AEROSOLS AND CLIMATE

THE SCIENTIFIC BASIS

Stephen E. Schwartz

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

BROOKHAVEN NATIONAL LABORATORY

Workshop on Climate Change Impacts and Integrated Assessment

Snowmass, Colorado

July 30 - August 8, 2001

OUTLINE

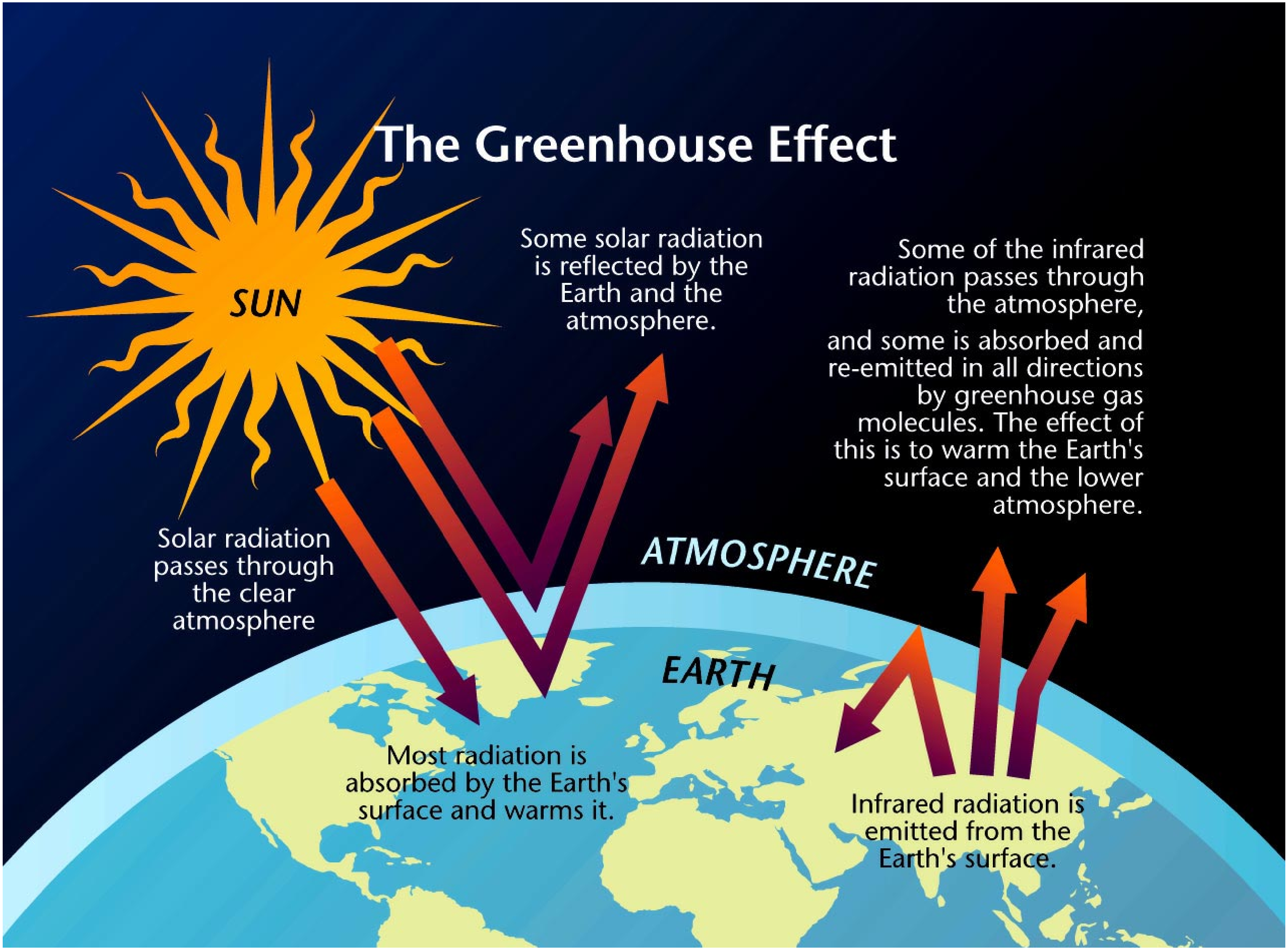
- Radiative forcing of climate change
- The role of aerosols
- Estimates of aerosol forcing and uncertainties
- Implications of these uncertainties

REMARKS BY THE PRESIDENT ON GLOBAL CLIMATE CHANGE

June 11, 2001

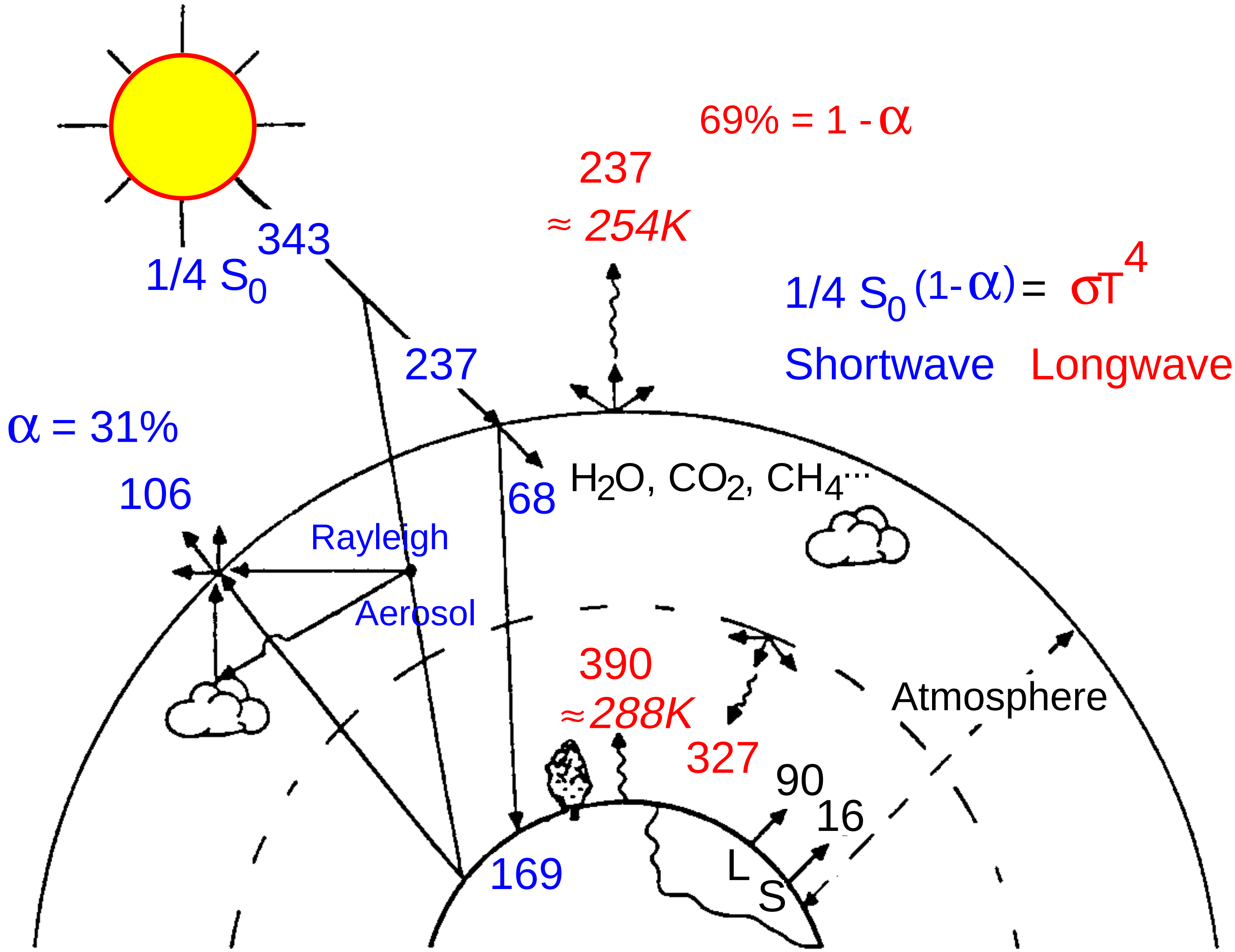
“Our useful efforts to reduce sulfur emissions may have actually increased warming, because ***sulfate particles*** reflect sunlight, bouncing it back into space.”

“Kyoto also failed to address two major pollutants that have an impact on warming: ***black soot*** and tropospheric ozone. Both are proven health hazards. Reducing both would not only address climate change, but also dramatically improve people's health.”


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

RADIATIVE FORCING

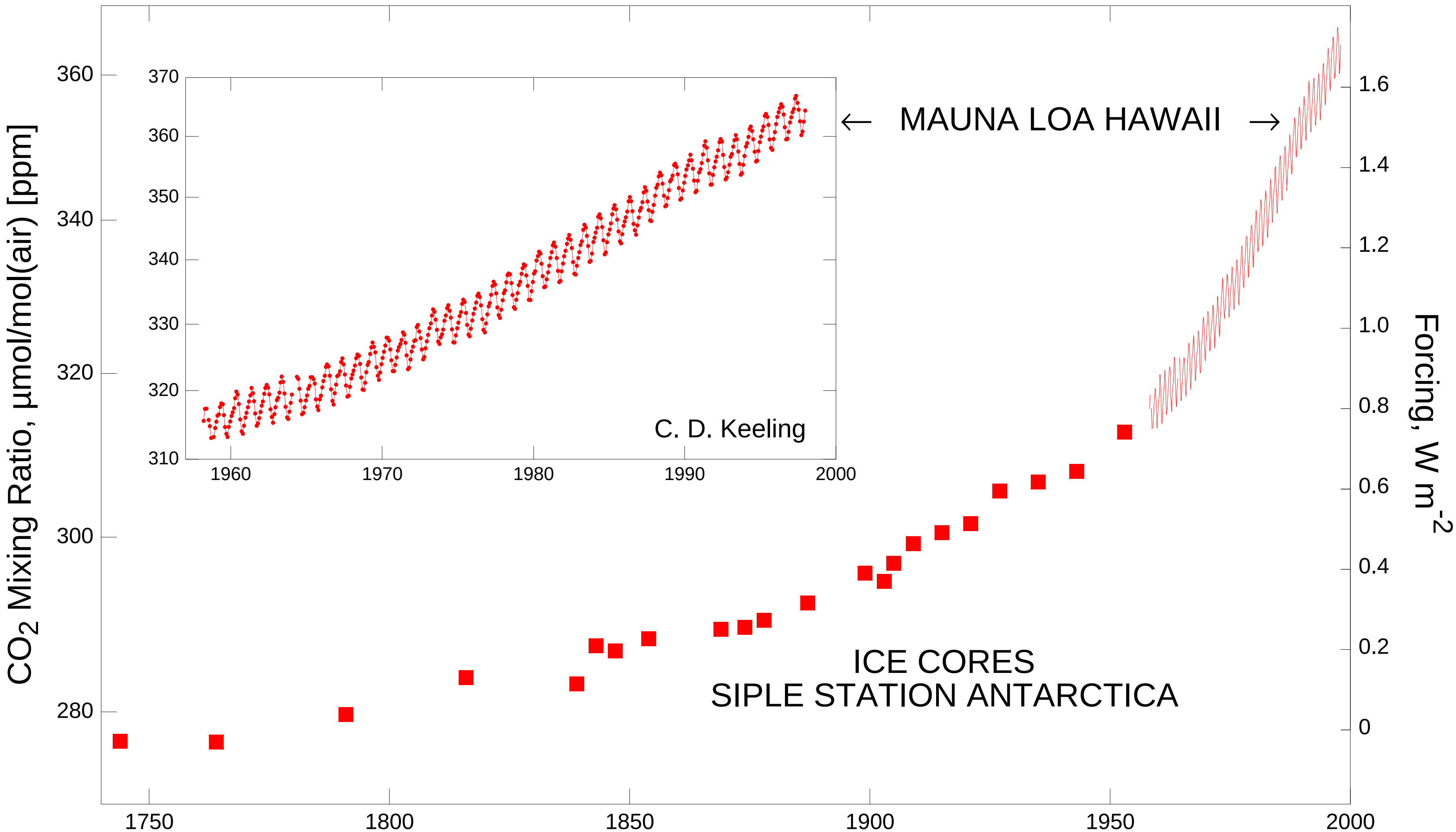
A ***change*** in a component of the Earth's radiation budget.

Working hypothesis:

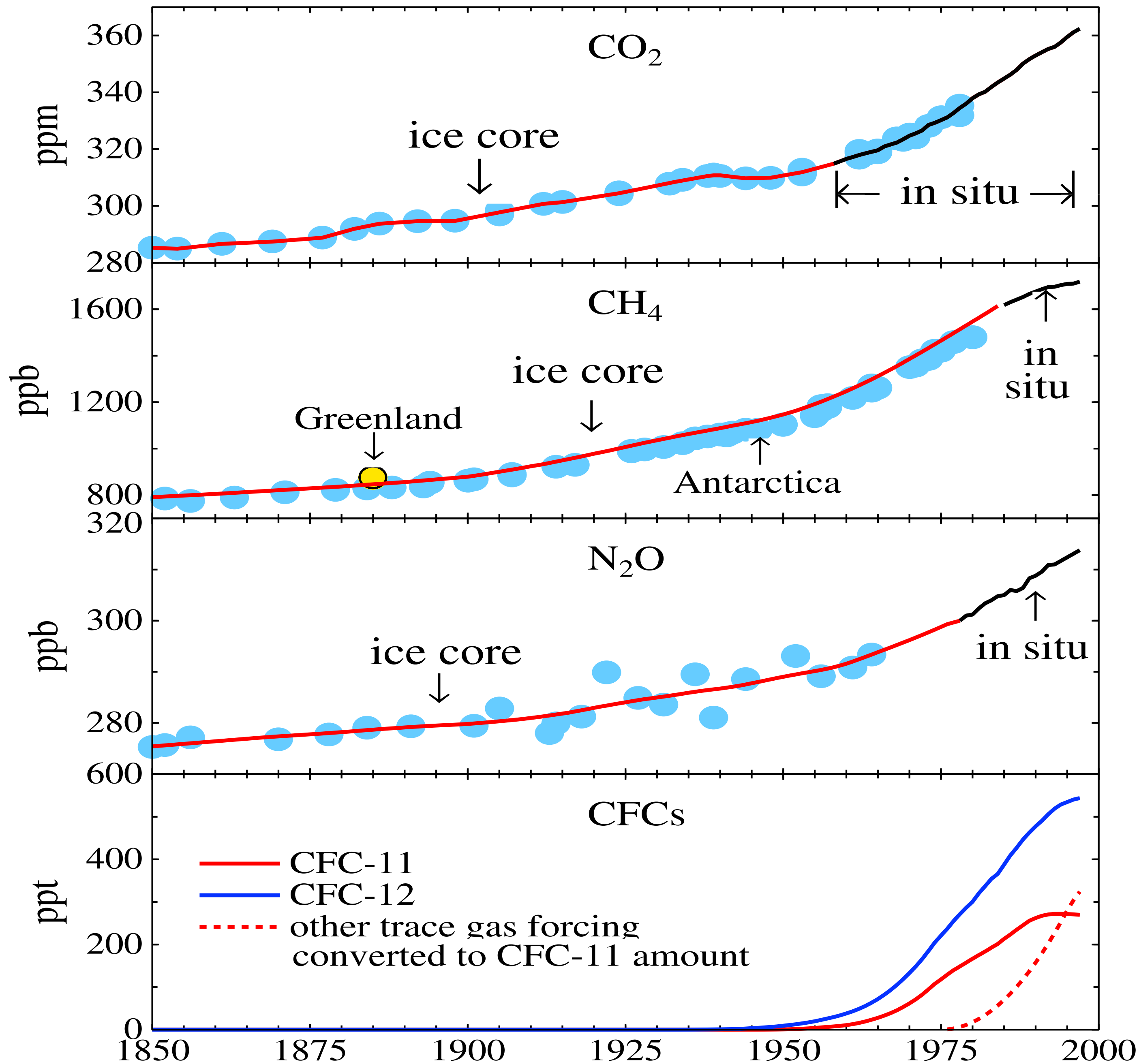
On a global basis radiative forcings are additive and fungible.

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

GLOBAL CARBON DIOXIDE OVER THE INDUSTRIAL PERIOD

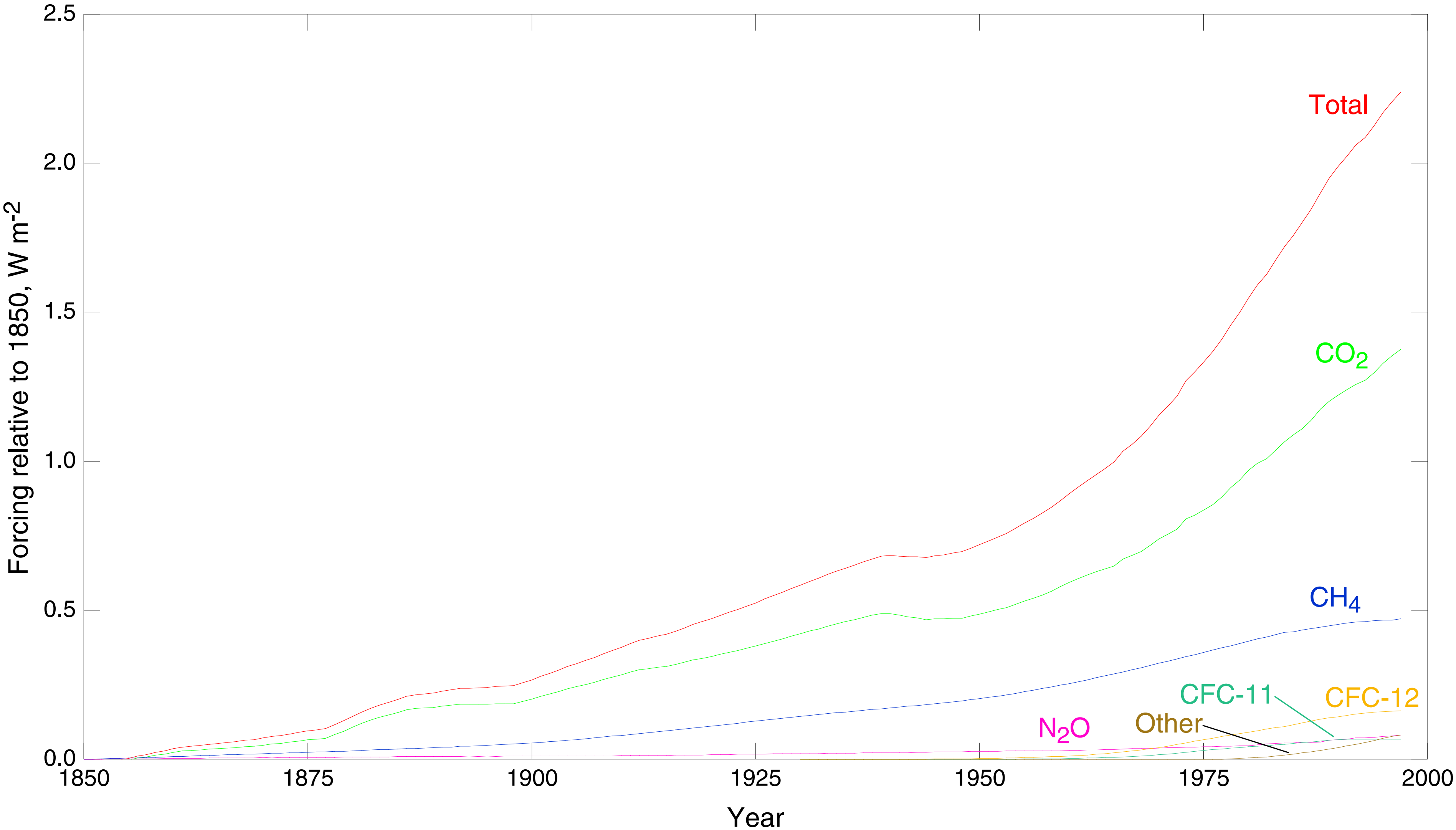


GREENHOUSE GAS MIXING RATIOS OVER THE INDUSTRIAL PERIOD



Hansen *et al.*, PNAS. 1998

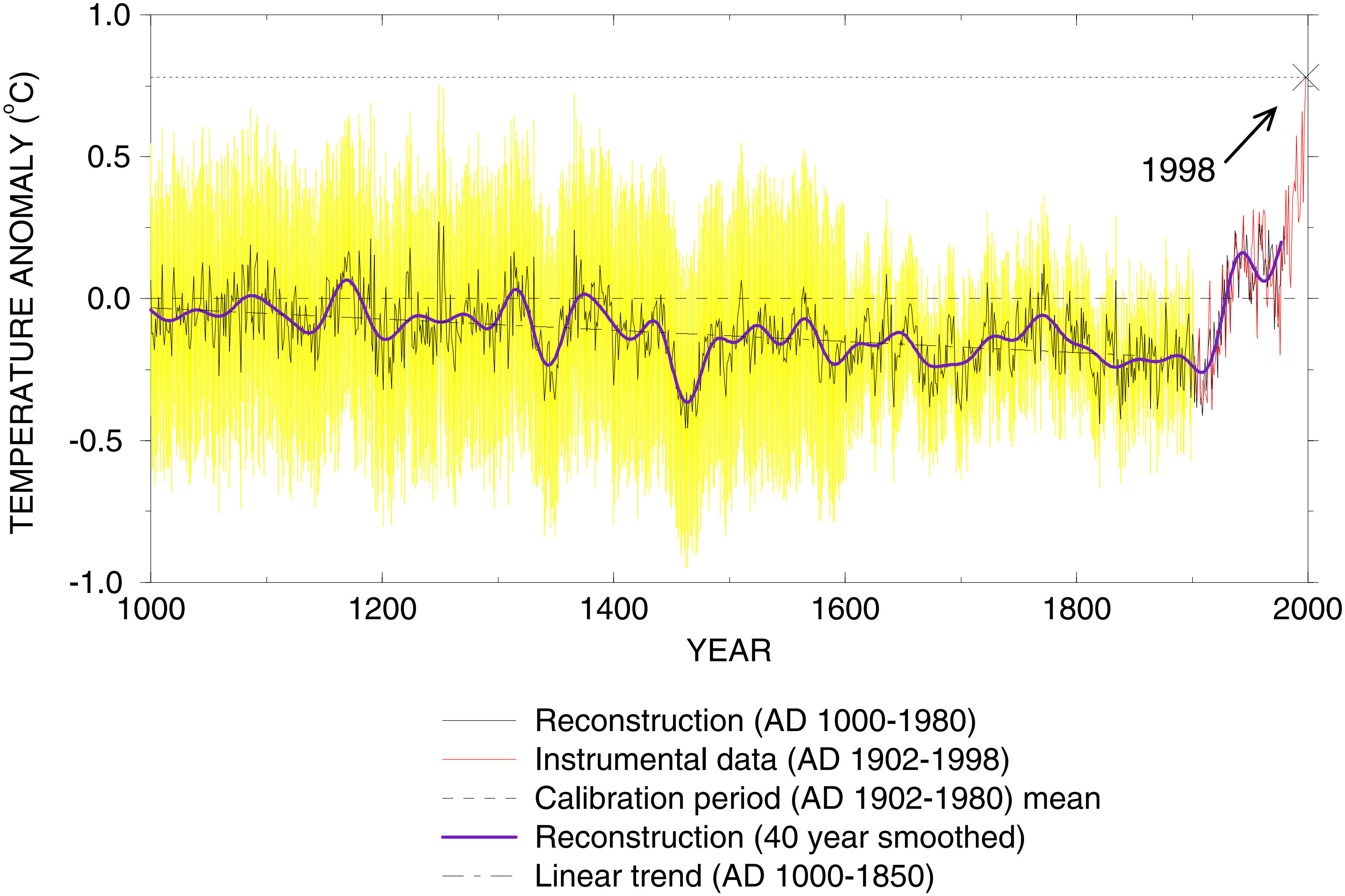
GREENHOUSE GAS FORCINGS OVER THE INDUSTRIAL PERIOD



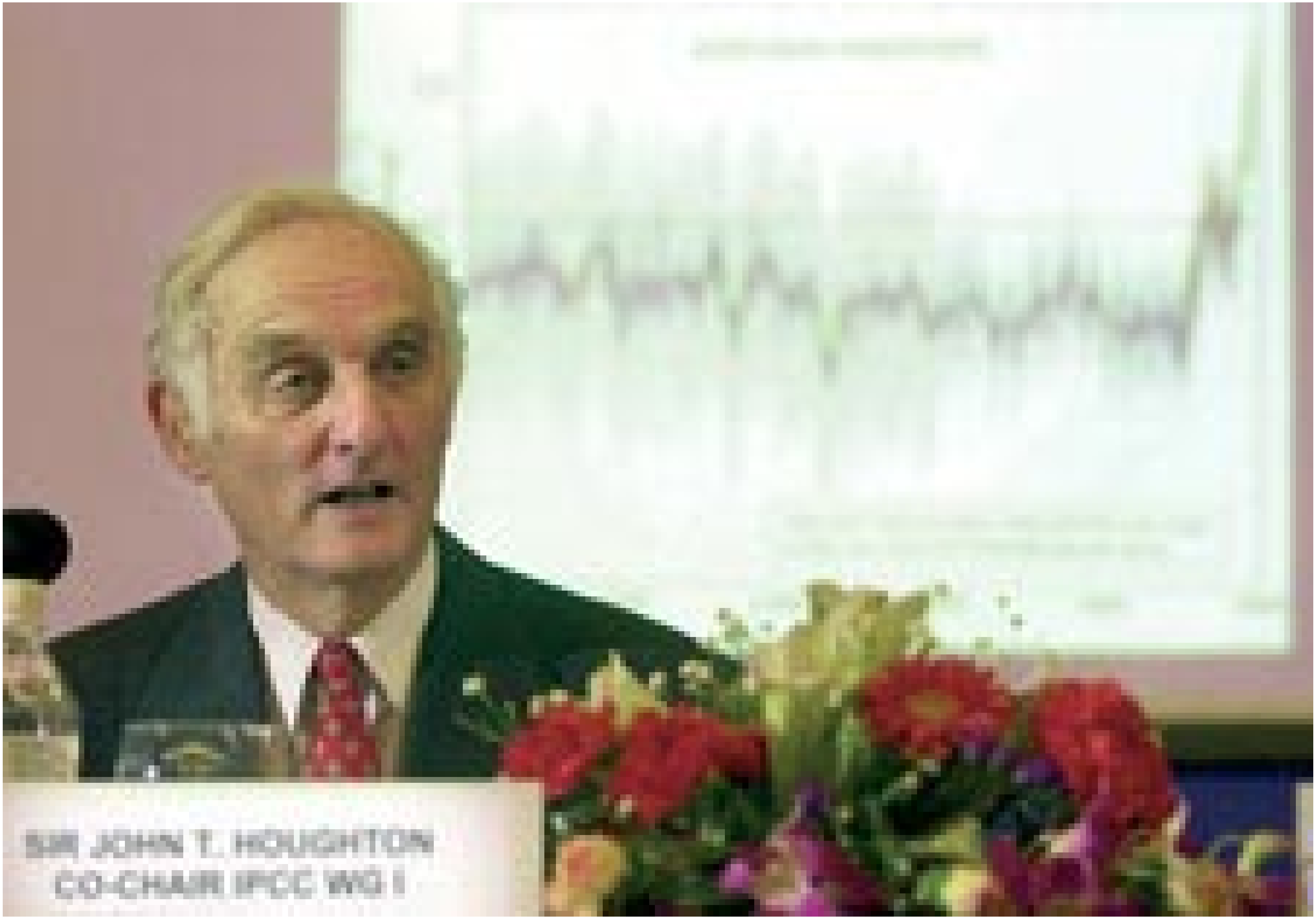
Data: GISS

NORTHERN HEMISPHERE TEMPERATURE TREND (1000-1998)

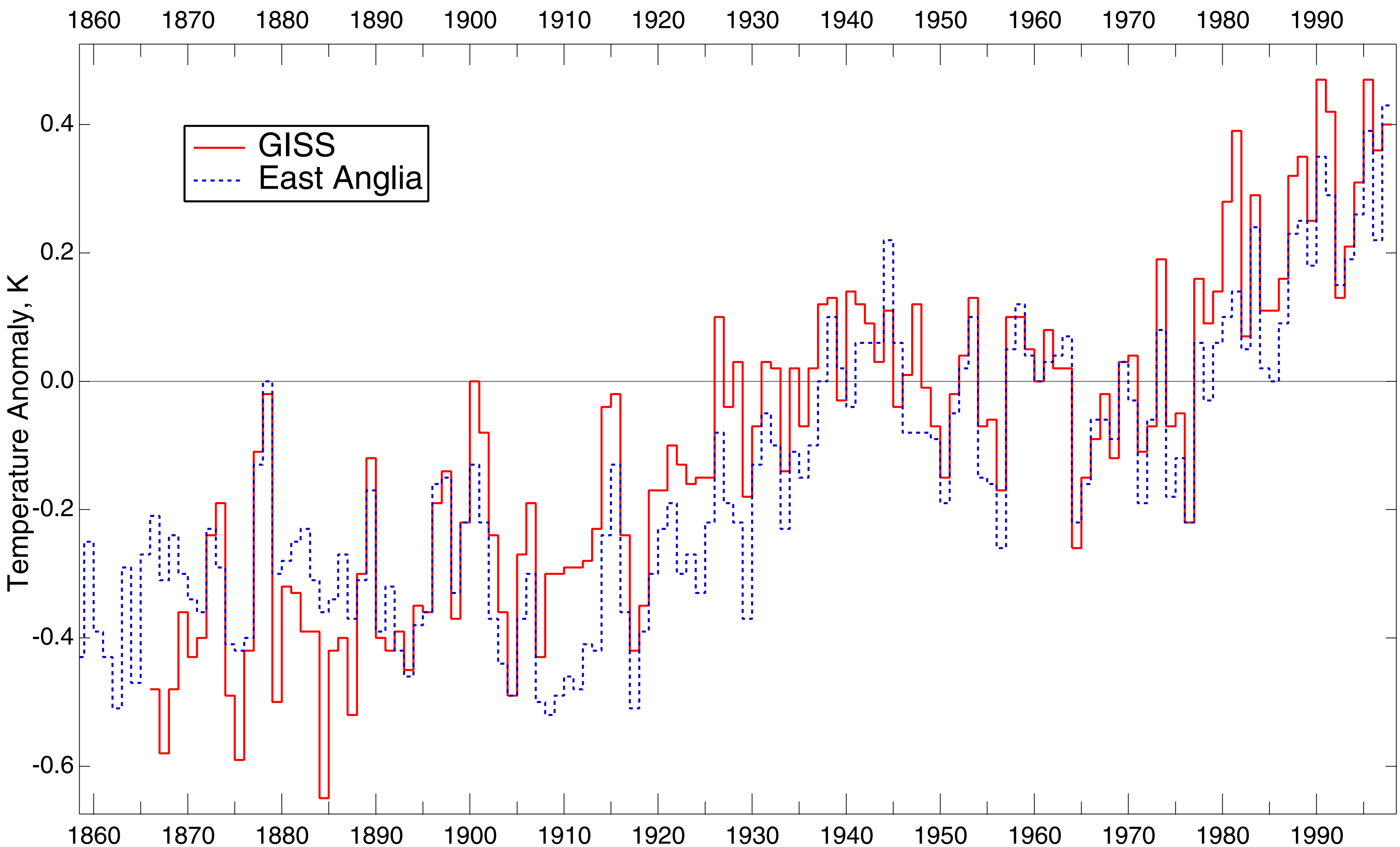
From tree-ring, coral, and ice-core proxy records
As calibrated by instrumental measurements



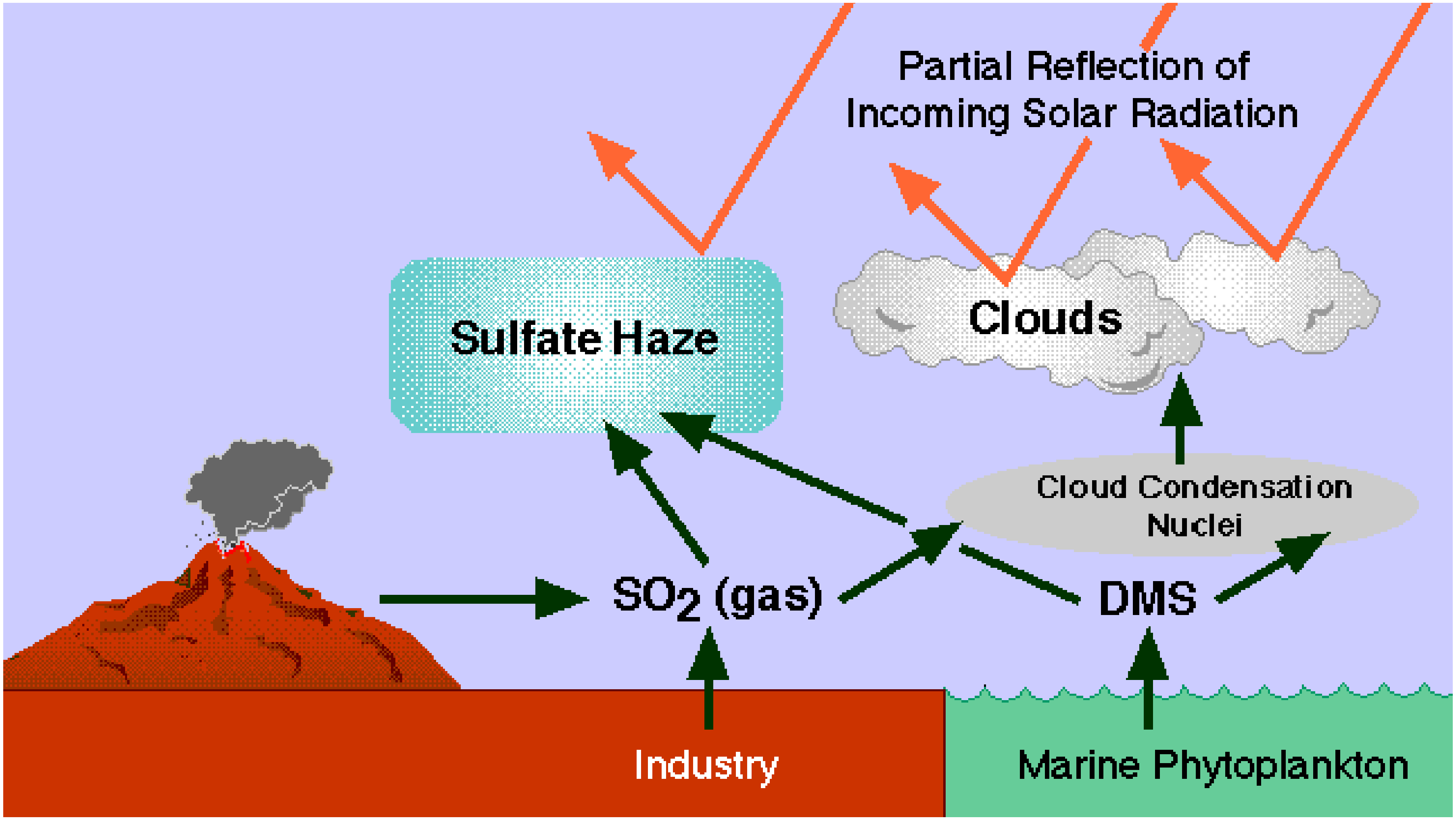
Mann et al., GRL, 1999


SIR JOHN T. HOUGHTON
CO-CHAIR IPCC WG I

GLOBAL TEMPERATURE TREND OVER THE INDUSTRIAL PERIOD



CLIMATE FORCING BY SULFATE AEROSOL



AEROSOL INFLUENCES ON RADIATION BUDGET AND CLIMATE

Direct Effect (Clear sky)

Light scattering -- Cooling influence

Light absorption -- Warming influence, depending on surface

Indirect Effects (Aerosols influence cloud properties)

More droplets -- Brighter clouds (Twomey)

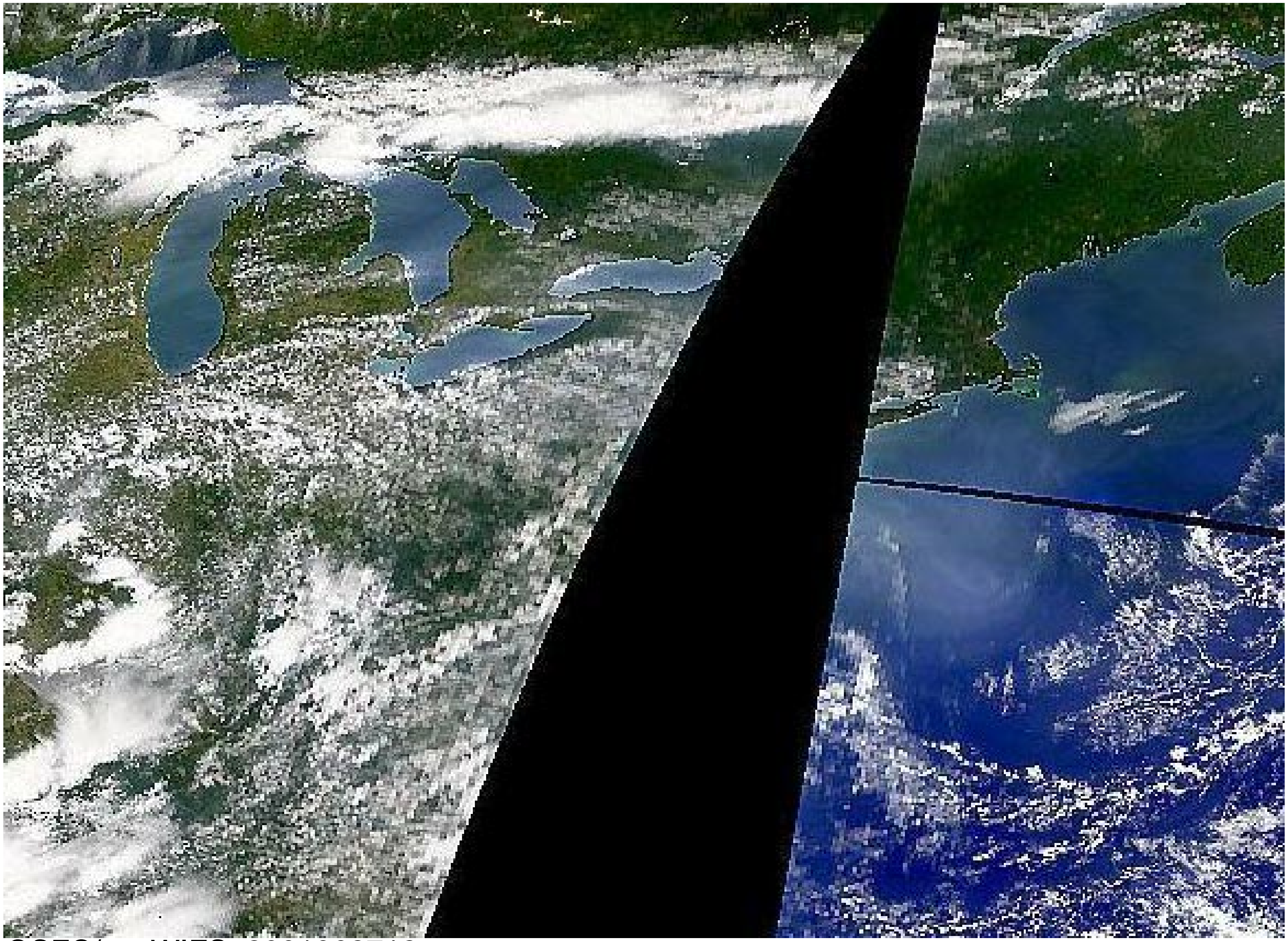
More droplets -- Enhanced cloud lifetime (Albrecht)

Semi-Direct Effect

Absorbing aerosol heats air and evaporates clouds

DIRECT EFFECT

SEAWIFS IMAGE OF NORTH AMERICAN AEROSOL

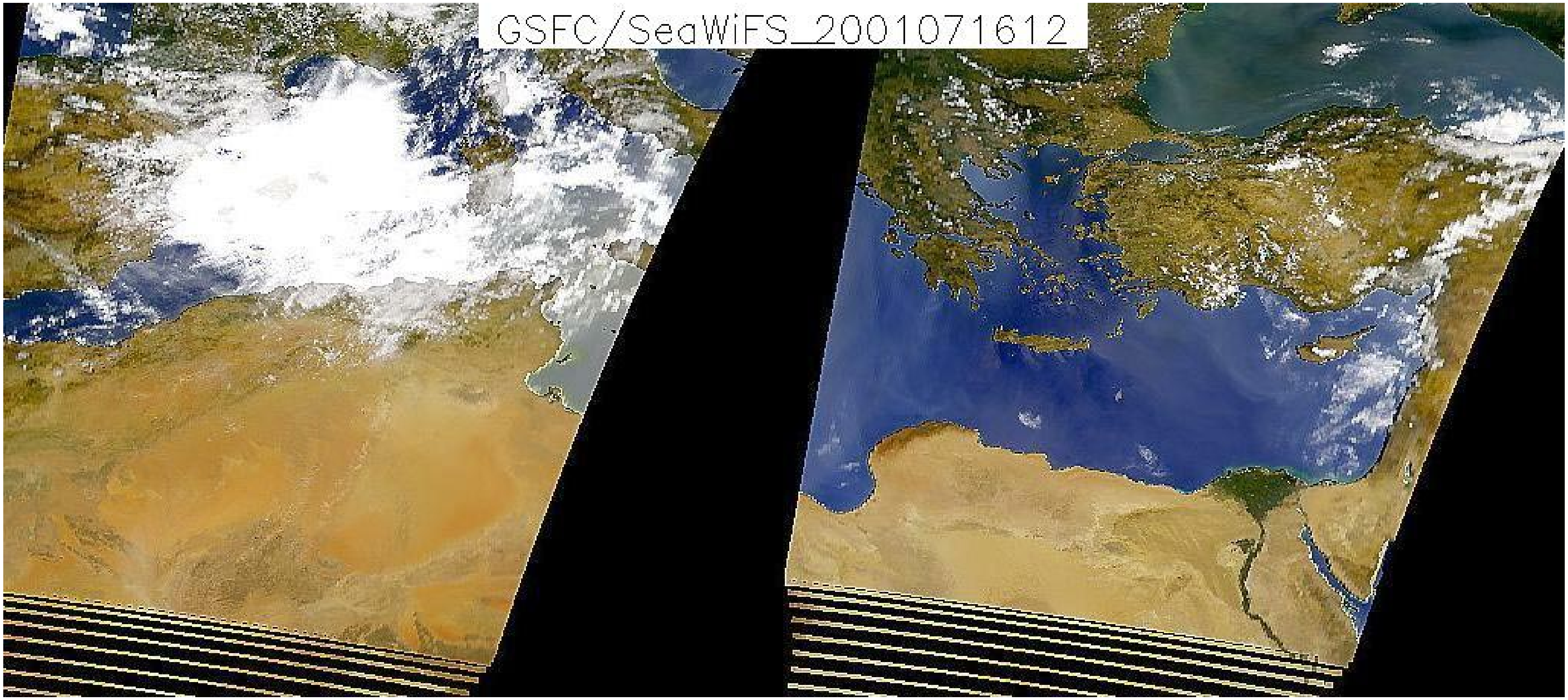


GSFC/seaWIFS_2001062712

Provided by the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE

http://www.nrlmry.navy.mil/aerosol/satellite/seawifs/conus/200106/2001062712_conus.jpg

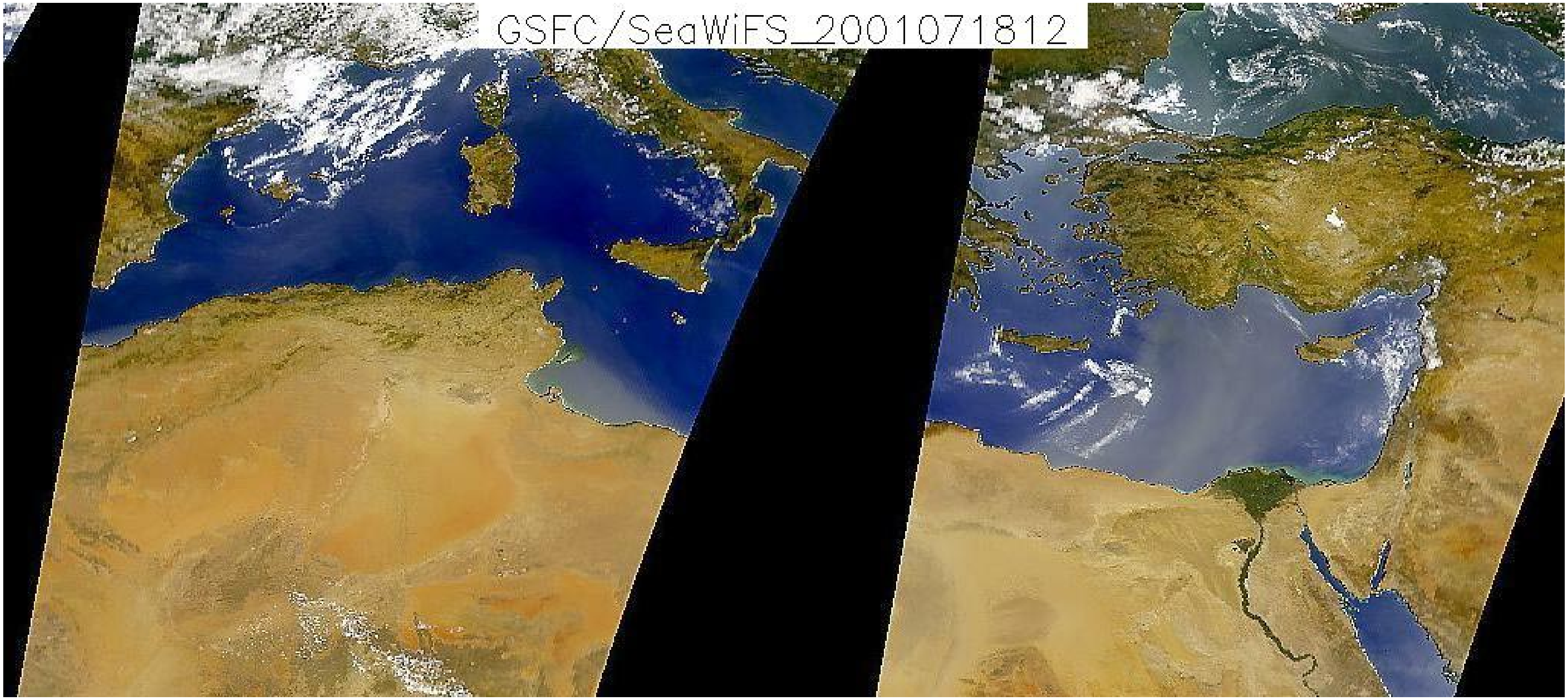
SEAWIFS IMAGE OF MEDITERRANEAN AEROSOL



Provided by the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE

http://www.nrlmry.navy.mil/aerosol/satellite/seawifs/med/200107/2001071612_med.jpg

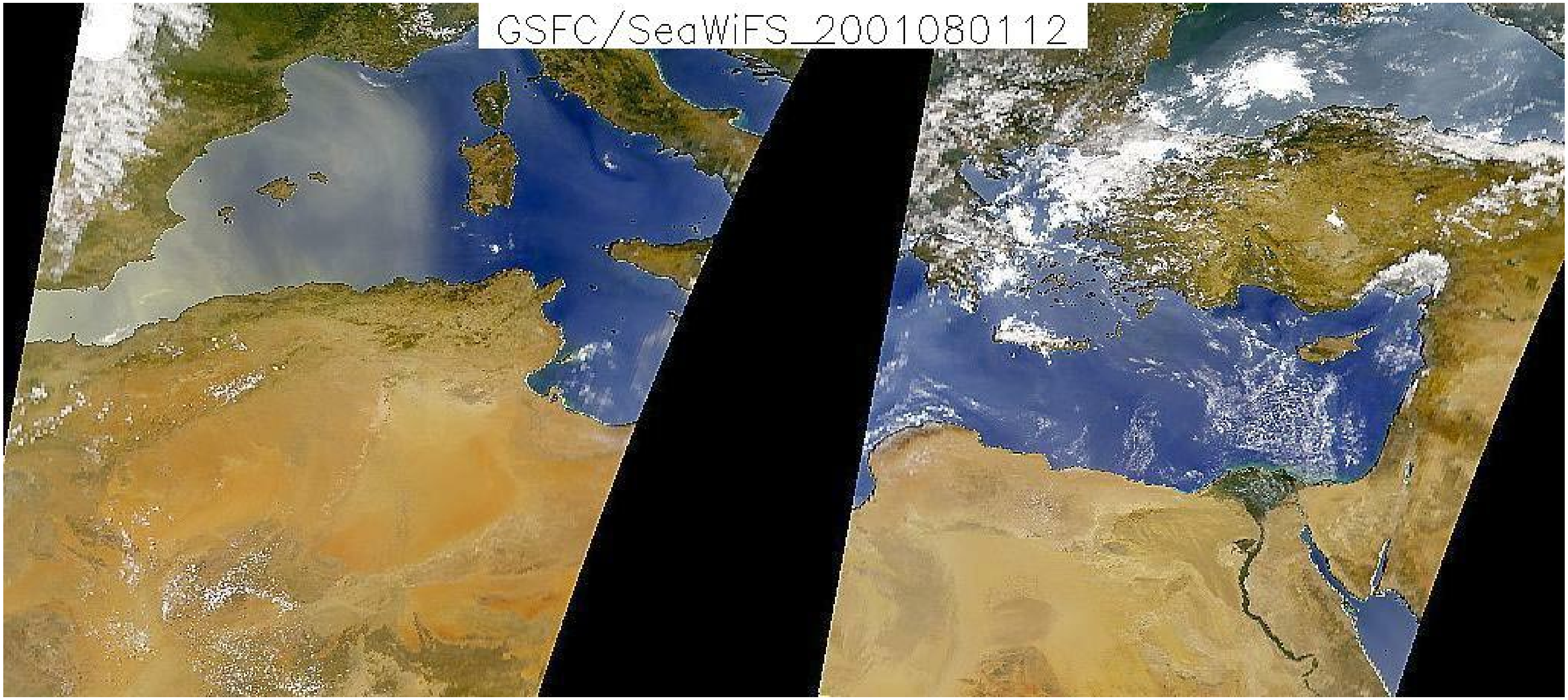
SEAWIFS IMAGE OF MEDITERRANEAN AEROSOL



Provided by the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE

http://www.nrlmry.navy.mil/aerosol/satellite/seawifs/med/200107/2001071812_med.jpg

SEAWIFS IMAGE OF MEDITERRANEAN AEROSOL



Provided by the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE

http://www.nrlmry.navy.mil/aerosol/satellite/seawifs/med/200108/2001080112_med.jpg

DIRECT RADIATIVE FORCING DUE TO ANTHROPOGENIC SULFATE AEROSOL

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

$\overline{\Delta F_R}$ 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

$\bar{\beta}$ 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-})$^{-1}$

$f(\mathrm{RH})$ 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-A_c	0.4	——	1.1
	T	0.76	——	1.15
	1-R_s	0.85	——	1.1
	$\overline{\beta}$	0.29	——	1.3
$\alpha^* = 8.5$ m^2 (g SO_4^{2-})$^{-1}$	$\alpha_{SO_4^{2-}}$	5	m^2 (g SO_4^{2-})$^{-1}$	**1.5**
	f(RH)	1.7	——	1.2
Column Burden 4 mg SO_4^{2-} m^{-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	—
Optical Depth = 0.03	$\overline{\Delta F_R}$	-1.1	W m^{-2}	2.4

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

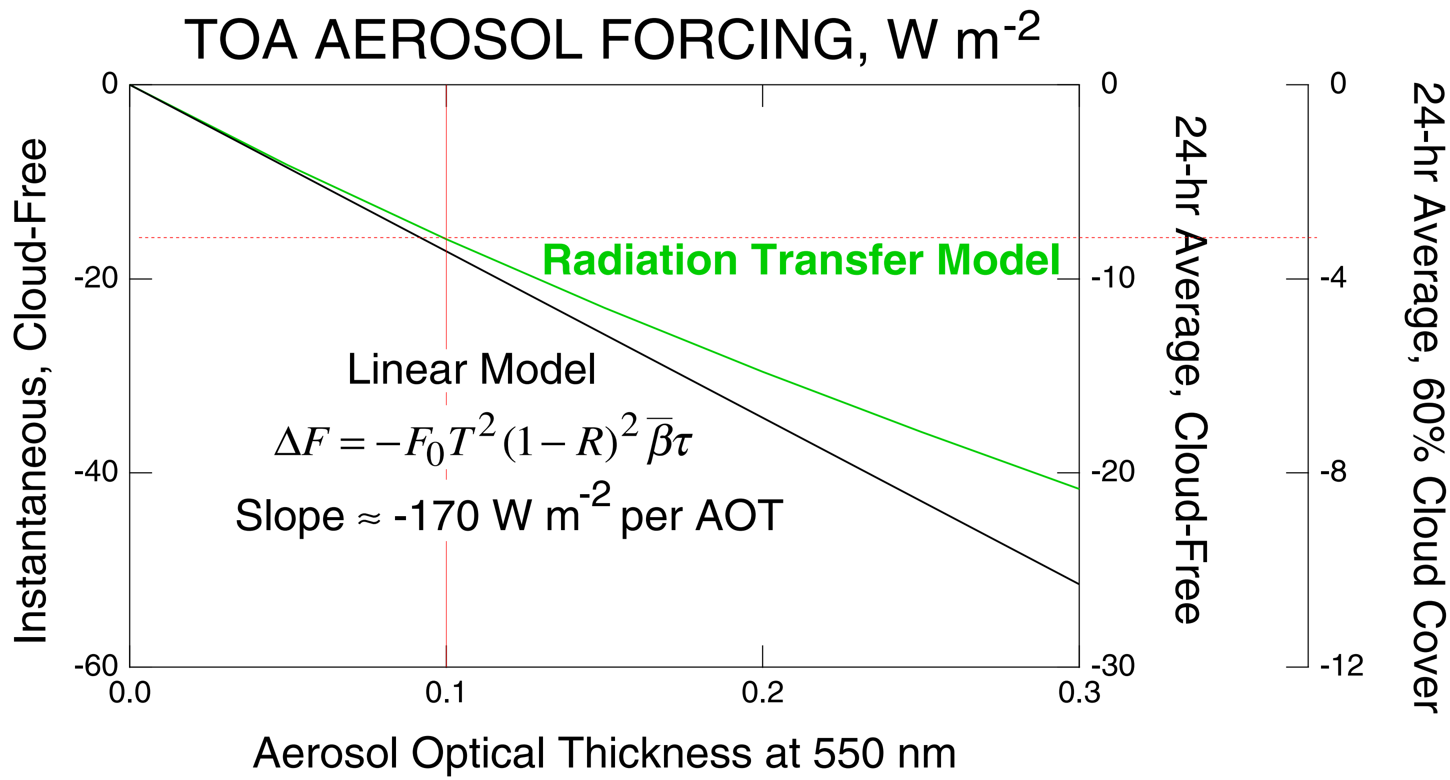
Penner, Charlson, Hales, Laulainen, Leifer, Novakov, Ogren, Radke, Schwartz & Travis, BAMS, 1994

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 $\omega_0 = 1$.

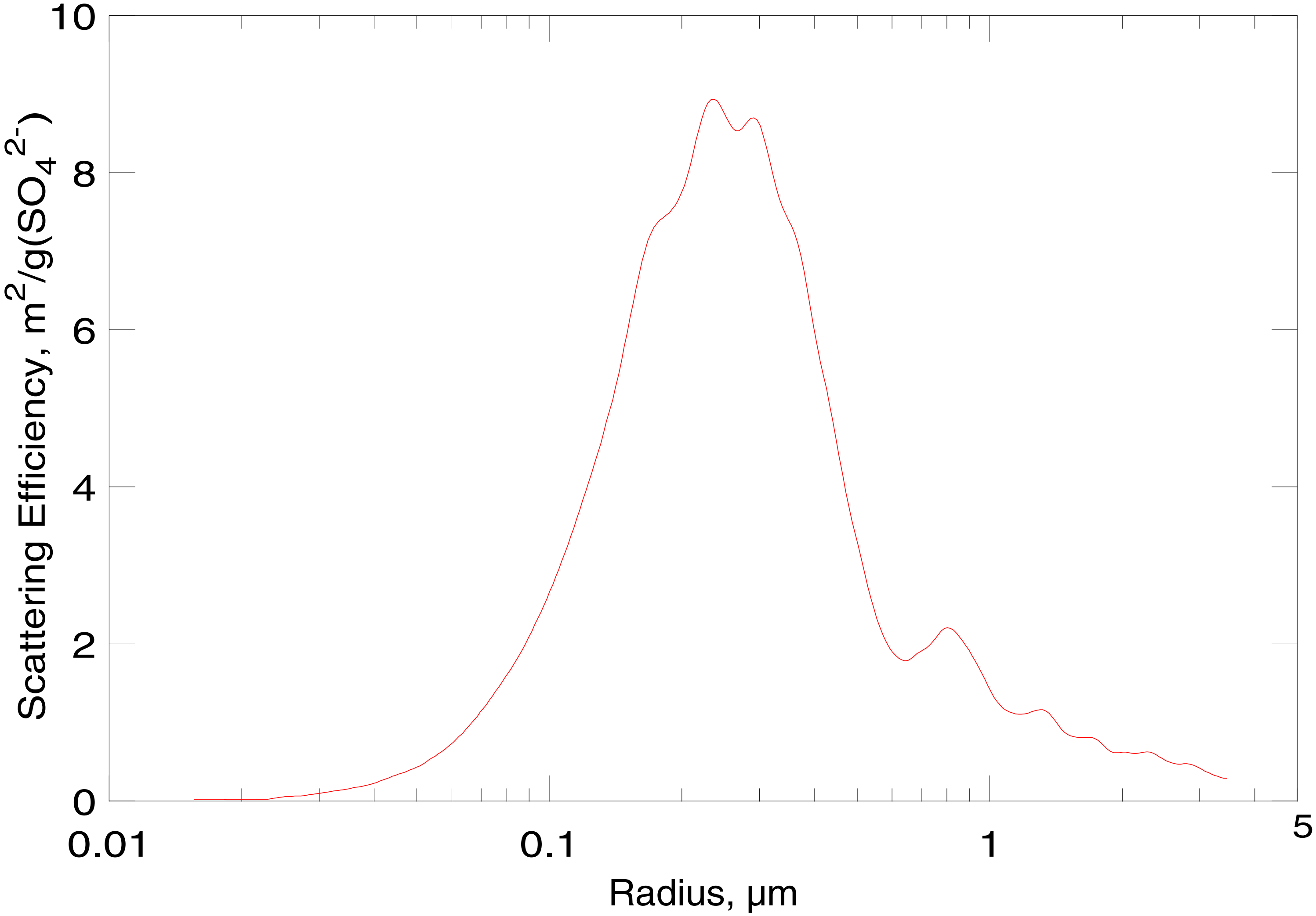


Global-average AOT 0.1 corresponds to global-average forcing -3.2 W m^{-2}.

LIGHT SCATTERING EFFICIENCY

Dependence on particle radius

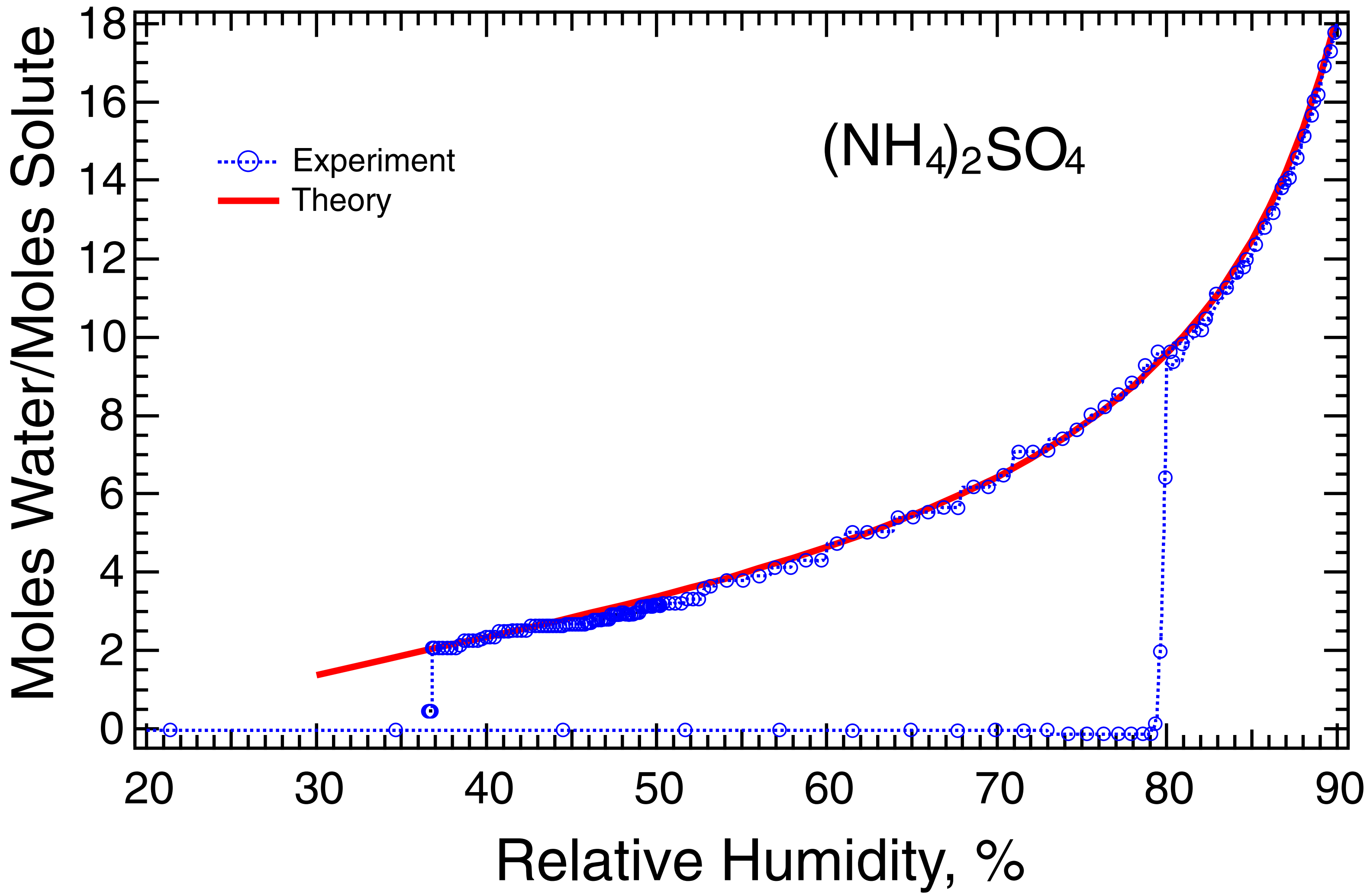
Ammonium Sulfate, 530 nm



Data of Ouimette and Flagan, 1982

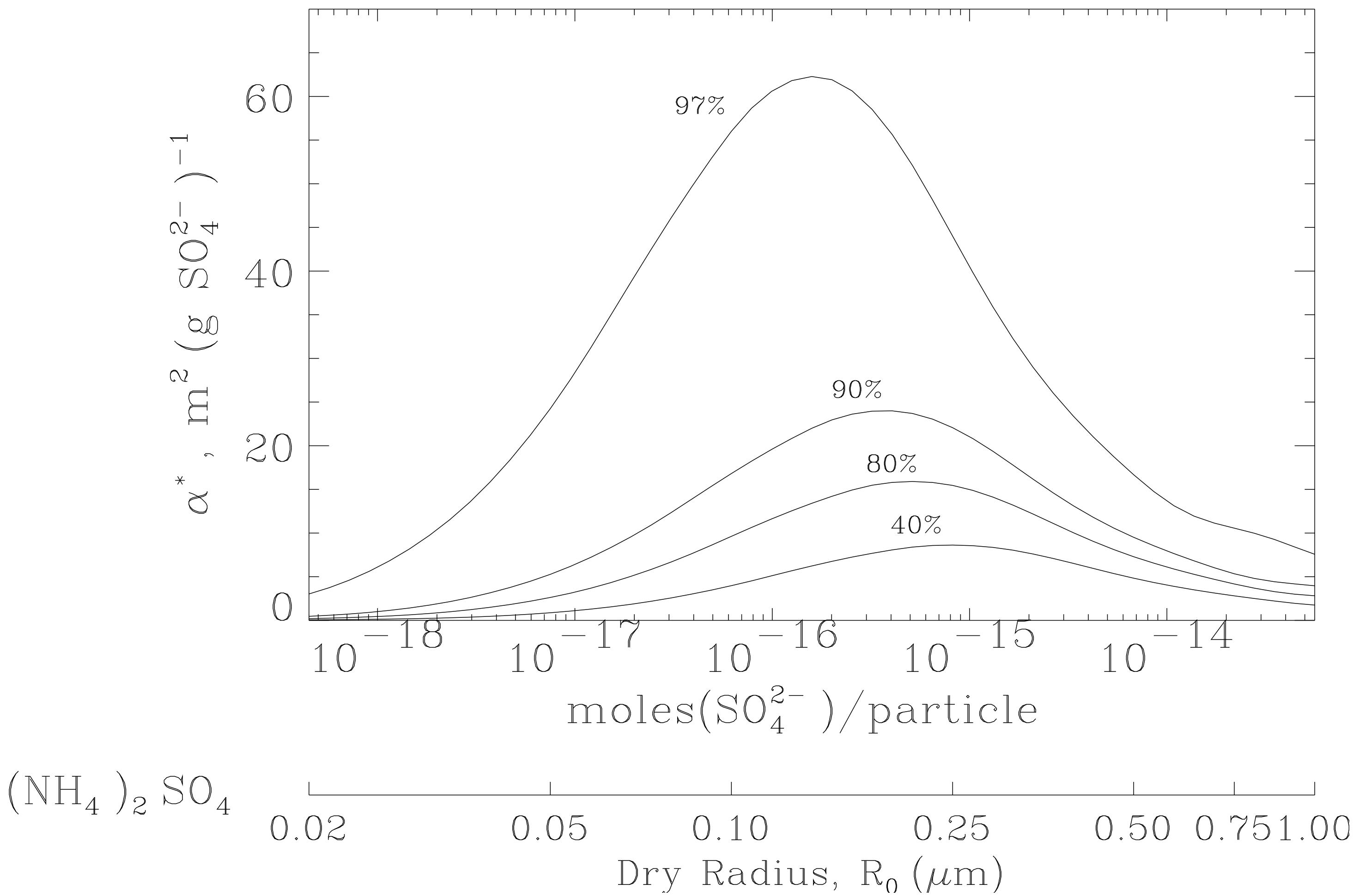
WATER UPTAKE AND LIGHT SCATTERING COEFFICIENT

Dependence on relative humidity



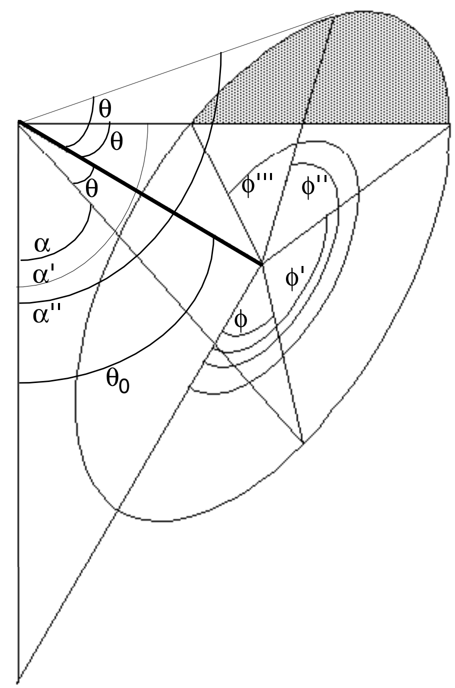
D. Imre, T. Onasch, BNL

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



UPSCATTER FRACTION

SCATTERING OF SOLAR RADIATION BY AEROSOL PARTICLE

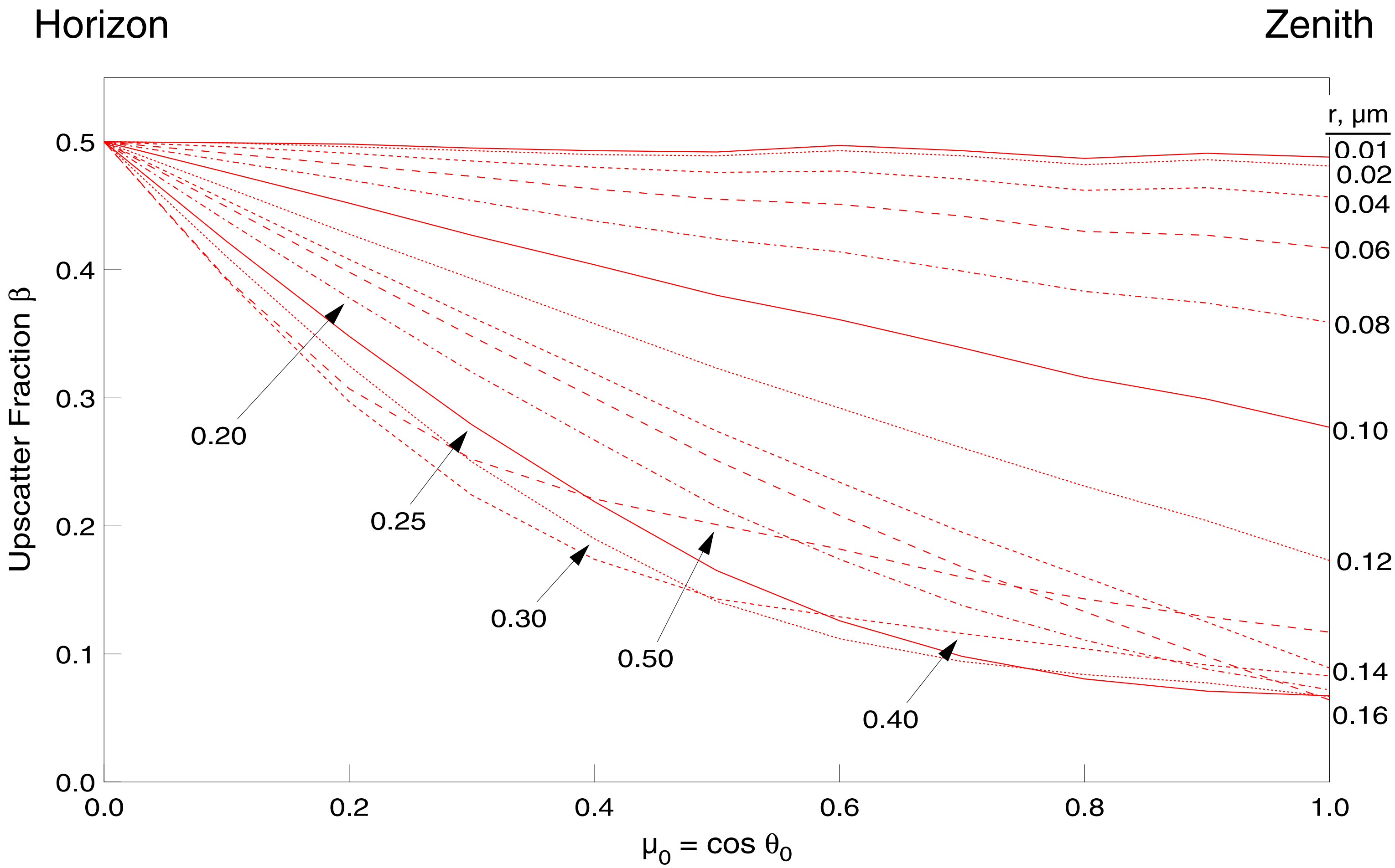


Upscatter fraction β is the fraction of radiation scattered into the upward hemisphere/

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

UPSCATTER FRACTION

Dependence on solar zenith angle and particle radius



$\lambda = 0.55\ \mu m$. $n = 1.40 - 0i$.

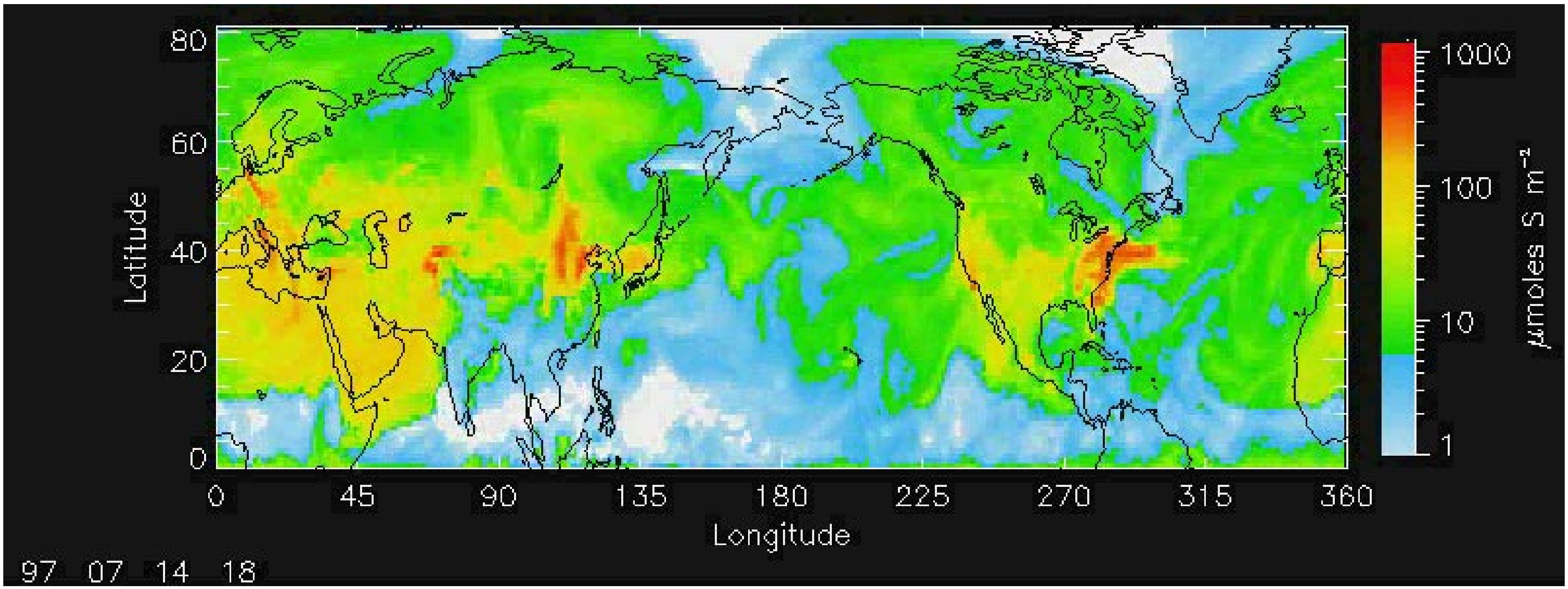
For sun at horizon $\beta = 0.5$ (by symmetry).

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

HEMISPHERIC DISTRIBUTION OF SULFATE COLUMN BURDEN

Vertical integral of concentration

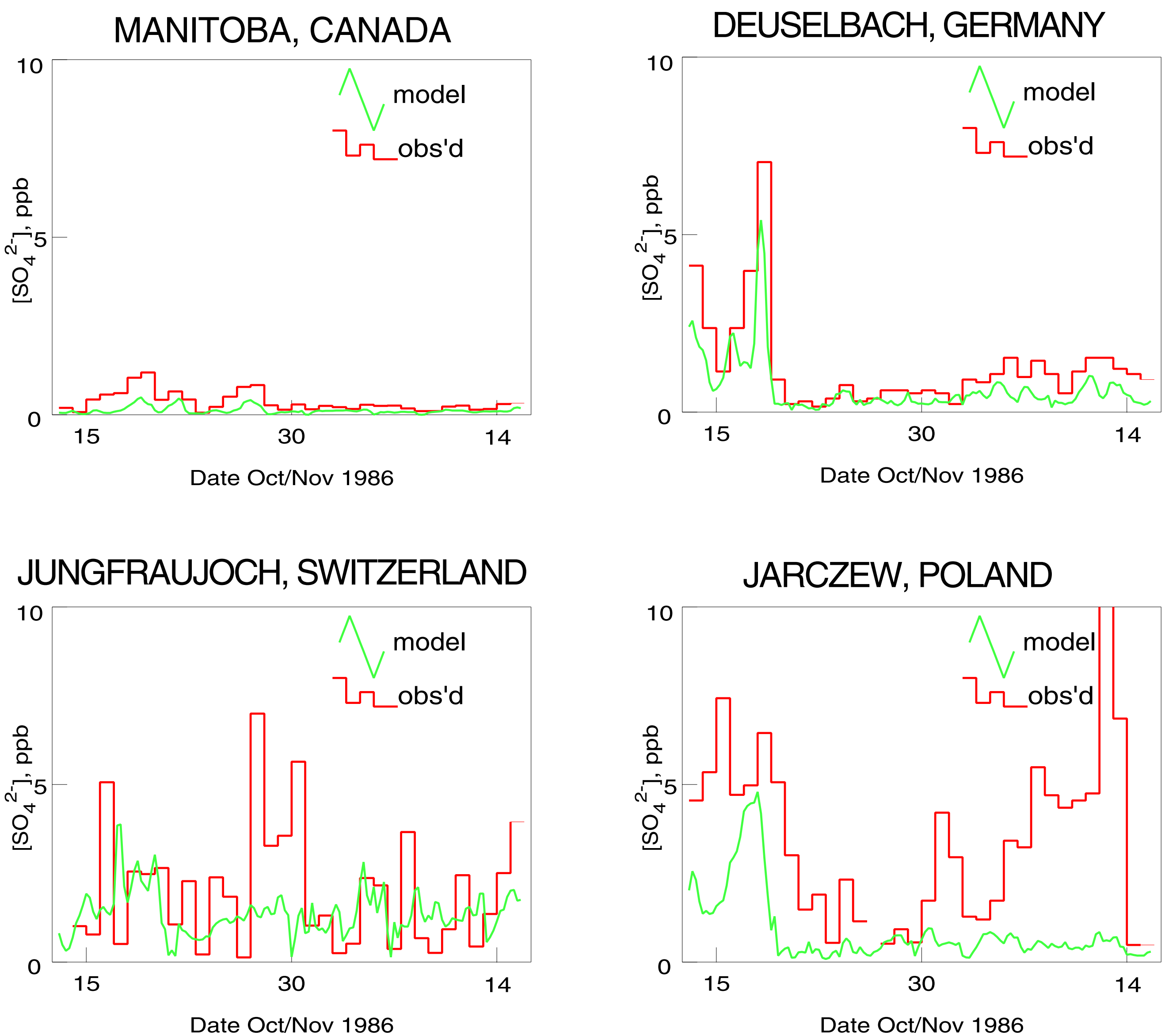
July 14, 1997, 1800 UTC



Brookhaven National Laboratory Chemical Transport Model

COMPARISON OF MODEL AND OBSERVATIONS

Comparisons for 24-hr sulfate mixing ratio at surface



COMPARISON OF MODEL AND OBSERVATIONS

Statistics of Comparisons

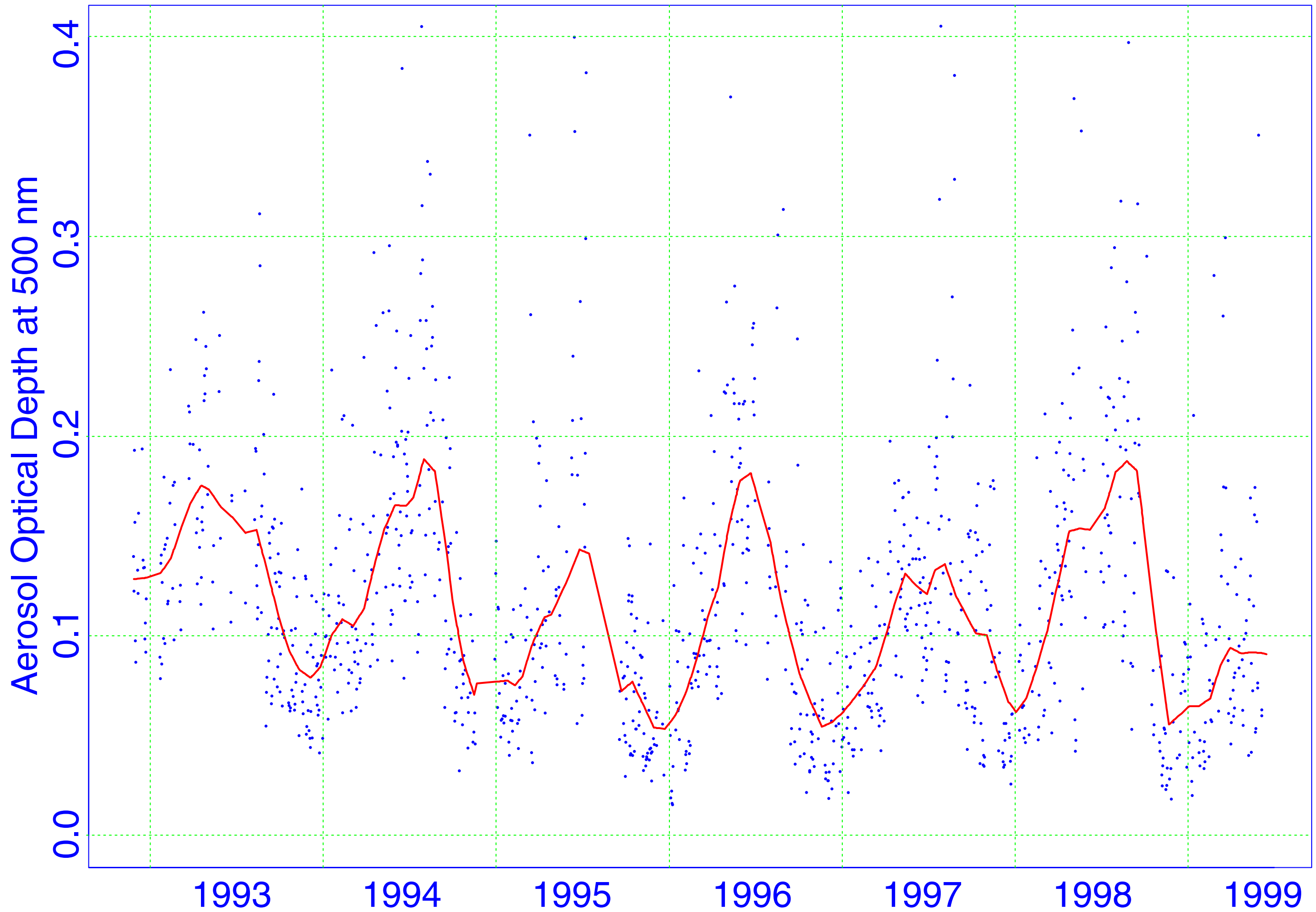
	N	Median Spread
Obs-Obs	503	1.5
Model-Obs Same locations	503	1.9
Model-Obs All locations	7907	2.3

Benkovitz and Schwartz, *JGR*, 1997

AEROSOL OPTICAL DEPTH

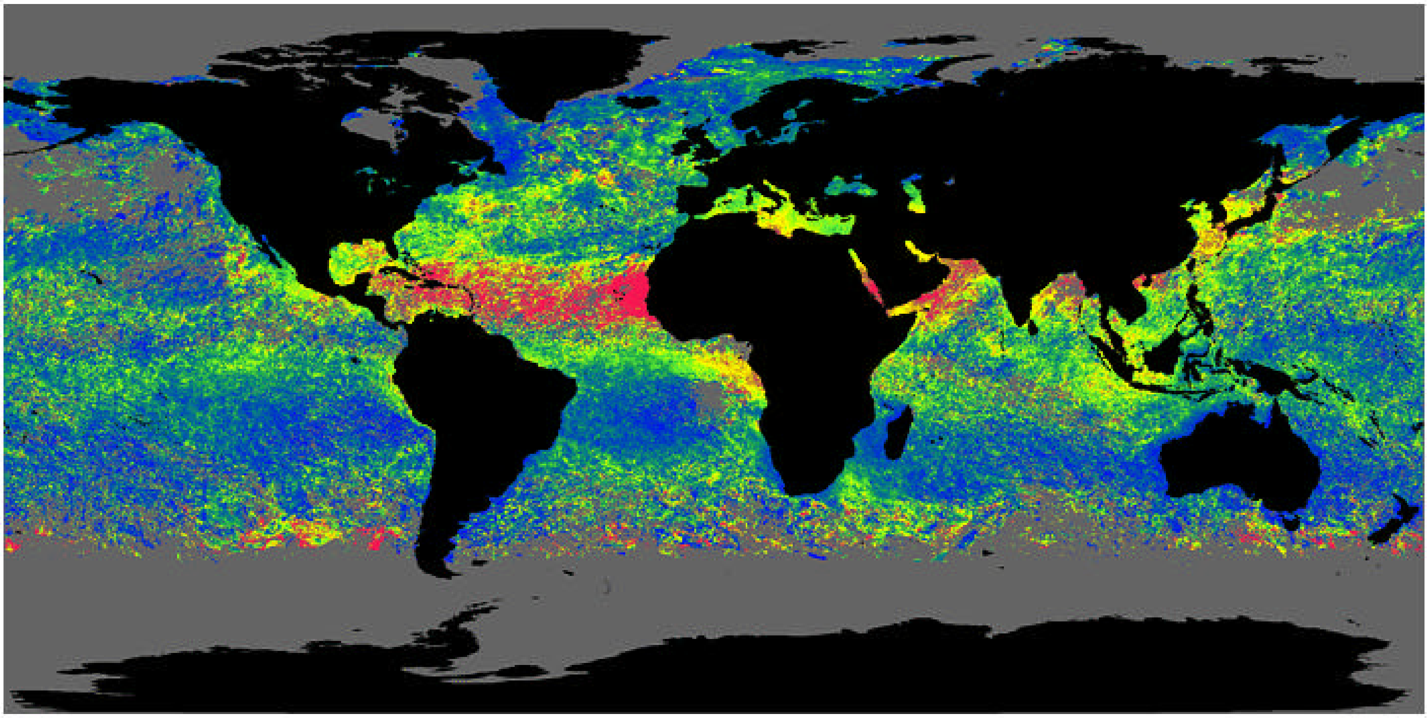
Determined by Sunphotometry

North Central Oklahoma

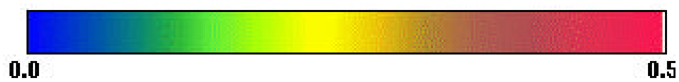


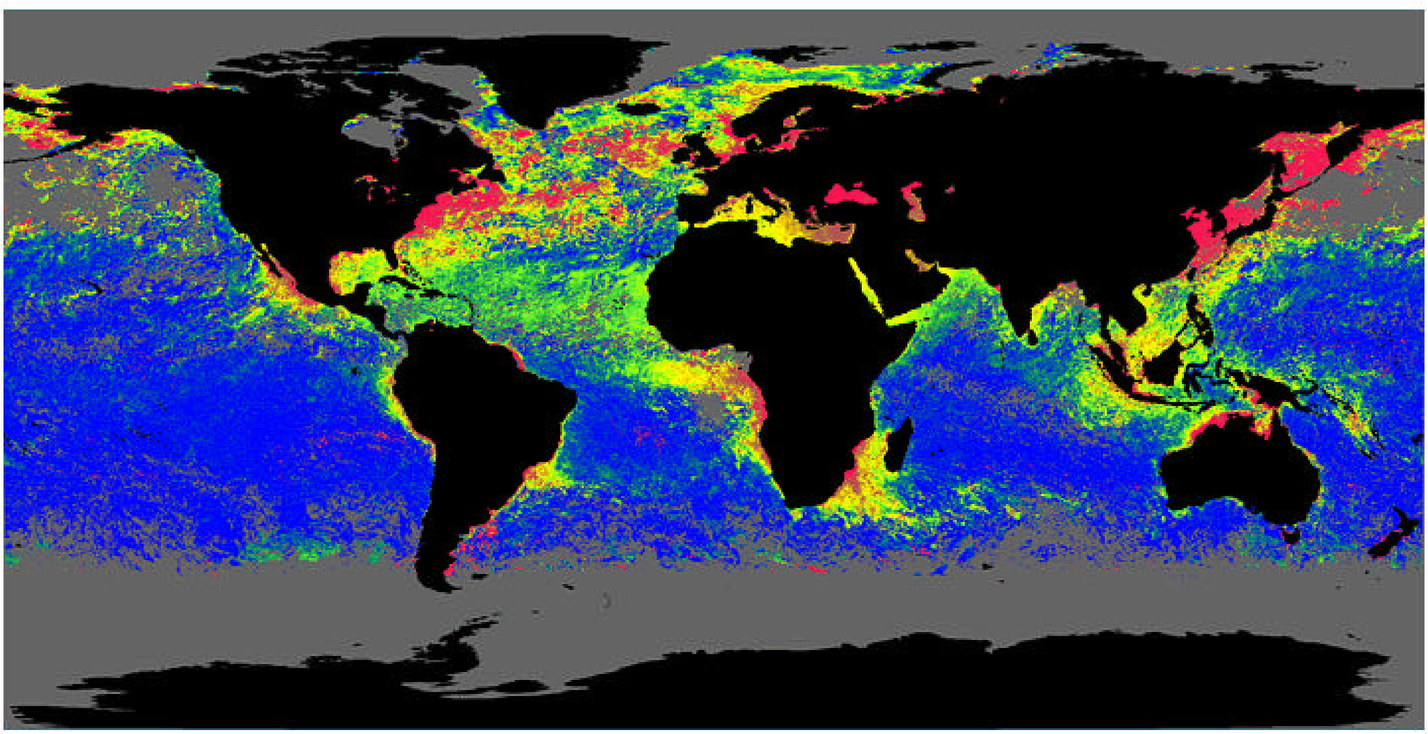
J. Michalsky, PNNL

MONTHLY AVERAGE AEROSOL JUNE 1997



Optical Thickness at 865 nm

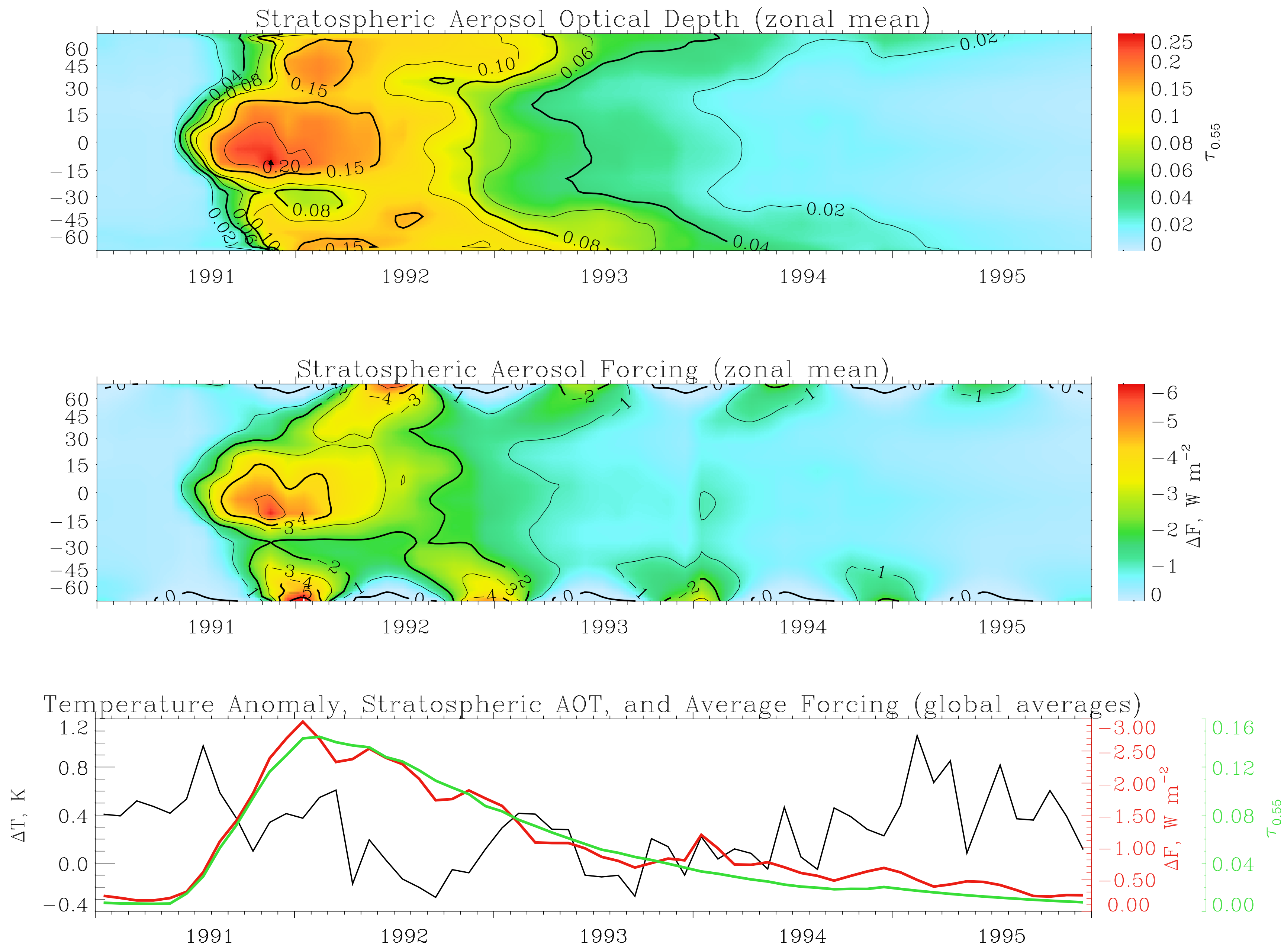




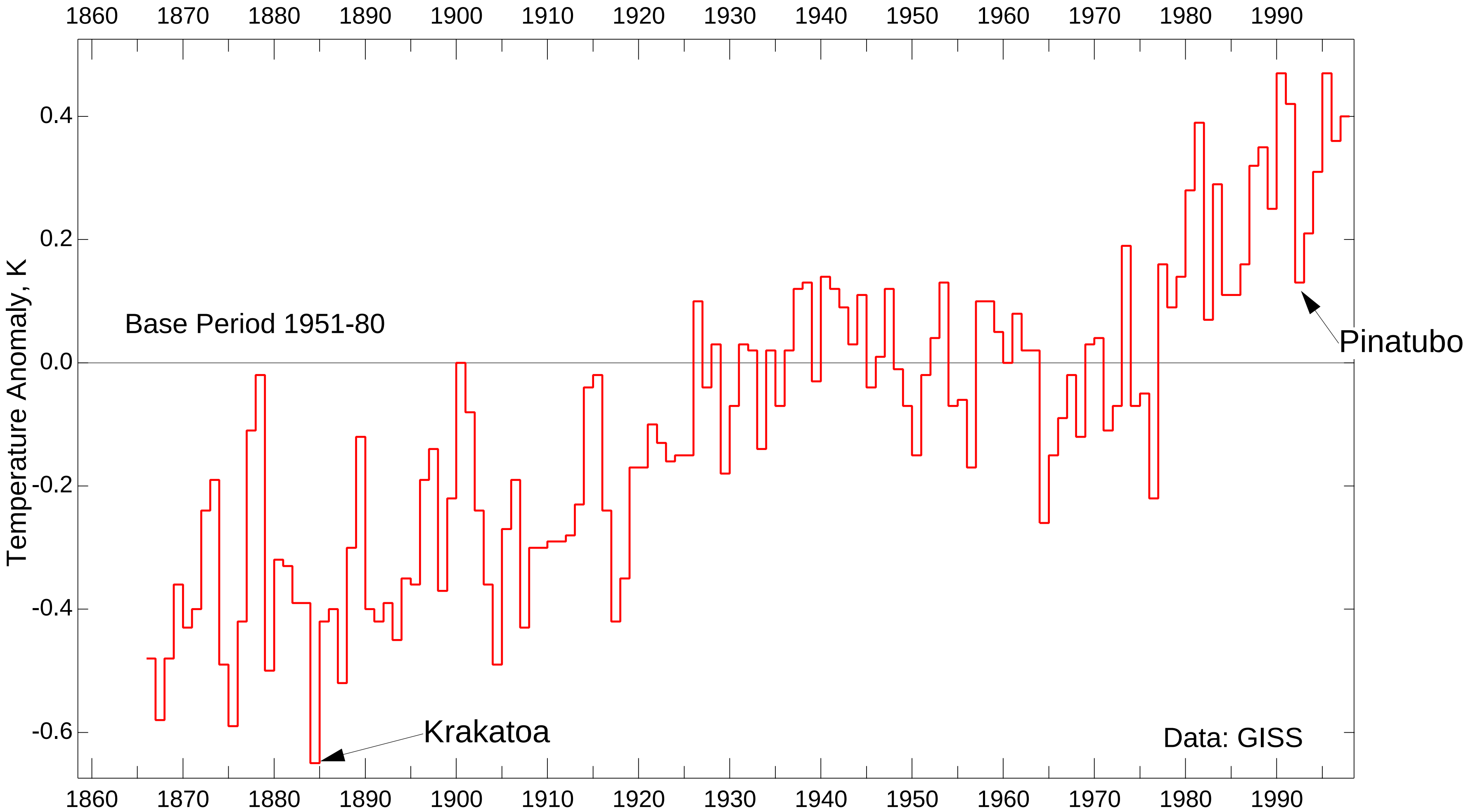
Ångström Exponent

Polder/Adeos CNES/NASDA LOA/LSCE

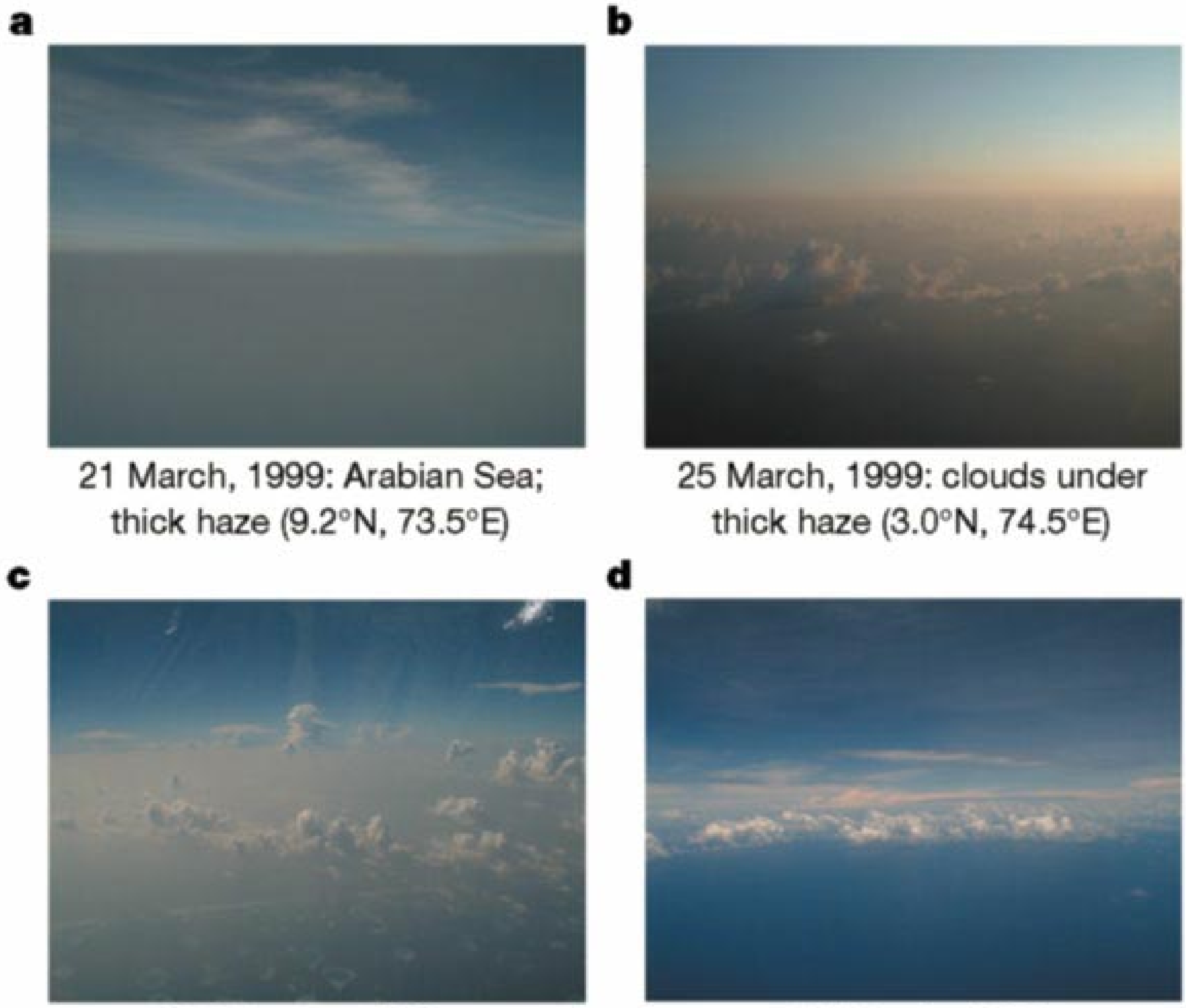
Influence of Pinatubo Eruption on Aerosol Forcing and Global Temperature



GLOBAL TEMPERATURE TREND OVER THE INDUSTRIAL PERIOD



CLOUDS AND AEROSOLS DURING INDOEX PROJECT



a 21 March, 1999: Arabian Sea; thick haze (9.2°N, 73.5°E)

b 25 March, 1999: clouds under thick haze (3.0°N, 74.5°E)

c 24 February, 1999: just north of ITCZ; haze extends up to top of Cu (0.5°N, 73.3°E)

d 24 March, 1999: south of ITCZ; almost pristine clouds (7.5°S, 73.5°E)

Satheesh and Ramanathan, *Nature*, 2000

AEROSOL DIRECT SHORTWAVE FORCING

Global Average for ***Nonabsorbing*** Aerosol

$$\Delta F = -\frac{1}{2} F_0 T^2 (1 - A_c)(1 - R)^2 \bar{\beta}\tau \qquad \tau = \int \alpha C dz = \int \sigma_{sp} dz$$

Light Scattering Coefficient
Mass Concentration
Mass Scattering Efficiency
Aerosol Optical Depth
Mean Upscatter Fraction
Surface Reflectance
Cloud Fraction
Atmospheric Transmittance
Solar Constant
Change in Net TOA Flux

Global Average for ***Absorbing*** Aerosol

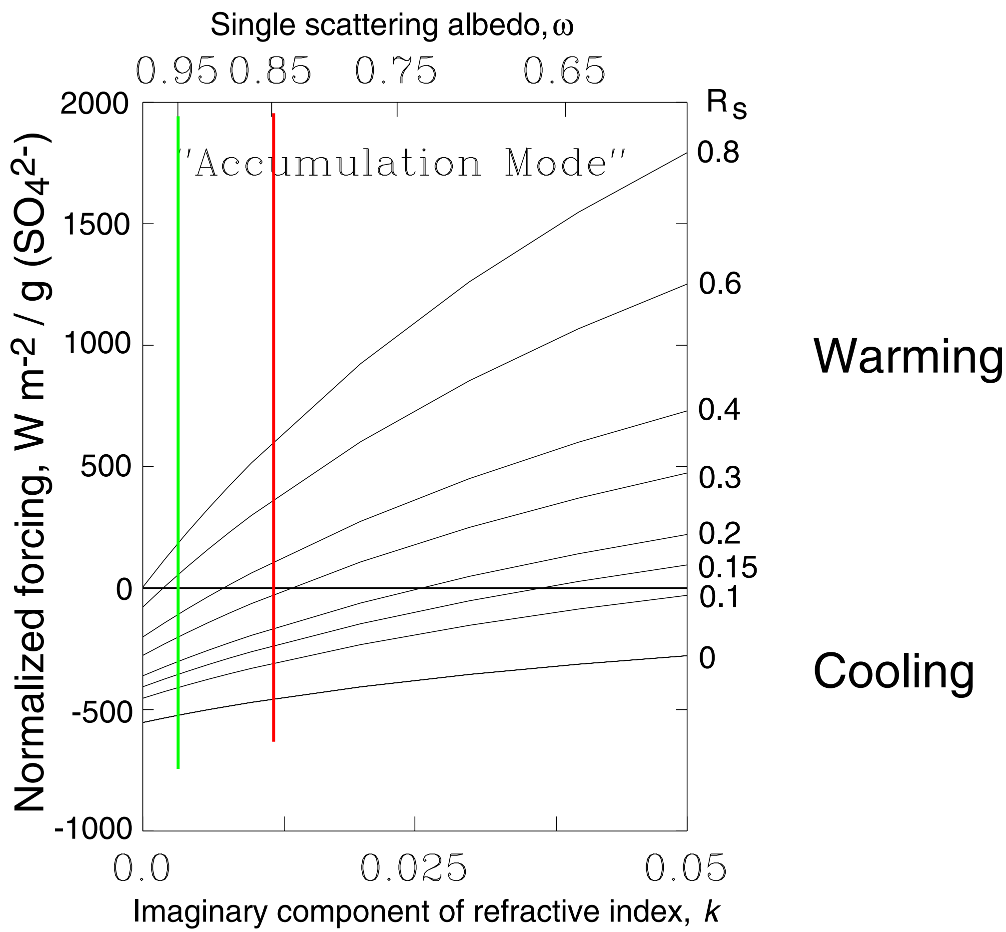
$$\Delta F = -\frac{1}{2} F_0 T^2 (1 - A_c)(1 - R)^2 \bar{\beta}\tau\omega \left\{ 1 - \frac{2R}{(1 - R)^2} \frac{(1 - \omega)}{\bar{\beta}\omega} \right\}$$

Single Scattering Albedo

RADIATIVE FORCING OF ABSORBING AEROSOL

Sulfate with uniformly admixed absorber

Dependence on imaginary component of refractive index *k* and surface reflectance R_S

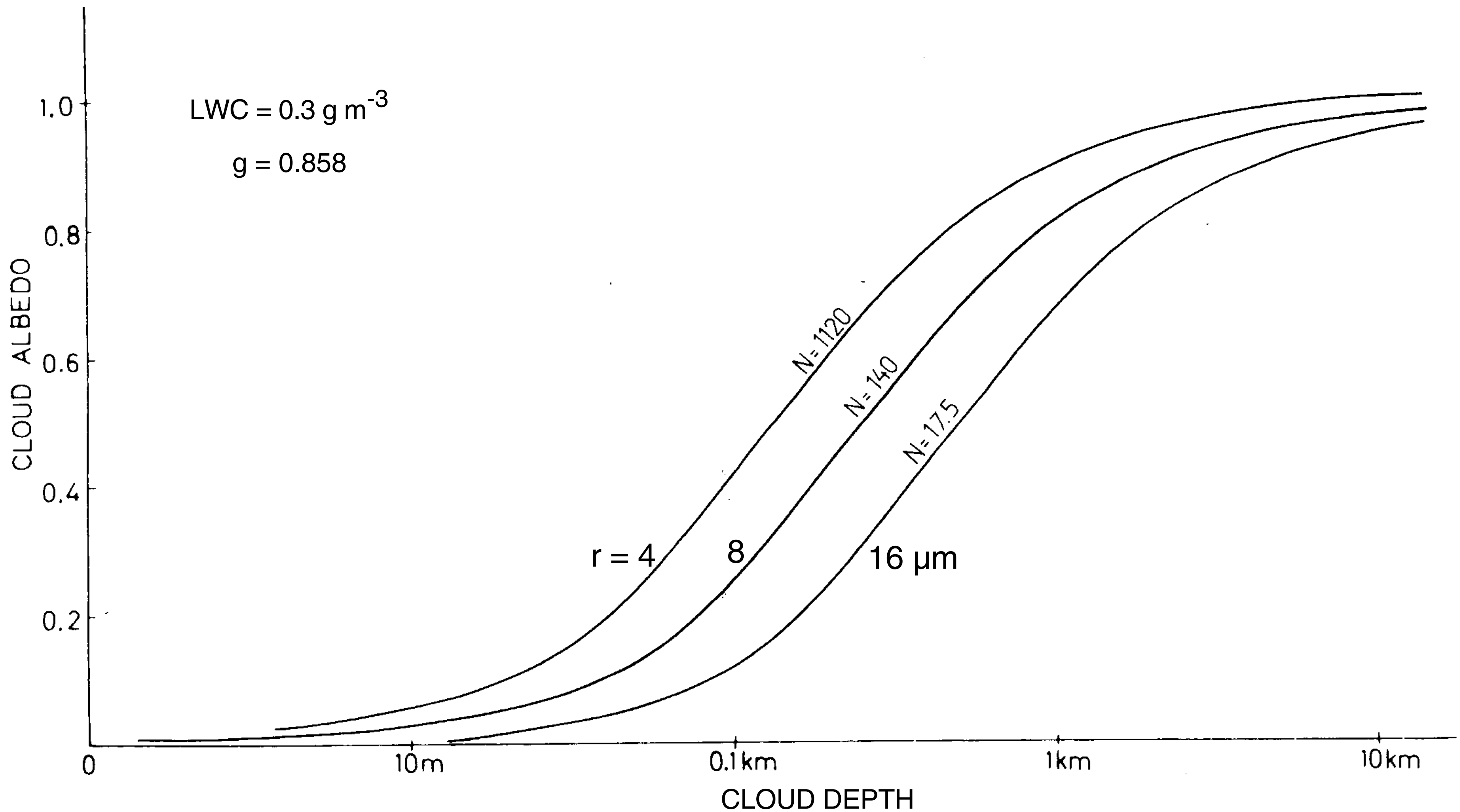


Compare to single scattering albedo w in north central Oklahoma, 0.92 ± 0.06 (one s.d.; 10,000 2-hour averages of 1-minute data).

INDIRECT EFFECT

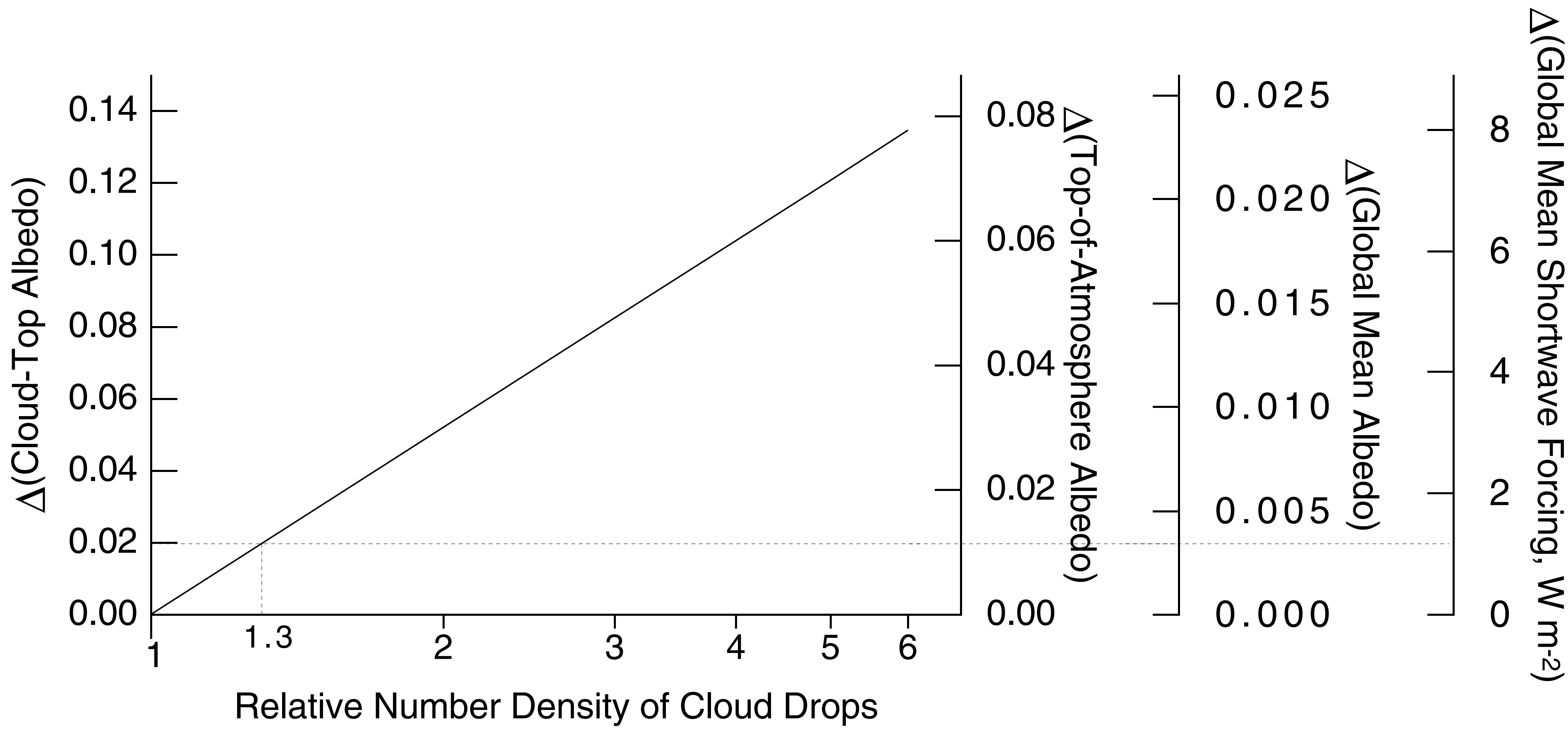
DEPENDENCE OF CLOUD ALBEDO ON CLOUD DEPTH

Influence of Cloud Drop Radius and Concentration



Twomey, *Atmospheric Aerosols*, 1977

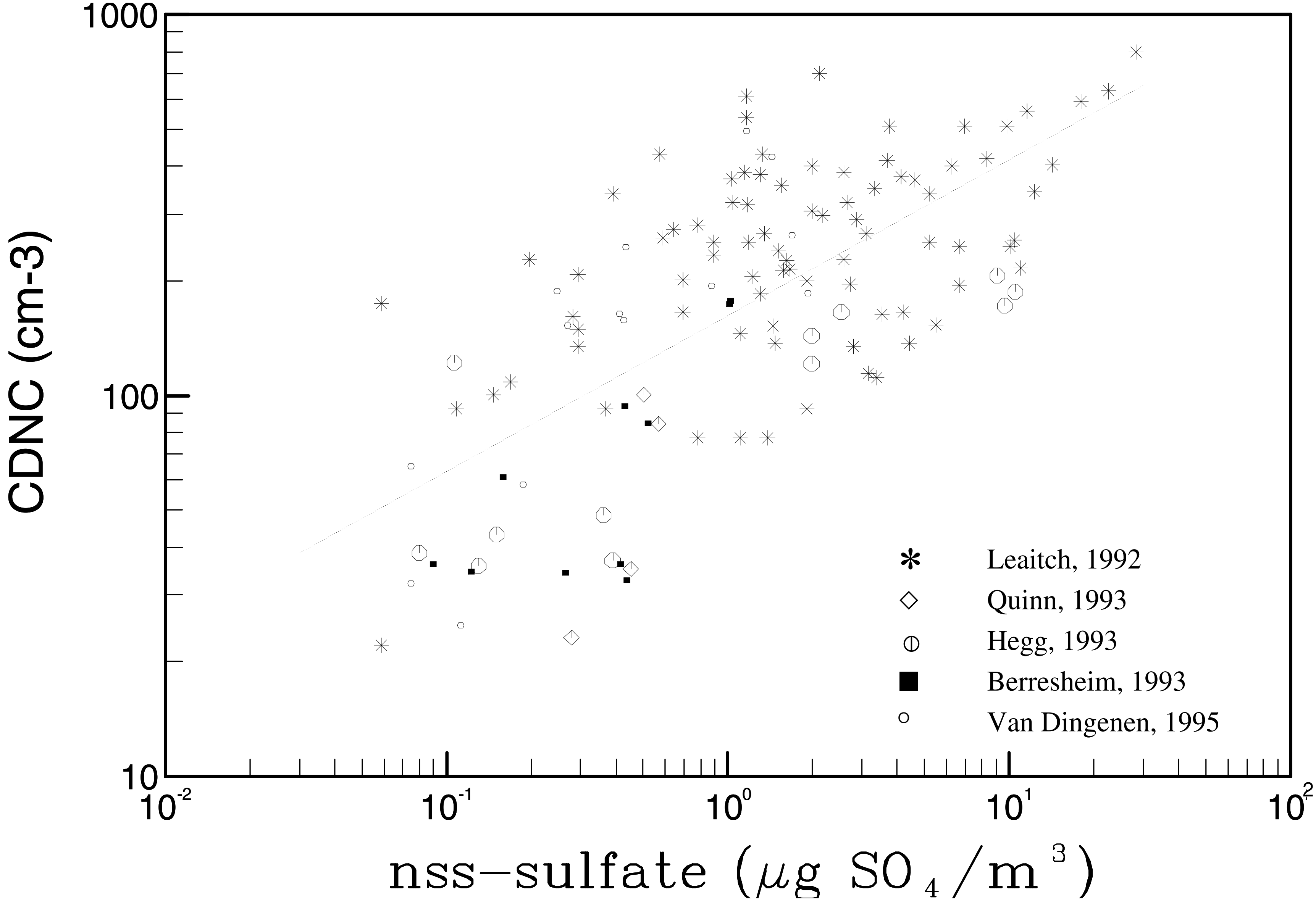
SENSITIVITY OF ALBEDO AND FORCING TO CLOUD DROP CONCENTRATION



Schwartz and Slingo (1996)

CLOUD DROPLET NUMBER CONCENTRATION

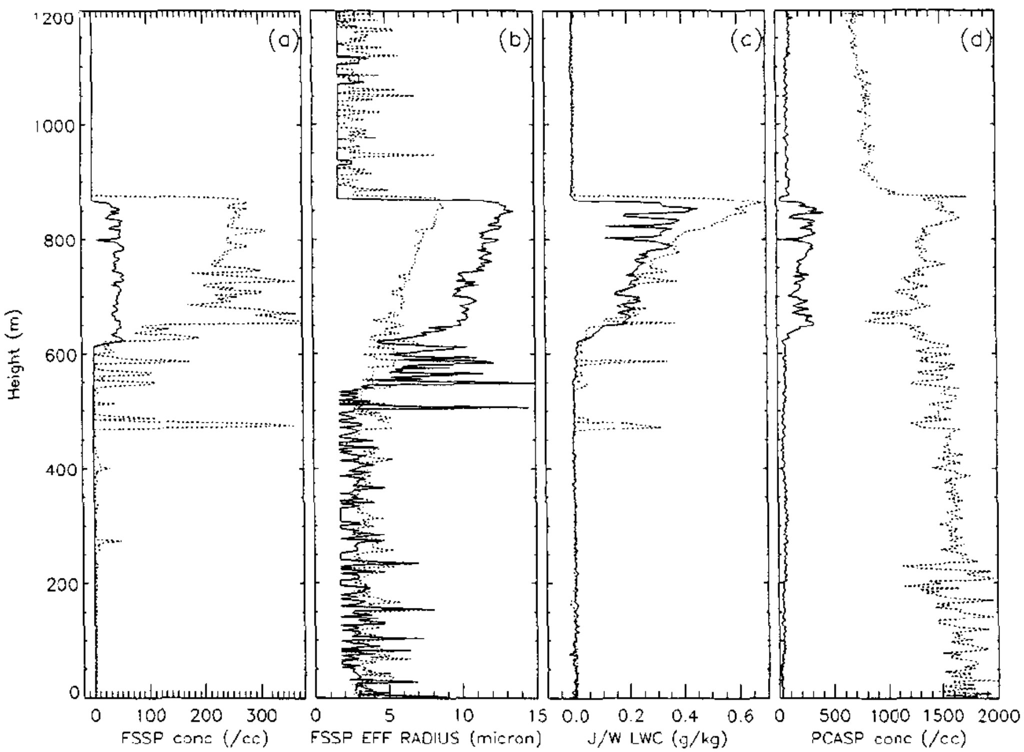
Dependence on Non-Seasalt Sulfate

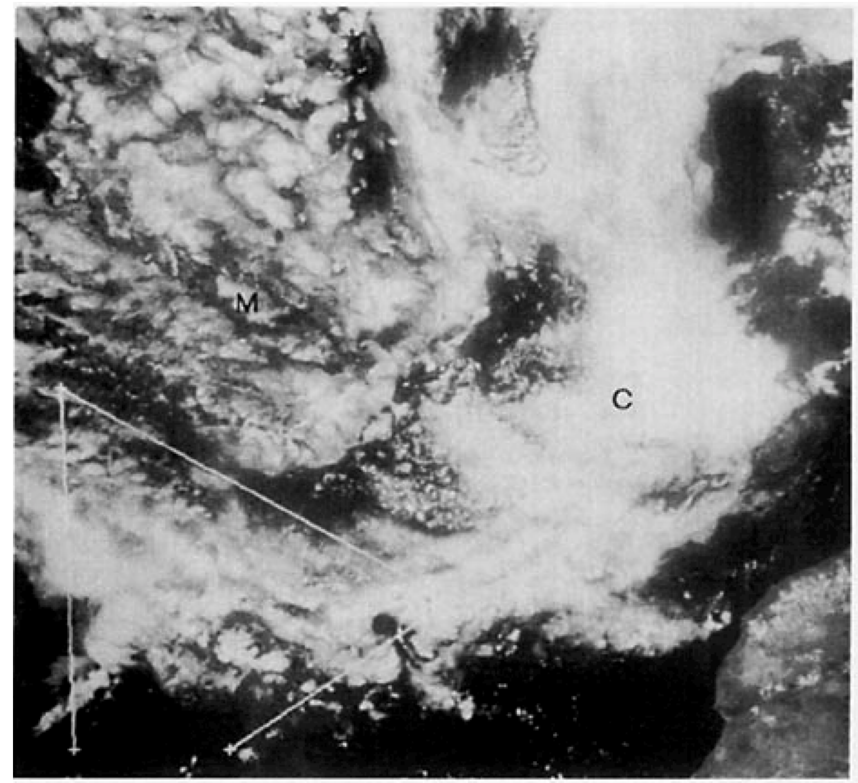


Boucher and Lohmann, 1995

CLOUD MICROPHYSICAL PROPERTIES AND SATELLITE VISIBLE RADIANCE

ASTEX, Northeast Atlantic, June, 1992

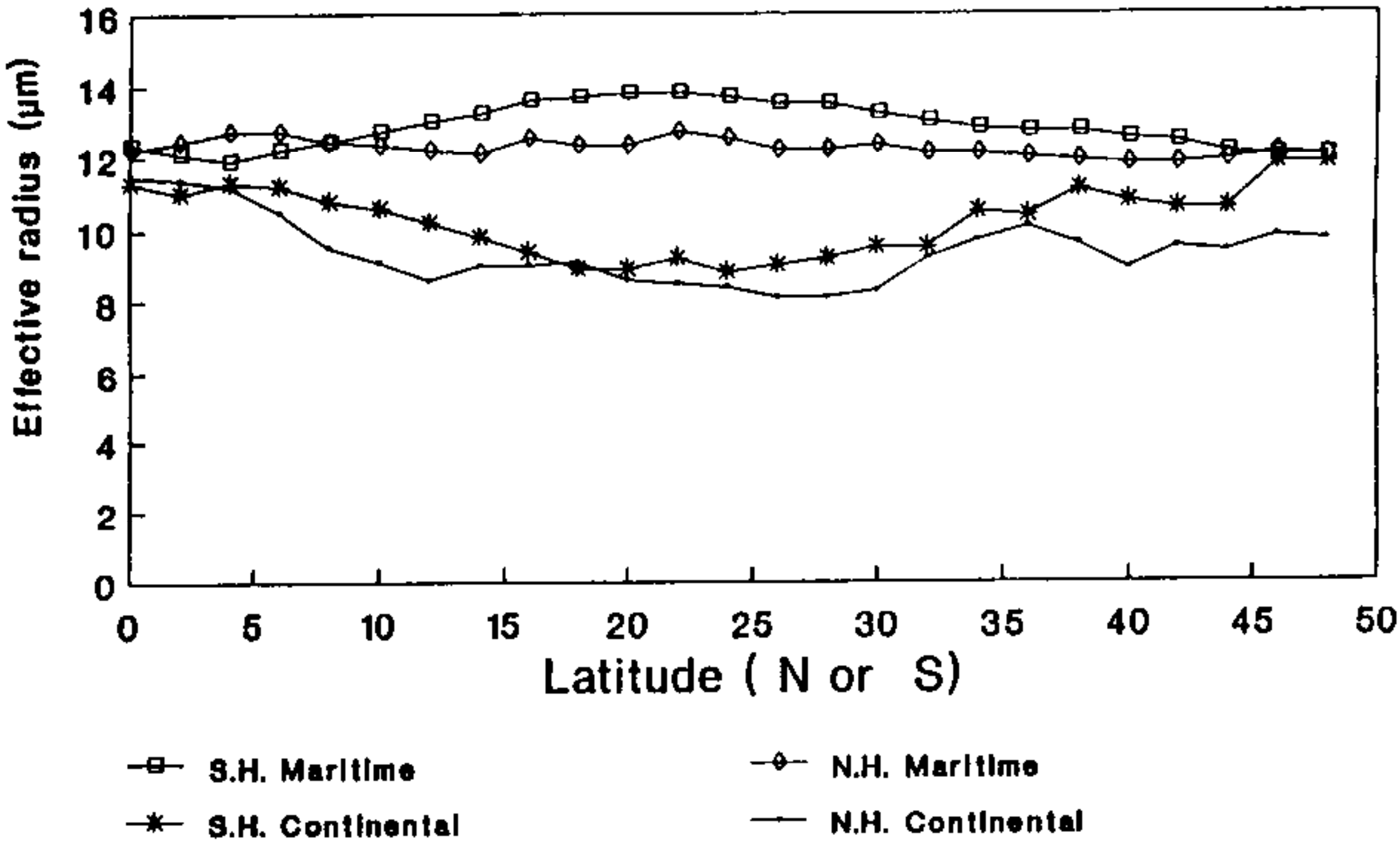




Albrecht et al., BAMS, 1995

LATITUDE DEPENDENCE OF CLOUD DROP RADIUS

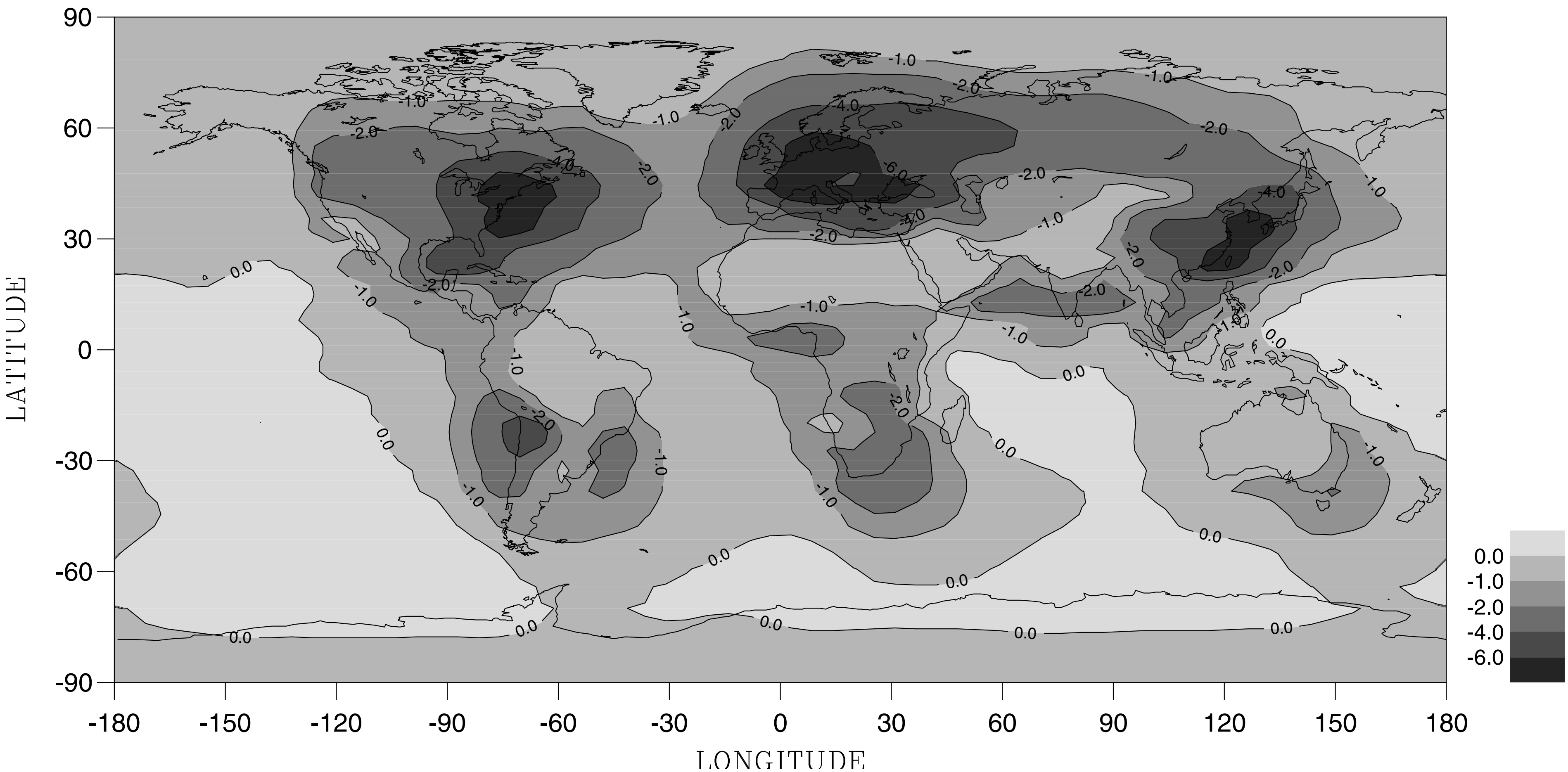
Test for Anthropogenic Influence in Northern Hemisphere vs. Southern Hemisphere as Control



Han , Rossow, and Lacis , J. Climate, 1994

INDIRECT FORCING OF SULFATE AEROSOL

Annual-mean loss of solar irradiance, W m^{-2}

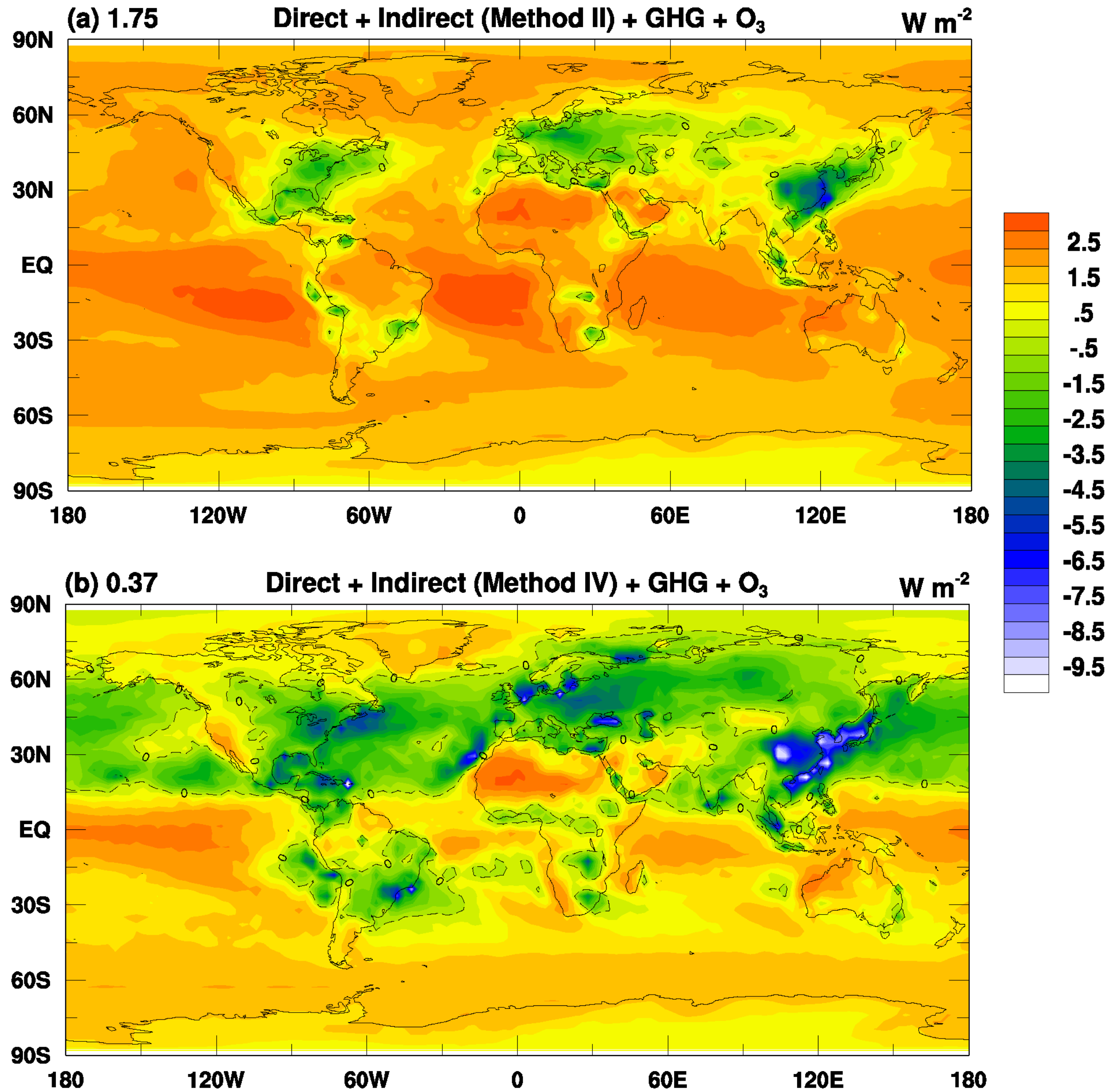


LMD model; Boucher and Lohmann, 1995

SHORTWAVE FORCING, ANNUAL AVERAGE

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

Two Formulations of Cloud Droplet Concentration



Kiehl et al., JGR, 2000

NRC REPORT TO PRESIDENT HIGHLIGHTS IMPORTANCE OF AEROSOL INDIRECT FORCING

The greatest uncertainty about the aerosol climate forcing—indeed, the largest of all the uncertainties about global climate forcings—is probably the indirect effect of aerosols on clouds.

Aerosols serve as condensation nuclei for cloud droplets.

Thus, anthropogenic aerosols are believed to have two major effects on cloud properties, the increased number of nuclei results in a larger number of smaller cloud droplets, thus increasing the cloud brightness (the Twomey effect); and the smaller droplets tends to inhibit rainfall, thus increasing cloud lifetime and the average cloud cover on Earth.

Both effects reduce the amount of sunlight absorbed by the Earth and thus tend to cause global cooling.

CLIMATE CHANGE SCIENCE

AN ANALYSIS OF SOME KEY QUESTIONS
Committee on the Science of Climate Change
National Research Council
June 6, 2001

NRC REPORT TO PRESIDENT HIGHLIGHTS IMPORTANCE OF AEROSOL INDIRECT FORCING (cont'd)

The existence of these effects has been verified in field studies, but it is extremely difficult to determine their global significance.

Climate models that incorporate the aerosol-cloud physics suggest that these effects may produce a negative global forcing on the order of 1 W/m^2 or larger.

The great uncertainty about this indirect aerosol climate forcing presents a severe handicap both for the interpretation of past climate change and for future assessments of climate changes.

CLIMATE CHANGE SCIENCE

AN ANALYSIS OF SOME KEY QUESTIONS
Committee on the Science of Climate Change
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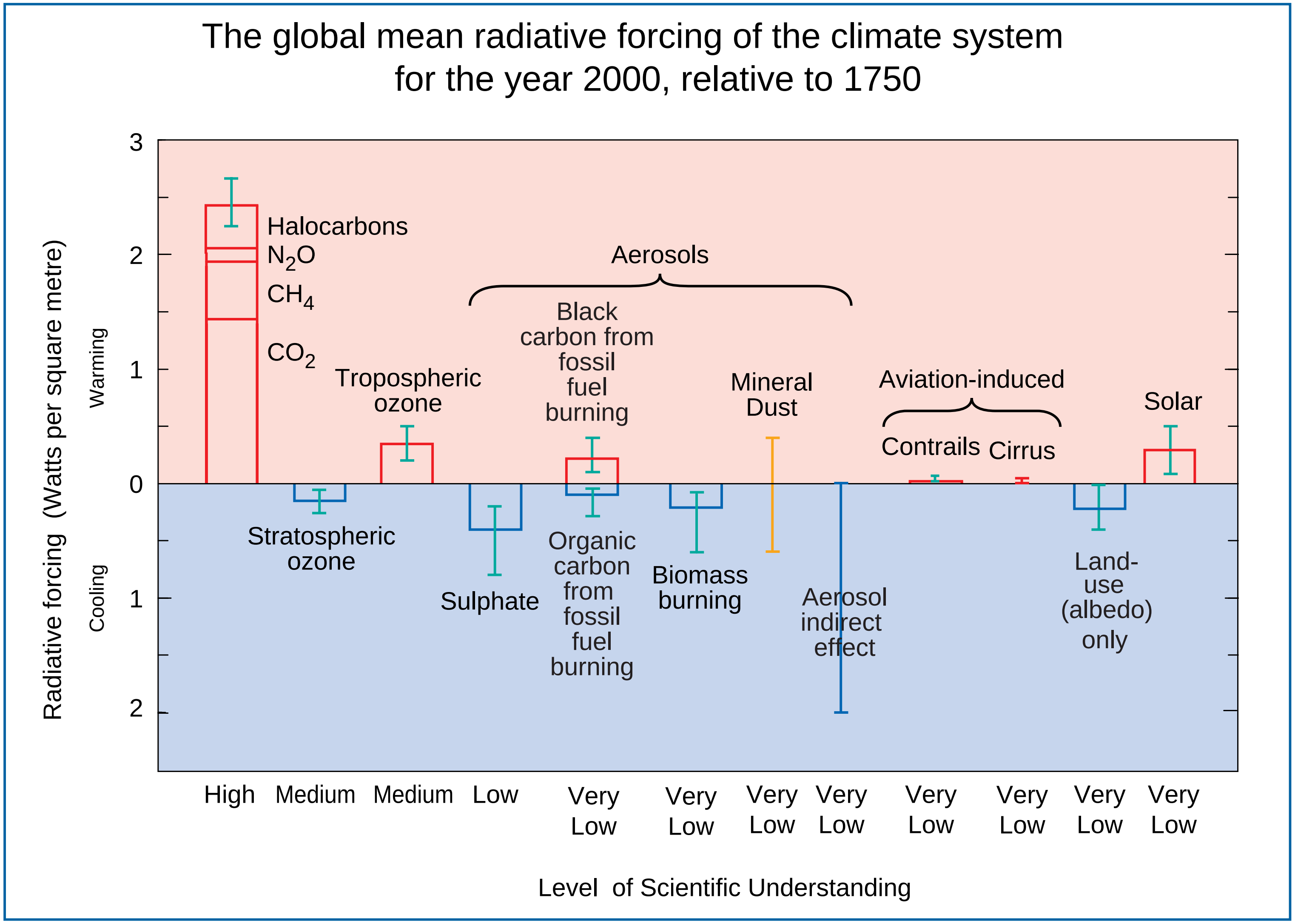
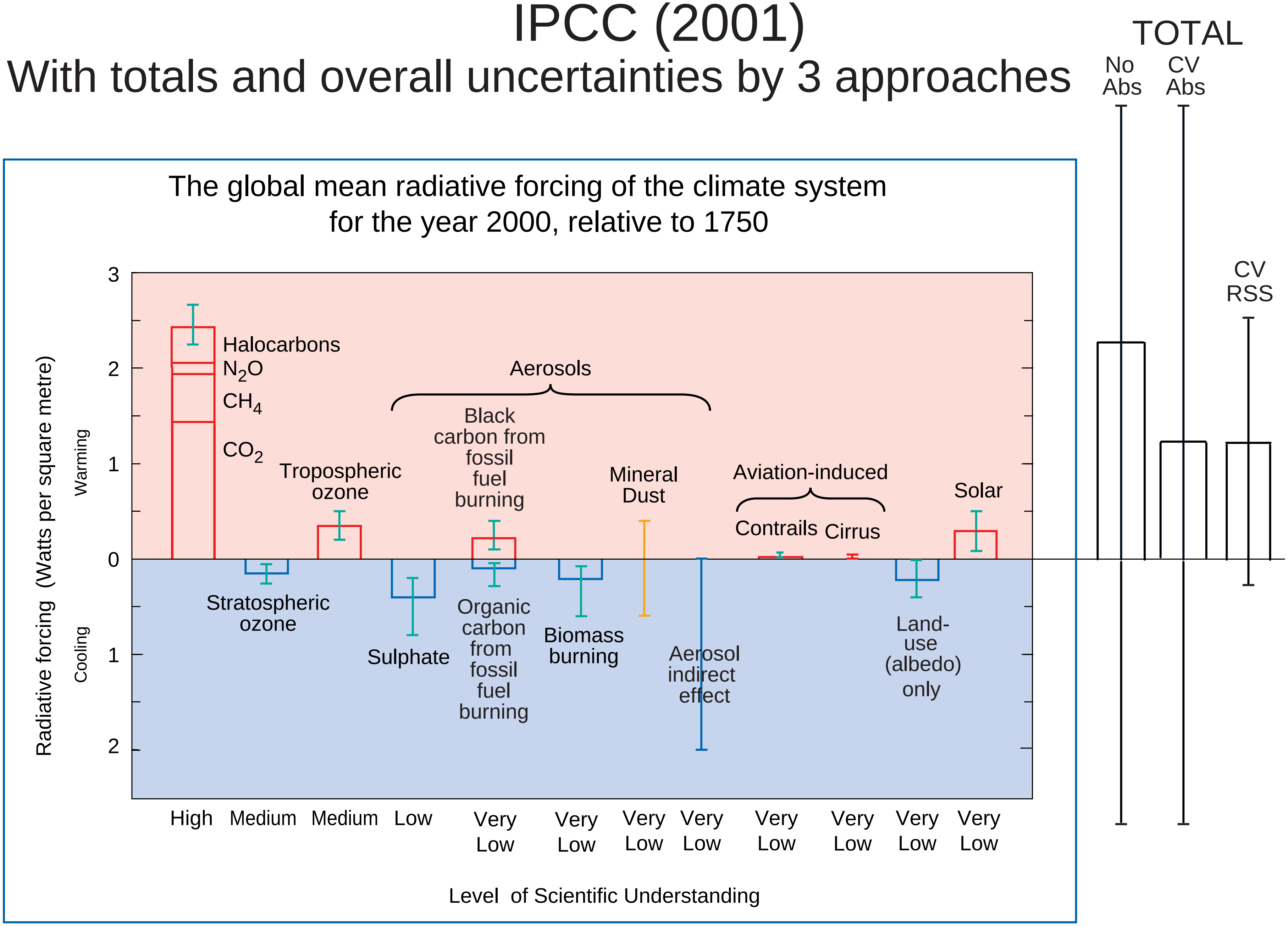
IPCC-2001 STATEMENT ON ATTRIBUTION OF CLIMATE CHANGE TO GREENHOUSE GASES

- In the light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations.

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)



RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)
With totals and overall uncertainties by 3 approaches



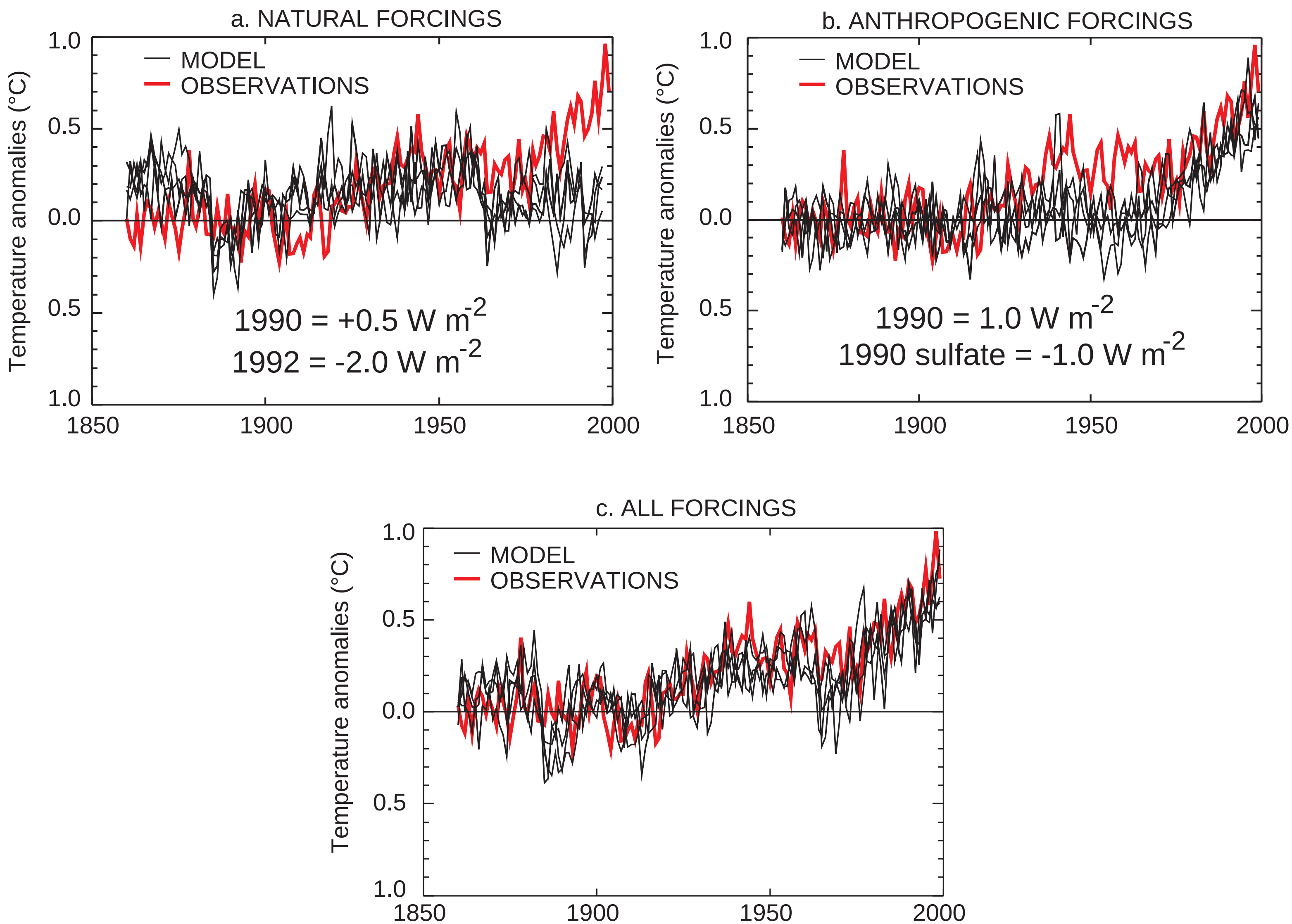
Summary for Policymakers A Report of Working Group I of the Intergovernmental Panel on Climate Change

IPCC-2001 STATEMENT AGAINST ADDING FORCINGS

- Some of the radiative forcing agents are well mixed over the globe, such as CO_2, thereby perturbing the global heat balance. Others represent perturbations with stronger regional signatures because of their spatial distribution, such as aerosols. For this and other reasons, ***a simple sum of the positive and negative bars cannot be expected to yield the net effect on the climate system***.

CLIMATE MODEL SIMULATIONS OVER THE INDUSTRIAL PERIOD (IPCC, 2001)

Annual global mean temperatures (1.5 m) with coupled ocean-atmosphere GCM



Technical Summary of the Working Group I Report

IPCC-2001 STATEMENT ON CONFIDENCE IN ABILITY OF MODELS TO PROJECT FUTURE CLIMATE

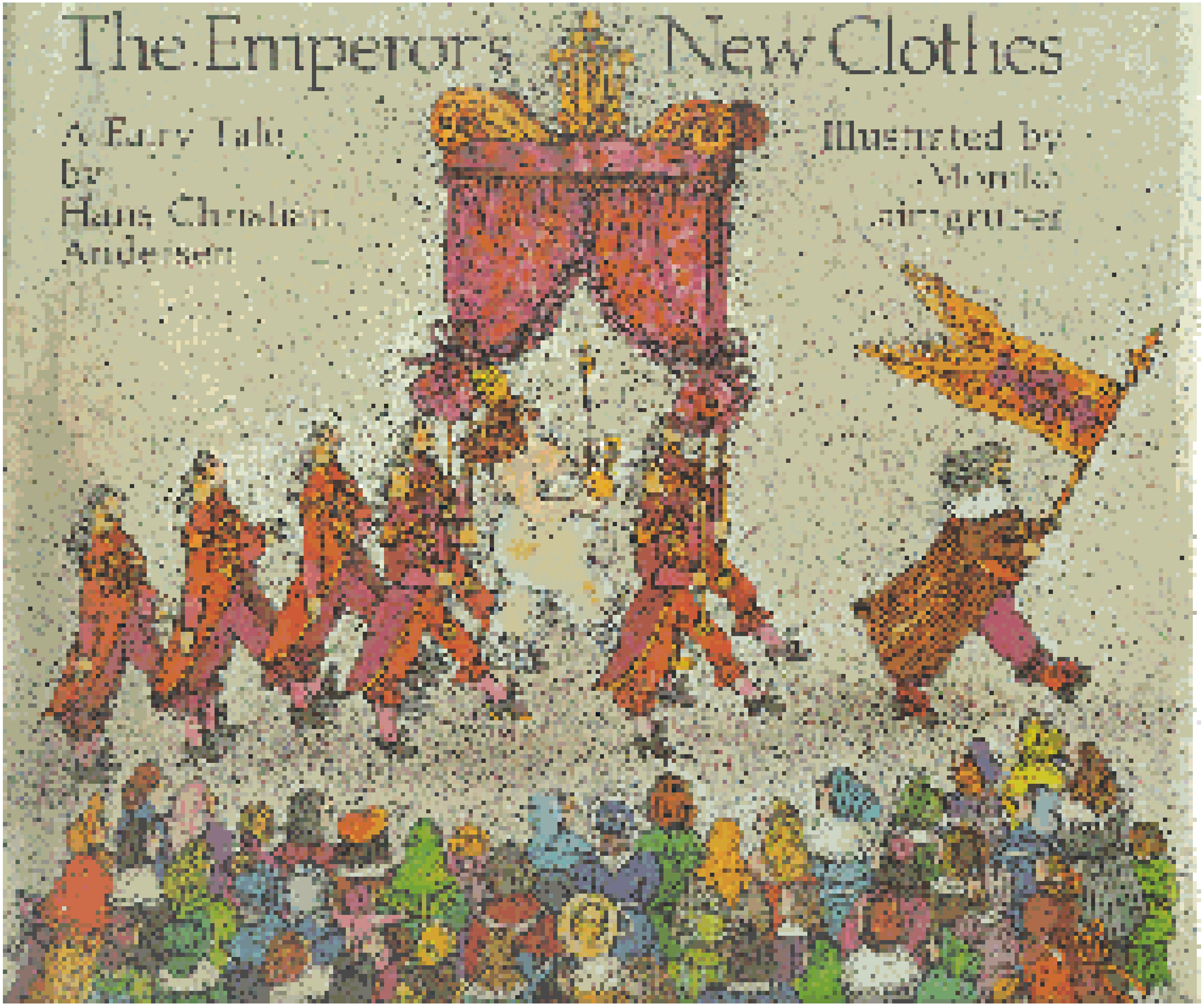
- ***Simulations that include estimates of natural and anthropogenic forcing reproduce the observed large-scale changes in surface temperature over the 20th century*** (Figure 4). However, contributions from some additional processes and forcings may not have been included in the models. Nevertheless, ***the large-scale consistency between models and observations*** can be used to provide an independent check on projected warming rates over the next few decades under a given emissions scenario.

IPCC-2001 STATEMENTS ON DETECTION AND ATTRIBUTION OF CLIMATE CHANGE

- ***Detection and attribution studies comparing model simulated changes with the observed record can now take into account uncertainty in the magnitude of modelled response to external forcing***, in particular that due to uncertainty in climate sensitivity.
- Most of these studies find that, over the last 50 years, the estimated rate and magnitude of warming due to increasing concentrations of greenhouse gases alone are comparable with, or larger than, the observed warming. ***Furthermore, most model estimates that take into account both greenhouse gases and sulphate aerosols are consistent with observations over this period.***

IPCC-2001 STATEMENTS ON DETECTION AND ATTRIBUTION OF CLIMATE CHANGE (cont'd)

- The best agreement between model simulations and observations over the last 140 years has been found when all the above anthropogenic and natural forcing factors are combined, as shown in Figure 4 (c). These results show that ***the forcings included are sufficient to explain the observed changes,*** but do not exclude the possibility that other forcings may also have contributed.


The Emperor's New Clothes
A Fairy Tale
by
Hans Christian
Andersen
Illustrated by
Monika
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CONCLUSIONS

- Radiative forcing of climate change by aerosols is highly uncertain but not negligible.
- This uncertainty is limiting in present estimates of radiative forcing over the industrial period.
- Little confidence can be placed on empirical estimates of climate sensitivity, or on conformance of climate models with observations over the industrial period, unless and until the uncertainty in aerosol forcing is greatly reduced.