AEROSOLS AND CLIMATE CHANGE

A TUTORIAL

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

AEROSOLS AND CLIMATE CHANGE

A Tutorial

OUTLINE

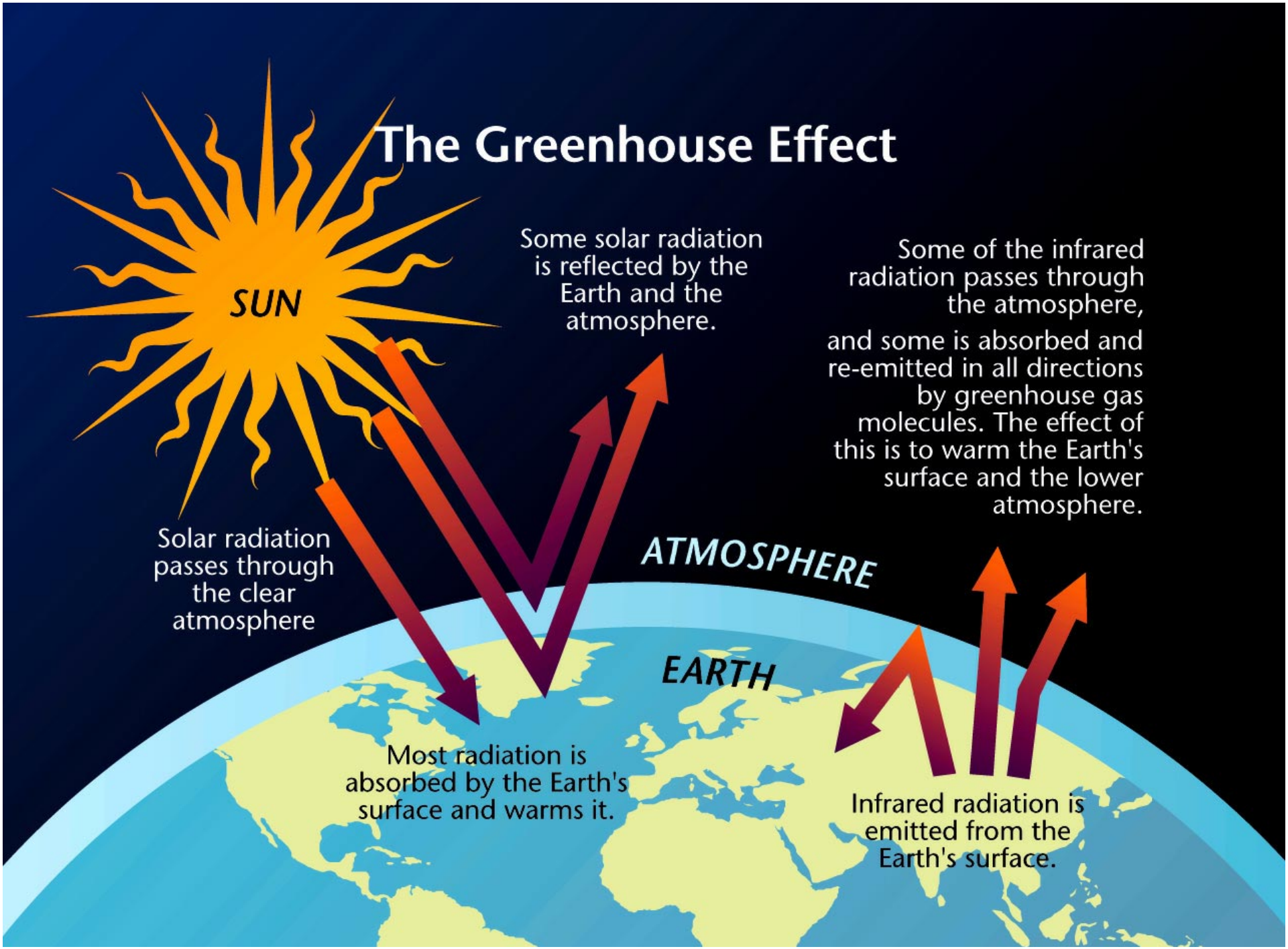
Climate and ***climate change***

Forcing of climate change and climate ***sensitivity***

Aerosol influences on climate change: ***mechanisms and magnitudes***

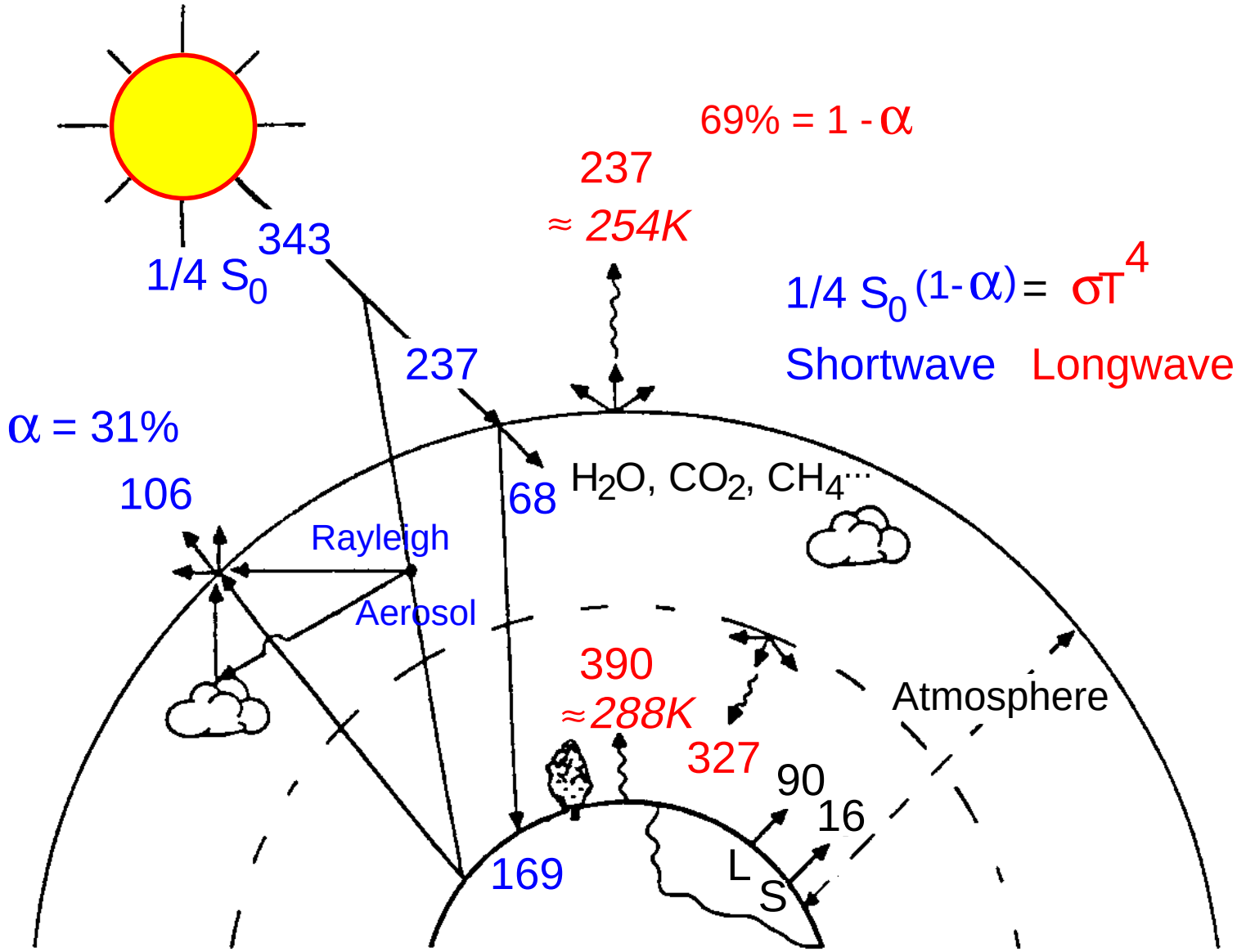
- Direct effects
- Indirect effects

Implications of uncertainties


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.

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

ATMOSPHERIC RADIATION

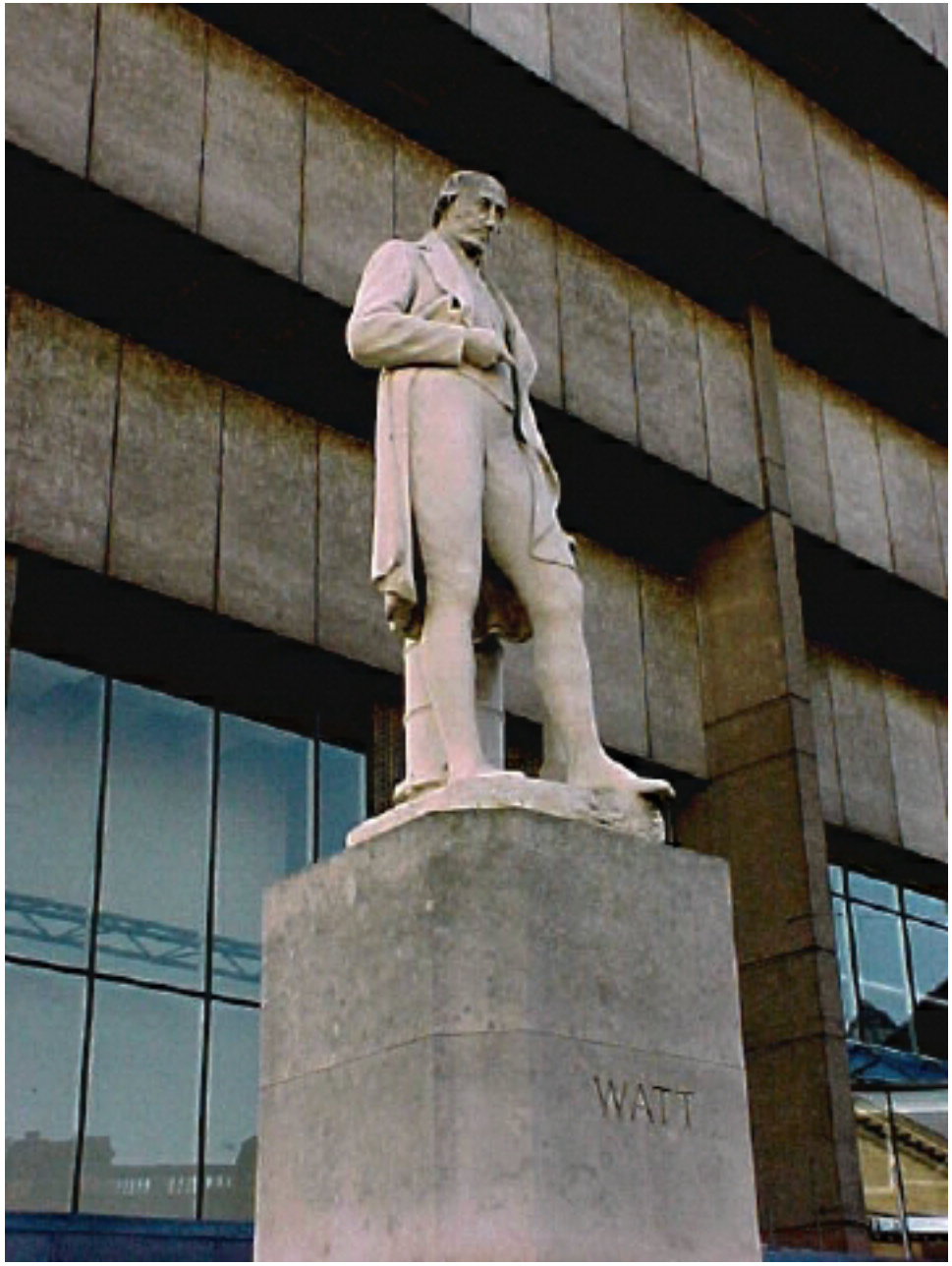
Energy per area per time

Power per area

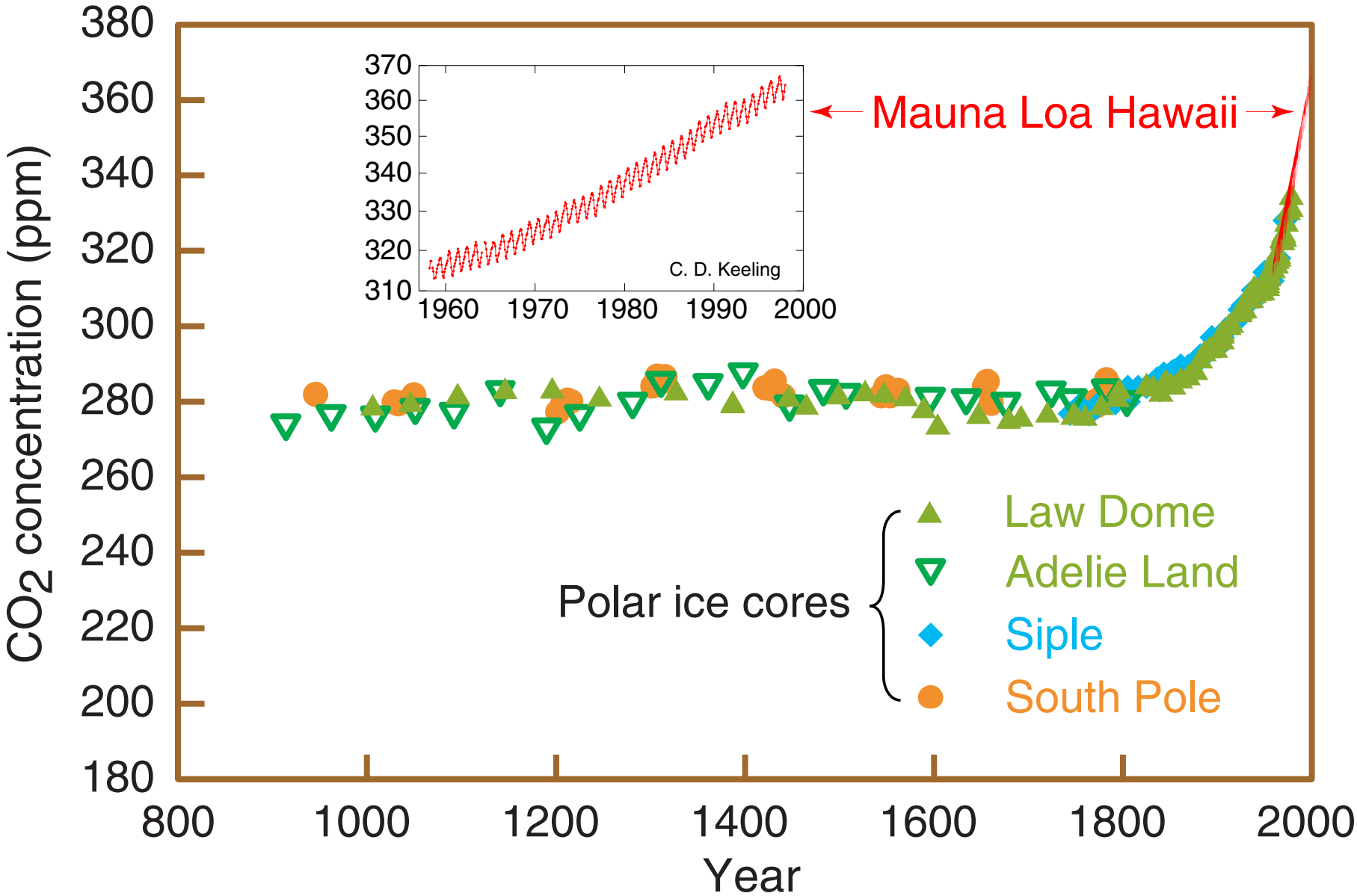
Unit:

Watt per square meter

W m^{-2}



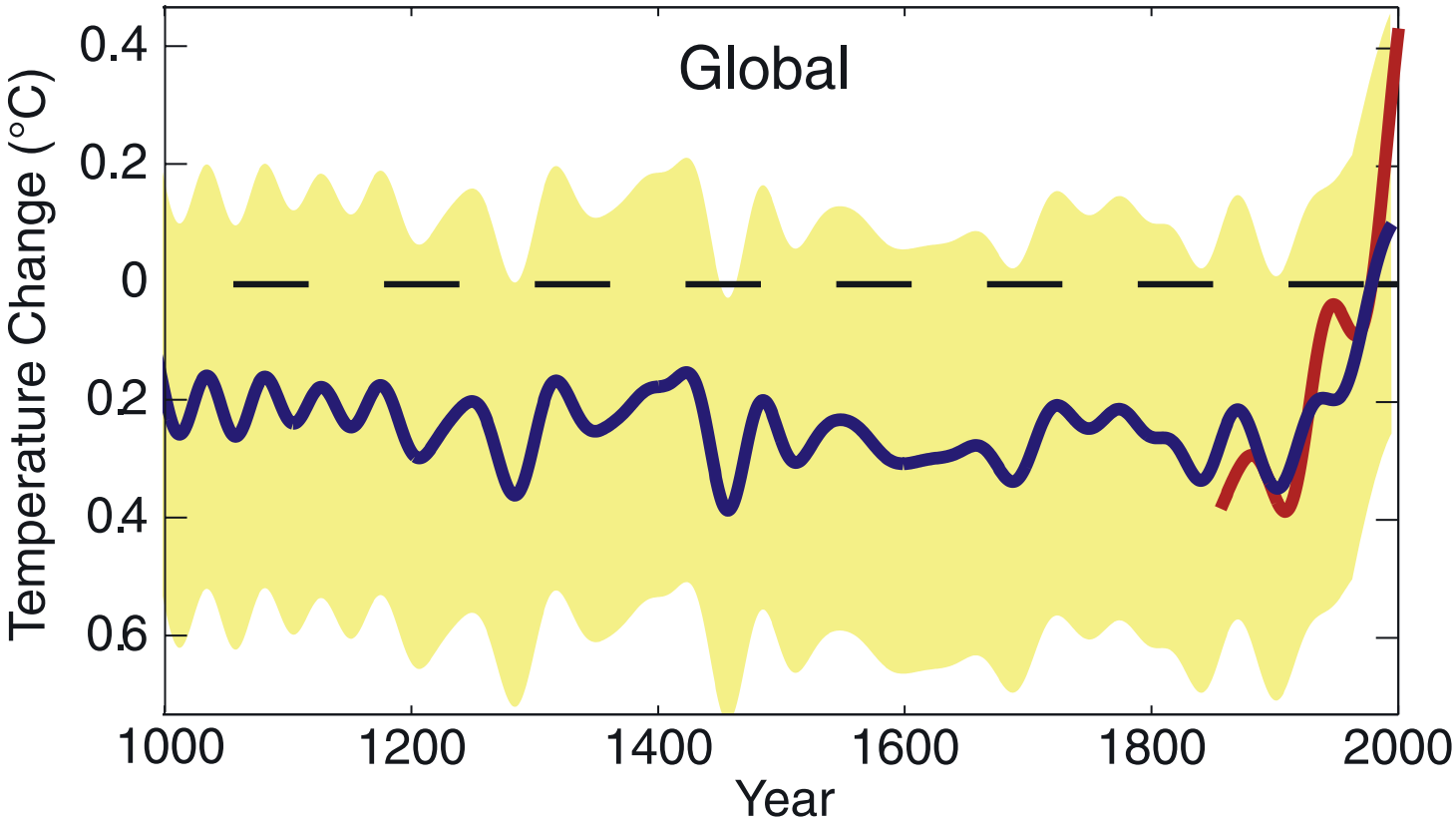
ATMOSPHERIC CARBON DIOXIDE IS INCREASING



Global carbon dioxide concentration over the last 1000 years

GLOBAL TEMPERATURE TREND (1000-2000)

From tree-ring, coral, and ice-core proxy records
As calibrated by instrumental measurements



Instrumental record

Proxy reconstruction

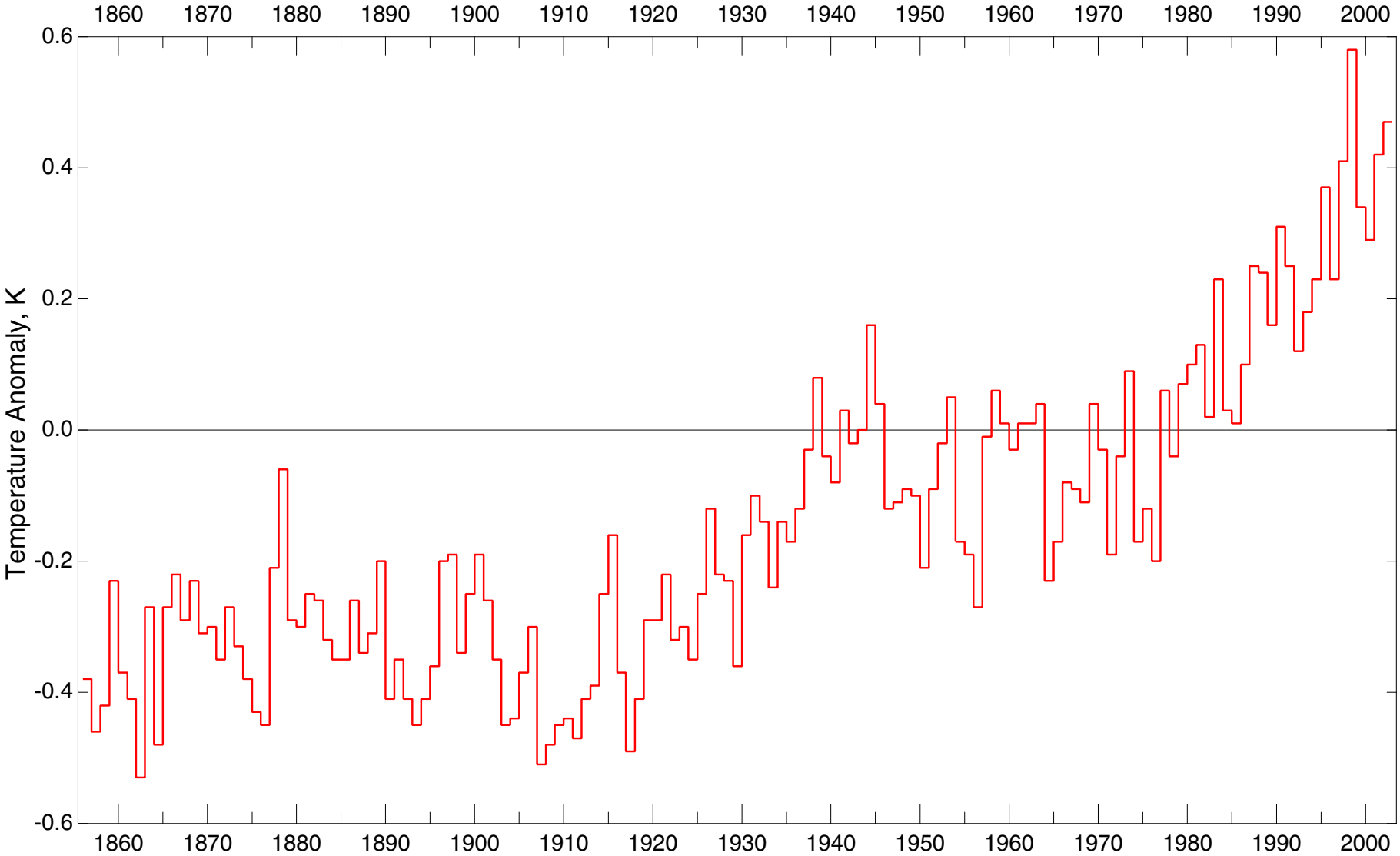
Uncertainty in proxy reconstruction

Jones & Mann, Revs. Geophys., 2004

GLOBAL AVERAGE TEMPERATURE TREND

1856-2002

Temperature Anomaly Relative to Base Period 1961-1990



Climate Research Unit, East Anglia UK

RADIATIVE FORCING OF CLIMATE CHANGE

-- An ***externally imposed perturbation*** in the radiative energy budget of Earth's climate system.

Pertinent to climate change over the industrial period is ***radiative forcing of the surface-troposphere system.***

EXAMPLES:

Shortwave forcing due to change in ***solar constant***

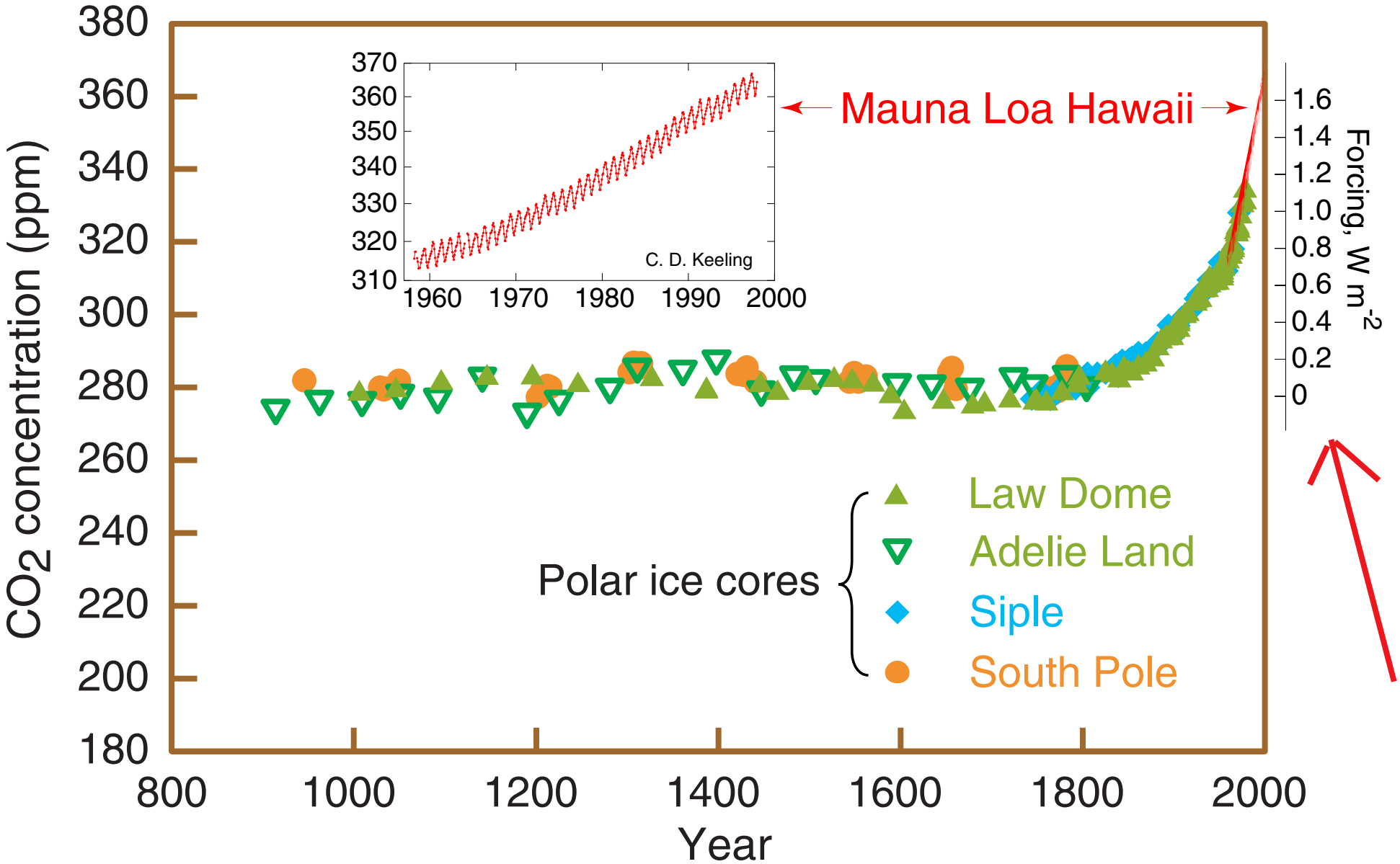
Longwave (thermal infrared) forcing due to increased ***greenhouse gas concentrations***

Shortwave forcing by changes in ***surface albedo***

Shortwave forcing due to enhanced light scattering by ***aerosols***

UNITS: Watts per square meter, W m^{-2}

ATMOSPHERIC CARBON DIOXIDE IS INCREASING



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

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?***

- 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***.

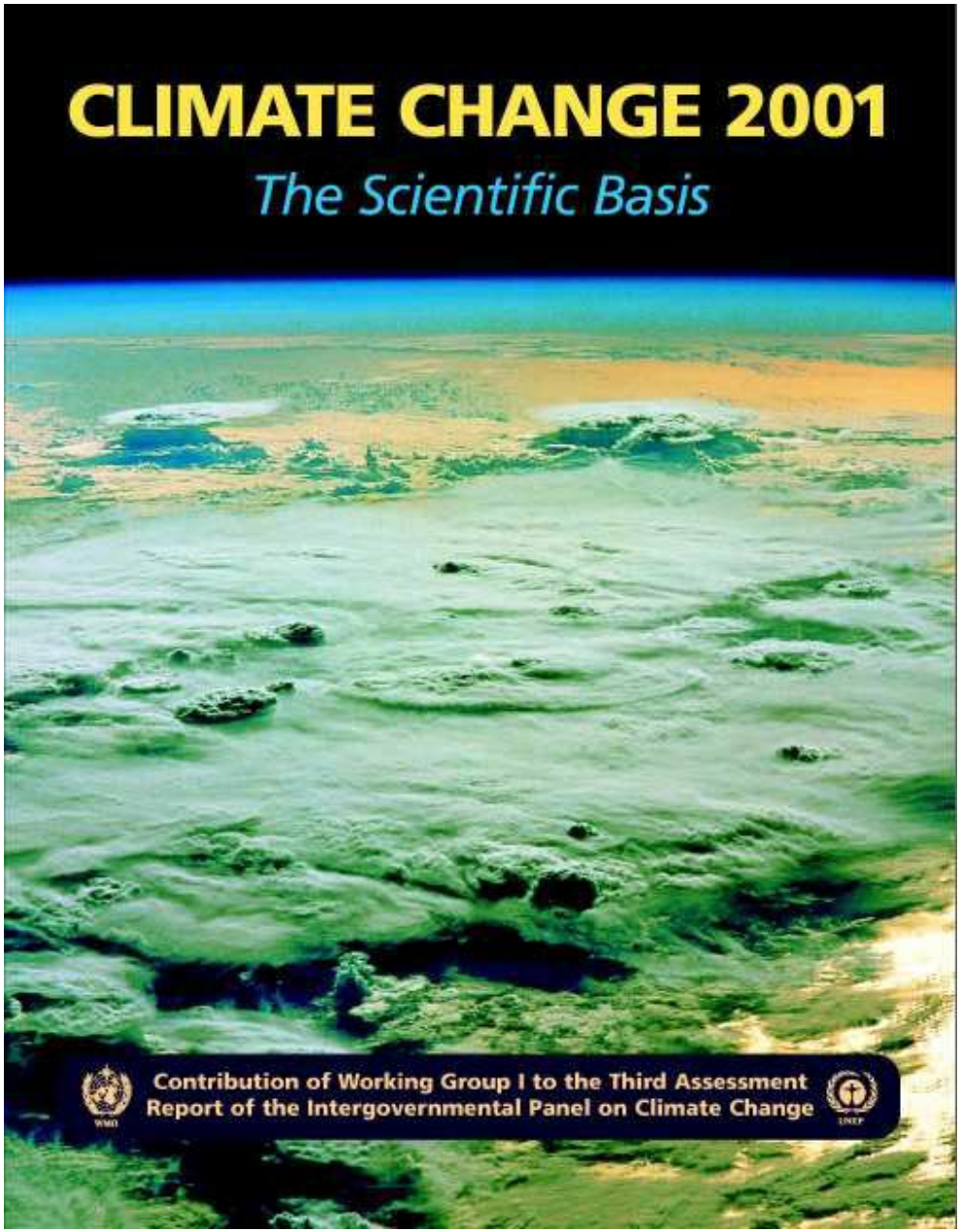
- Intergovernmental Panel on Climate Change (IPCC, 2001):

"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.

THE “BIBLE” OF CLIMATE CHANGE RESEARCH

WMO

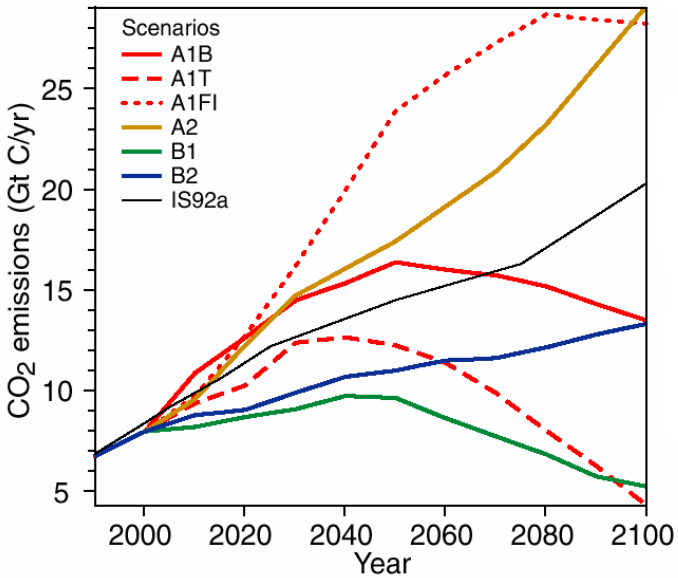


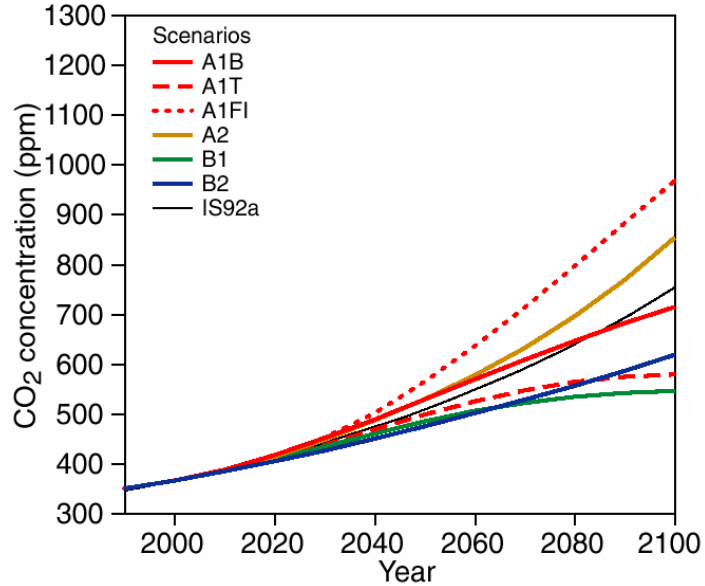
UNEP

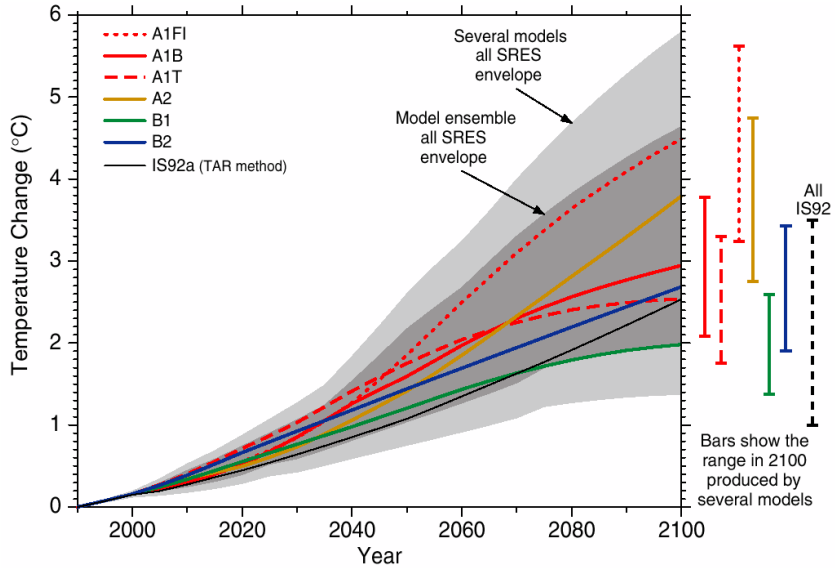
Cambridge University Press, 2001

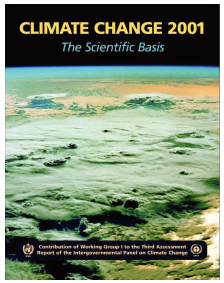
http://www.grida.no/climate/ipcc_tar/wg1/

FUTURE CLIMATE IS HIGHLY UNCERTAIN







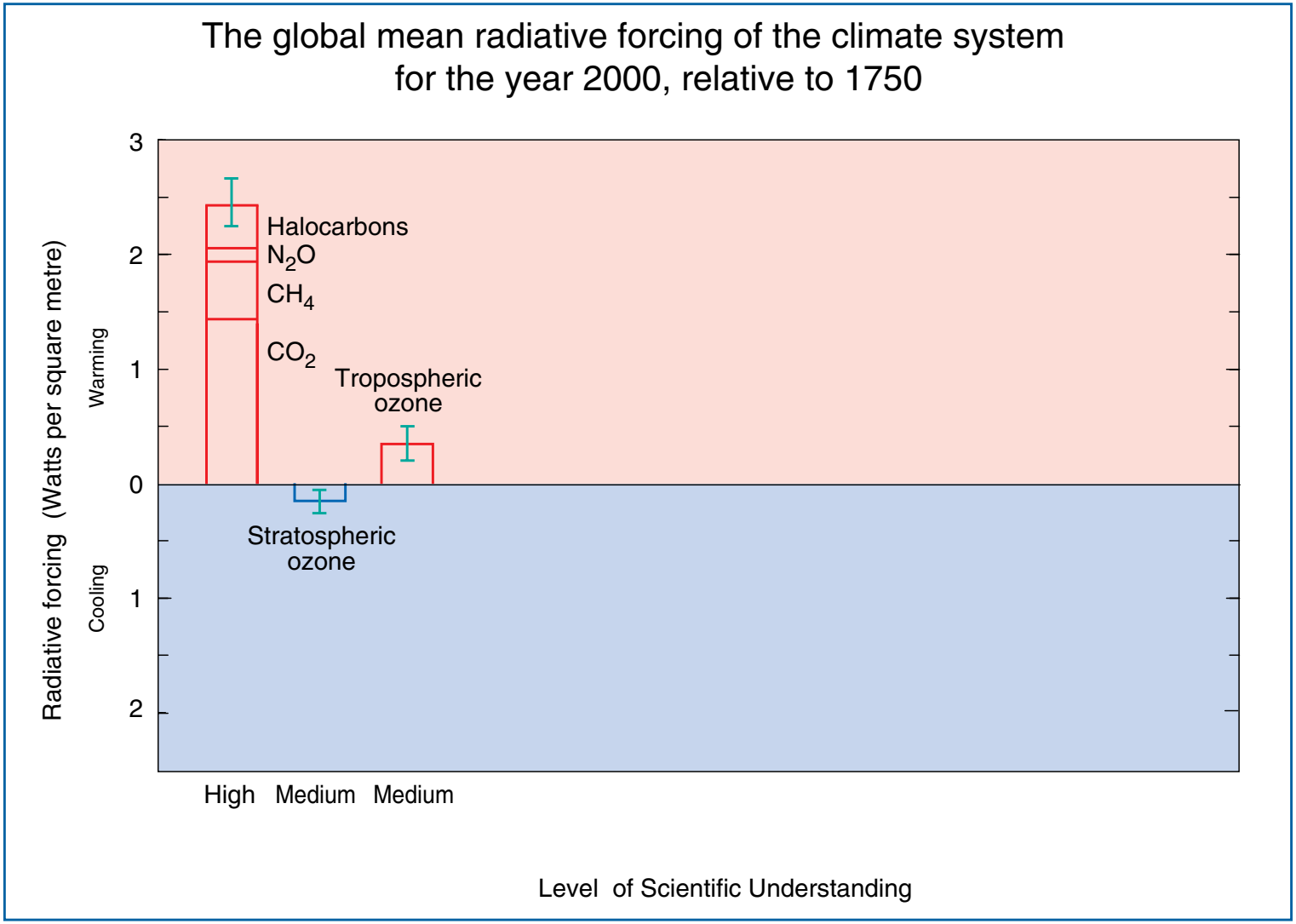


(*IPCC, 2001*)

Contributors to uncertainty in future temperature include ***emissions***, ***concentrations***, and Earth's ***climate sensitivity***. ***And other forcings.***

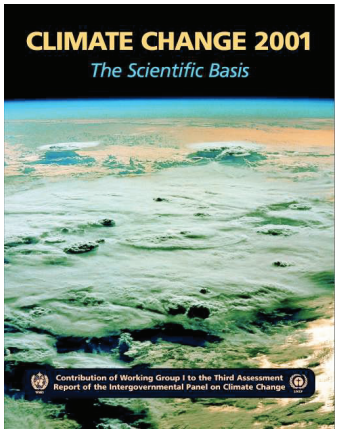
RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)

Greenhouse gases only



Summary for Policymakers

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



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 → Broadening 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)

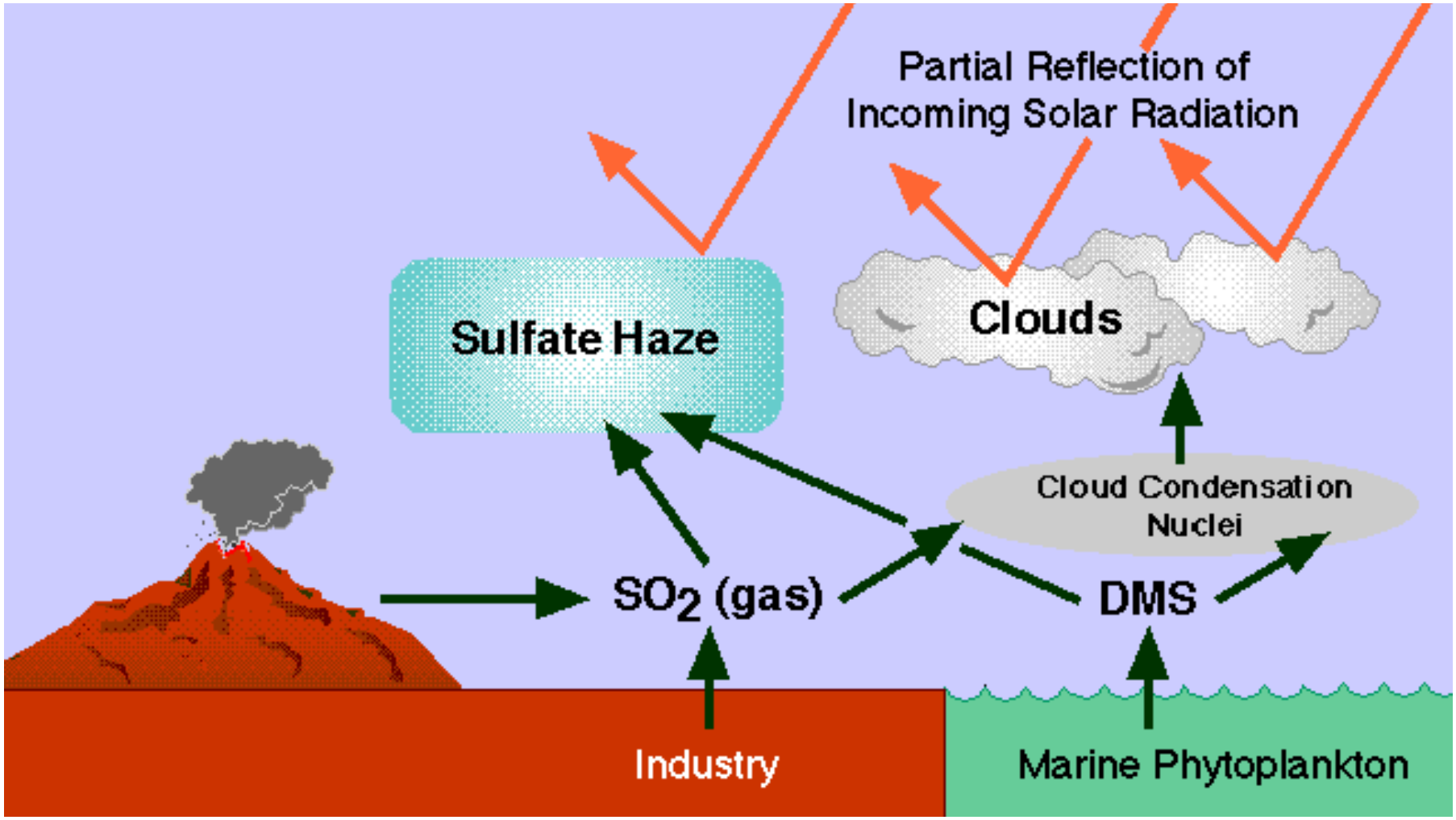
Hydrological Effects

Suppressed surface evaporation -- Spinning down the water cycle

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

THE “WHITEHOUSE EFFECT”

RADIATIVE FORCING OF CLIMATE CHANGE BY AEROSOLS



DIRECT EFFECT

AEROSOL DIRECT SHORTWAVE FORCING

Local, instantaneous, cloud-free for absorbing aerosol

Single-scattering limit (optically thin aerosol)

$$\boxed{\Delta F = -F_0 T(\theta_0) T'(1-R)^2 \beta(\theta_0) \tau \Omega}$$

Master Equation

- Ω — Absorption Factor
- τ — Aerosol Optical Depth
- β — Upscatter Fraction
- R — Surface Reflectance
- T' — Transmittance (upward)
- θ_0 — Solar Zenith Angle
- T — Atmospheric Transmittance (downward)
- F_0 — Solar Constant
- ΔF — Change in Net TOA Flux

Aerosol Optical Depth

$$\tau = \int \sigma_{ep} dz = \int \alpha C dz$$

- C — Mass Concentration
- α — Mass Extinction Efficiency
- σ_{ep} — Light Extinction Coefficient

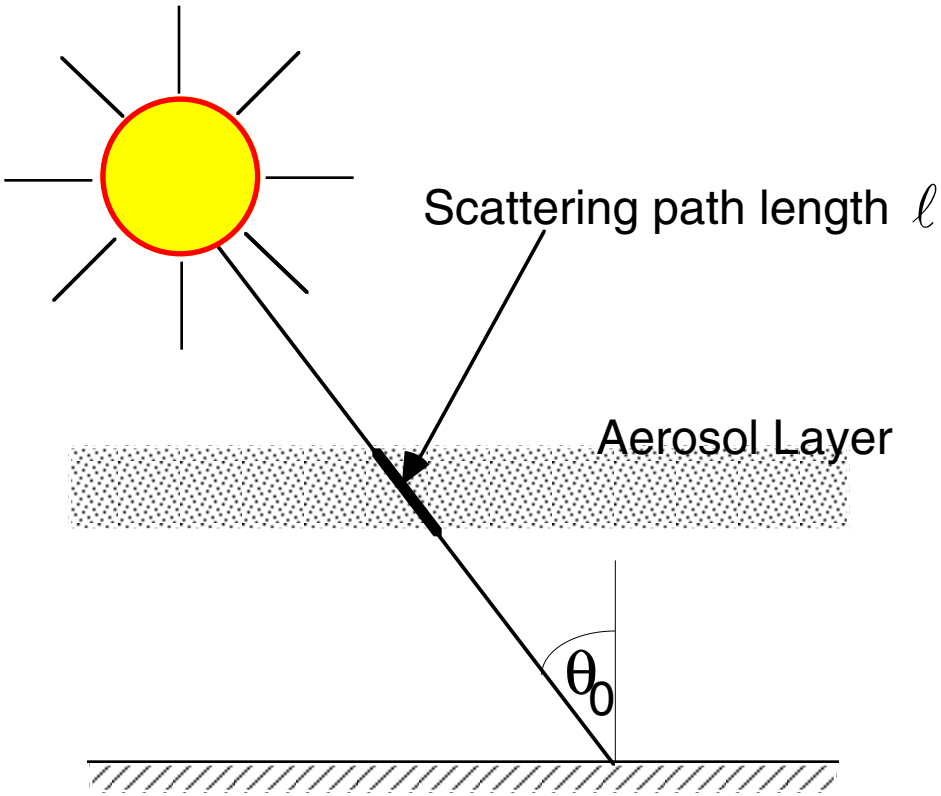
Absorption Factor

$$\Omega = \omega \left\{ 1 - \frac{2R}{(1-R)^2} \frac{(1-\omega)}{\beta\omega} \right\}$$

For $\omega = 1,\ \Omega = 1$

DIRECT AEROSOL FORCING

Dependence on solar zenith angle



The scattering path length ℓ varies as sec θ_0, ***canceling the* cos θ_0 *dependence*** of direct beam irradiance, so . . .

To first approximation, the direct aerosol forcing is ***independent of solar zenith angle* θ_0**.

DIRECT RADIATIVE FORCING DUE TO ANTHROPOGENIC SULFATE AEROSOL

$$\overline{\Delta F_R} = -\frac{1}{2} F_T T^2 (1 - A_c)(1 - R_s)^2 \cdot \overbrace{\overbrace{\overline{\beta}\alpha_{SO_4^{2-}} f(\mathrm{RH})}^{\text{Aerosol Microphysics}} \cdot \overbrace{Q_{SO_2} Y_{SO_4^{2-}} \left(\frac{MW_{SO_4^{2-}}}{MW_S}\right) \tau_{SO_4^{2-}} \Big/ A}^{\text{Column Burden Atmospheric Chemistry}}}^{\text{Aerosol Optical Depth}}$$

Geophysics

$\overline{\Delta F_R}$ 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

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

$\alpha_{SO_4^{2-}}$ 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_{SO_2} is the source strength of anthropogenic SO_2 g S yr^{-1}

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

MW is the molecular weight

$\tau_{SO_4^{2-}}$ 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}	1.004
$1\text{-}A_c$	0.4	——	1.1
T	0.76	——	1.15
$1\text{-}R_s$	0.85	——	1.1
$\bar{\beta}$	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 $f_t = \exp\left[\sum (\log f_i)^2\right]^{1/2}$

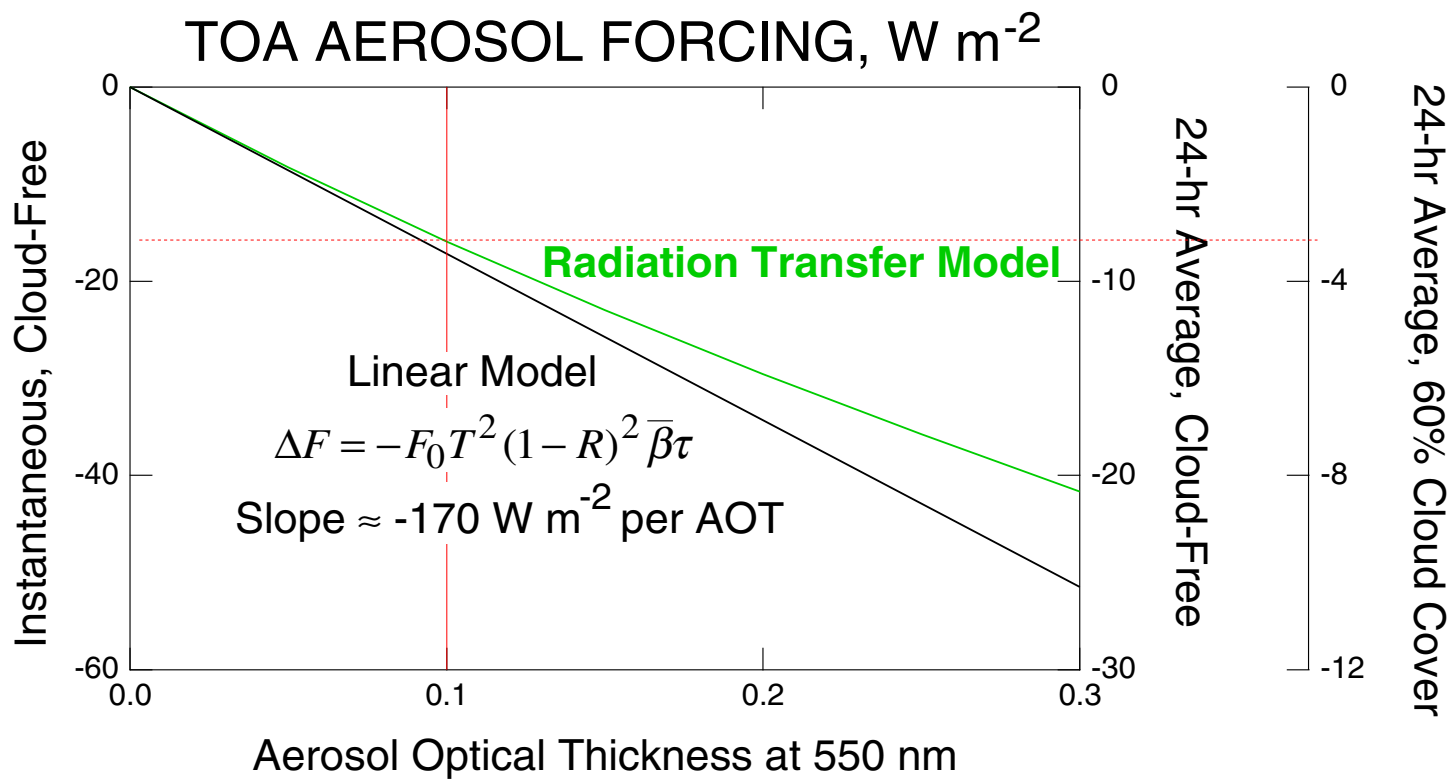
Penner, Charlson, Hales, Laulainen, Leifer, Novakov, Ogren, Radke, Schwartz & Travis, BAMS, 1994

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.

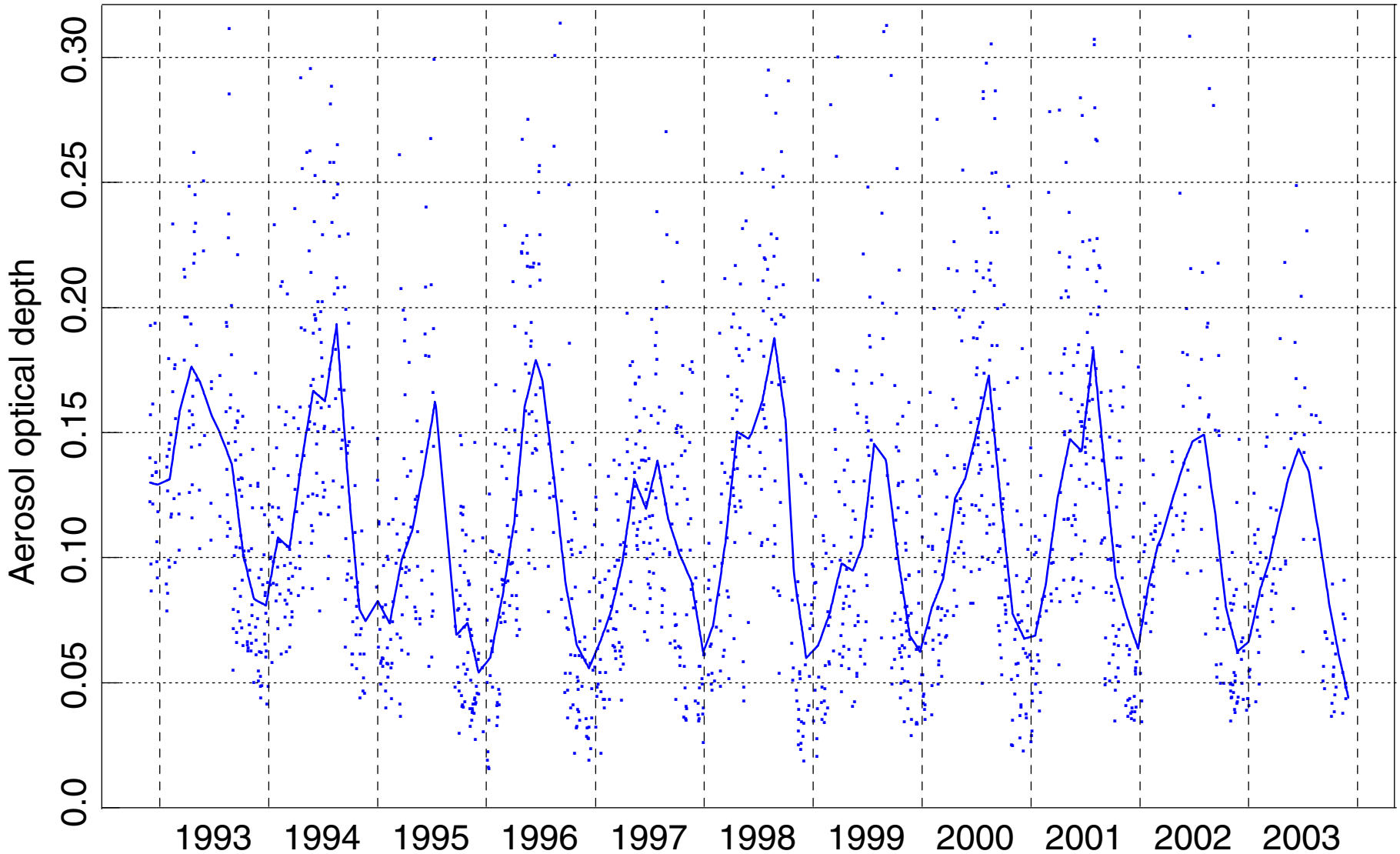
Global-average AOT 0.1 corresponds to global-average forcing -3.2 W m^{-2}.

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

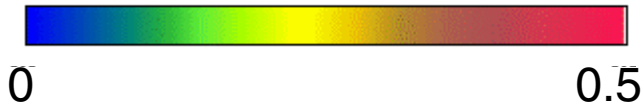
Variability is due to variability in tropospheric aerosols.
Optical depth variability of 0.1 is common even at a rural mid-continental site.

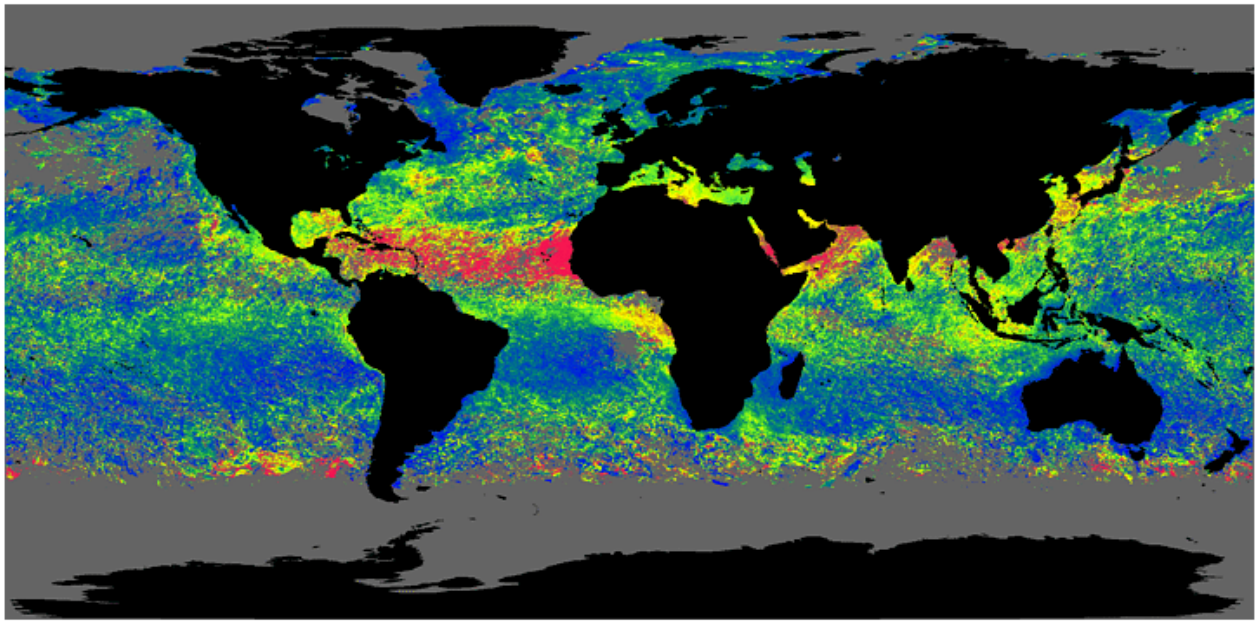
MONTHLY AVERAGE AEROSOL JUNE 1997

Polder radiometer on Adeos satellite

Optical Thickness τ

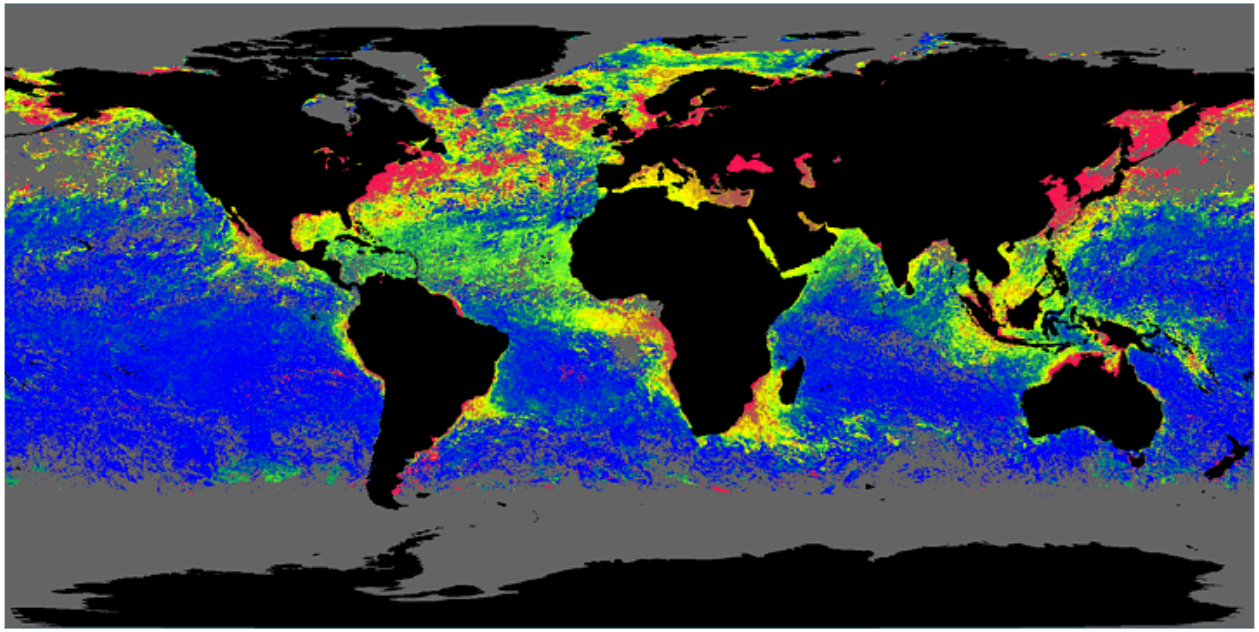
$\lambda = 865$ nm





Ångström Exponent α

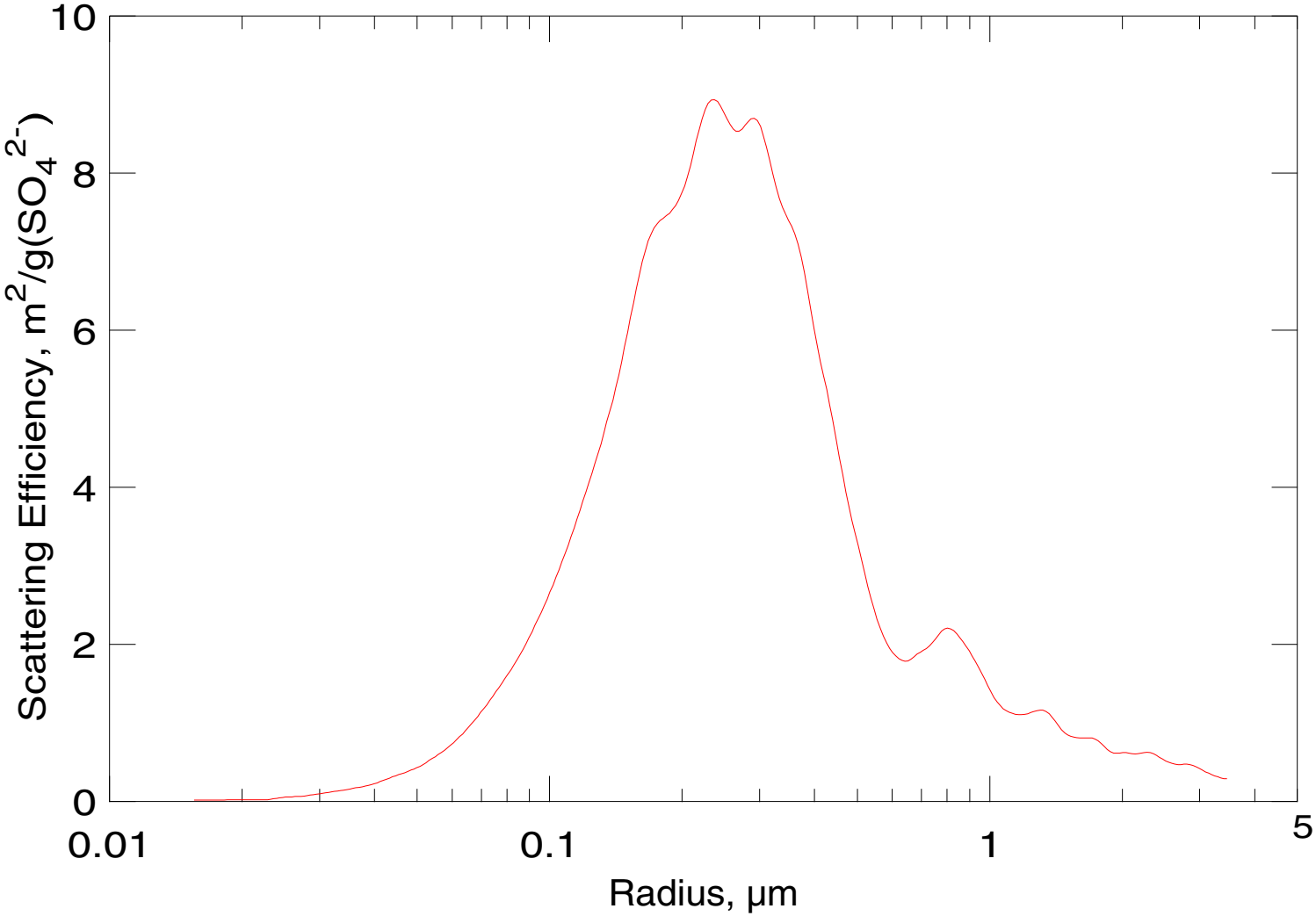
$$\alpha = -d \ln \tau / d \ln \lambda$$



LIGHT SCATTERING EFFICIENCY

Dependence on particle radius -- Size matters!

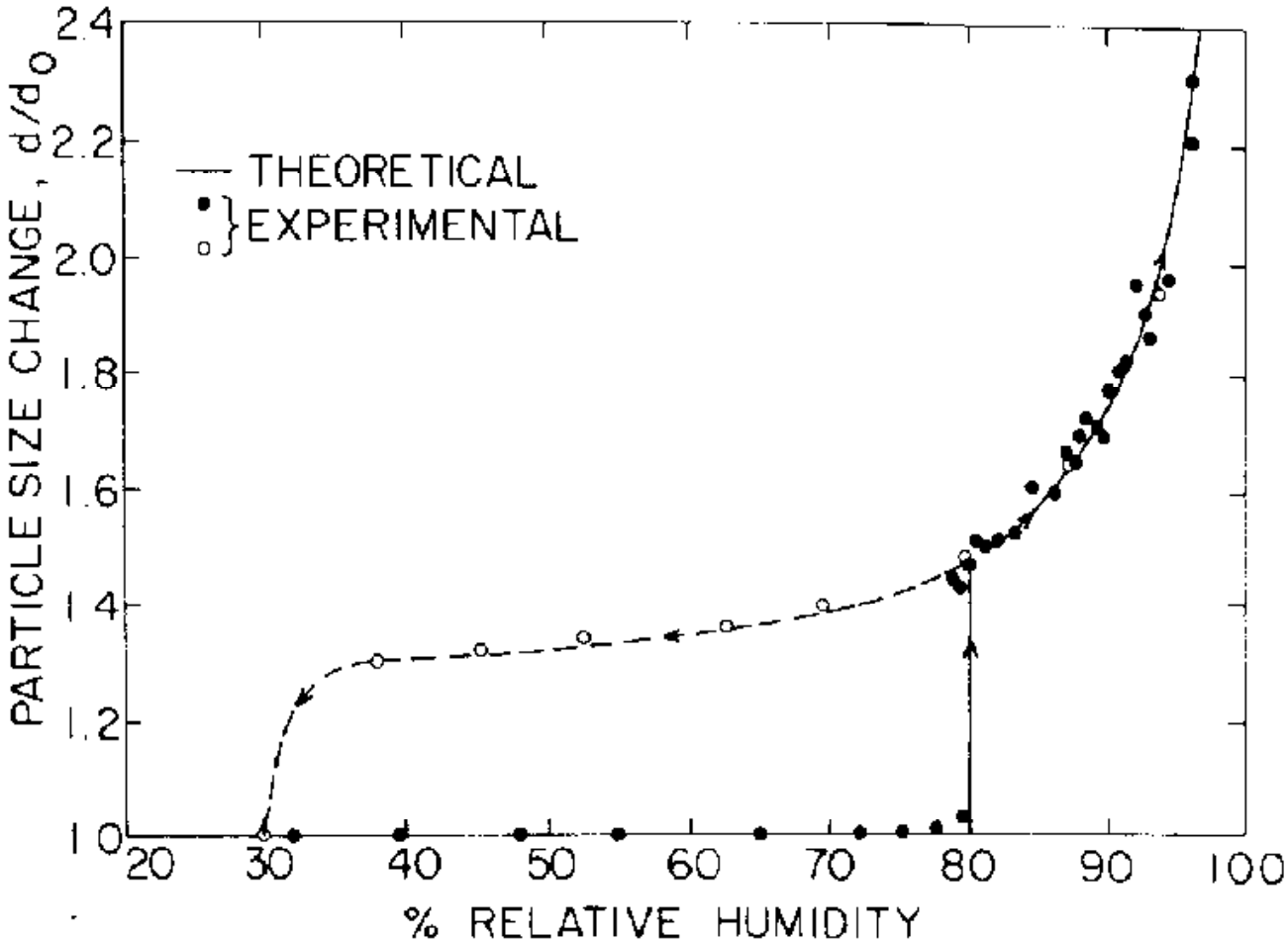
Ammonium Sulfate, 530 nm



Ouimette and Flagan, 1982

DELIQUESCENCE, SIZE CHANGE, AND EFFLORESCENCE OF HYGROSCOPIC PARTICLES

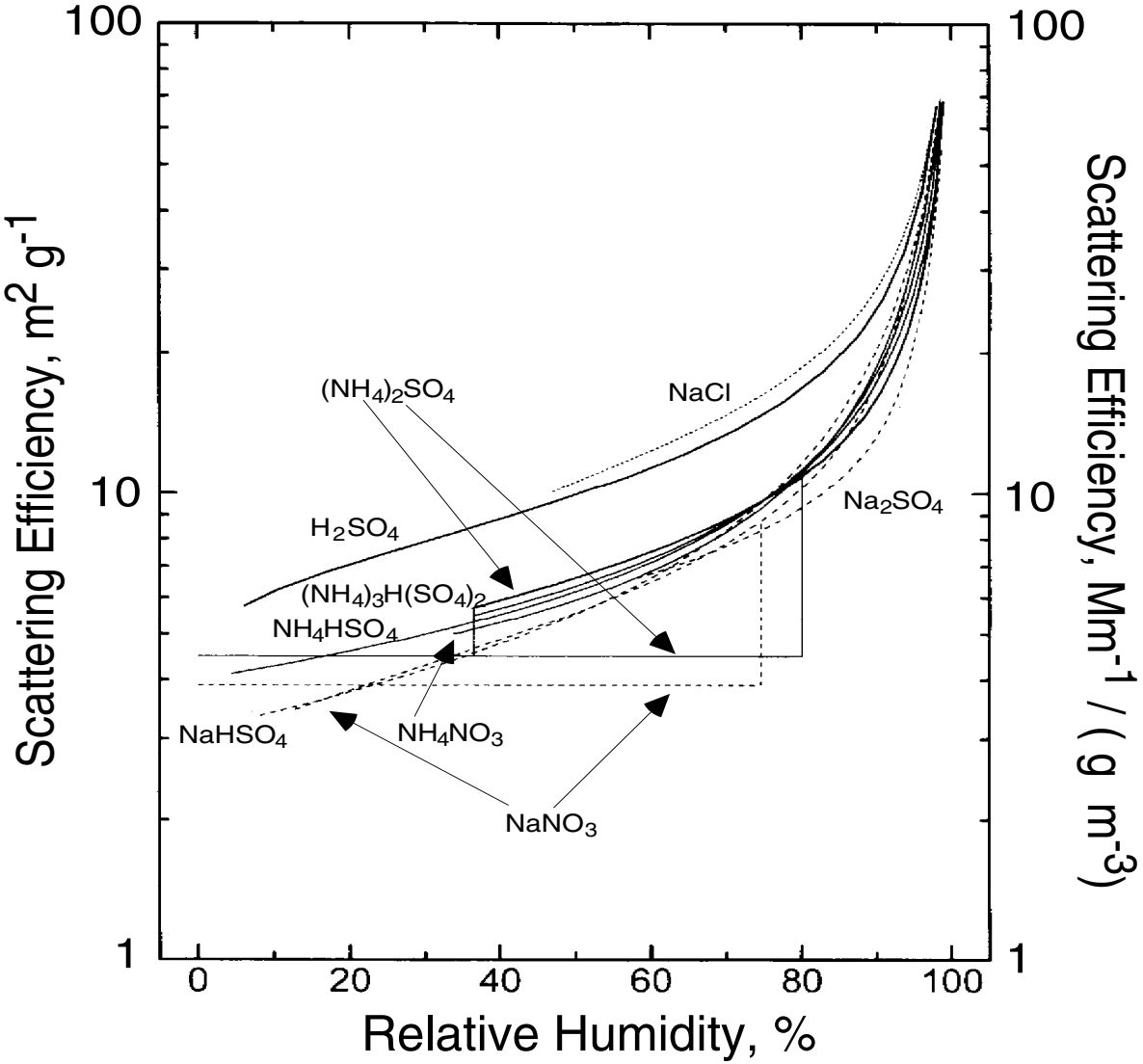
Ammonium Sulfate at 25°C



Tang and Munkelwitz, 1984

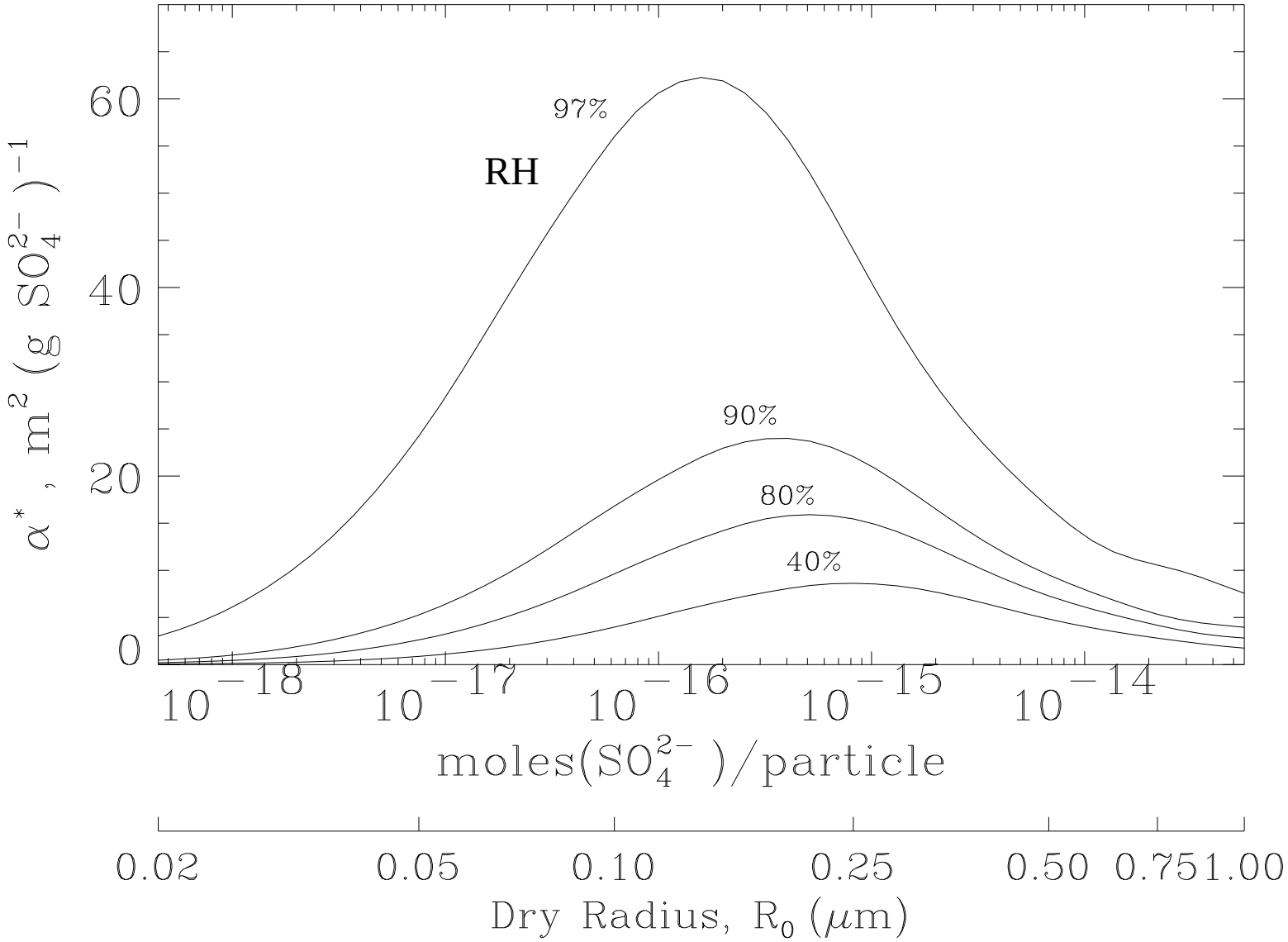
WATER UPTAKE AND LIGHT SCATTERING COEFFICIENT

Dependence on relative humidity for various substances



Lognormal, D_g = 0.3 μm; σ_g = 1.5; I. Tang, JGR, 1996

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

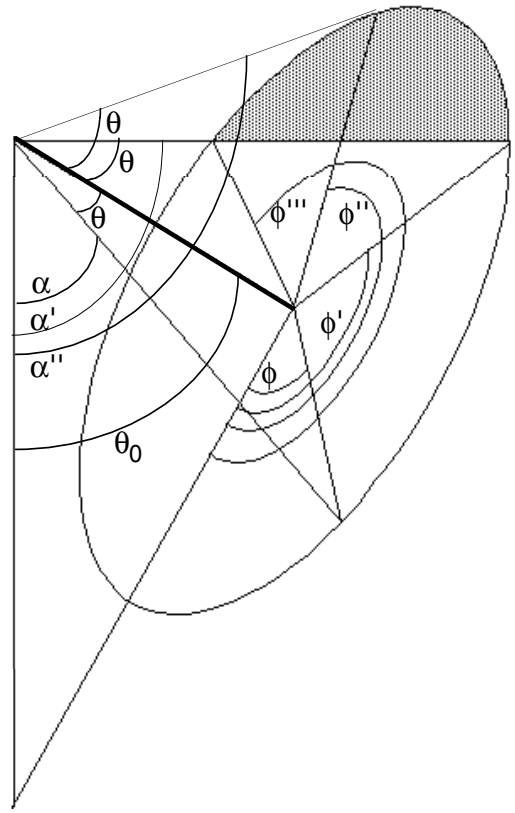


Nemesure, Wagener & Schwartz, JGR, 1995

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

UPSCATTER FRACTION

SCATTERING OF SOLAR RADIATION BY AEROSOL PARTICLE

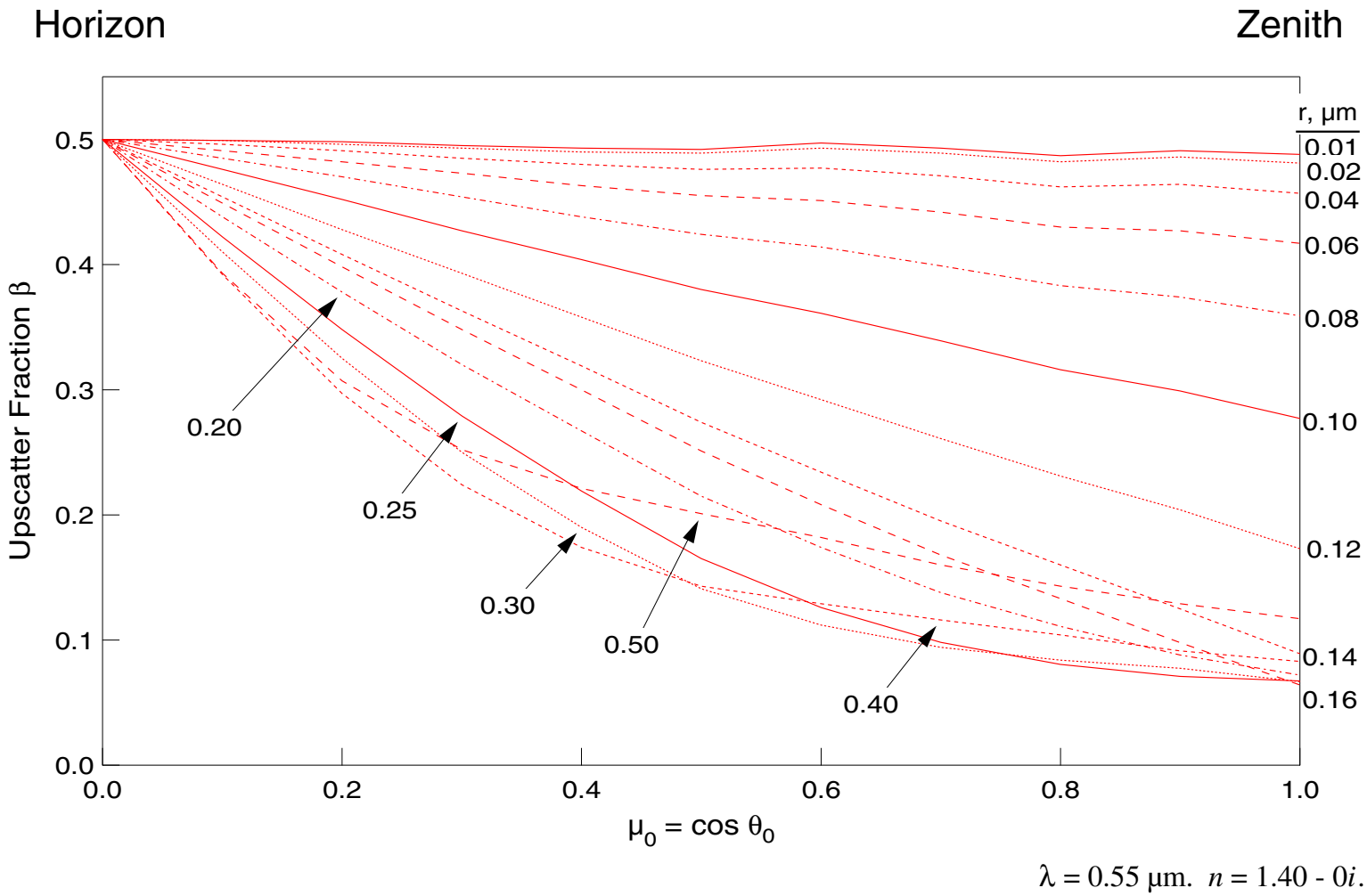


Upscatter fraction β is the fraction of radiation scattered into the upward hemisphere.

$$\beta = \int_{\substack{\text{upward}\\ \text{hemisphere}}} P(\theta,\phi)\,d\Omega \Big/ \int_{4\pi} P(\theta,\phi)\,d\Omega = \int_{\cos\alpha<0} P(\theta,\phi)\,d\Omega \Big/ 4\pi$$

UPSCATTER FRACTION

Dependence on solar zenith angle and particle radius



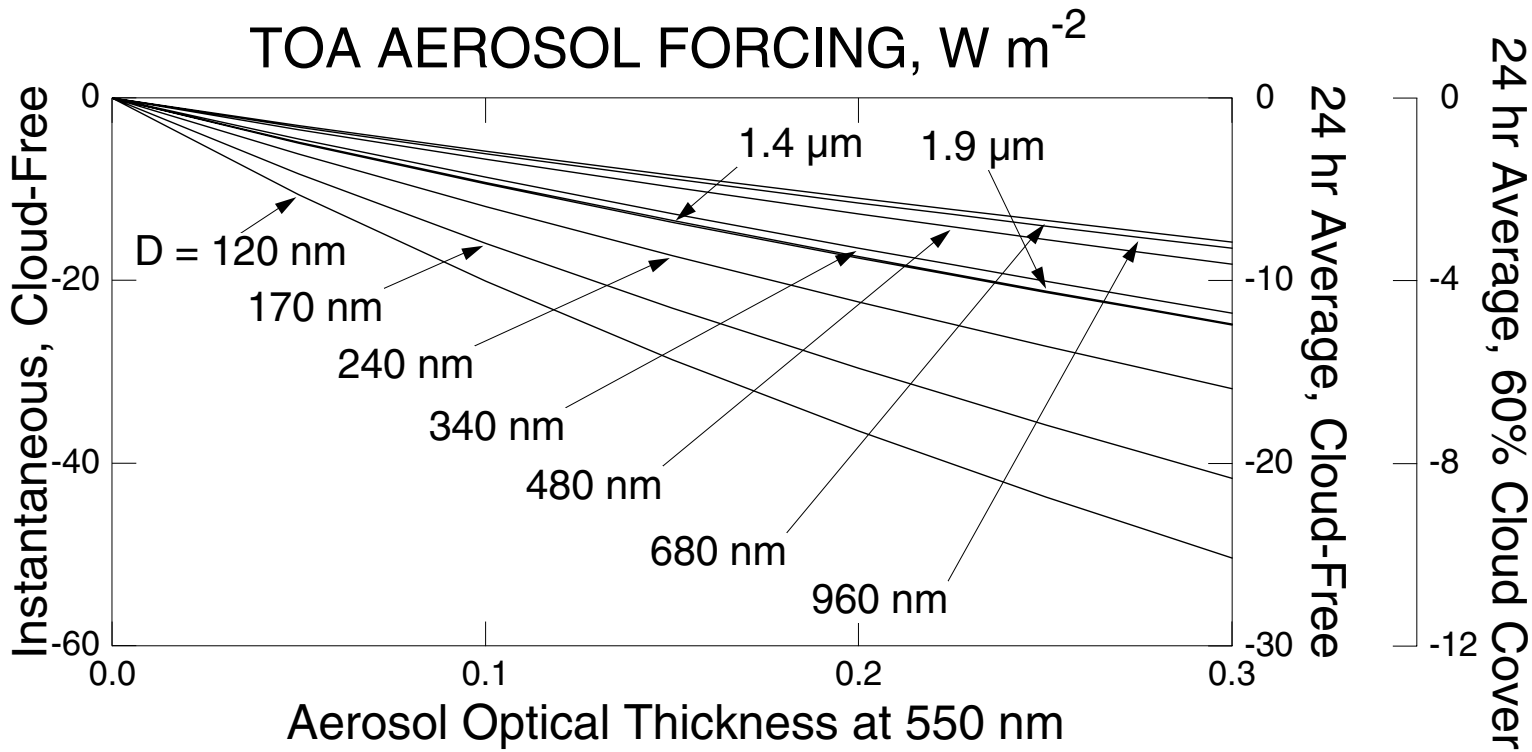
For sun at horizon $\beta = 0.5$ (by symmetry).

For small particles, $r << \lambda$, upscatter fraction approaches that for Rayleigh scattering (0.5).

DIRECT AEROSOL TOA FORCING

Dependence on particle diameter

Surface reflectance $R = 0.15$; single scatter albedo $\omega_0 = 1$.

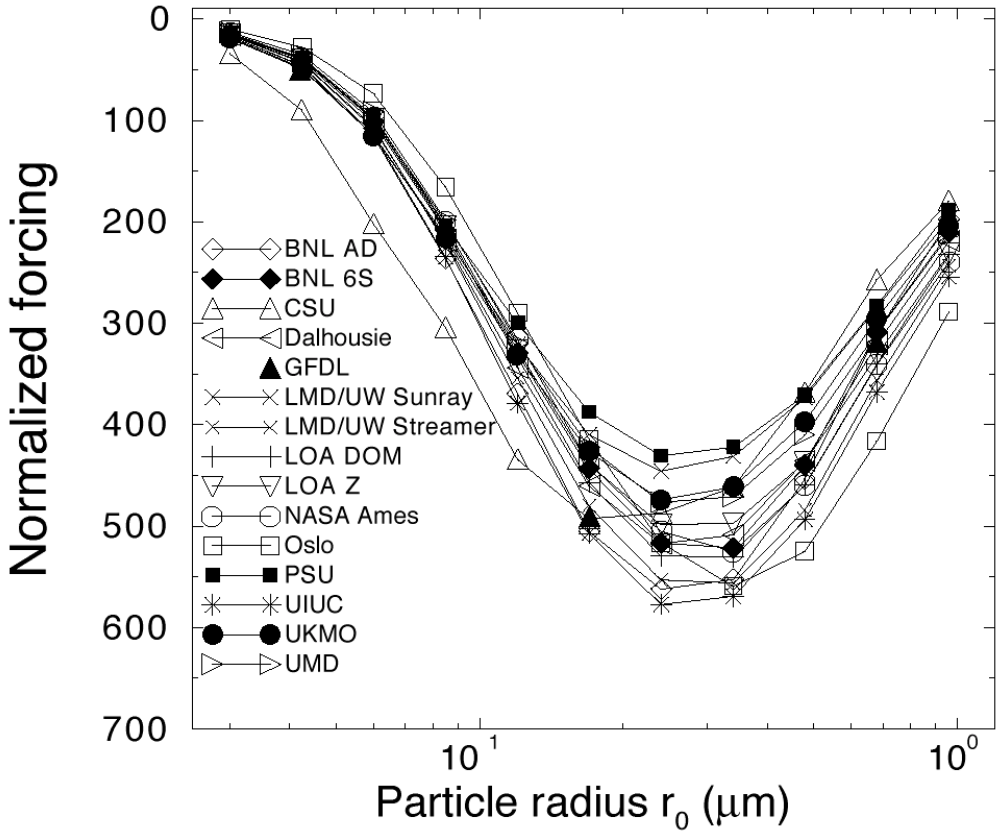


Forcing per optical depth depends on particle size.

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



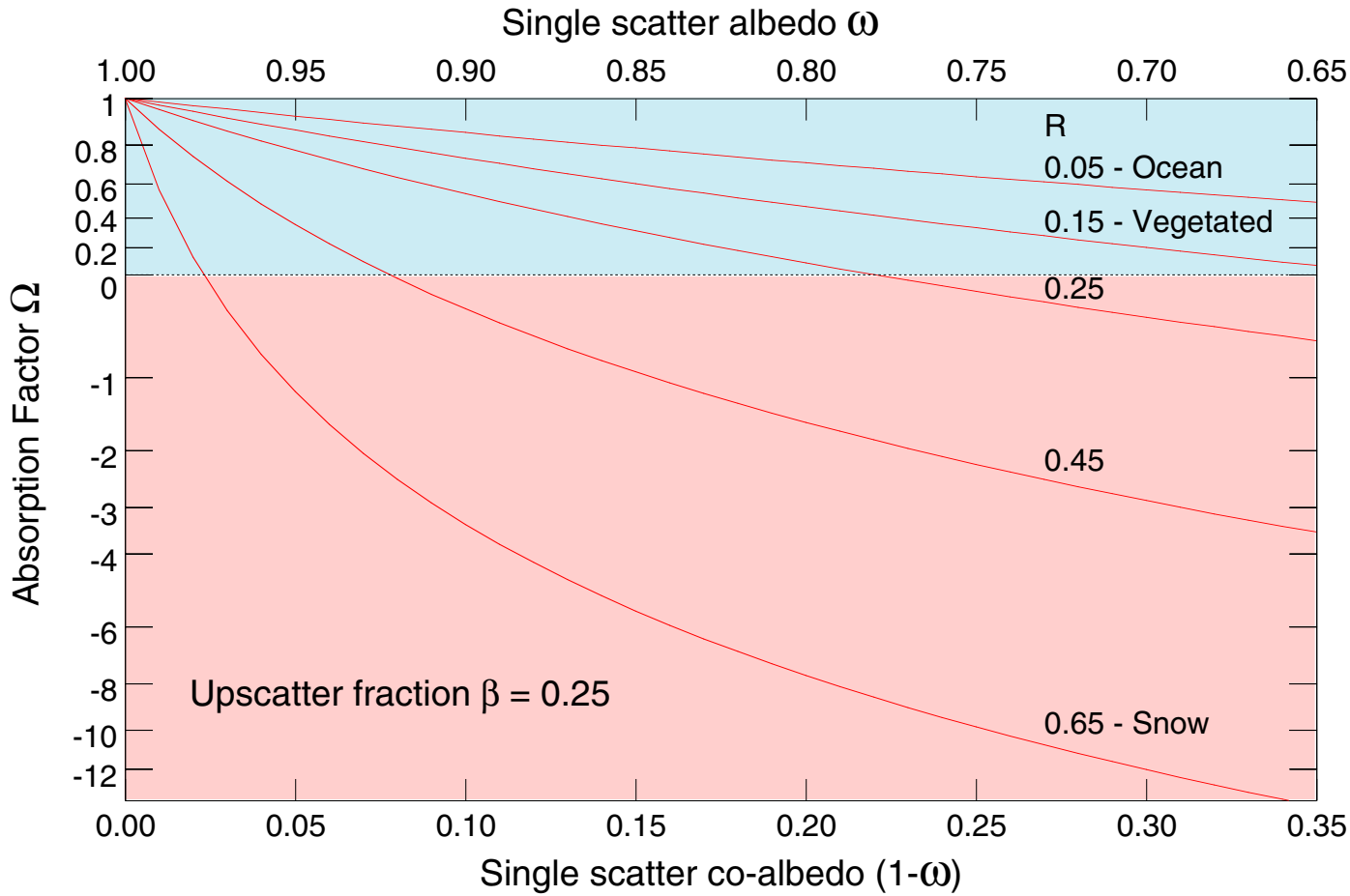
Standard deviation ~8% for 15 models at radius ~ 200 nm.

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

Radiation transfer models agree closely for well specified aerosol.

DECREASE IN FORCING DUE TO ABSORPTION

Dependence on single scattering albedo ω and surface reflectance *R*



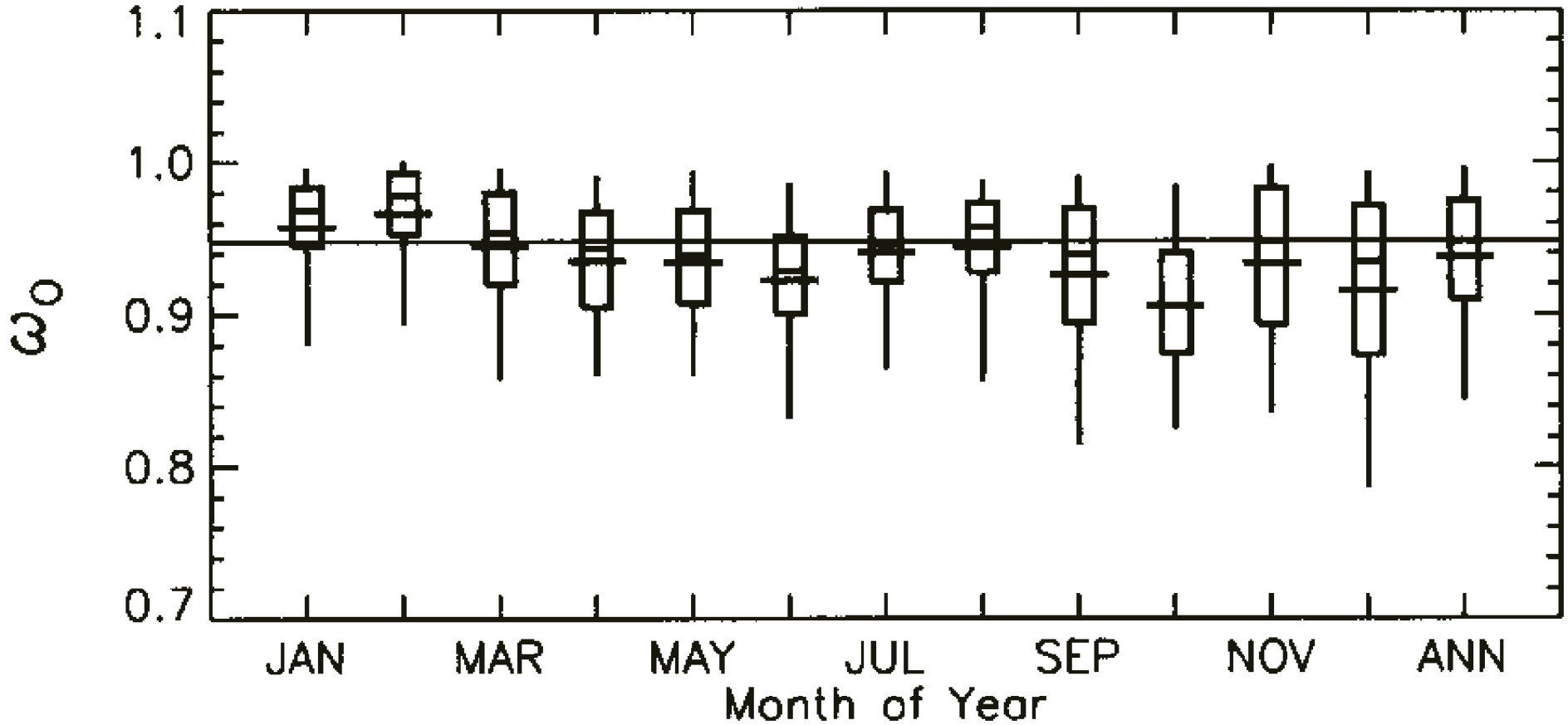
Note nonlinear scale.

Negative absorption factor results in positive (warming) forcing.

Forcing can be strongly warming over snow or clouds.

AEROSOL SINGLE SCATTERING ALBEDO

North central Oklahoma, 4 years of hourly data, sub 10 μm diameter



Sheridan, Delene & Ogren, JGR, 2001

Median $\omega = 0.95$

For great majority of data $\omega > 0.9$

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.

REPRESENTING AEROSOL PROCESSES IN CTMs

Sources of primary particles and precursor gases

3-D transport as controlled by governing meteorology

Gas to particle conversion (clear air and cloud)
New particle formation
Accretion onto existing particles

Particle size evolution (clear air and cloud)

Particle ***morphology*** and intra-particle structure

Removal of particles and precursor gases, controlled by meteorology

Aerosol properties as ***bivariate functions of particle size and composition***

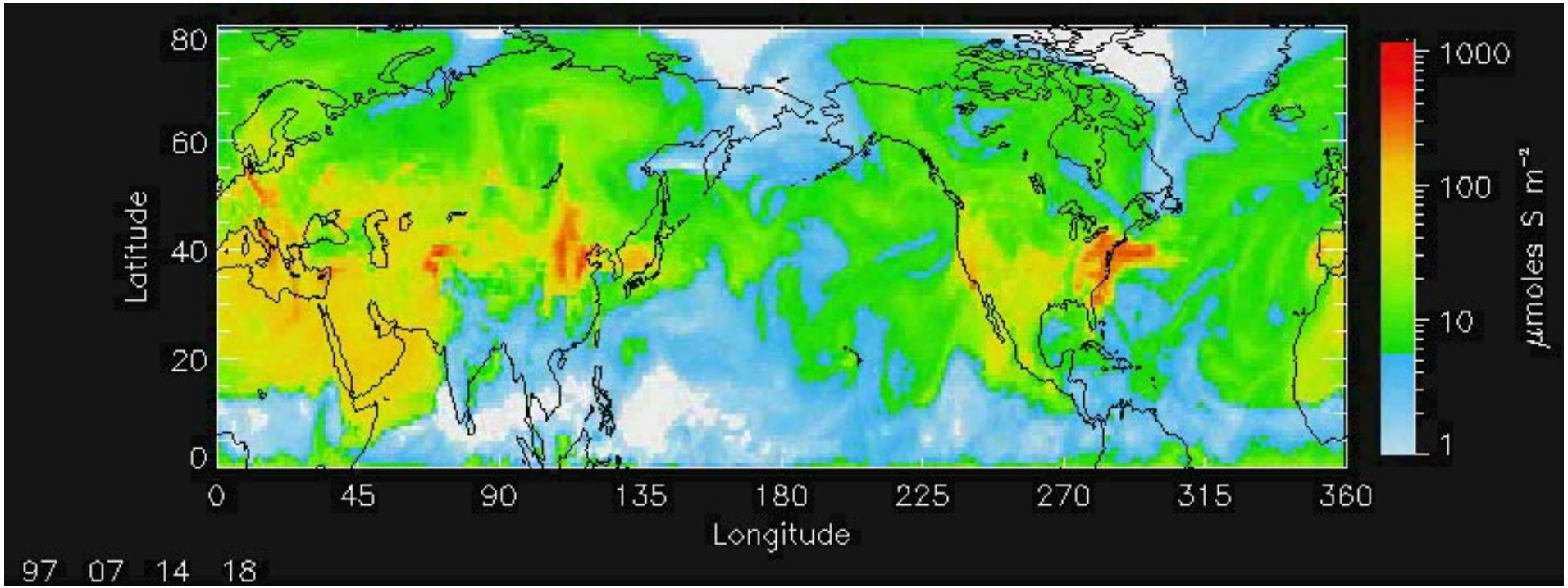
Aerosol optical properties (extinction coefficient, single scatter albedo, asymmetry parameter) as integrals over single particle properties (Mie)

All as a function of ***3-D location and secular time***

HEMISPHERIC DISTRIBUTION OF SULFATE COLUMN BURDEN

Vertical integral of concentration

July 14, 1997, 1800 UTC

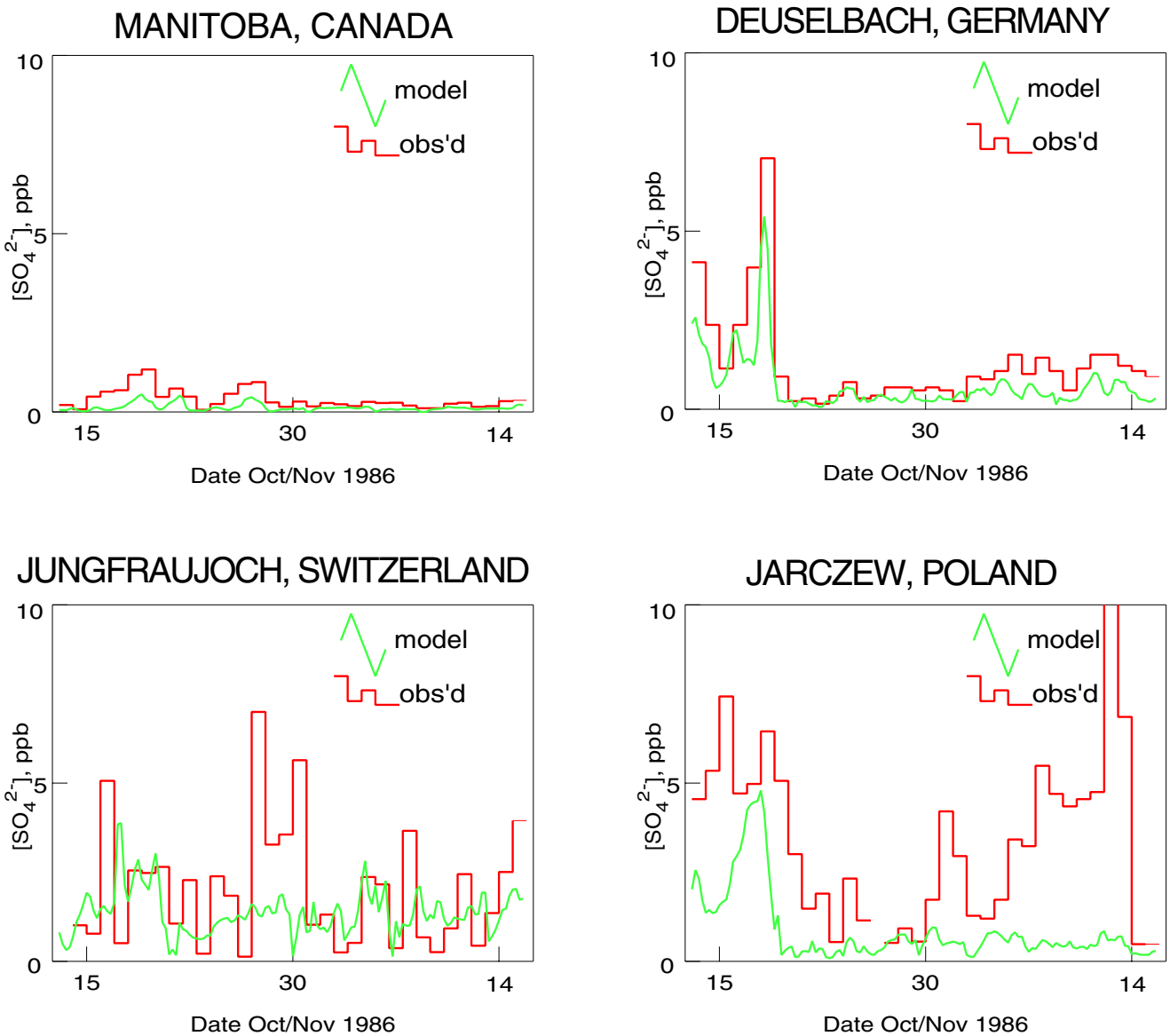


Brookhaven National Laboratory Chemical Transport Model

Benkovitz & Schwartz, JGR, In press 2004

COMPARISON OF MODEL AND OBSERVATIONS

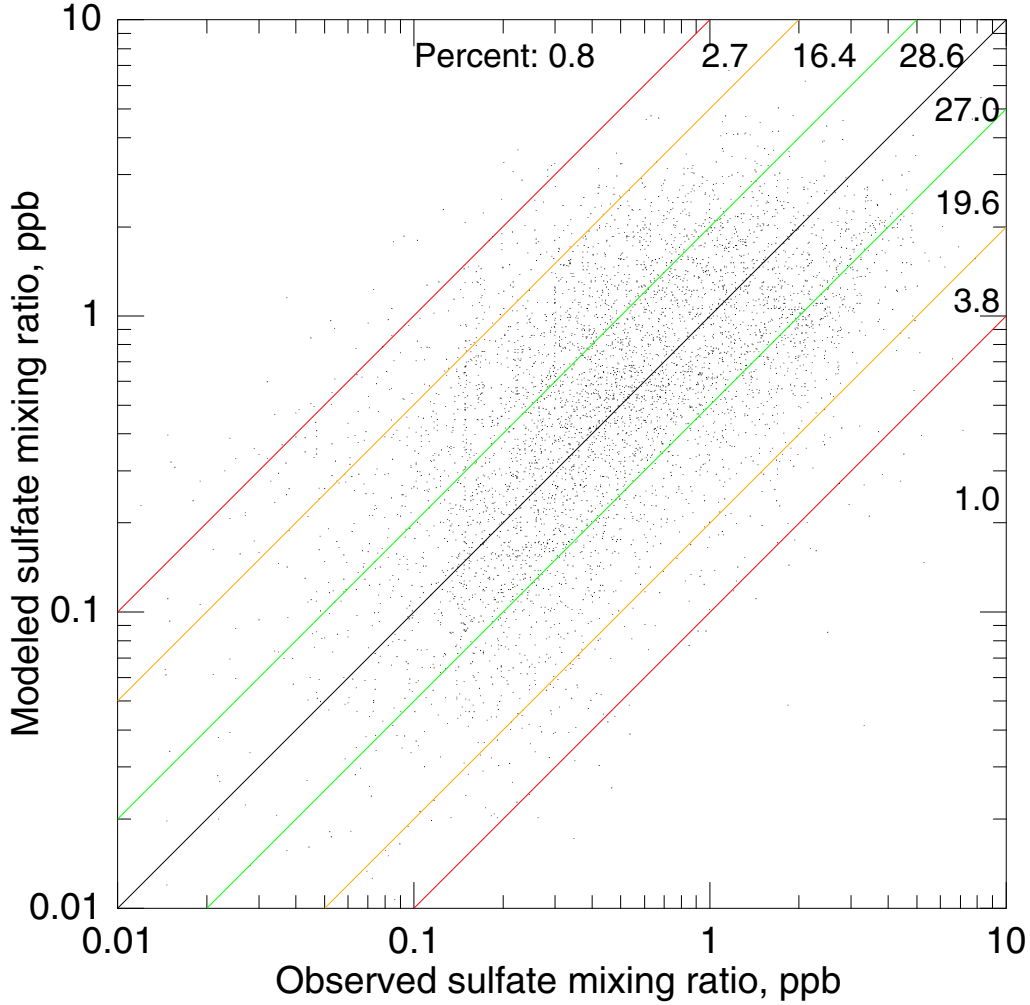
Comparisons for 24-hr sulfate mixing ratio at surface



Benkovitz et al., JGR, 1994

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 & Schwartz, JGR, In press 2004

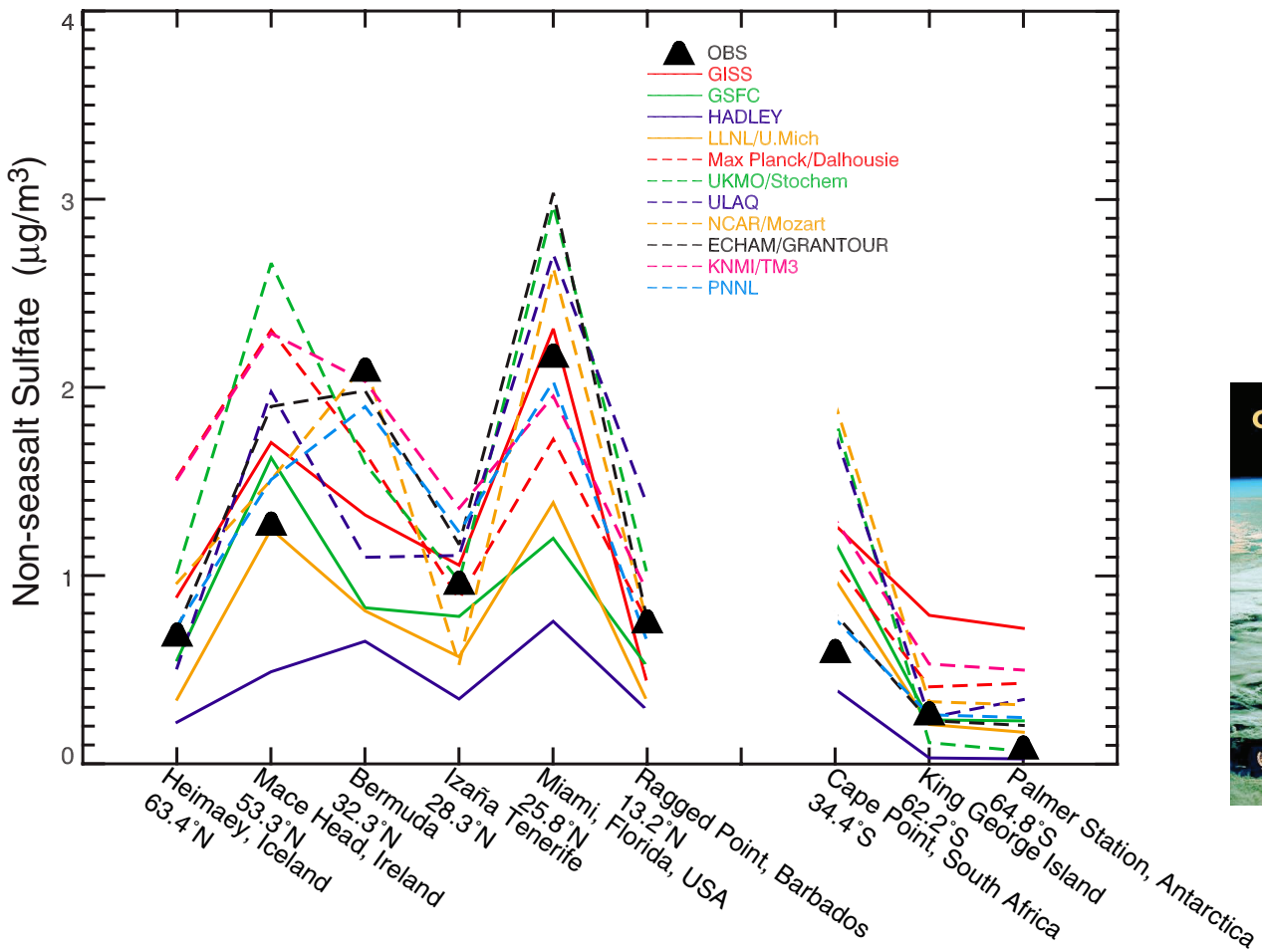
STATISTICS OF SEVERAL SULFATE CTMs

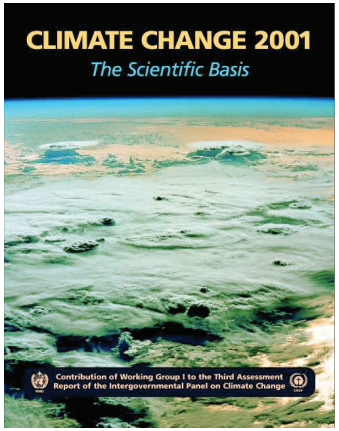
Model	F96	L97	R98	K99	R00	C00	B97	B04
SO_2 Sink Rate (%/day)								
Dry Deposition	26	10	8	17	16	26	12	24
Wet Deposition	5	0	0	0	1	7	0	4×10^{-4}
Gas Conversion	11	7	8	6	6	9	8	14
Aqueous Conversion to sulfate	22	26	27	15	29	15	16	30
Oxidation & immediate wet dep								21
Sulfate Sink Rate (%/day)								
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





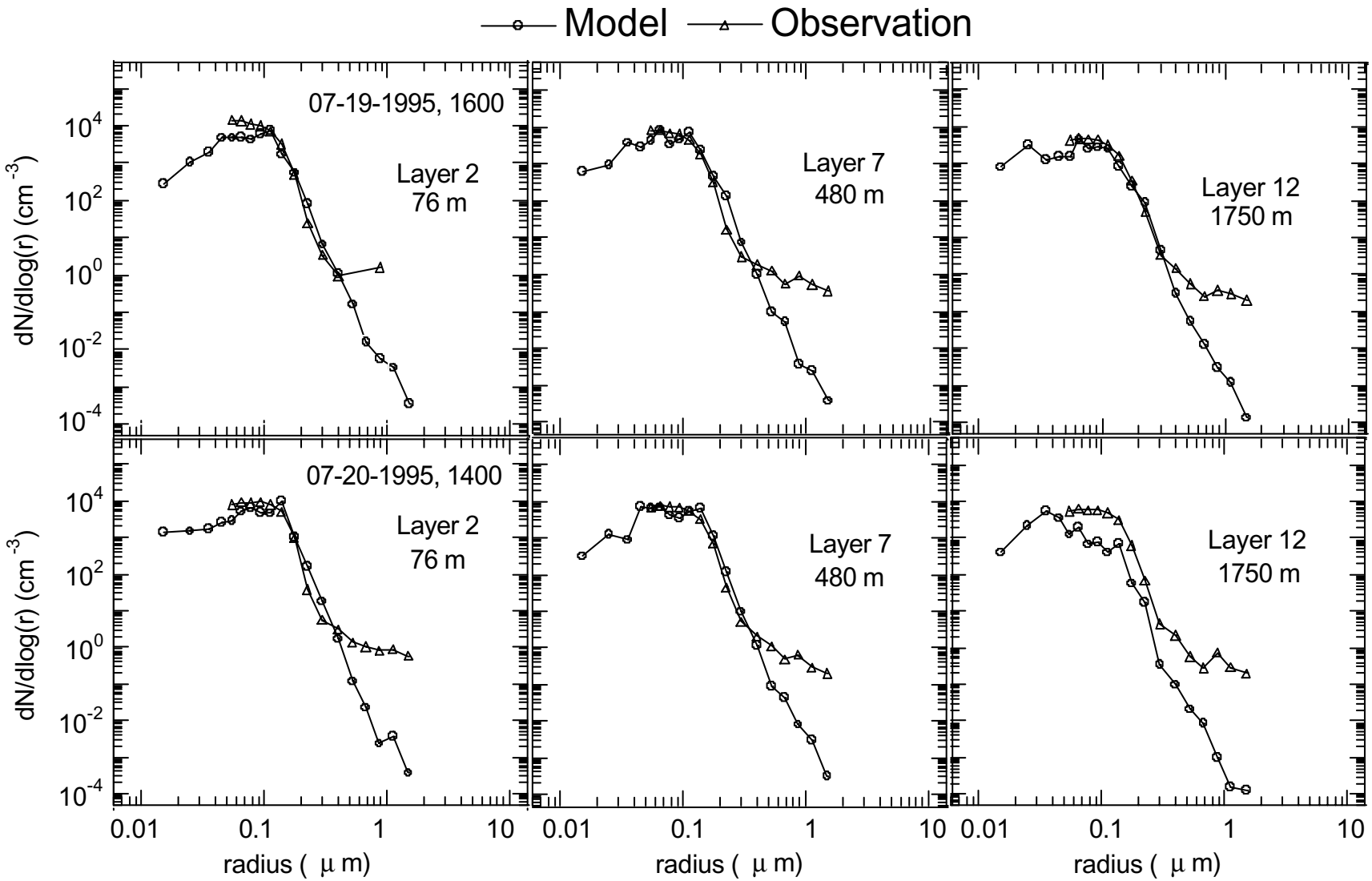
Penner et al., IPCC, 2001

"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."

SIZE DISTRIBUTIONS

Comparison of Measurement and Retrieval from Model At 3 Altitudes near Nashville TN

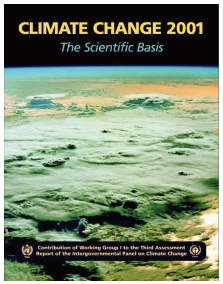


Yu, Kasibhatla, Wright, Schwartz, McGraw & Deng, *JGR*, 2003

UNCERTAINTY BUDGET FOR *DIRECT* FORCING BY INDUSTRIAL AEROSOLS

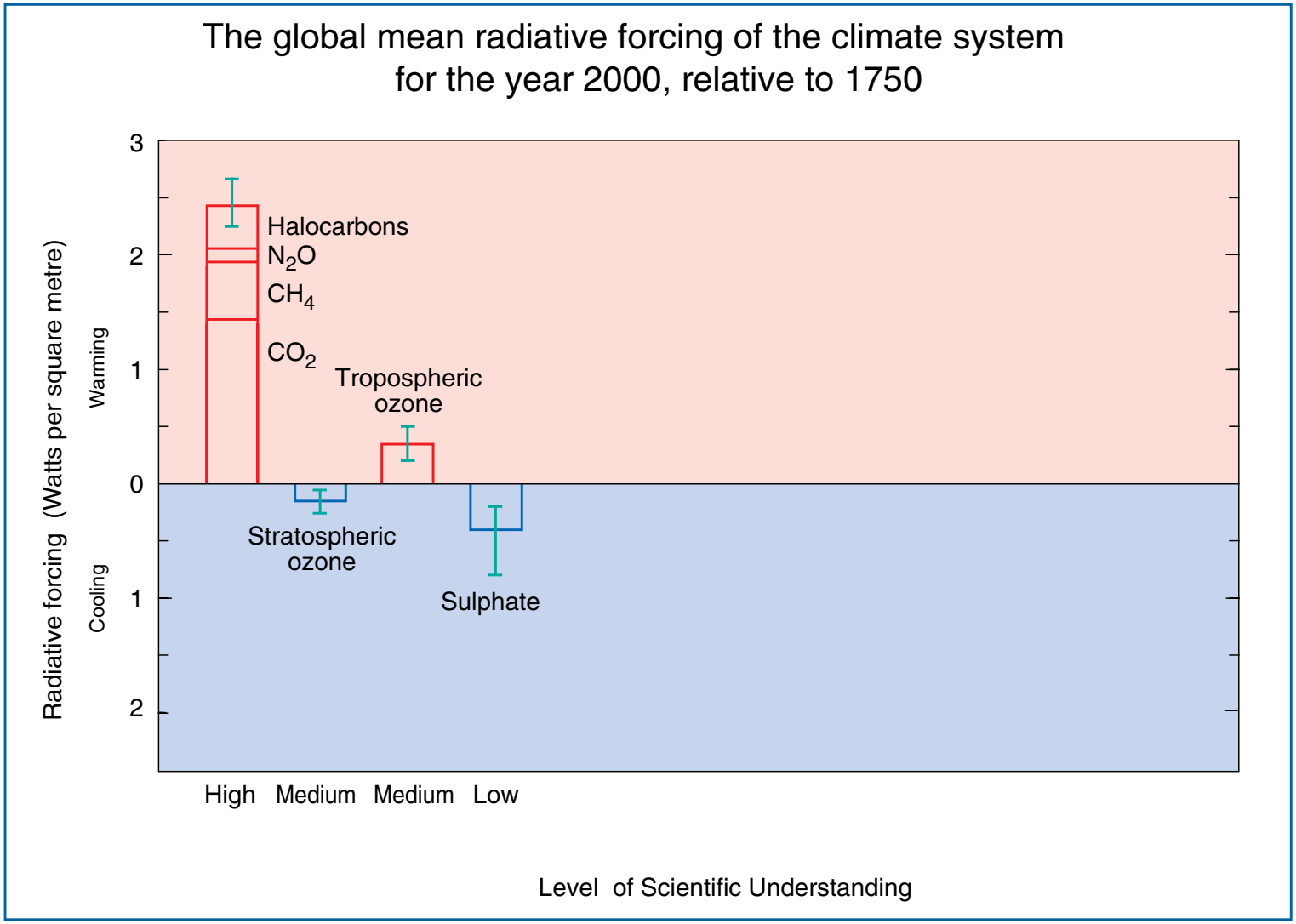
Quantity	Central Value	2/3 Uncertainty Range	Uncertainty Factor
Total emission of anthropogenic sulfate from fossil fuel burning (Tg/yr)	69	57.5 to 82.8	1.4
Atmospheric burden of sulfate from fossil fuel burning (Tg S)	0.525	0.35 to 0.79	**2.3**
Fraction of light scattered into upward hemisphere, $\bar{\beta}$	0.23	0.17 to 0.29	1.7
Aerosol mass scattering efficiency ($m^2 g^{-1}$), α_s	3.5	2.3 to 4.7	**2.0**
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	1.4
Fractional increase in aerosol scattering efficiency due to hygroscopic growth at RH=80%	2.0	1.7 to 2.3	1.4
Fraction of Earth not covered by cloud	0.39	0.35 to 0.43	1.2
Mean surface albedo, co-albedo	0.15	0.08 to 0.22	2.8, 1.2
Result: Central value of forcing is $-0.5\ Wm^{-2}$; the uncertainty range is from -0.25 to -1 Wm^{-2}.			**4**

Modified from Penner et al., IPCC, 2001



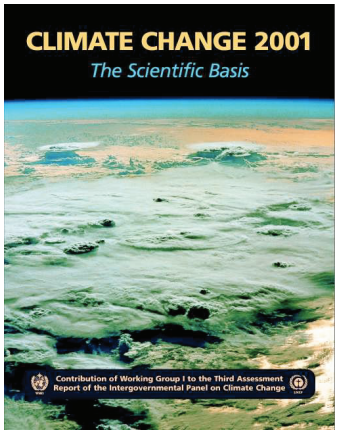
Greatest uncertainties are in burden and optical properties.

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



Summary for Policymakers

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



UNCERTAINTY BUDGET FOR *DIRECT* FORCING BY INDUSTRIAL AEROSOLS

Quantity	Central Value	2/3 Uncertainty Range	Uncertainty Factor
Total emission of anthropogenic OC from fossil fuel burning (Tg/yr)	20	10 to 30	**3.0**
Atmospheric burden of OC from fossil fuels (Tg)	0.48	0.33 to 0.70	**2.1**
Total emission of anthropogenic BC from fossil fuel burning (Tg/yr)	7	4.67 to 10.5	**2.2**
Atmospheric burden of BC from fossil fuel burning (Tg)	0.133	0.11 to 0.16	1.5
Total emission of anthropogenic sulfate from fossil fuel burning (Tg/yr)	69	57.5 to 82.8	1.4
Atmospheric burden of sulfate from fossil fuel burning (Tg S)	0.525	0.35 to 0.79	**2.3**
Fraction of light scattered into upward hemisphere, $\bar{\beta}$	0.23	0.17 to 0.29	1.7
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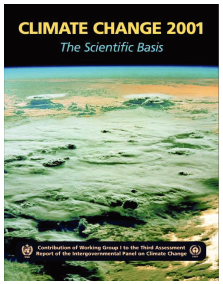
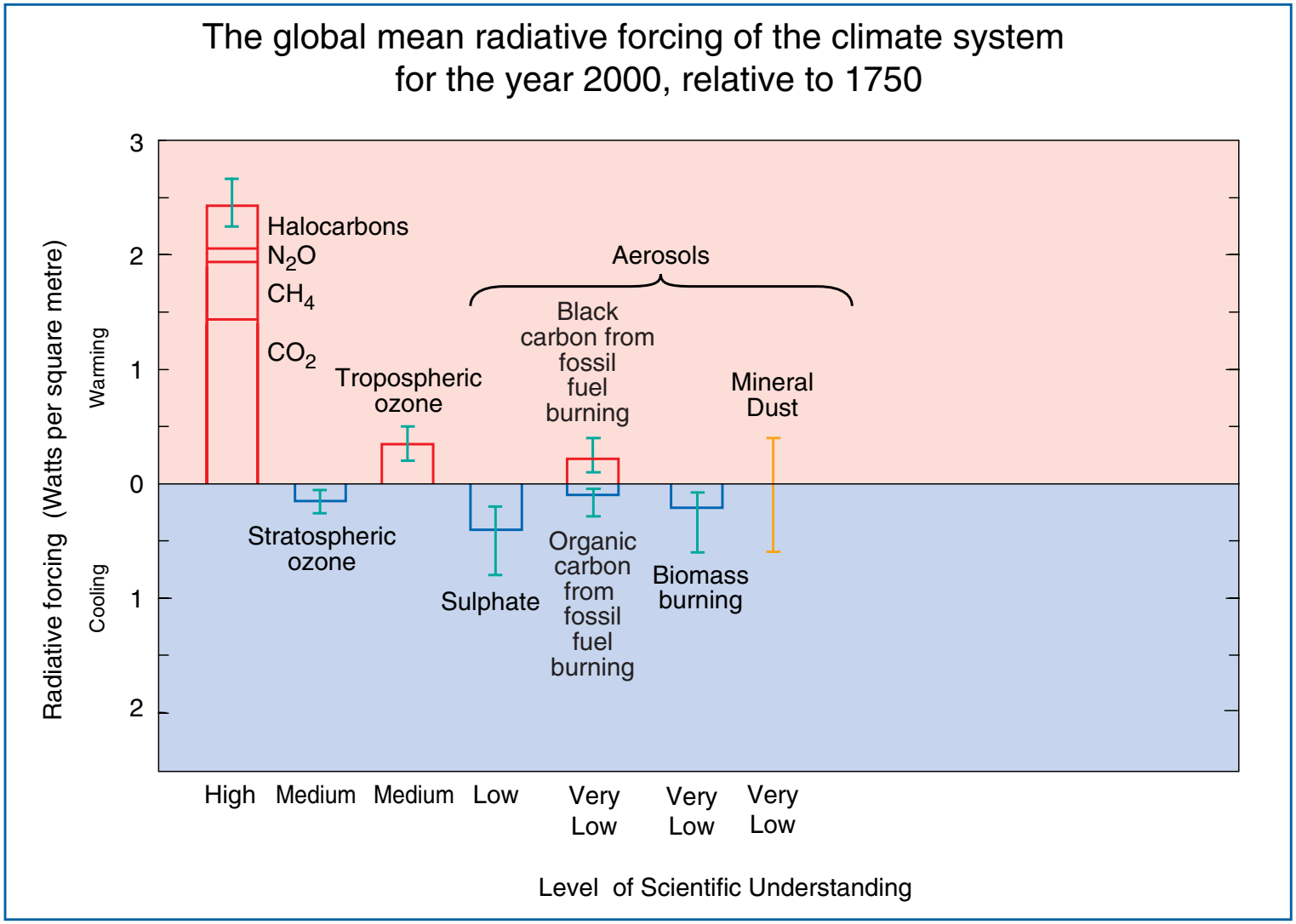
Aerosol single scattering albedo, co-albedo (dry), ω_0, $1-\omega_0$	0.92	0.85 to 0.97	1.1, **5**
T_a, atmospheric transmittance above aerosol layer	0.87	0.72 to 1.00	1.4
Fractional increase in aerosol scattering efficiency due to hygroscopic growth at RH=80%	2.0	1.7 to 2.3	1.4
Fraction of Earth not covered by cloud	0.39	0.35 to 0.43	1.2
Mean surface albedo, co-albedo	0.15	0.08 to 0.22	2.8, 1.2
Result: If central value is –0.6 Wm^{-2} the 2/3 uncertainty range is from 0.1 to 1.0 Wm^{-2}.			**10.0**

Modified from Penner et al., IPCC, 2001



Greatest uncertainties are in chemical, microphysical, and optical properties.

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



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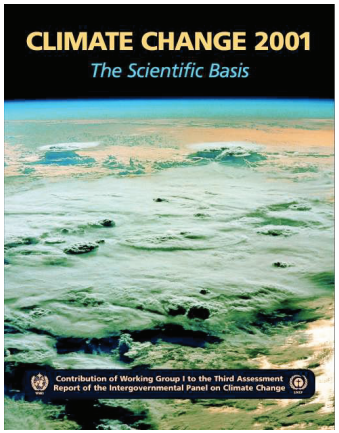
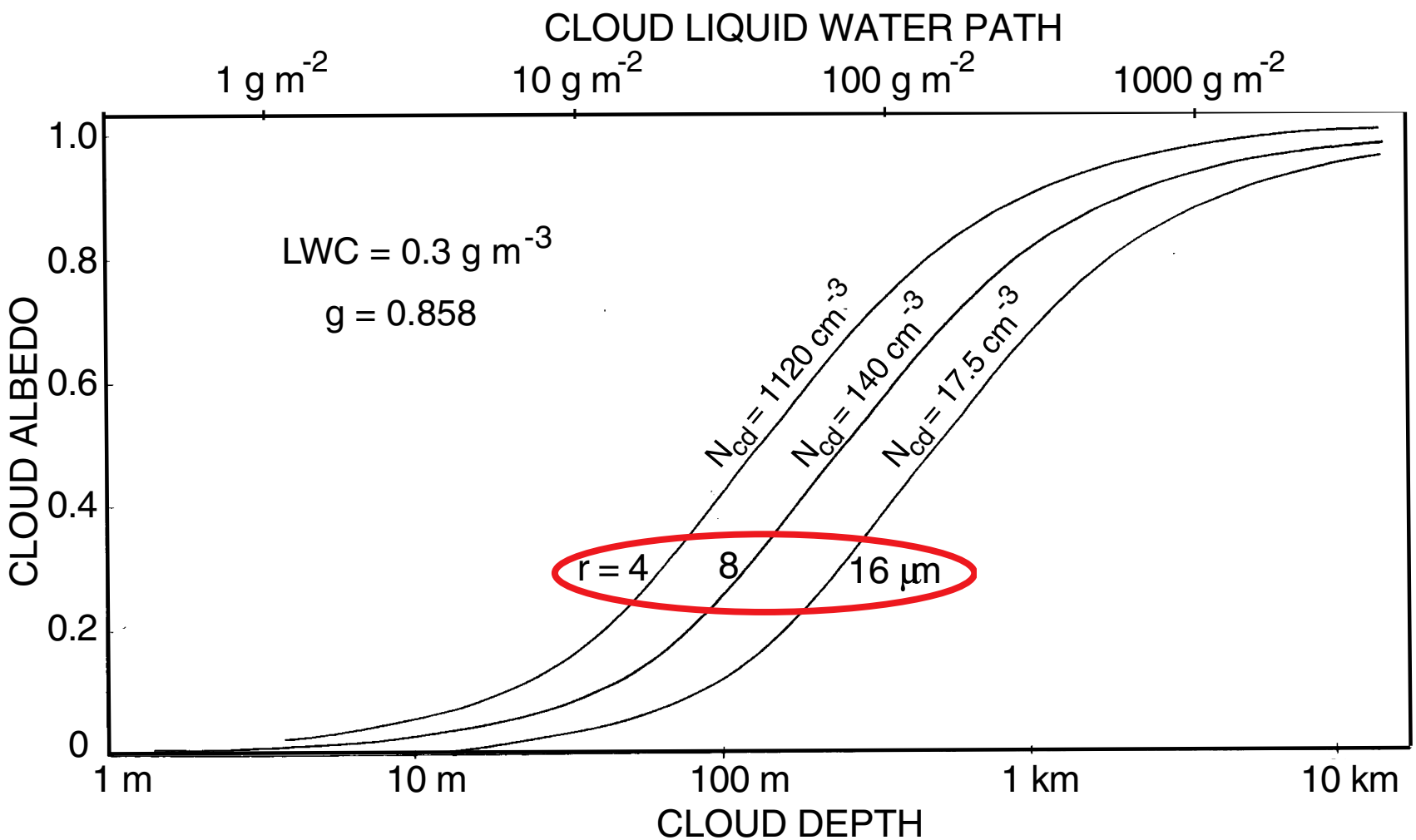


THE TWOMEY EFFECT

PHYSICAL BASIS AND SENSITIVITY

DEPENDENCE OF CLOUD ALBEDO ON CLOUD DEPTH

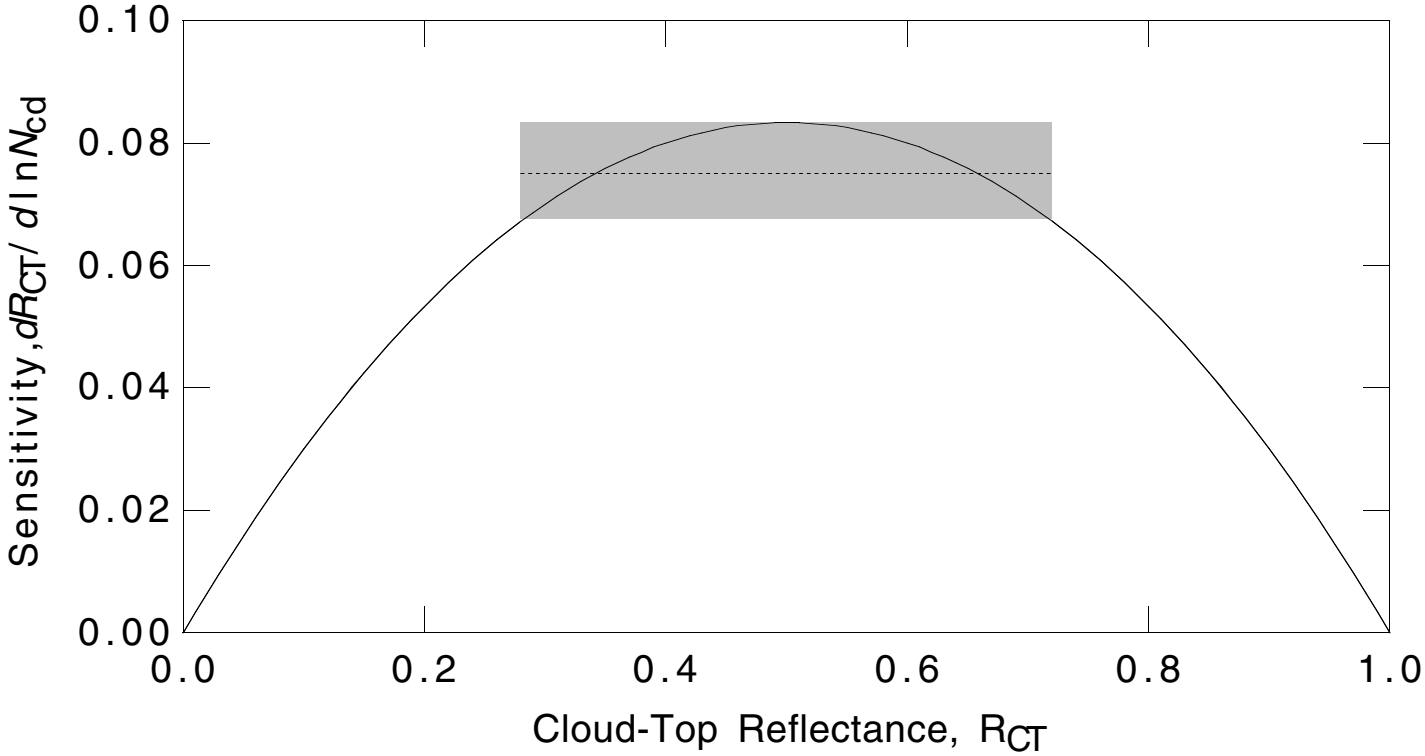
Influence of Cloud Drop Radius and Concentration



Twomey, *Atmospheric Aerosols*, 1977

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

TWOMEY SENITIVITY
Dependence on cloud-top reflectance

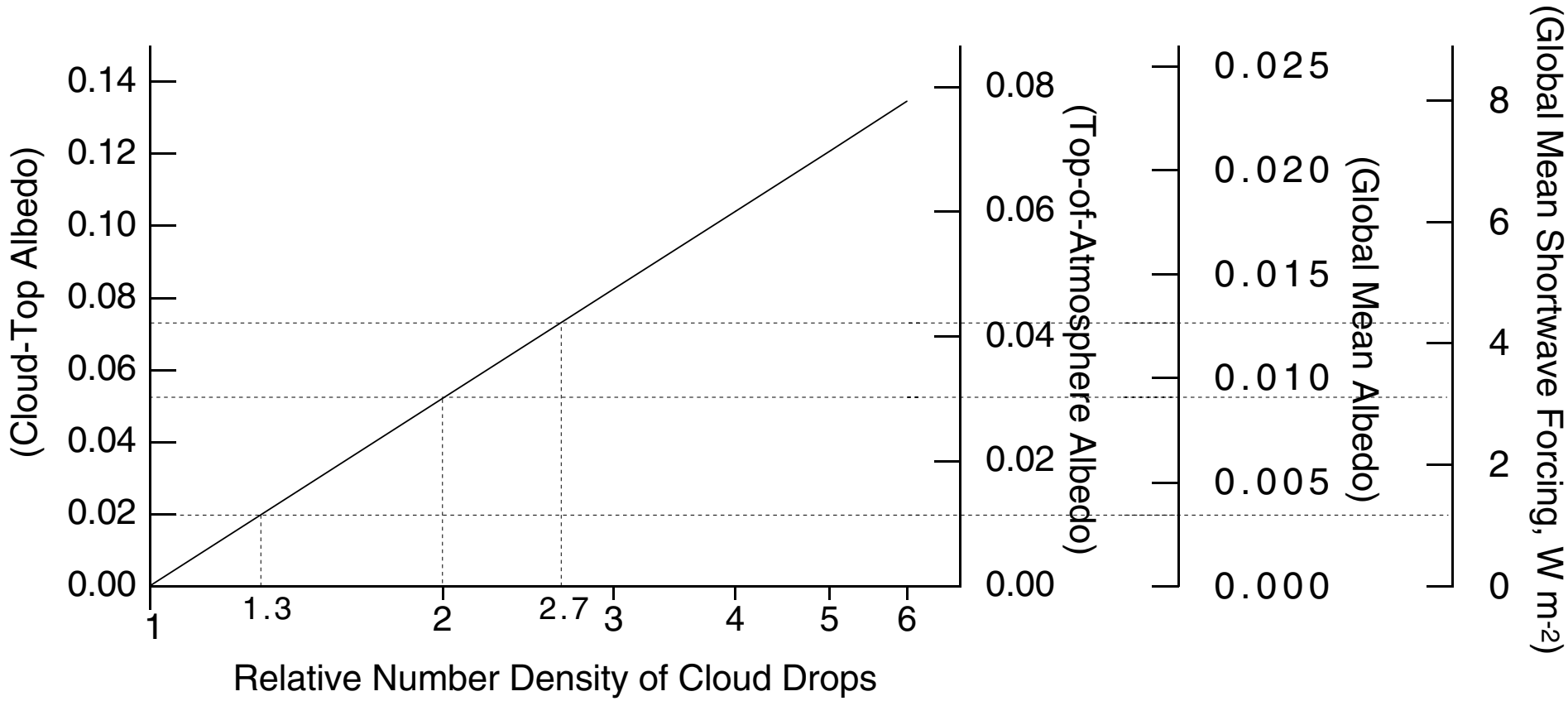


Modified from Charlson et al., 1992

Sensitivity is greatest for clouds of intermediate optical depth.

For $dR_{\mathrm{CT}} / d\ln N_{\mathrm{cd}} = 0.08 = 0.08$, a 10% increase in N_{cd} increases cloud-top reflectivity by 0.008.

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.

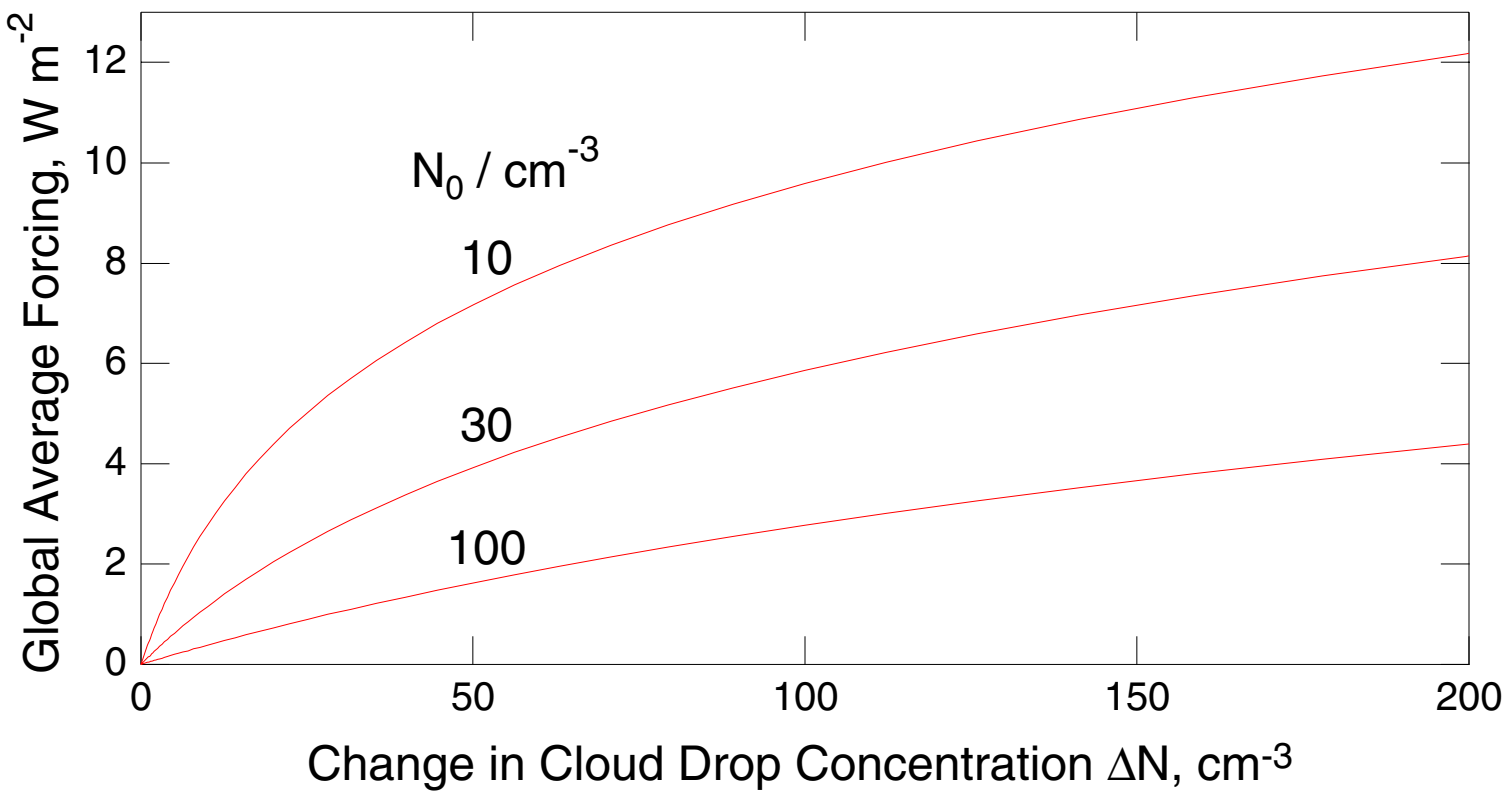
A 30% increase in cloud drop concentration results in a forcing of ~1 W m^{-2}.

INDIRECT (TWOMEY) FORCING

Dependence on incremental cloud drop concentration ΔN and

Sensitivity to initial cloud drop concentration N_0

$$F\,/\,(\mathrm{W\ m^{-2}}) \approx 4\ln\left(\frac{N_0+\Delta N}{N_0}\right) = 4\ln\left(1+\frac{\Delta N}{N_0}\right)$$

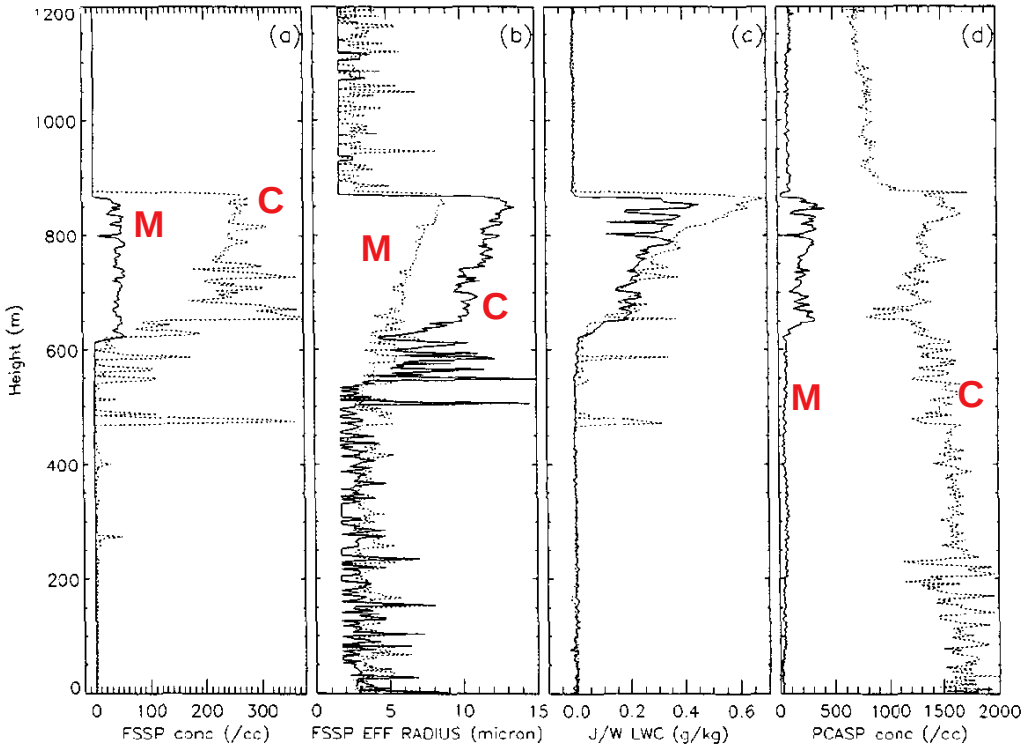


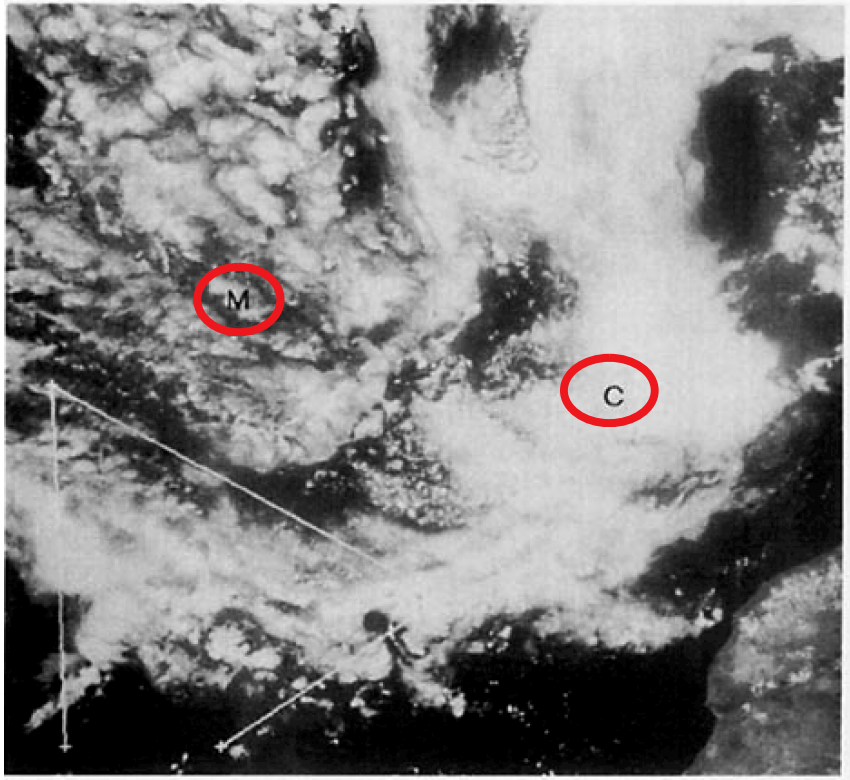
Aerosol indirect forcing is highly sensitive to background CCN concentration.

RELATION BETWEEN AEROSOL CONCENTRATIONS AND CLOUD DROP CONCENTRATIONS

CLOUD MICROPHYSICAL PROPERTIES AND SATELLITE VISIBLE RADIANCE

ASTEX, Northeast Atlantic, June, 1992

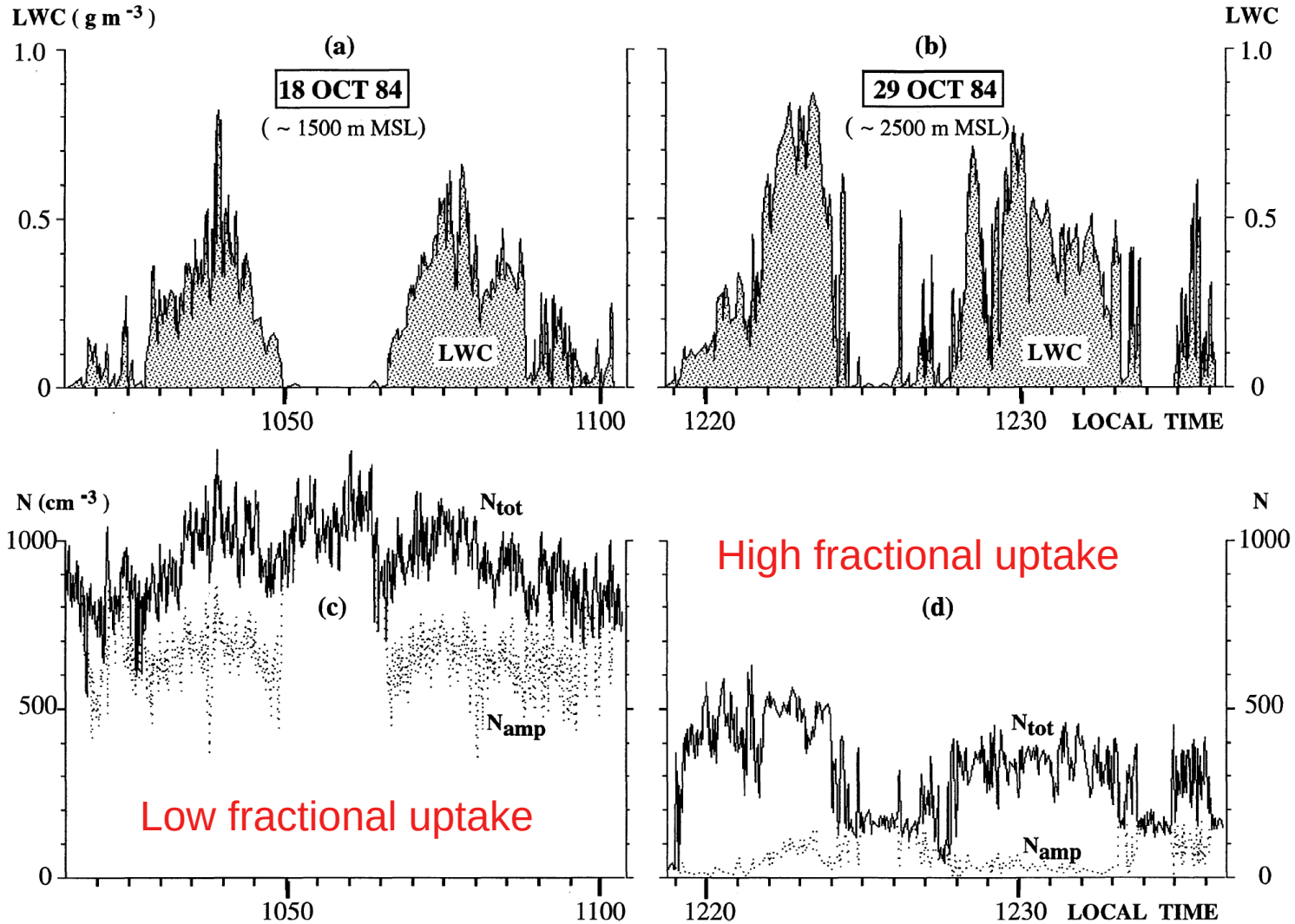




Albrecht et al., BAMS, 1995

FRACTIONAL UPTAKE OF ACCUMULATION MODE PARTICLES INTO CLOUDWATER

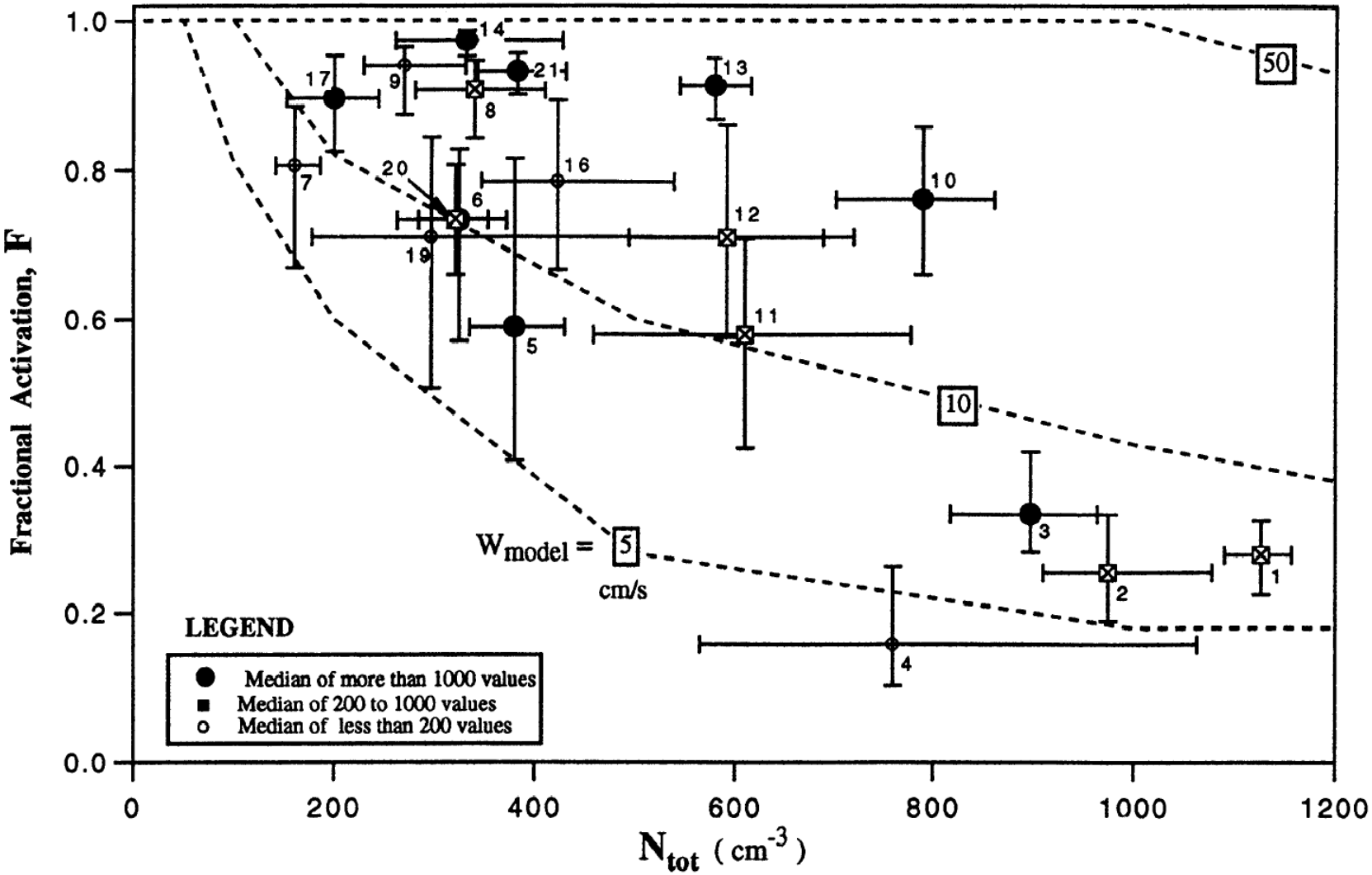
Aircraft measurements of ASASP (0.17 - 2 μm diameter) and FSSP (2 - 35 μm diameter) particles



Gillani et al., JGR, 1995

FRACTION OF ACTIVATED AEROSOL PARTICLES

Dependence on particle number concentration

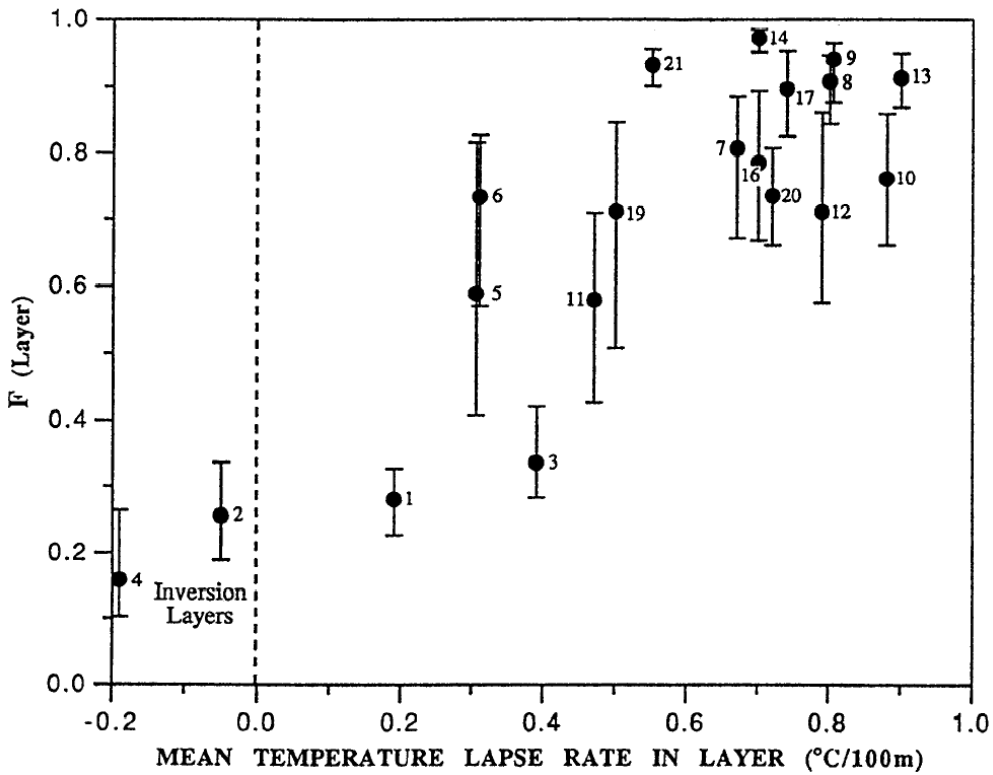


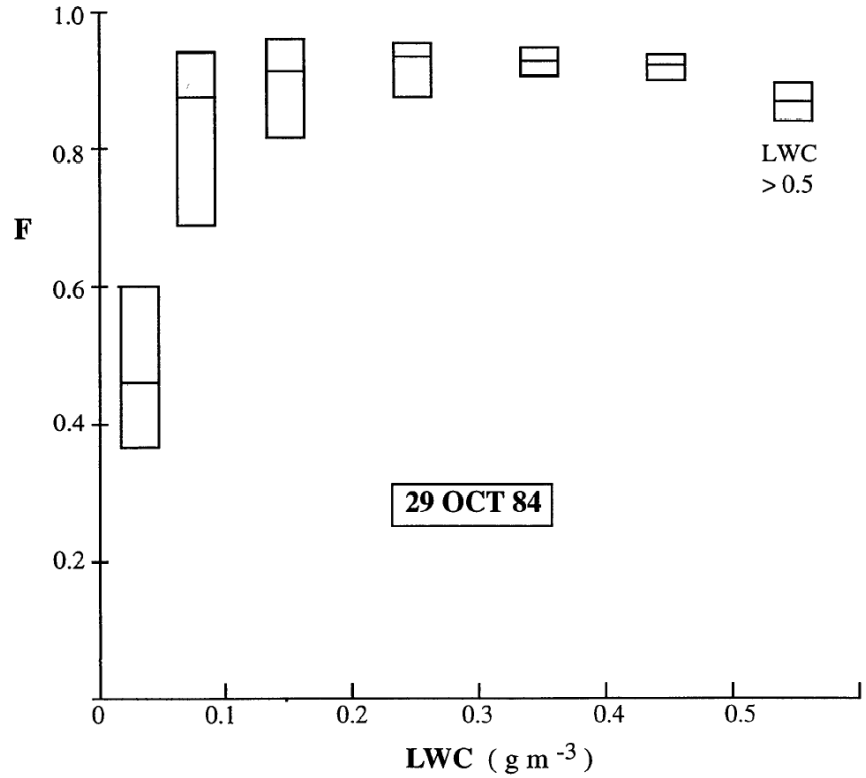
Gillani et al., JGR, 1995

Uptake decreases with increasing number concentration of aerosol particles

FRACTION OF ACTIVATED AEROSOL PARTICLES

Dependence on Lapse Rate and Liquid Water Content





Gillani et al., JGR, 1995

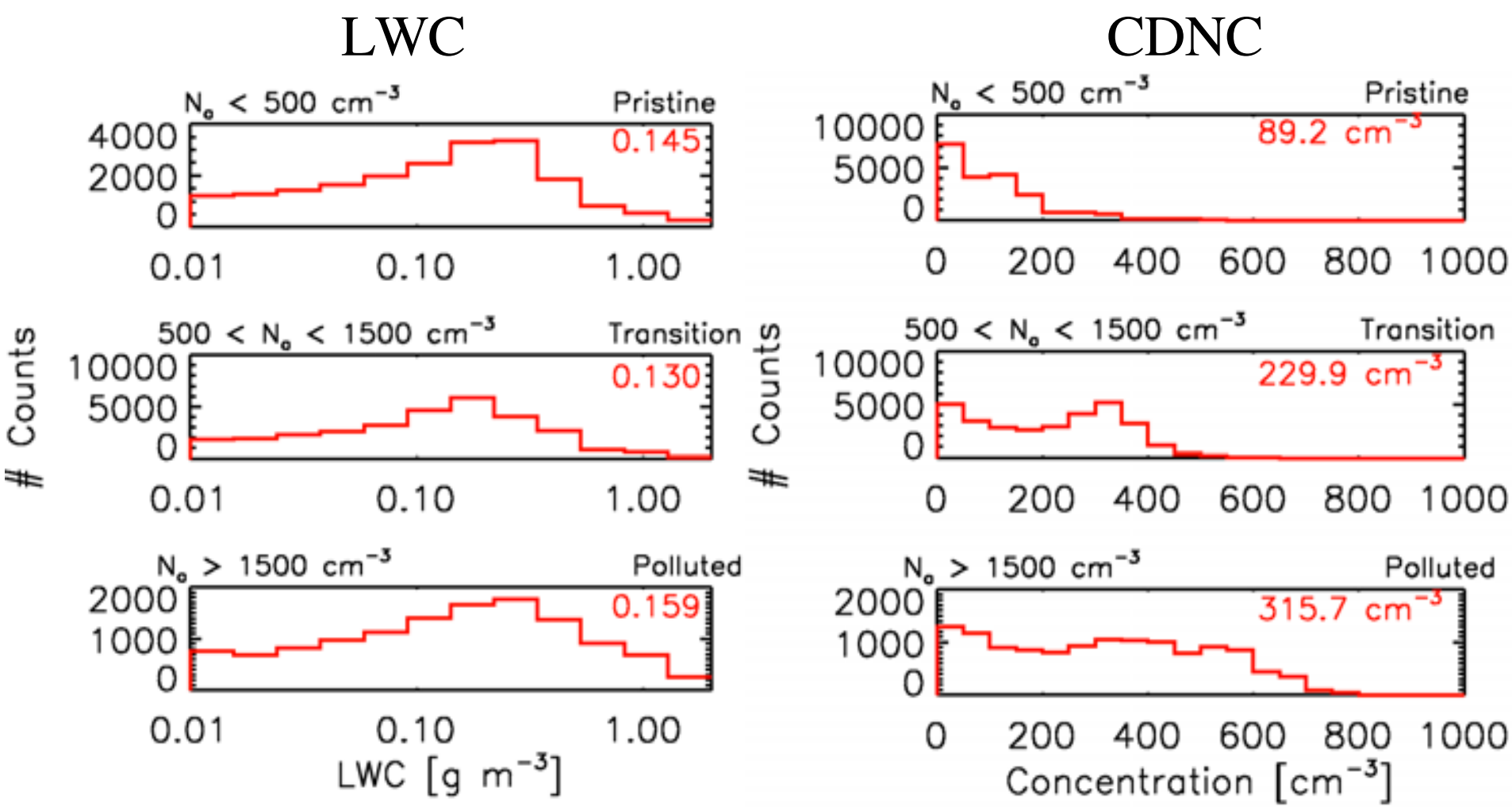
Uptake increases with increasing instability

Uptake increases with increasing liquid water content

PRISTINE *vs*. POLLUTED CLOUDS IN INDOEX

In-situ aircraft measurements during cross-Equatorial transects

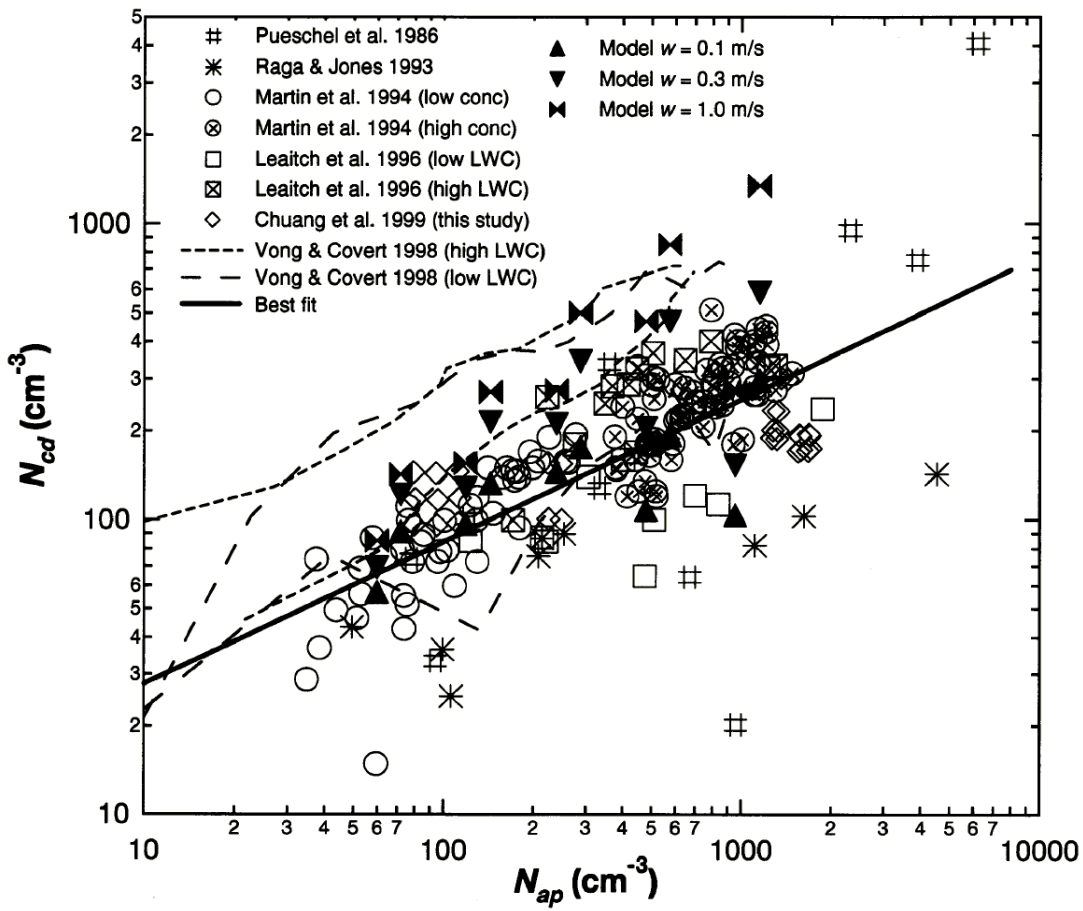
Classified by concentration of aerosol particles



Heymsfield and McFarquhar, JGR, 2001

CLOUD DROP NUMBER CONCENTRATION

Dependence on accumulation-mode aerosol particle concentration

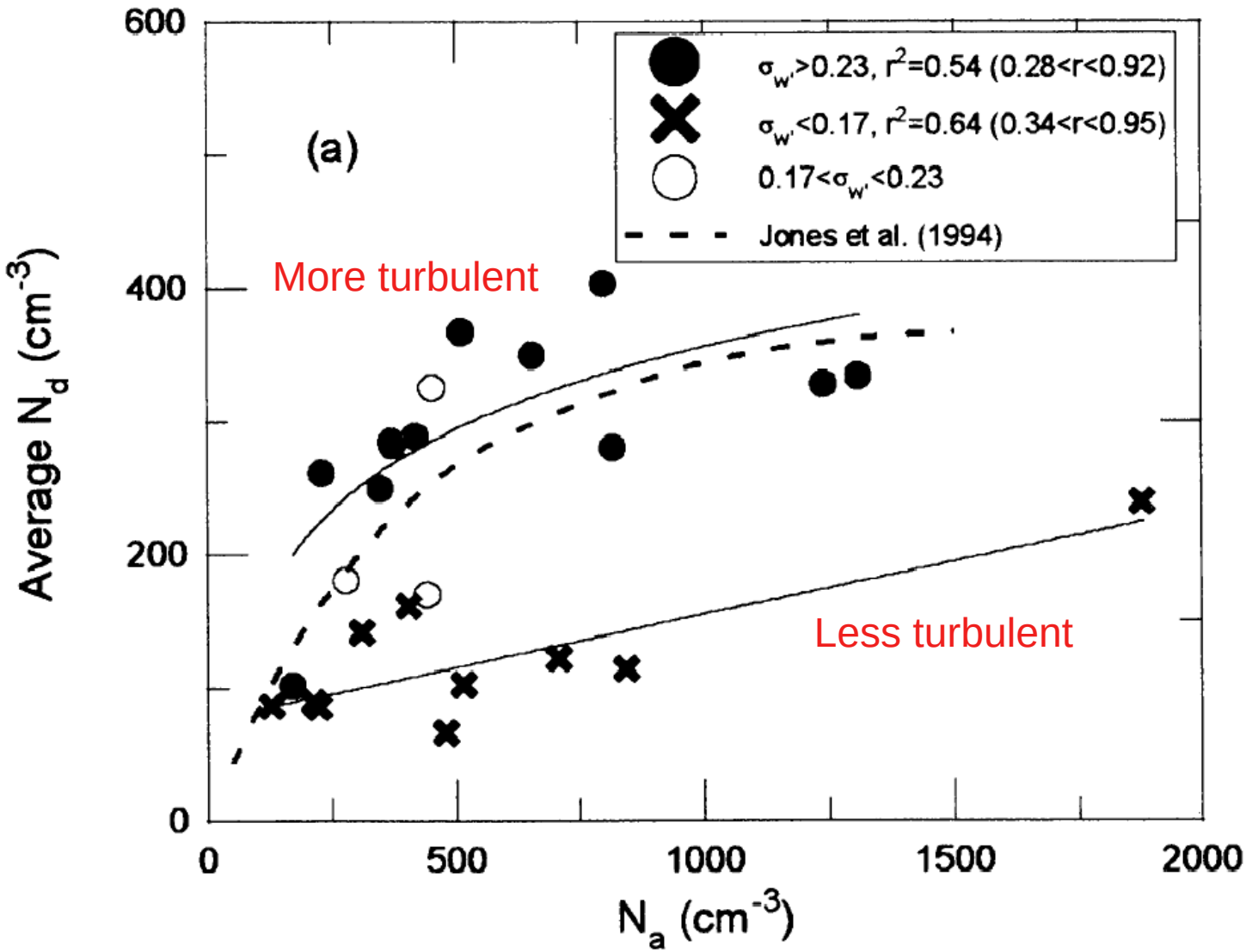


Chuang et al., 2000

N_{cd} increases with increasing N_{ap}, but scatter at any N_{ap} is comparable to increase in N_{cd} over range of N_{ap}.

CLOUD DROP NUMBER CONCENTRATION

Dependence on below-cloud aerosol particle concentration
Stratified by turbulent intensity

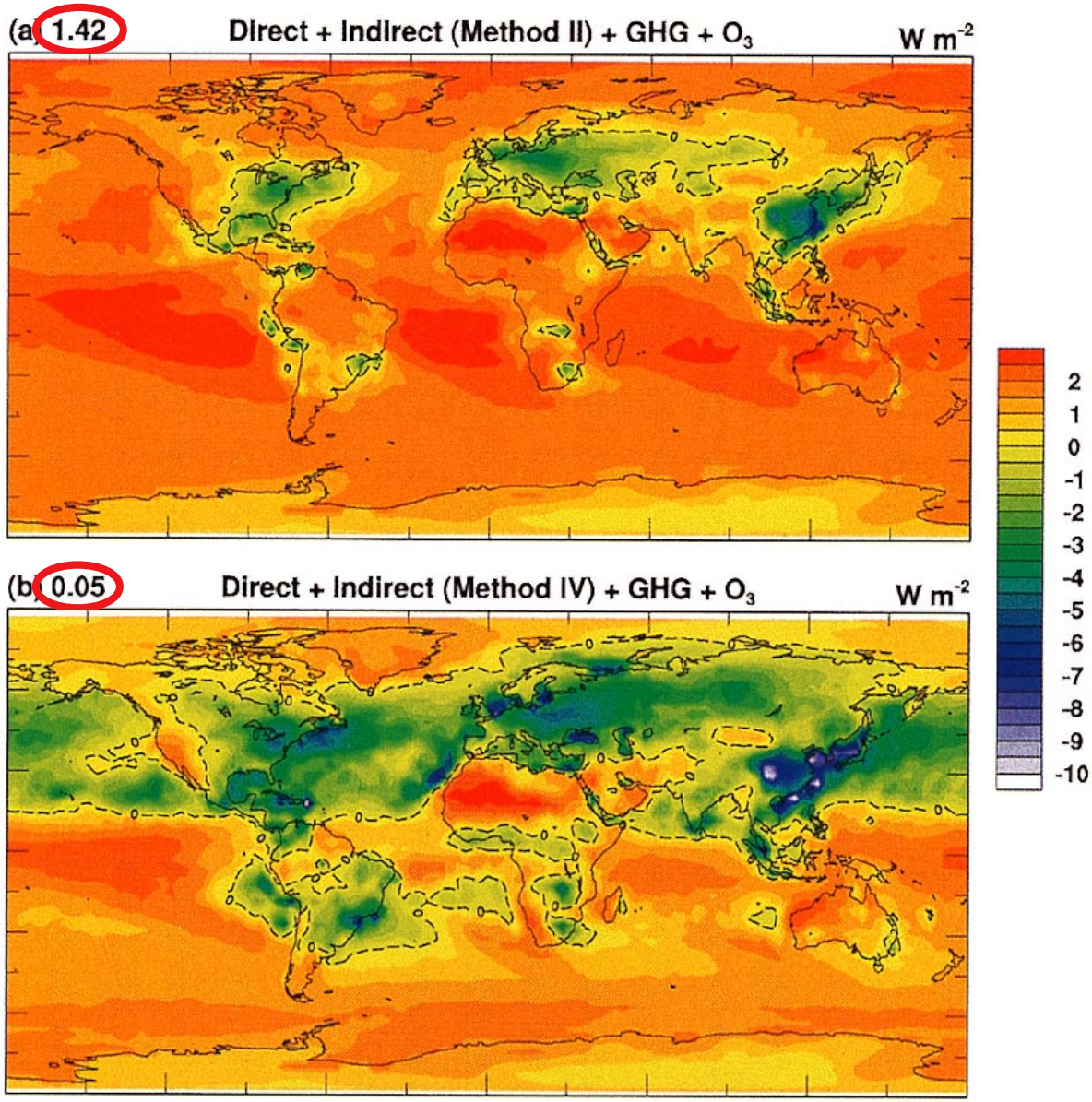


Leaitch et al., JGR, 1996

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.

ESTIMATES OF AEROSOL INDIRECT FORCING

Global-annual average; from IPCC (2001)

Table 6.6: *The global mean annual average aerosol indirect radiative forcing from different global studies. Letters P (prescribed) and C (computed) refer to off-line and on-line sulphate aerosol calculations, respectively. CCN and CDN stand for cloud condensation nuclei and cloud droplet number, respectively. In studies indicated by an asterisk, the estimate in flux change due to the indirect effect of aerosols was computed as the difference in top of atmosphere fluxes between two distinct simulations and therefore does not represent a forcing in the strict sense (see text). When several simulations are performed in the same study, base indicates the baseline calculation, while the range of estimates is given in parenthesis.*

Reference	Aerosol Type	Forcing estimate (Wm^{-2})				Remarks
		First effect	Second effect	Both effects		
Boucher and Rodhe (1994)*	Sulphate			-0.65 to -1.35	P	Uses 3 relationships between sulphate mass and CCN/CDN concentrations.
Chuang *et al.* (1994)	Sulphate	-0.47			C	Includes a parametrization of cloud nucleation processes.
Jones *et al.* (1994)	Sulphate	-1.3			P	Uses a relationship between aerosol and droplet number concentrations.
Boucher and Lohmann (1995)	Sulphate	-0.5 to -1.4			P	LMD GCM — Uses 4 different relationships between sulphate mass and CCN/CDN concentrations (A, B, C, and D).
Boucher and Lohmann (1995)	Sulphate	-0.45 to -1.5			P	ECHAM
Jones and Slingo (1996)	Sulphate	-0.3 to -1.5			P	Uses 2 different sulphate distributions. Follows Jones *et al.* (1994), Hegg (1994), Boucher and Lohmann (1995) D .
Kogan *et al.* (1996) Kogan *et al.* (1997)	Sulphate	-1.1				Uses a cloud climatology rather than GCM-simulated clouds.
Chuang *et al.* (1997)	Sulphate	-0.4 to -1.6			C	Includes a parametrization of cloud nucleation processes. Uses a mixture of pre-existing aerosols.
Feichter *et al.* (1997)	Sulphate	-0.76			C	Uses Boucher and Lohmann (1995) A relationship.

cont'd

ESTIMATES OF AEROSOL INDIRECT FORCING

Global-annual average; from IPCC (2001), *cont'd*

Reference	Aerosol Type	Forcing estimate (Wm^{-2}) First effect	Second effect	Both effects		Remarks
Jones and Slingo (1997)	Sulphate	-0.55 to -1.50			P	Uses 2 different versions of the Hadley Centre model.
Lohmann and Feichter (1997)*	Sulphate	-1		-1.4 to -4.8	C	Uses Boucher and Lohmann (1995) A relationship.
Rotstayn (1999)*	Sulphate	base -1.2 (-1.1 to -1.7)	base -1.0 (-0.4 to -1.0)	base -2.1 (-1.6 to -3.2)	P	Includes a (small) long-wave radiative forcing.
Jones *et al.* (1999)* [a]	Sulphate	-0.91	base -0.66	1.18	C	Includes a (small) long-wave radiative forcing. The two effects add non-linearly.
Kiehl *et al.* (2000)	Sulphate	-0.40 to -1.78			C	
Ghan *et al.* (2001a)*	Sulphate	~50% for base	~50% for base	base -1.7 (-1.6 to -3.2)	C	Includes a parametrization of cloud nucleation. Predicted aerosol size distribution.
Lohmann *et al.* (2000)*	Sulphate			base -0.4 (0 to -0.4)	C	Includes a parametrization of cloud nucleation processes.
	Carb.			base -0.9 (-0.9 to -1.3)	C	
	Sulphate and Carb.	40% for base	60% for base	base -1.1 (-1.1 to -1.9)	C	
Chuang *et al.* (2000b)	Sulphate	-0.30			C	Includes a parametrization of cloud nucleation processes. Includes the effect of BC absorption in clouds.
	Carb.	base -1.51 (-1.27 to -1.67)			C	
	Sulphate and Carb.	-1.85			C	

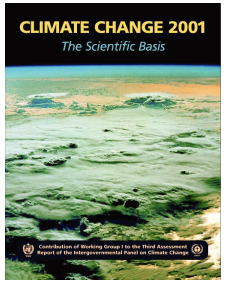
Estimates vary enormously within a given study (sensitivity to parameters) and between studies.

UNCERTAINTY BUDGET FOR *INDIRECT* FORCING BY INDUSTRIAL AEROSOLS

Quantity	Central Value	2/3 Uncertainty Range	Uncertainty Factor
Background N_d for Northern Hemisphere marine (cm^{-3})	140	66 to 214	**3.2**
Perturbed N_d for Northern Hemisphere marine (cm^{-3})	217	124 to 310	**2.5**
Cloud mean liquid water content (LWC) ($g\ m^{-3}$)	0.225	0.125 to 0.325	2.6
Background sulfate concentration ($\mu g\ m^{-3}$)	1.5	0.85 to 2.15	**2.5**
Cloud layer thickness (m)	200	100 to 300	3.0
Perturbed sulfate concentration ($\mu g\ m^{-3}$)	3.6	2.4 to 4.8	**2.0**
Susceptible cloud fraction, f_c	0.24	0.19 to 0.29	1.5
Atmospheric transmission above cloud layer, T_a	0.92	0.78 to 1.00	1.3
Mean surface albedo	0.06	0.03 to 0.09	~~3.0~~ 1.1
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

The greatest uncertainties are in aerosol and cloud microphysics properties, such as dependence of cloud drop concentration on ***aerosol composition, loading, and microphysical properties.***



These uncertainties are not well quantified.

ISSUES IN DETERMINING AEROSOL INDIRECT FORCING

1. Enhancement in ***aerosol particle concentration*** (and 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.

These requirements can be met only by models . . .

Based on improved understanding and evaluated by comparison with observation:

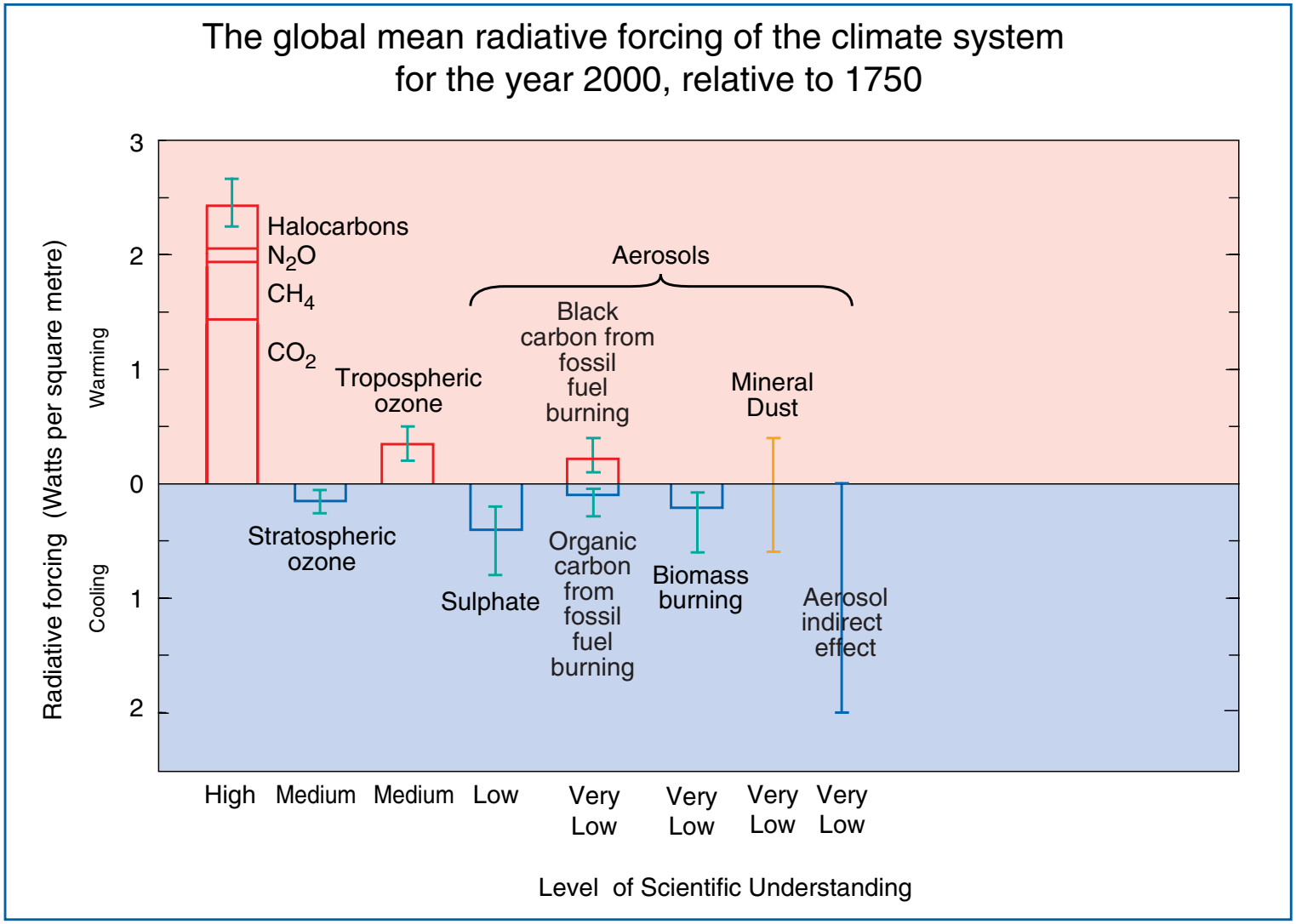
Emissions

Chemical transport and transformation

Cloud drop activation and microphysics

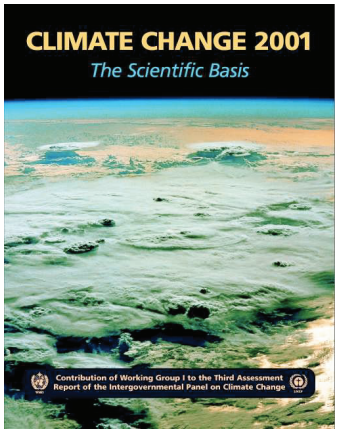
Radiation transfer

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

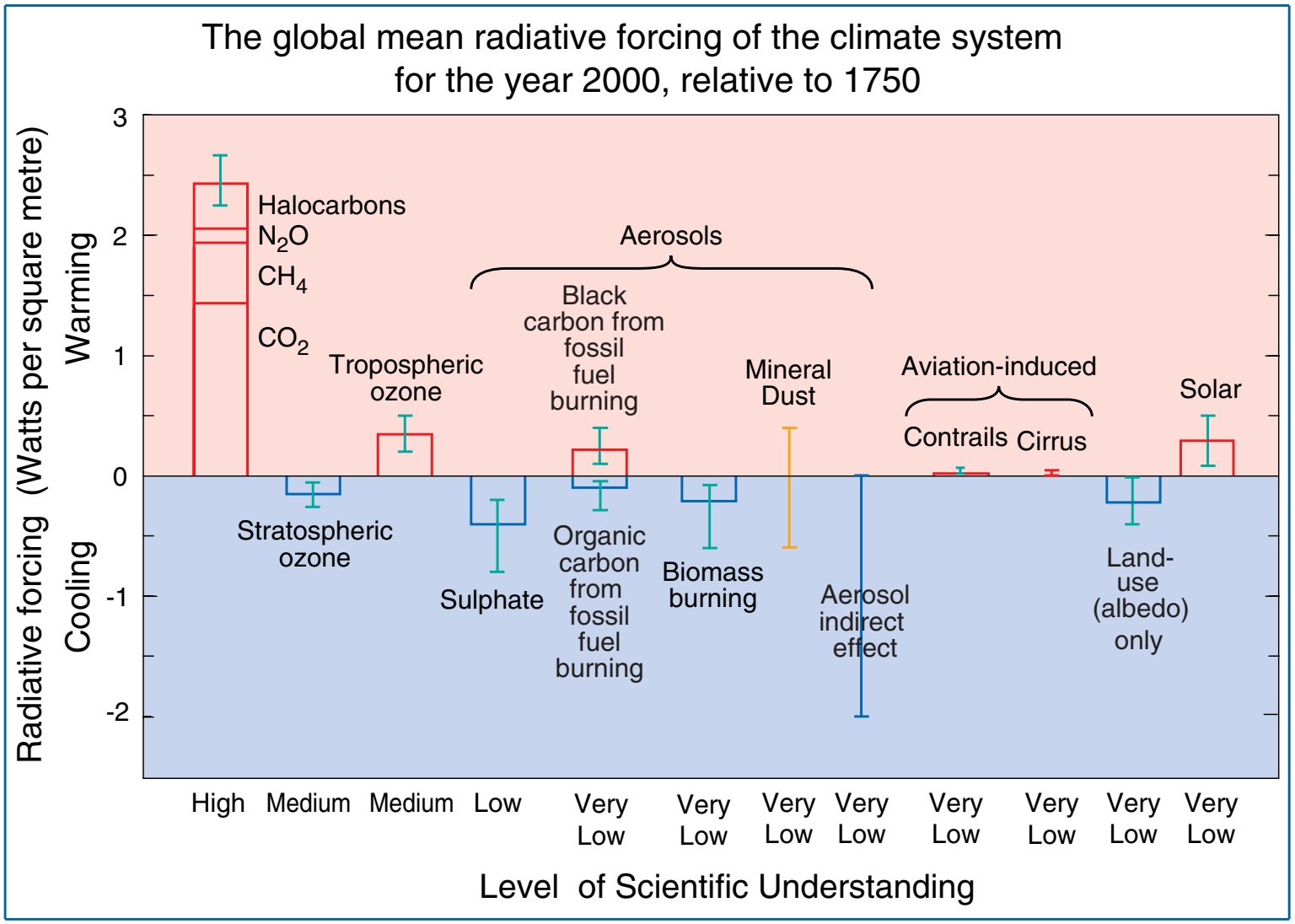


Summary for Policymakers

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



RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)



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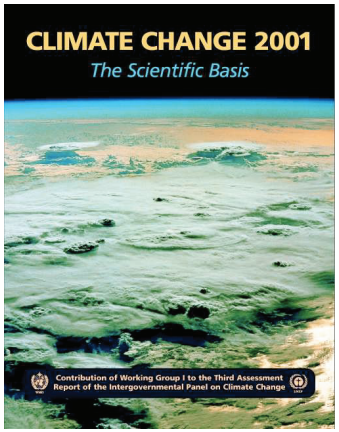


WHY SO LARGE UNCERTAINTY IN AEROSOL FORCING?

- ***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.

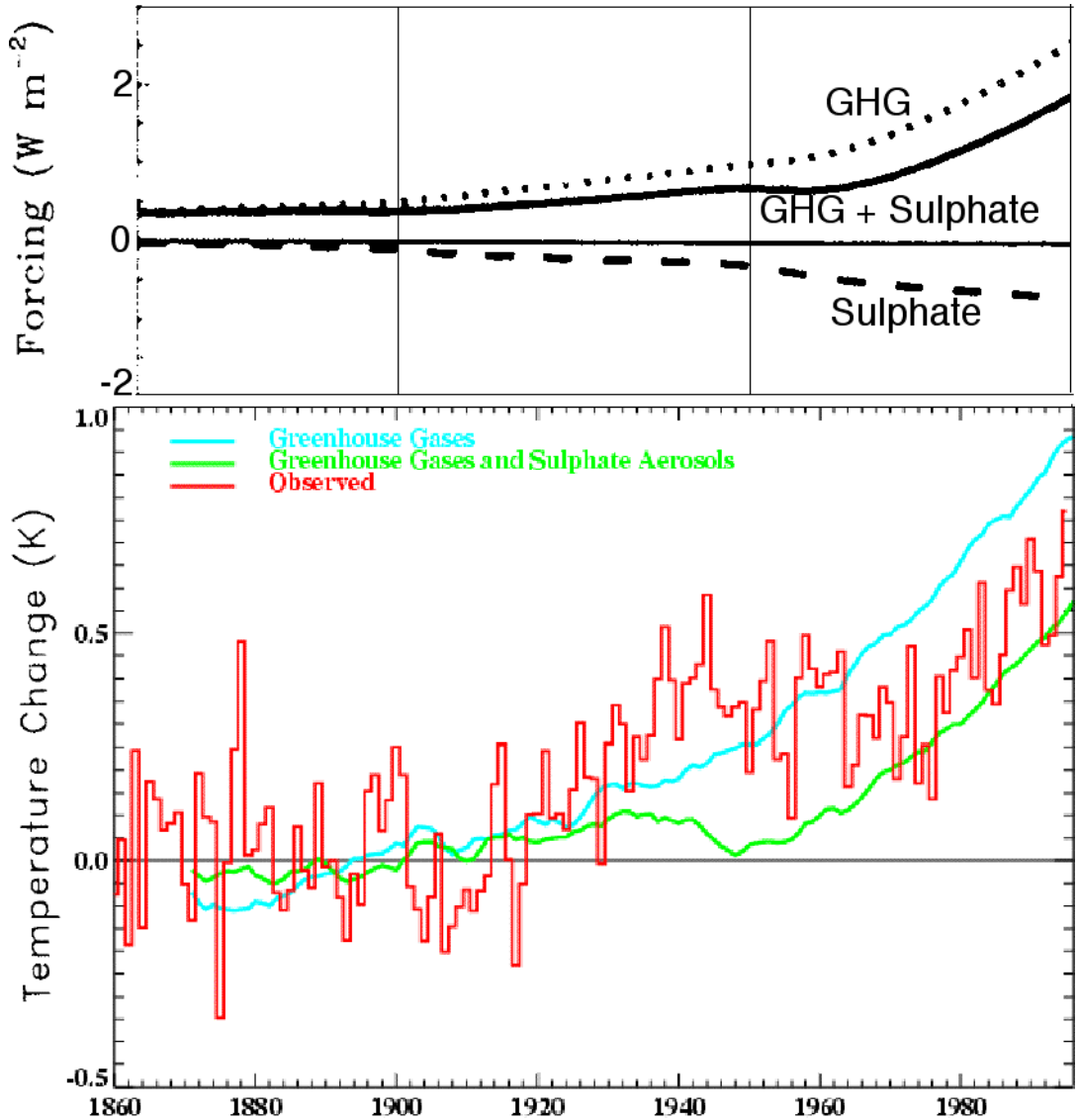
- ***Uncertainties in knowledge of atmospheric physics of aerosols***

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

REPRESENTING AEROSOL FORCING IN CLIMATE MODELS

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

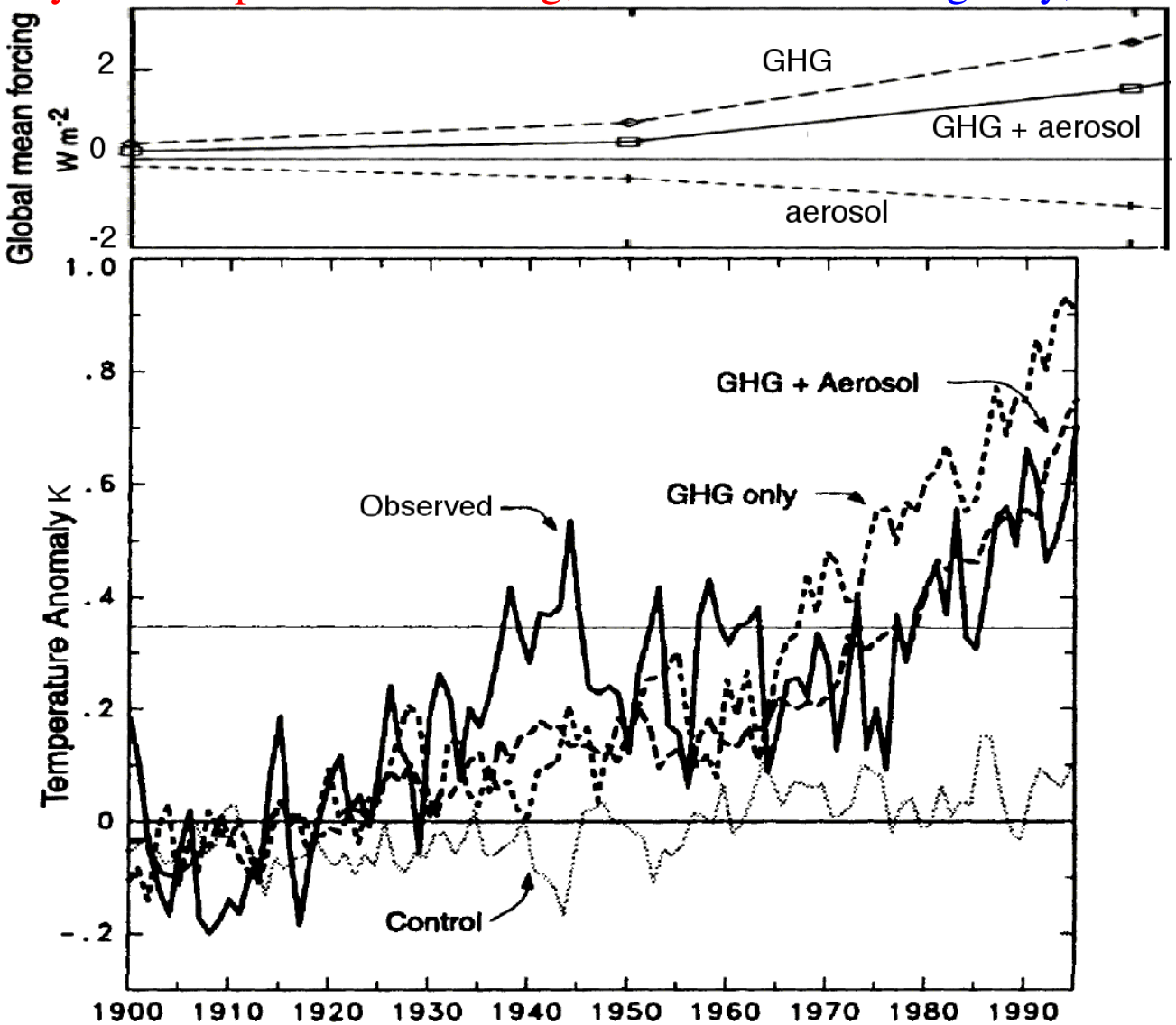
Model sensitivity = 2.5 K per CO_2 doubling; sulfate direct forcing only, -0.6 W m^{-2} (1990)



"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)

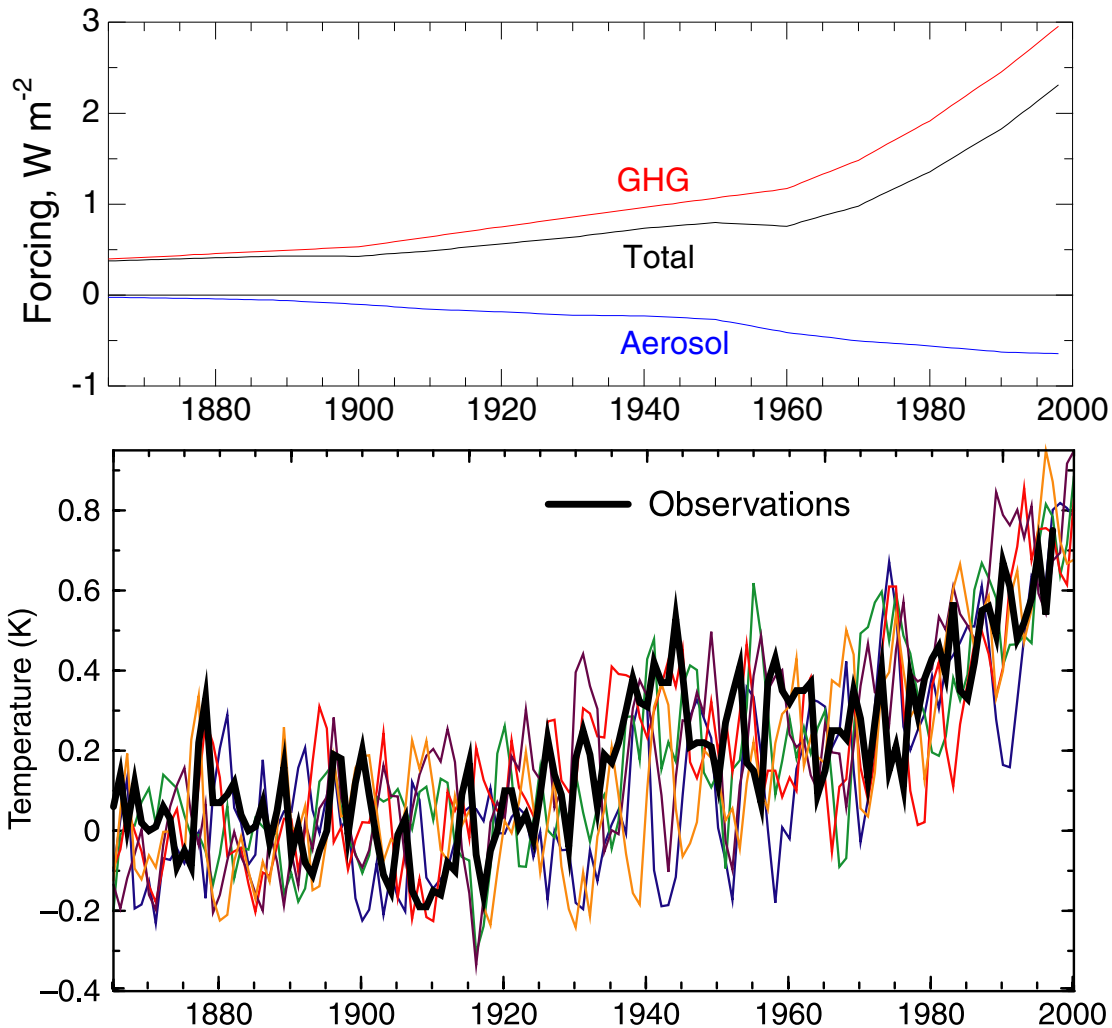
Model sensitivity = 3.5 K per CO_2 doubling; sulfate direct forcing only, -1.0 W m^{-2} (1990)



"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)

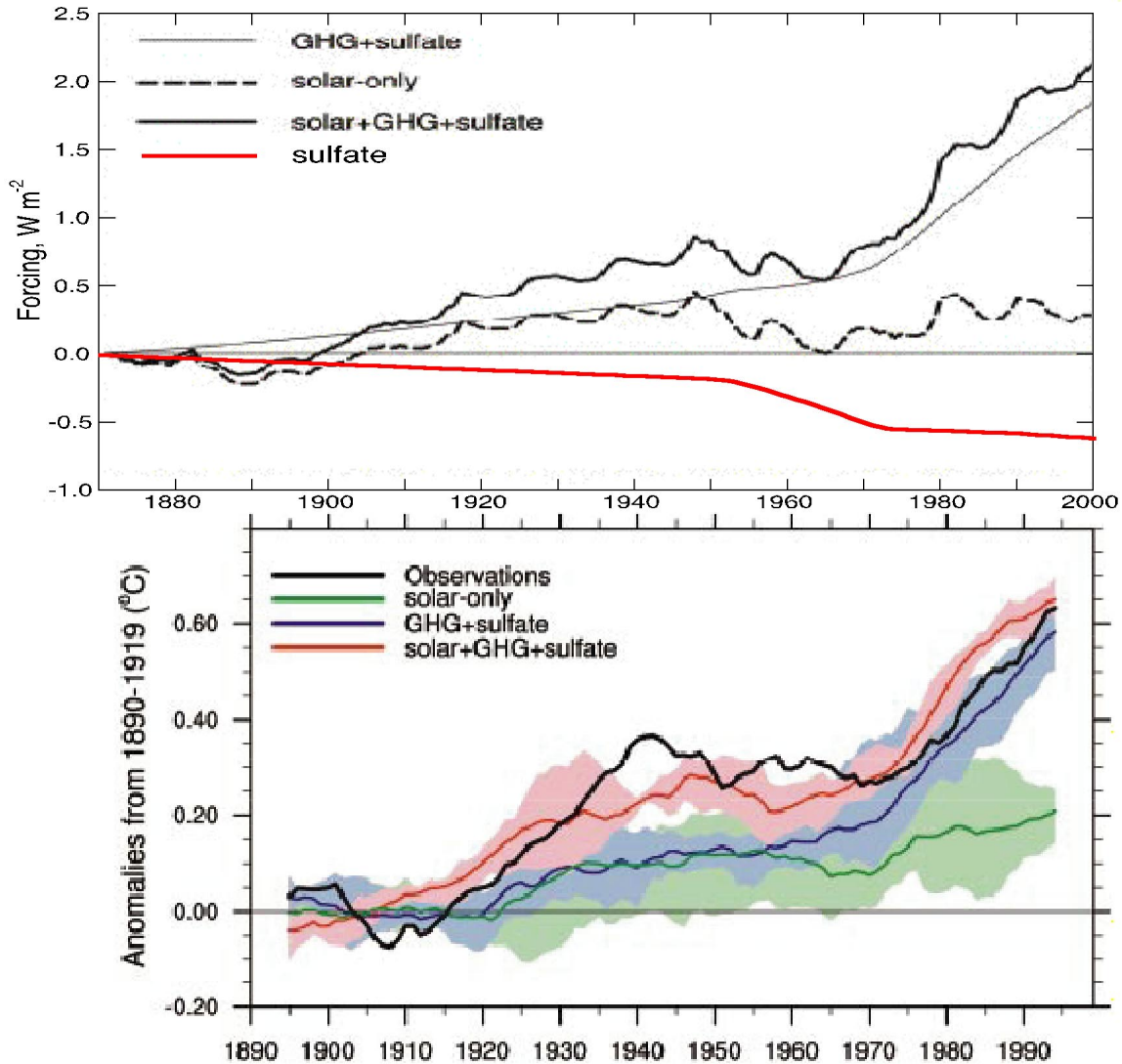
Model sensitivity = 3.4 K per CO_2 doubling; sulfate forcing, -0.62 W m^{-2} (1990)



"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)

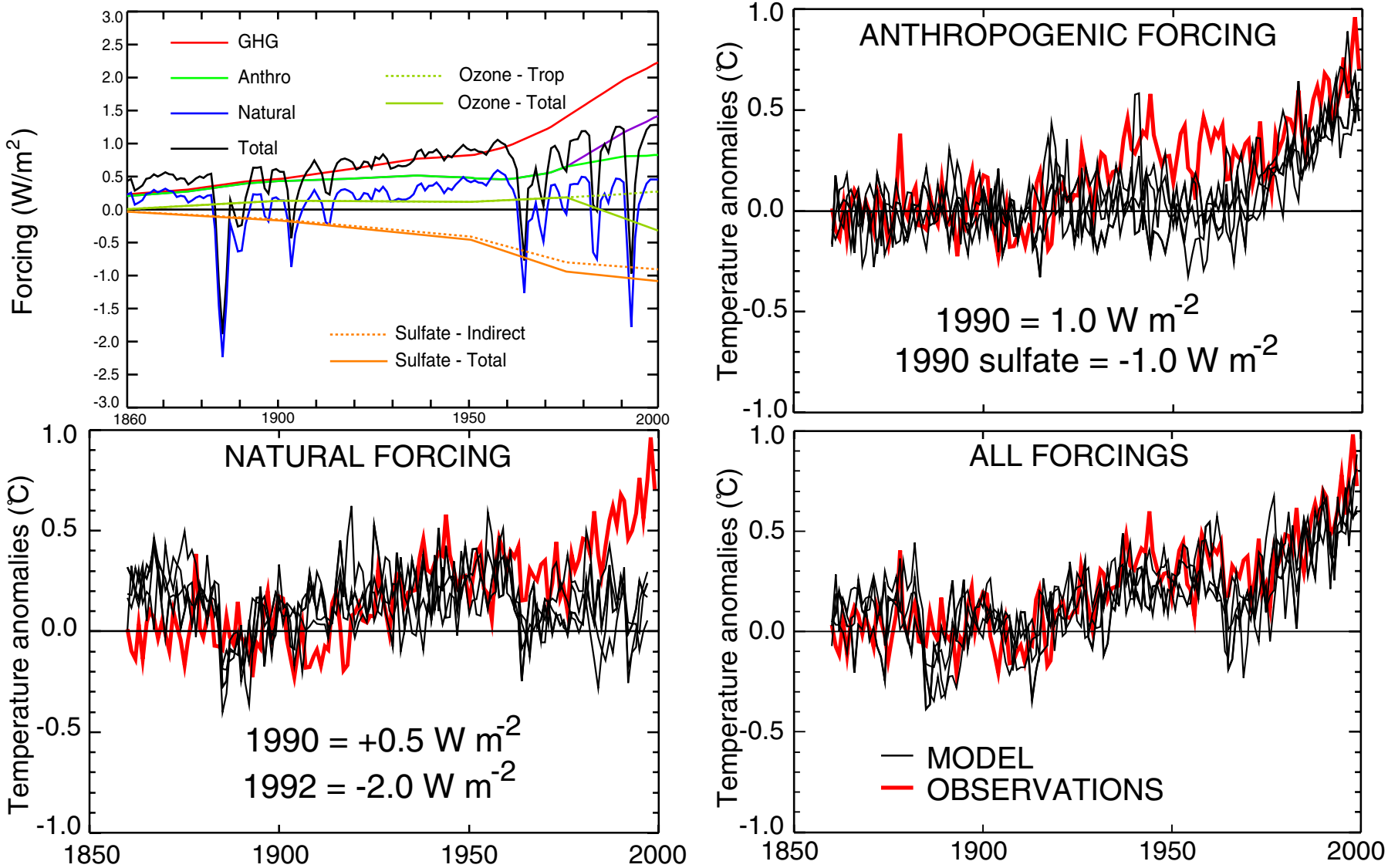
Model sensitivity = 2.18 K per CO_2 doubling; sulfate direct forcing only, -0.6 W m^{-2} (1990)



"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)



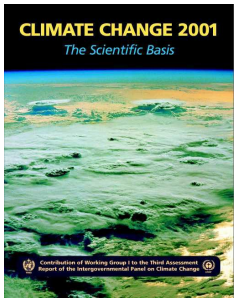
"The ALL ensemble ***captures the main features*** of global mean temperature changes observed since 1860." -- *Stott, Tett, Mitchell, et al., Science, 2000*

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



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IMPLICATIONS OF UNCERTAINTY IN AEROSOL FORCING

Present uncertainty in forcing of climate change, caused largely by uncertainty in forcing by aerosols, ***precludes evaluation of climate models and empirical determination of climate sensitivity***.

Uncertainty in aerosol forcing must be reduced ***at least three-fold*** (~0.5 W m^{-2}) for uncertainty in climate sensitivity to be meaningfully reduced and bounded.

Such a reduction in uncertainty in aerosol forcing presents an ***enormous challenge*** to the aerosol research community.

Atlanta, Georgia
AAAR 04

Thank You

Stephen E. Schwartz

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NATIONAL LABORATORY

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