science, 2000*

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


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

The truth that is suppressed by friends is the readiest weapon of the enemy.

– Robert Lewis Stevenson

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:

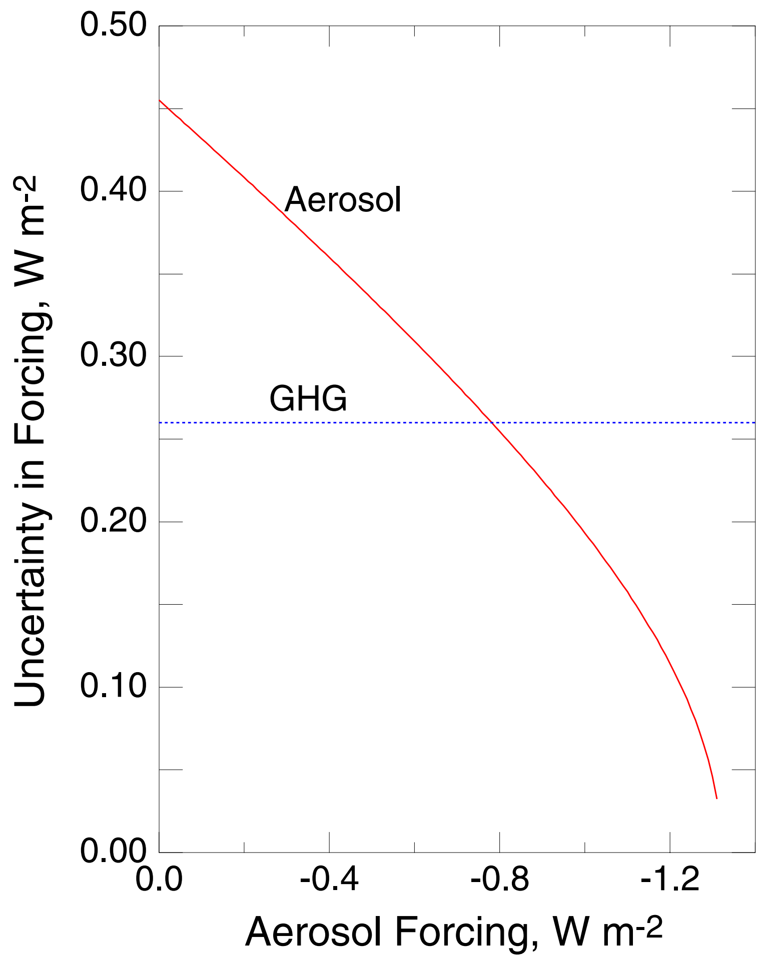
$$\frac{\delta\Delta T}{\Delta T} \approx \frac{\delta F}{F} \approx 20\%.$$

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.

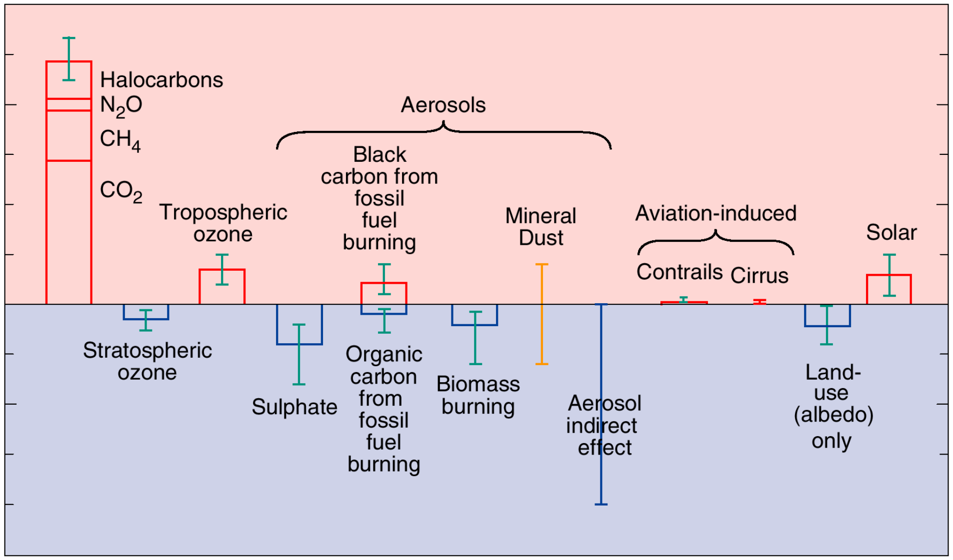
- ***Uncertainty in aerosol forcing must be reduced at least three-fold for uncertainty in climate sensitivity to be meaningfully reduced and bounded.***

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).

RADIATIVE FORCING OF CLIMATE CHANGE BY AEROSOLS

WHY THIS IS IMPORTANT
AND HOW WELL IT NEEDS TO BE KNOWN



Thank You

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