AEROSOLS AND CLIMATE CHANGE
CERTAINTIES AND UNCERTAINTIES

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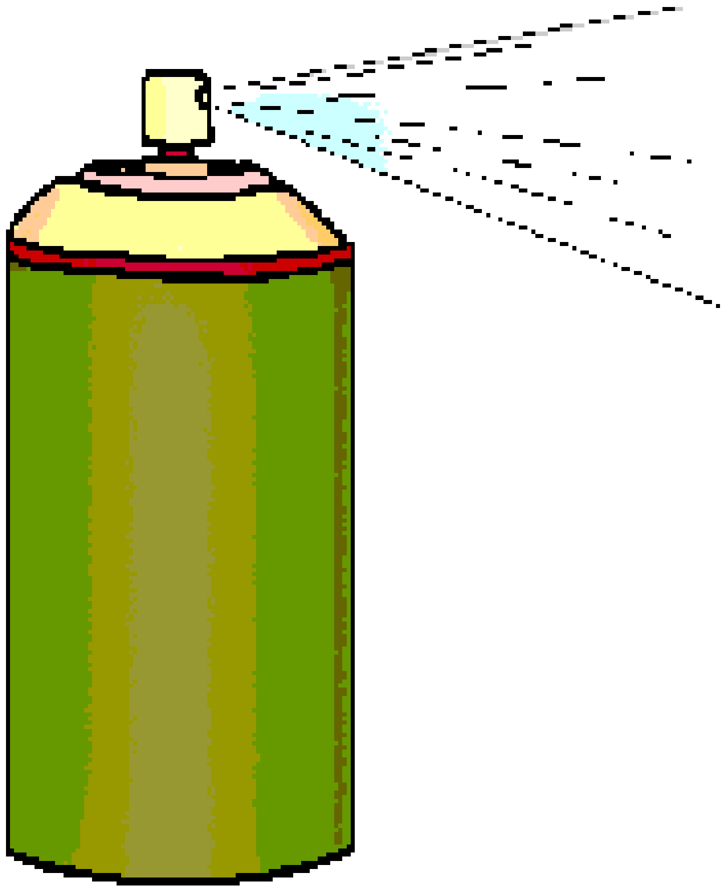
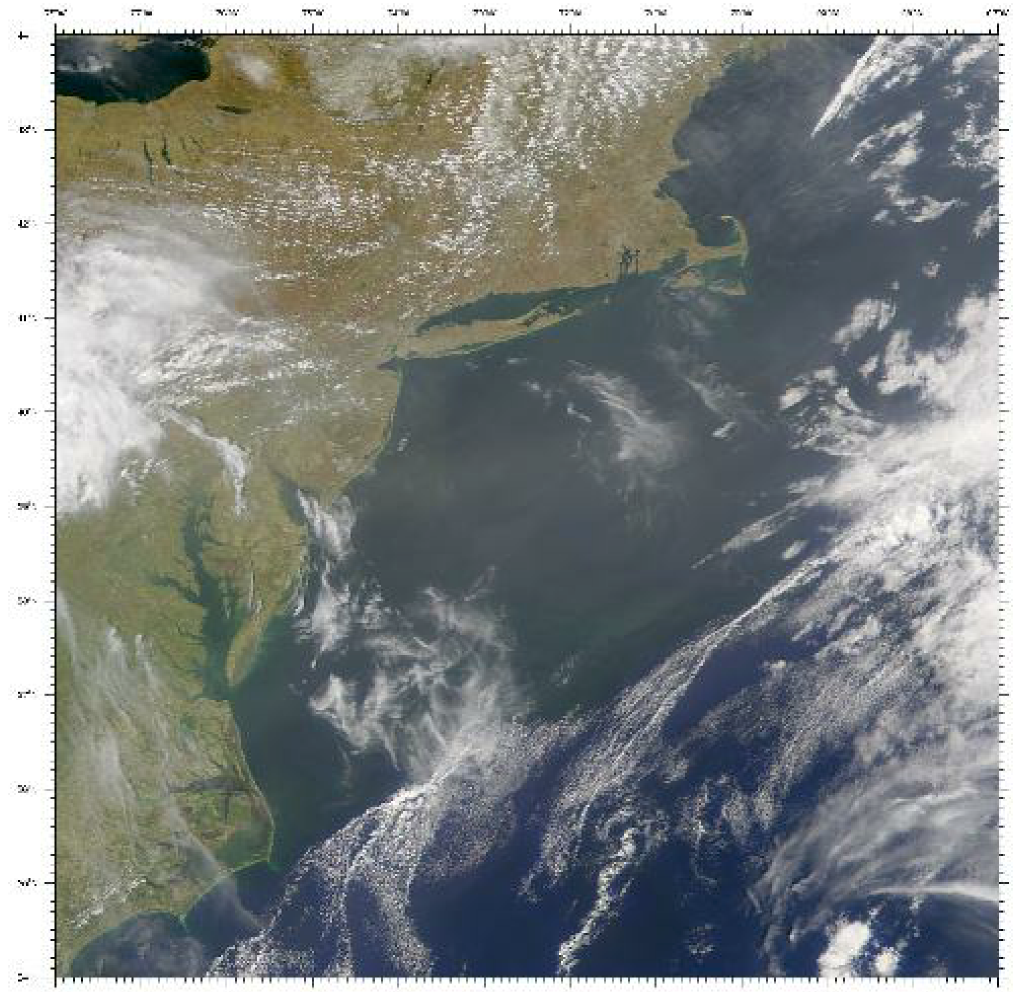
November 8, 2002

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

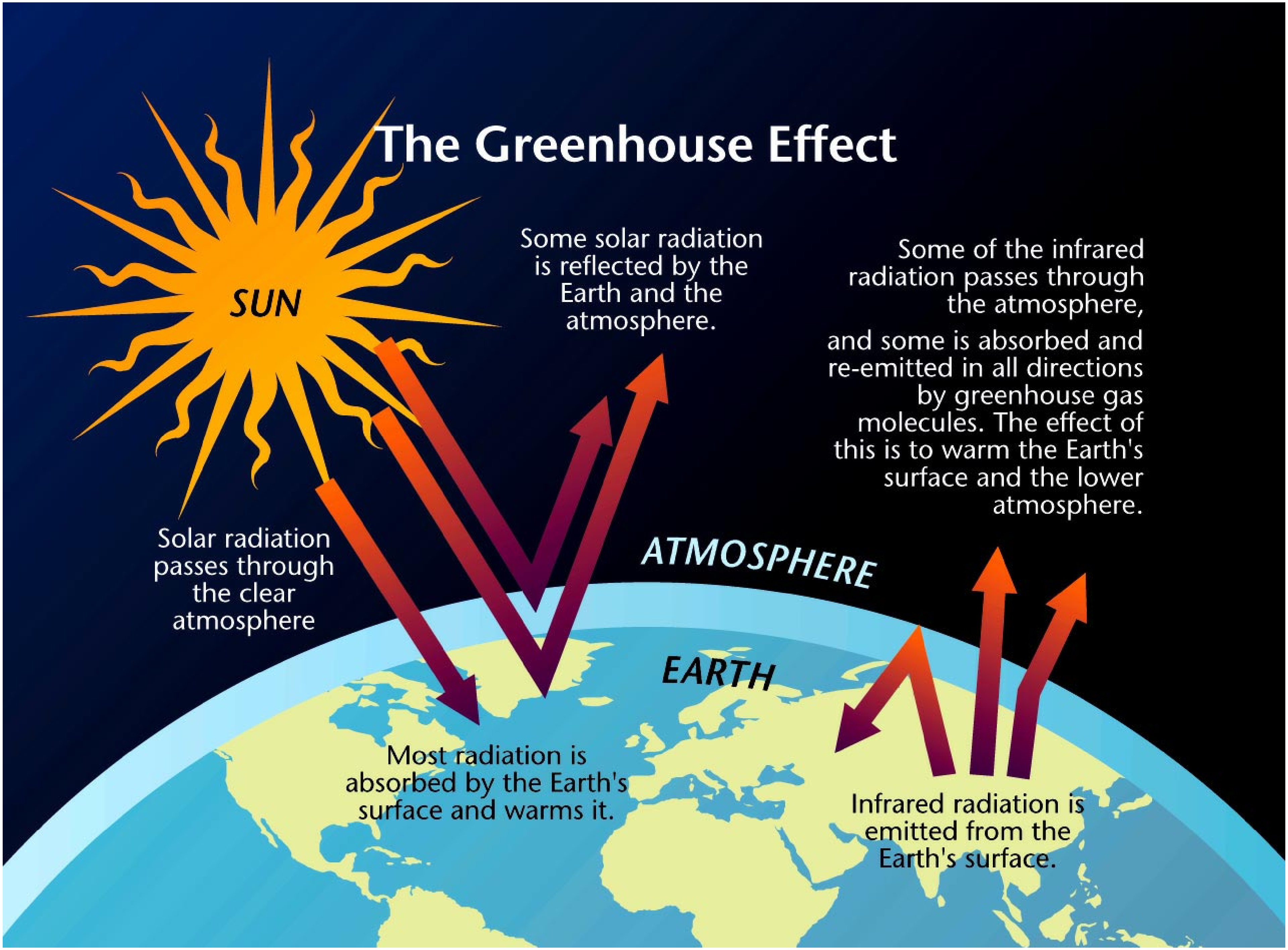
AEROSOL: A suspension of particles in air





2001-04-22-17:28
SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE

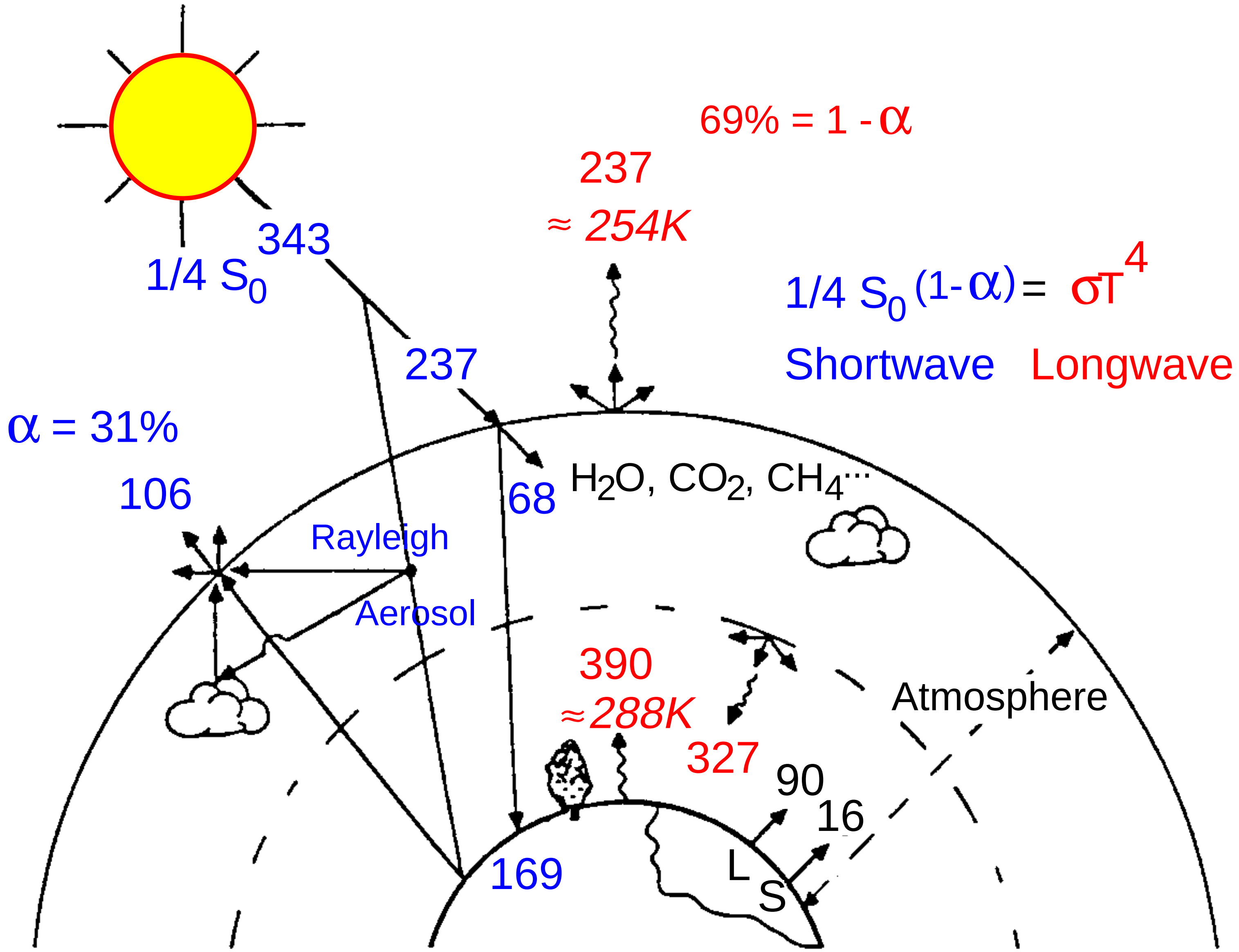
Atmospheric aerosols may result from primary emissions (dust, smoke) or from gas to particle conversion in the atmosphere (haze, smog).



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



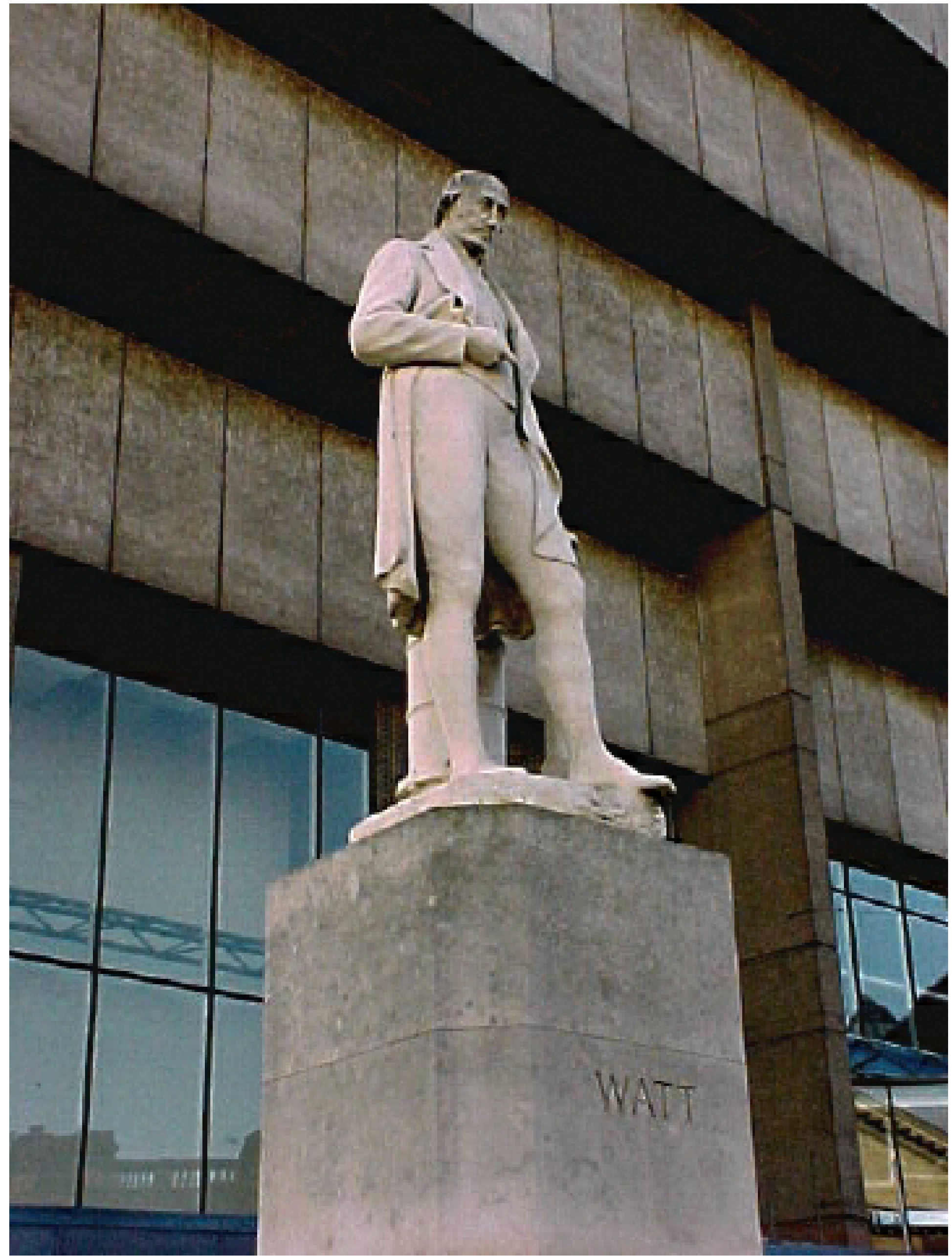
Schwartz, 1996, modified from Ramanathan, 1987

ATMOSPHERIC RADIATION

Energy per area per time

Power per area

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



RADIATIVE FORCING

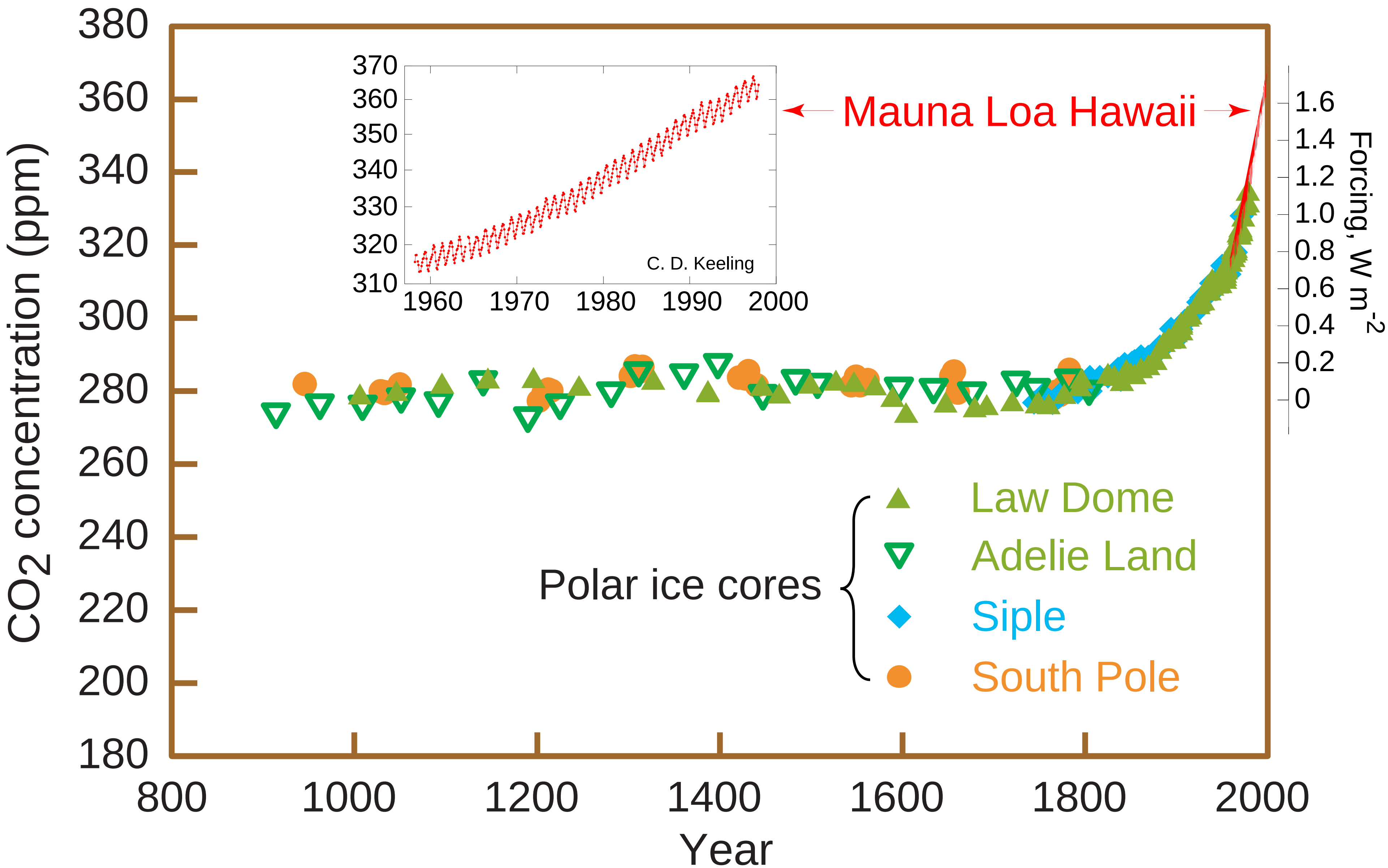
A ***change*** in a radiative flux term in the Earth's radiation budget, ΔF, W m^{-2}.

Working hypothesis:

On a global basis radiative forcings are additive and fungible.

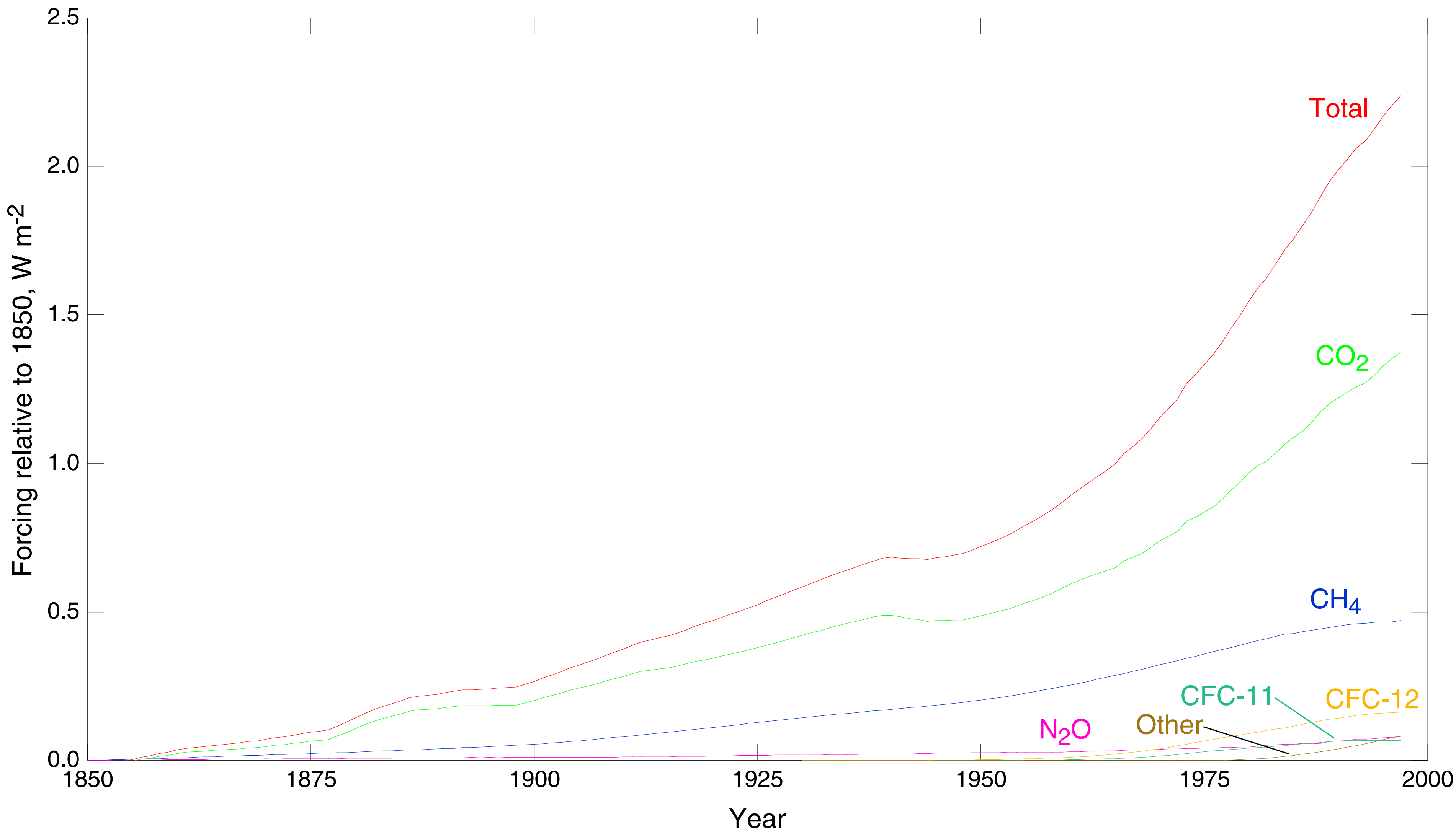
- This hypothesis is fundamental to the radiative forcing concept.
- This hypothesis underlies much of the assessment of climate change over the industrial period.

ATMOSPHERIC CARBON DIOXIDE IS INCREASING



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

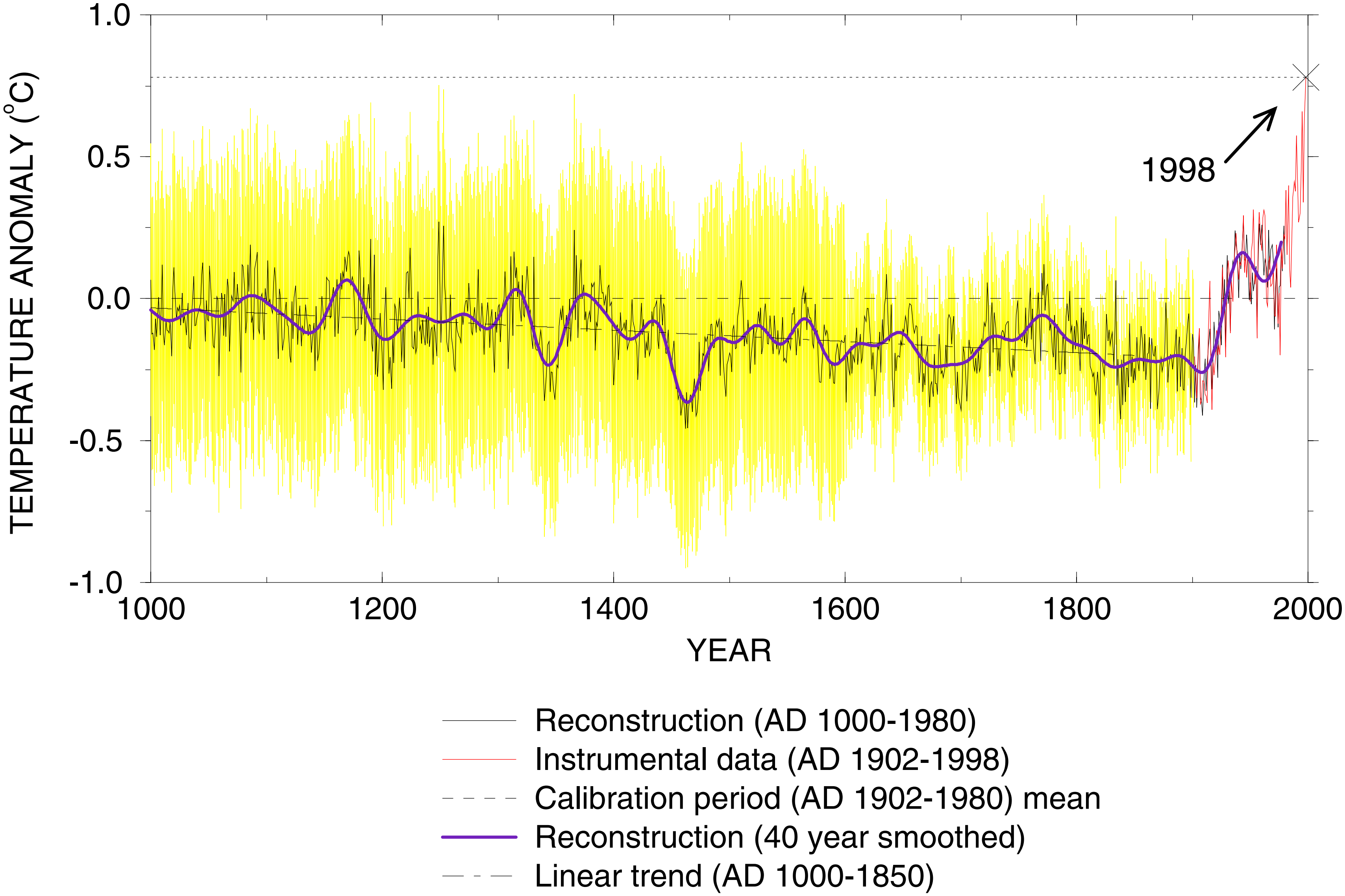
GREENHOUSE GAS FORCINGS OVER THE INDUSTRIAL PERIOD



Data: GISS

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

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.

$$\Delta T = \lambda \, \Delta F$$

CLIMATE SENSITIVITY

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

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.

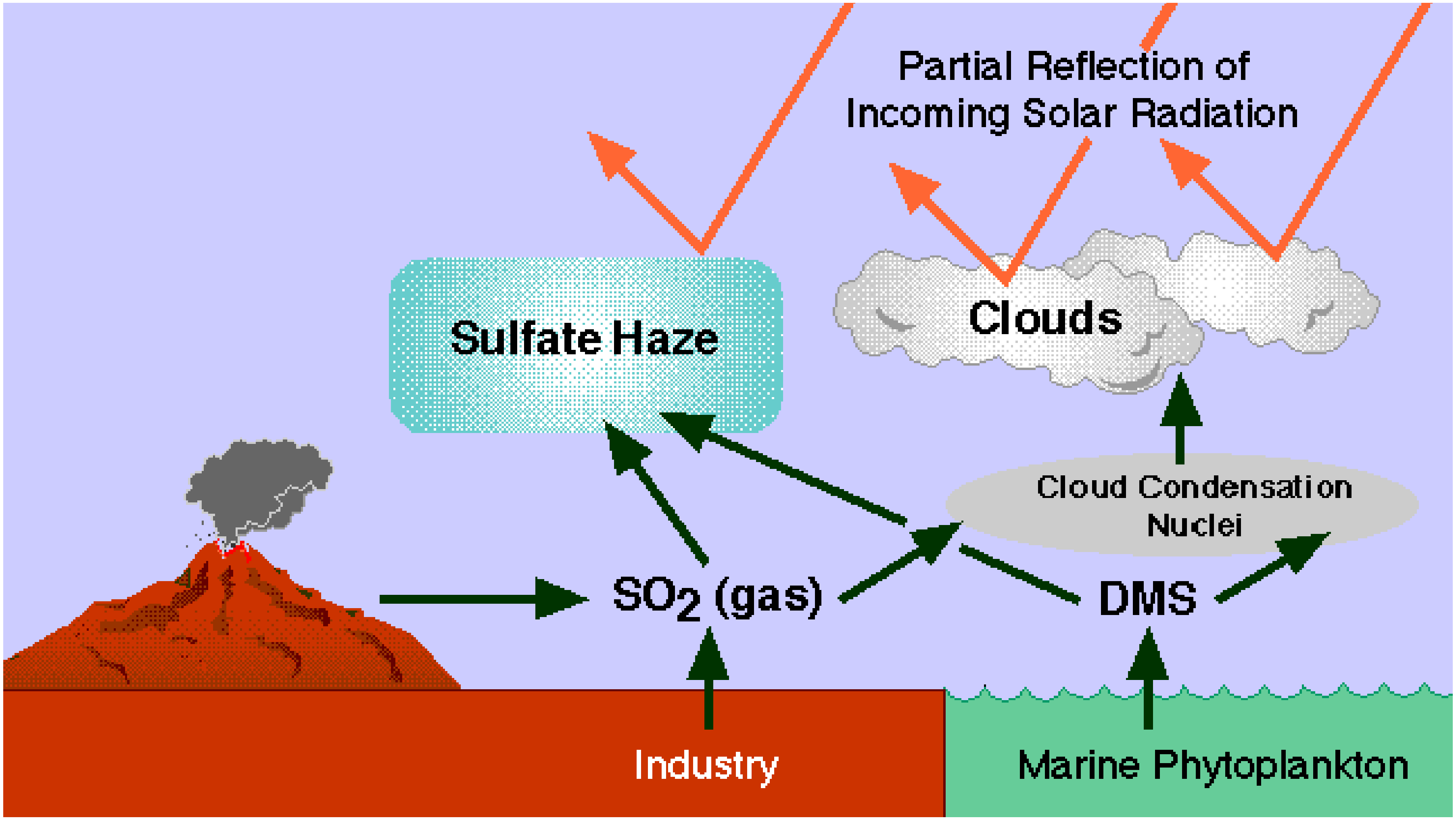
Empirical Sensitivity: $\lambda = \frac{dT}{dF} = \frac{0.6\ \text{K}}{2.5\ \text{W m}^{-2}} = 0.24\ \text{K} \ / \ (\text{W m}^{-2})$

CLIMATE CHANGE SENSITIVITY
Summary of Current Models
Units: K / (W m^{-2})

Number of Models	Mean	Standard Deviation	Range
15	0.87	0.23	0.5 - 1.25

IPCC, Climate Change 2001, Cambridge University Press, 2001

RADIATIVE FORCING OF CLIMATE CHANGE BY AEROSOLS



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

BIOMASS BURNING AND WIDESPREAD AEROSOL
Northeastern Oklahoma, 2000-12-01

DIRECT RADIATIVE FORCING DUE TO ANTHROPOGENIC SULFATE AEROSOL

Geophysics — Aerosol Optical Depth

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

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

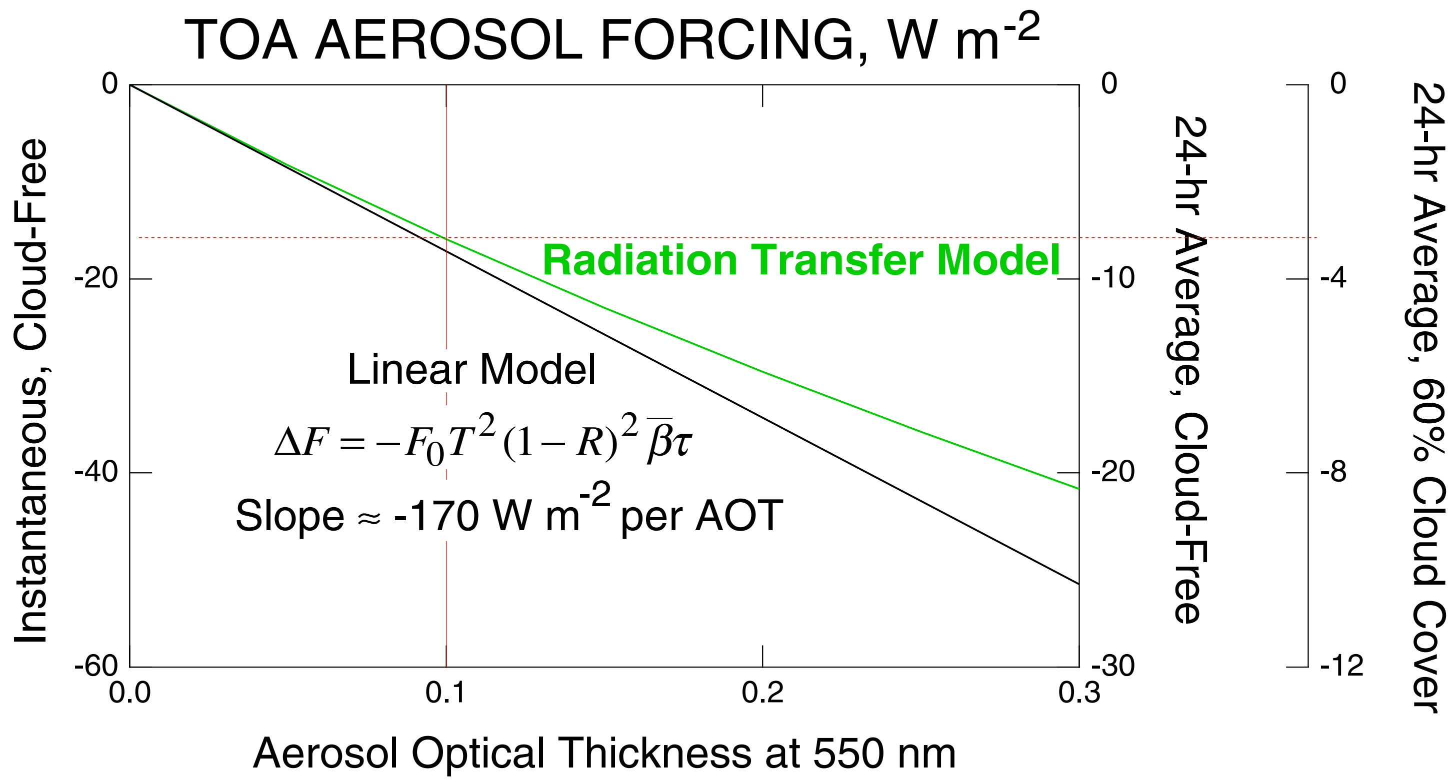
Penner, Charlson, Hales, Laulainen, Leifer, Novakov, Ogren, Radke, Schwartz & Travis, BAMS, 1994

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 $\omega_0 = 1$.

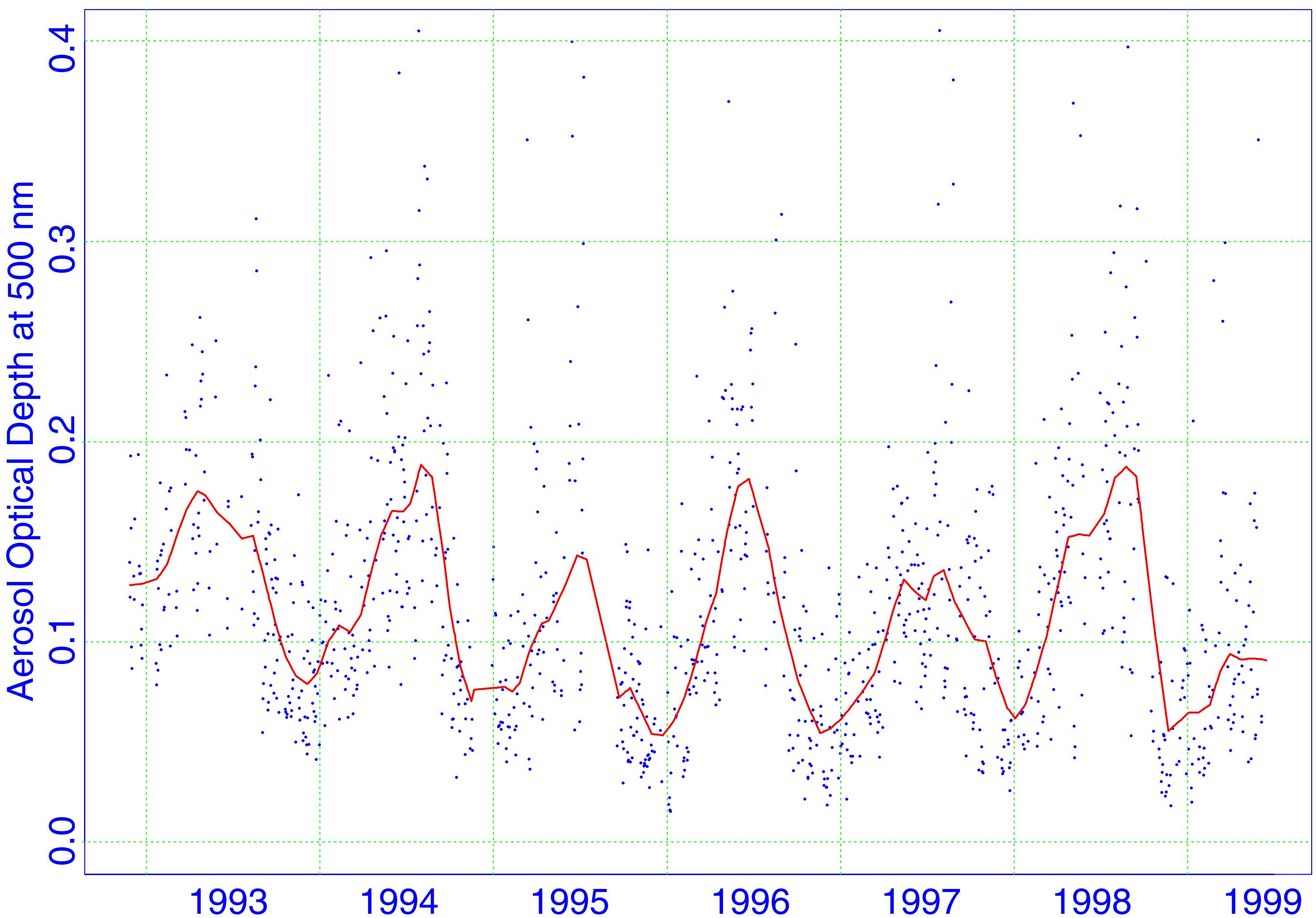


Global-average AOT 0.1 corresponds to global-average forcing -3.2 W m^{-2}.

AEROSOL OPTICAL DEPTH

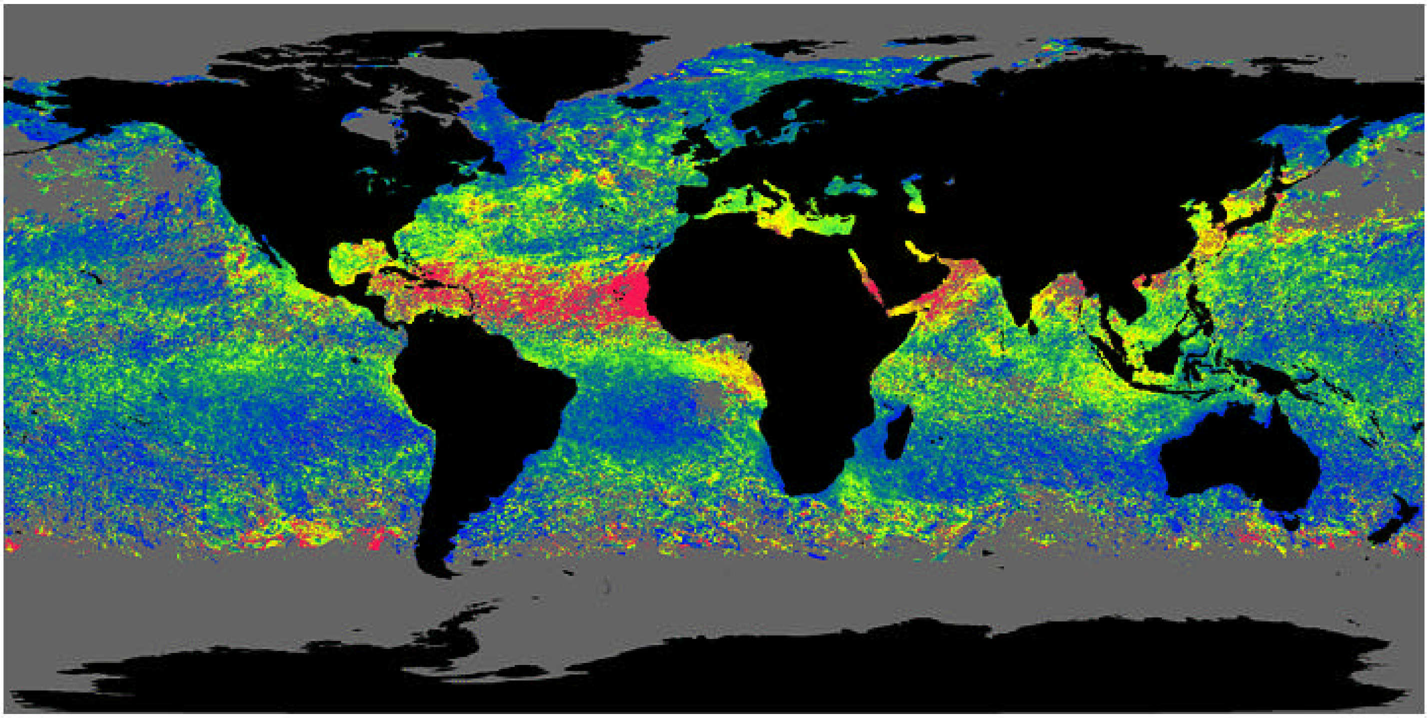
Determined by Sunphotometry

North Central Oklahoma

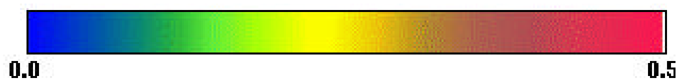


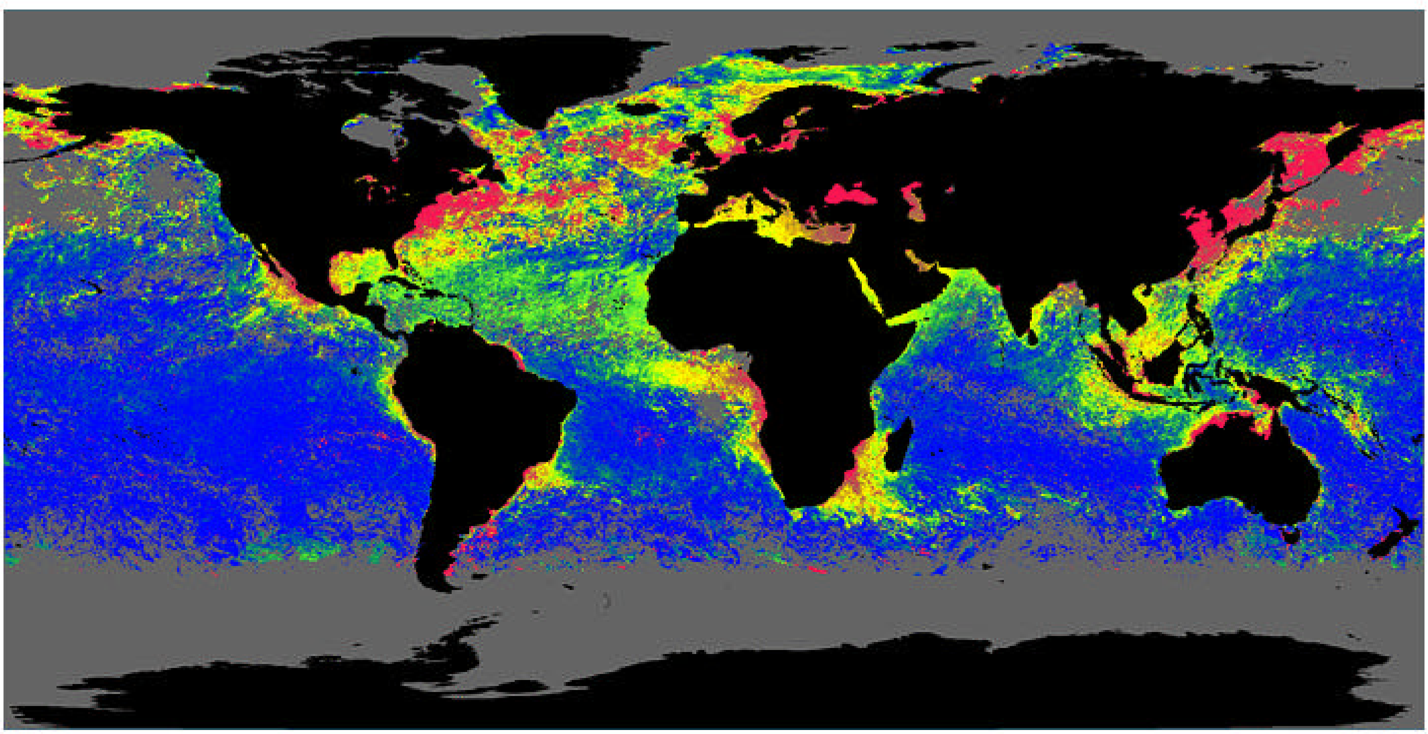
J. Michalsky et al., JGR, 2001

MONTHLY AVERAGE AEROSOL JUNE 1997



Optical Thickness at 865 nm

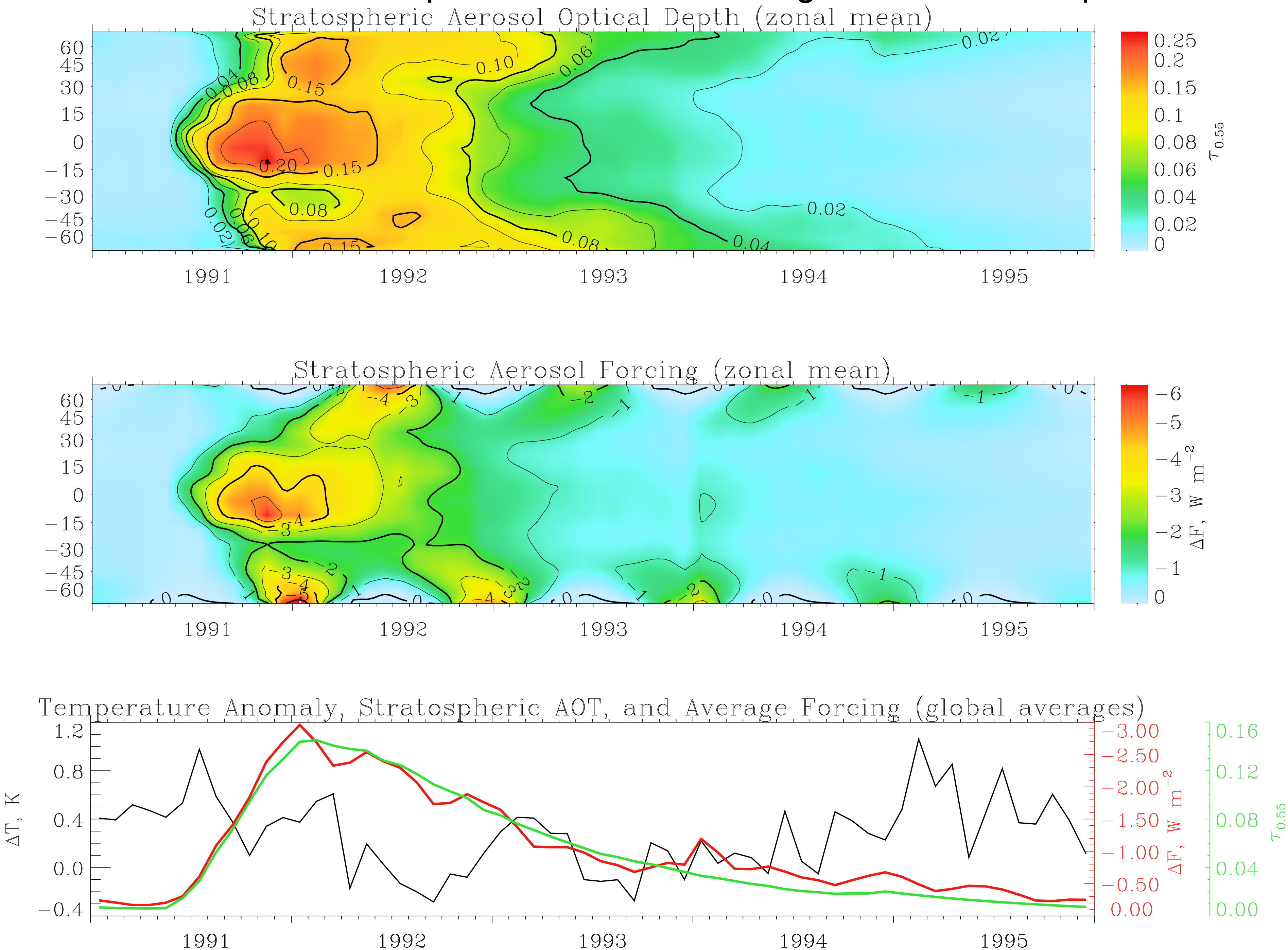




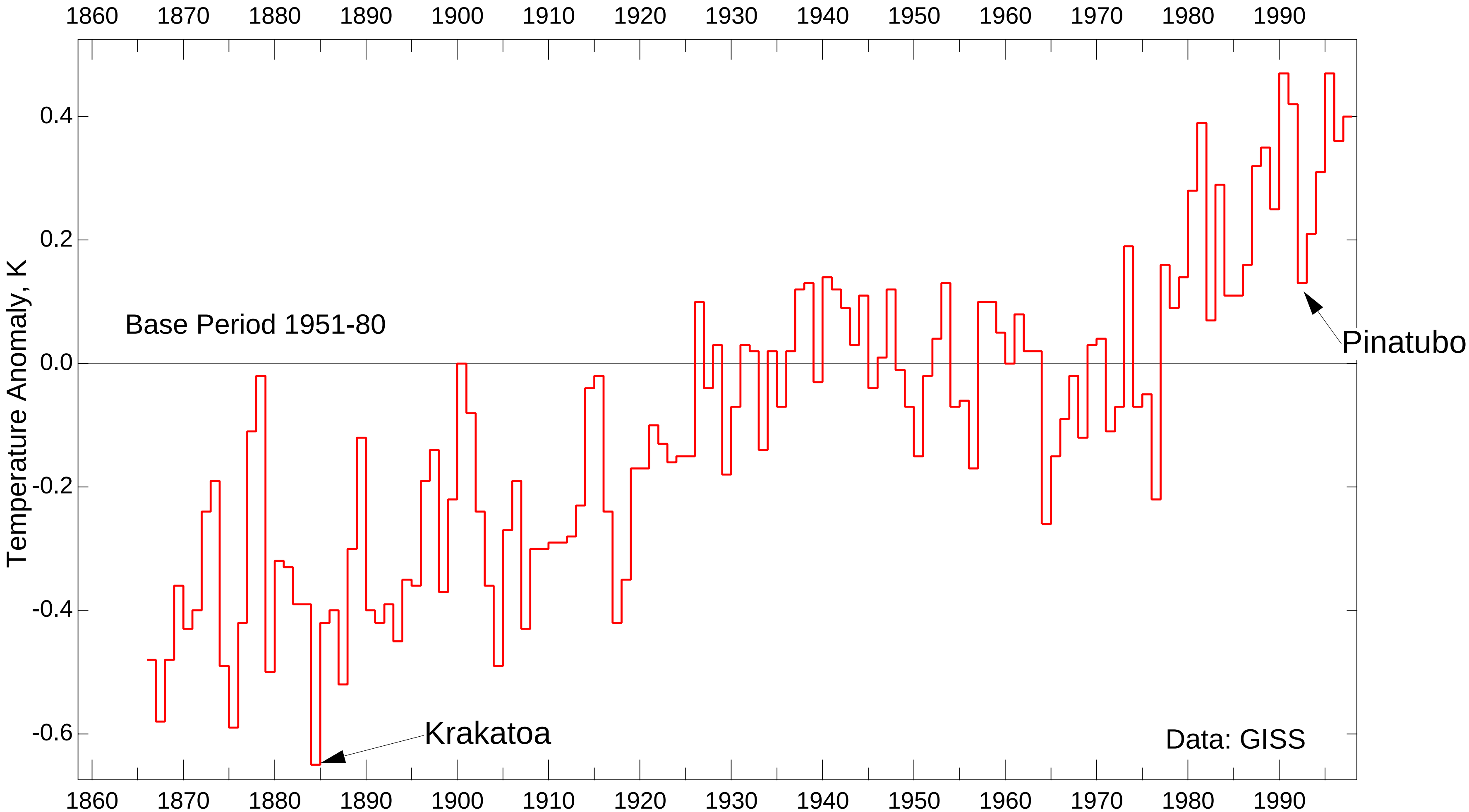
Ångström Exponent

Polder/Adeos CNES/NASDA LOA/LSCE

Influence of Pinatubo Eruption on Aerosol Forcing and Global Temperature



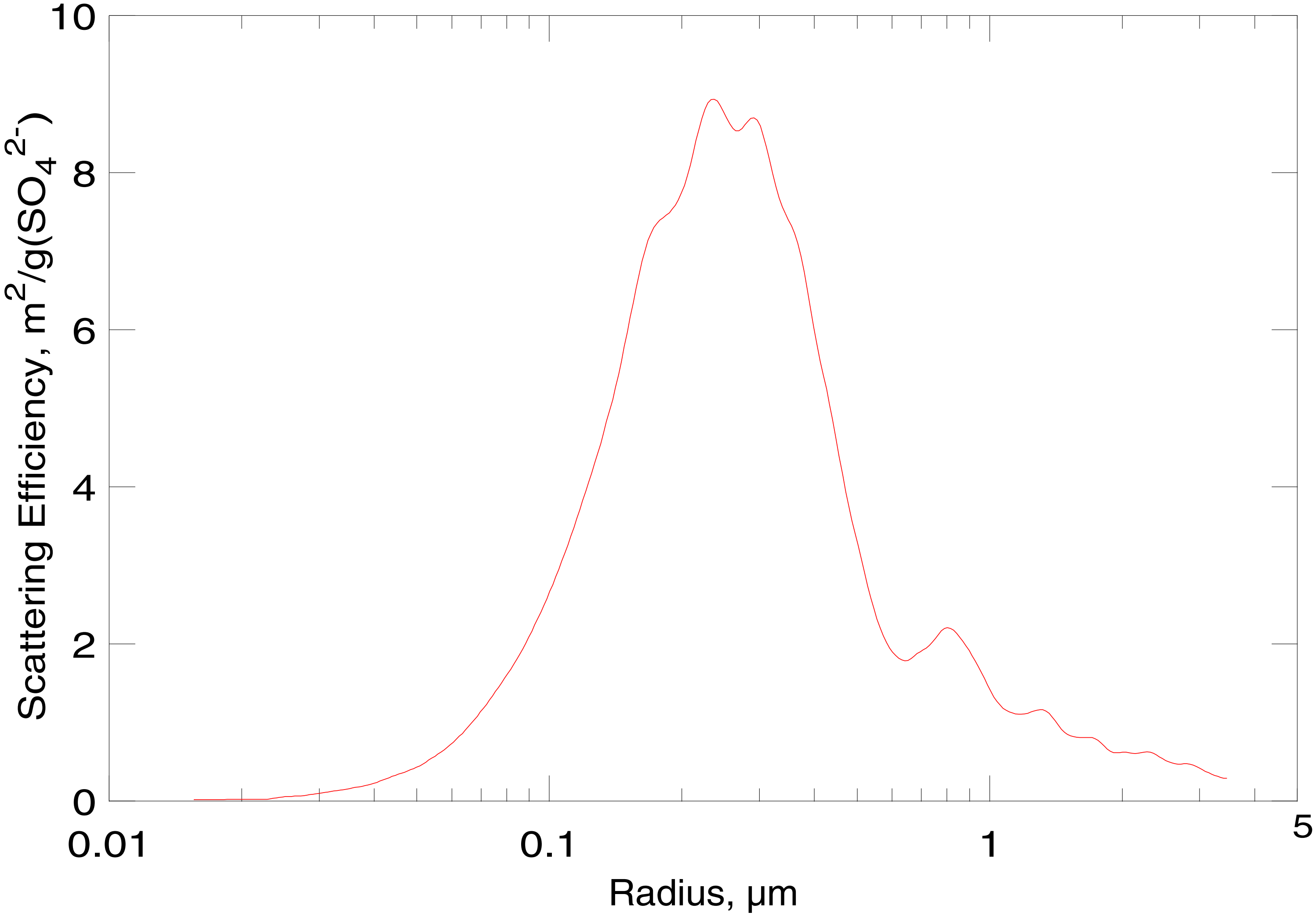
GLOBAL TEMPERATURE TREND OVER THE INDUSTRIAL PERIOD



LIGHT SCATTERING EFFICIENCY

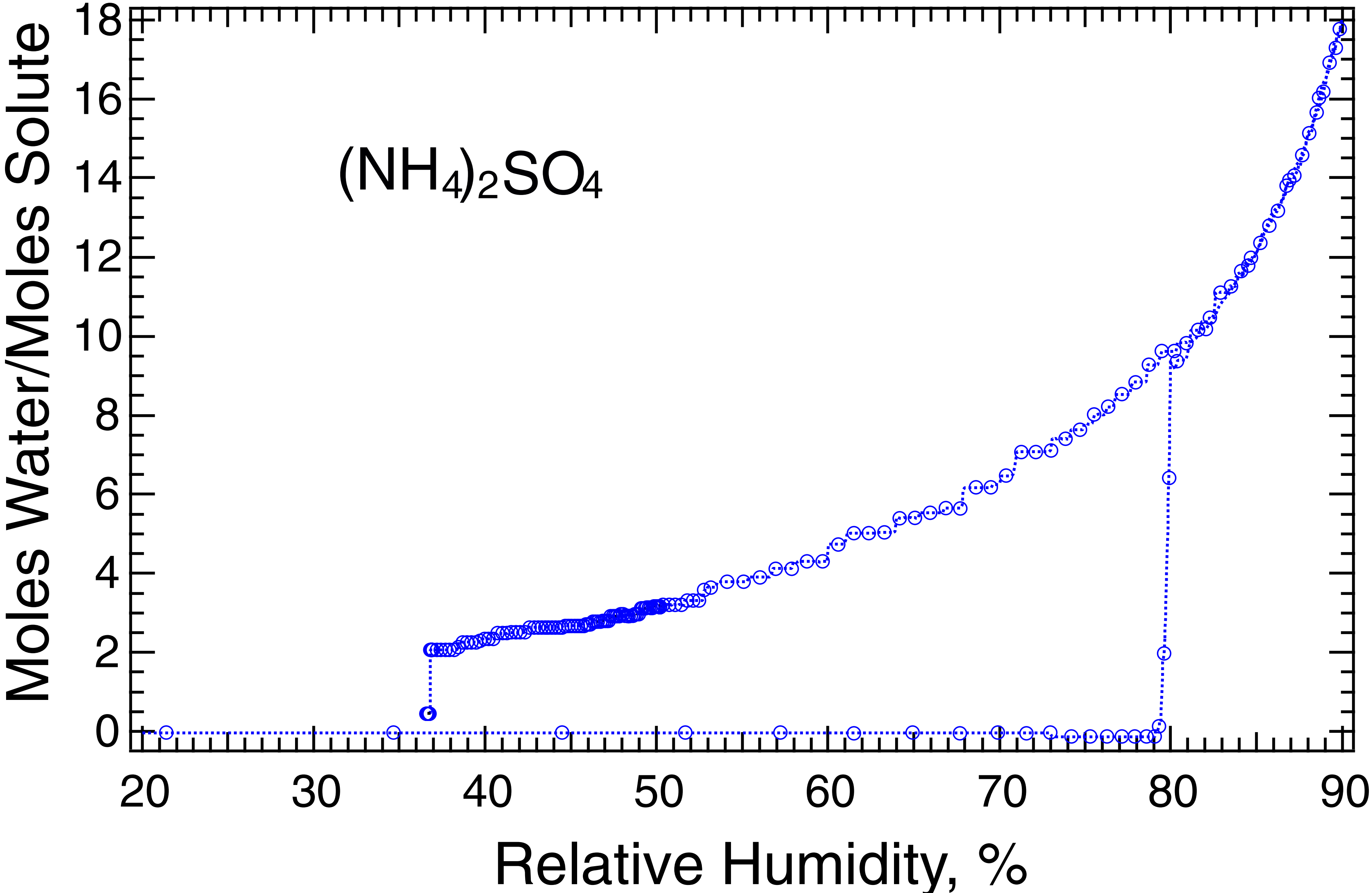
Dependence on particle radius

Ammonium Sulfate, 530 nm



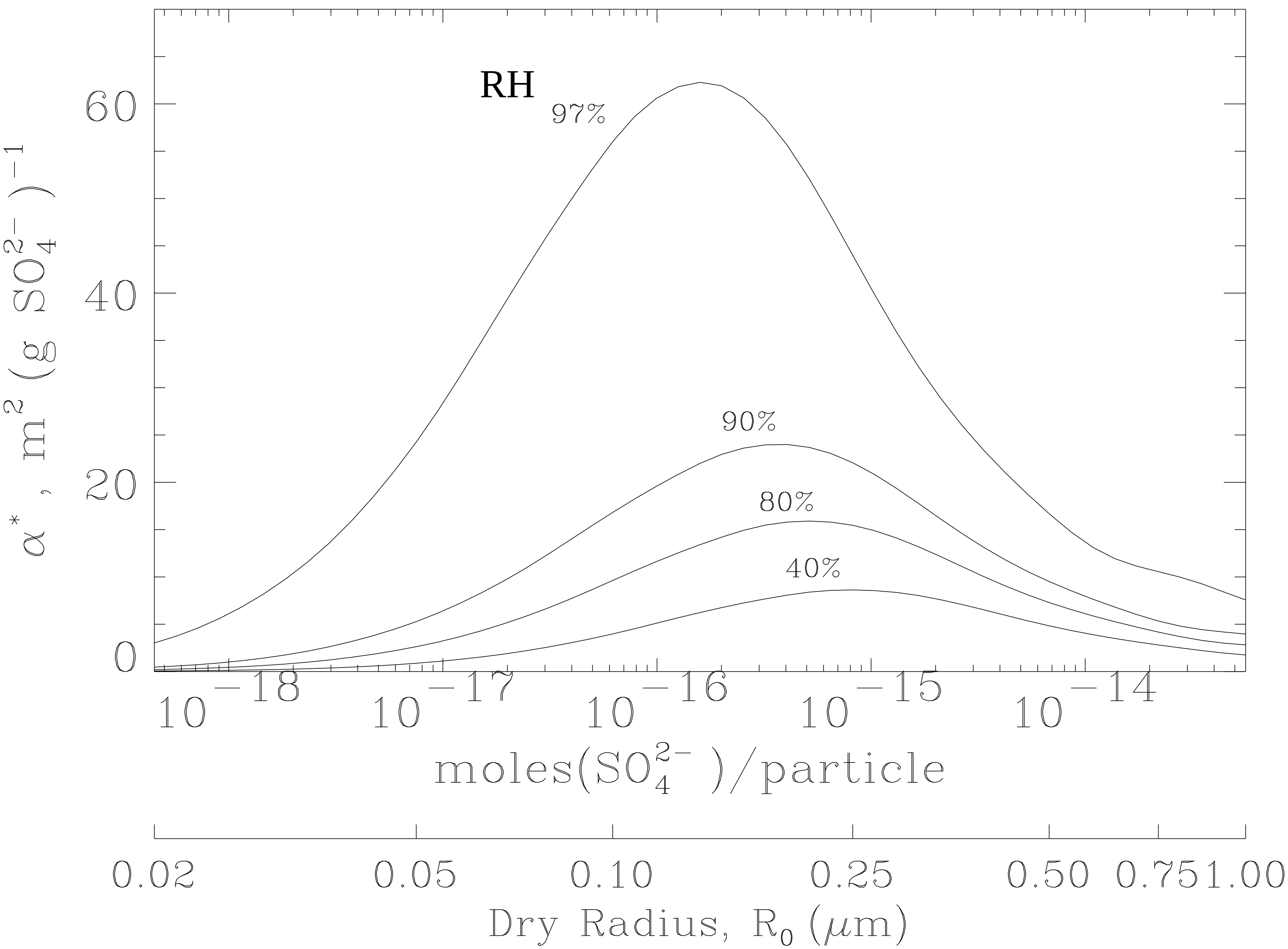
Data of Ouimette and Flagan, 1982

WATER UPTAKE BY HYGROSCOPIC PARTICLE
Dependence on relative humidity



D. Imre, T. Onasch, BNL

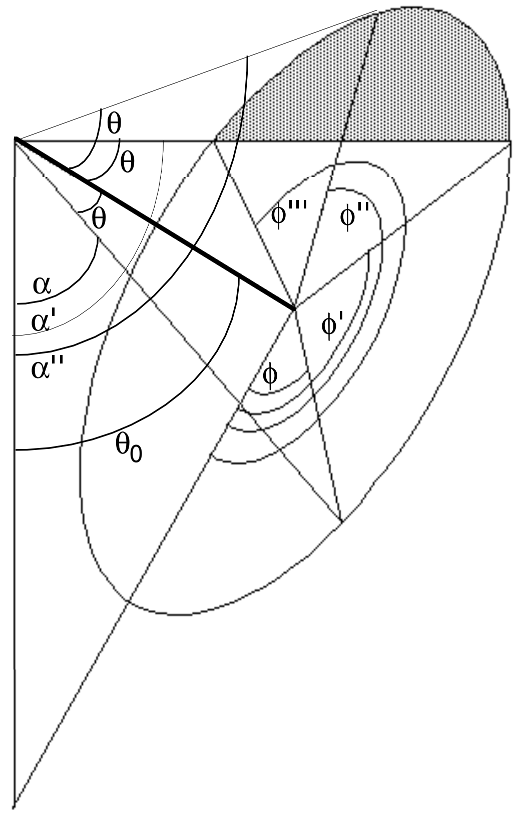
LIGHT SCATTERING EFFICIENCY OF $(NH_4)_2SO_4$ DEPENDENCE ON PARTICLE SIZE AND RH



Nemesure et al., JGR, 1995

UPSCATTER FRACTION

SCATTERING OF SOLAR RADIATION BY AEROSOL PARTICLE

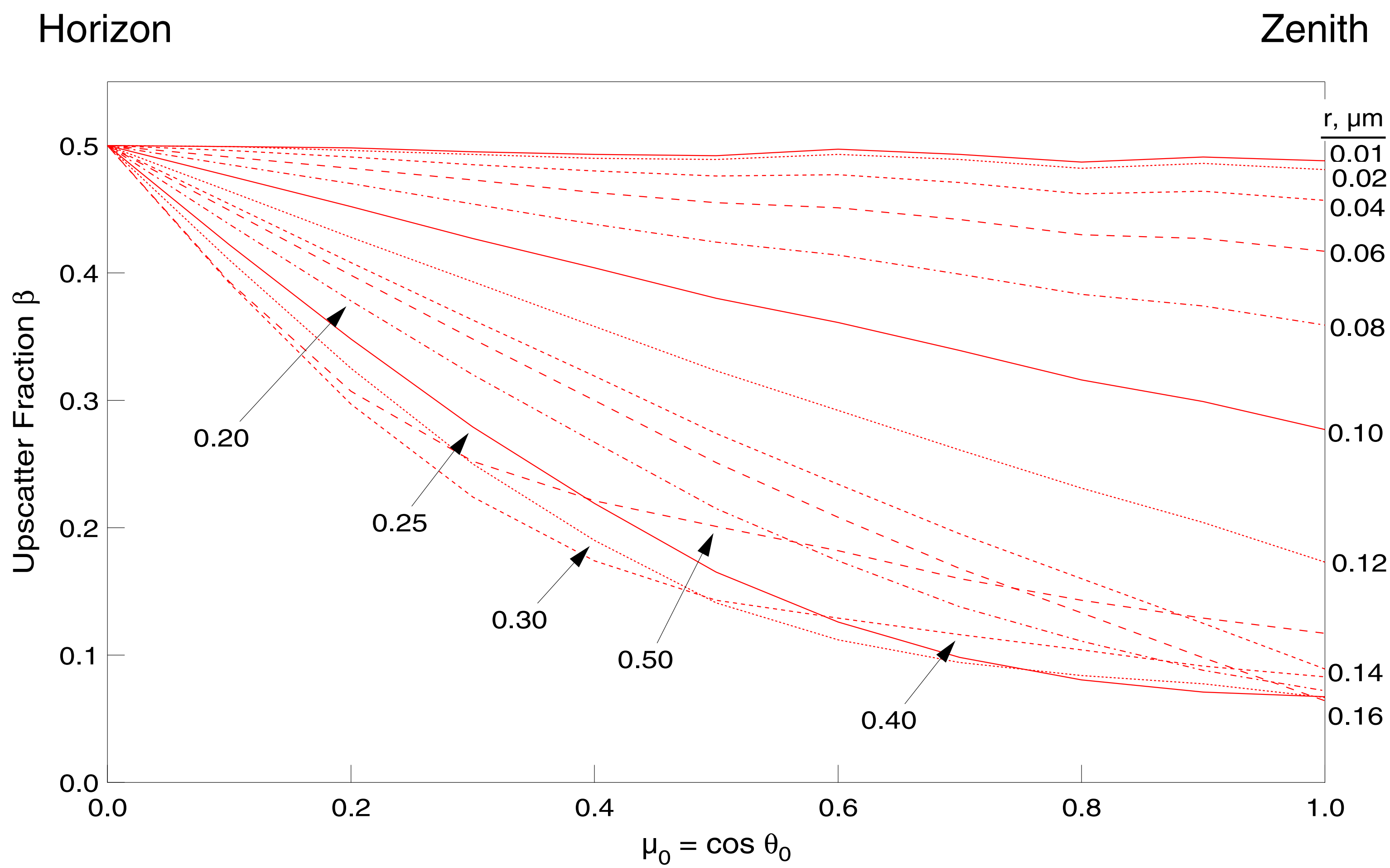


Upscatter fraction β is the fraction of radiation scattered into the upward hemisphere.

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

UPSCATTER FRACTION

Dependence on solar zenith angle and particle radius



λ = 0.55 μm. *n* = 1.40 - 0*i*.

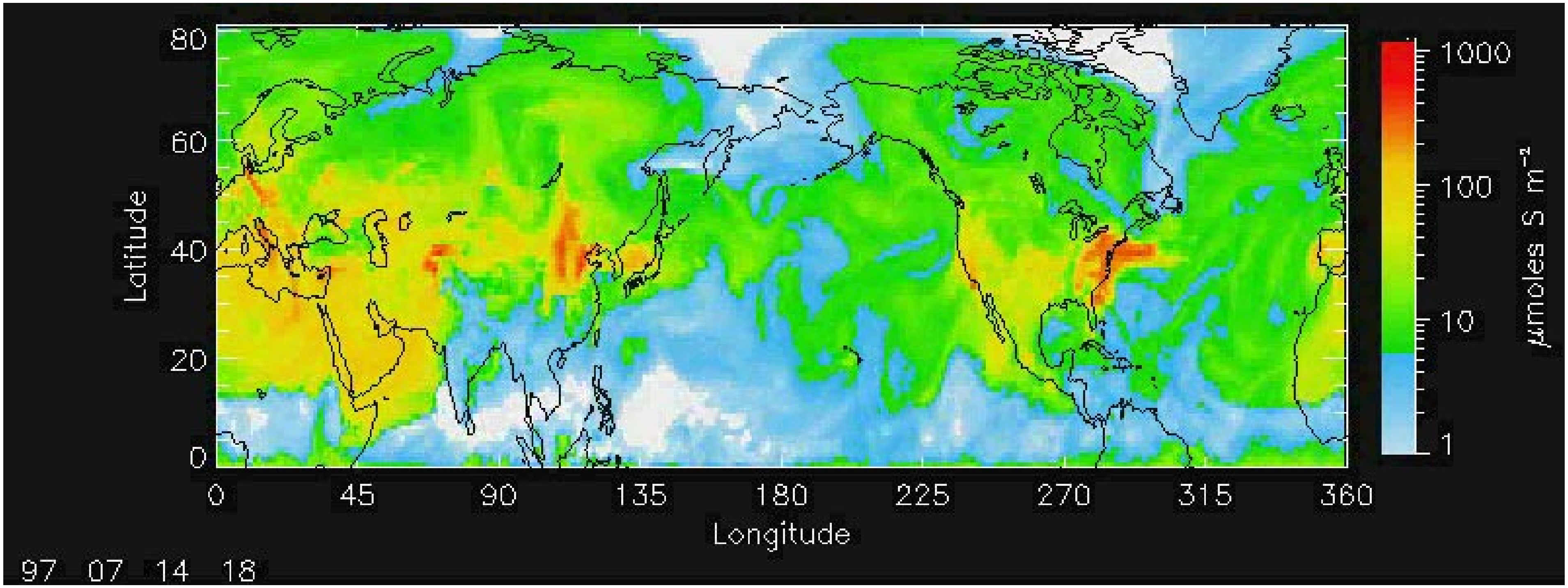
For sun at horizon β = 0.5 (by symmetry).

For small particles, *r* << λ, upscatter fraction approaches that for Rayleigh scattering (0.5).

HEMISPHERIC DISTRIBUTION OF SULFATE COLUMN BURDEN

Vertical integral of concentration

July 14, 1997, 1800 UTC

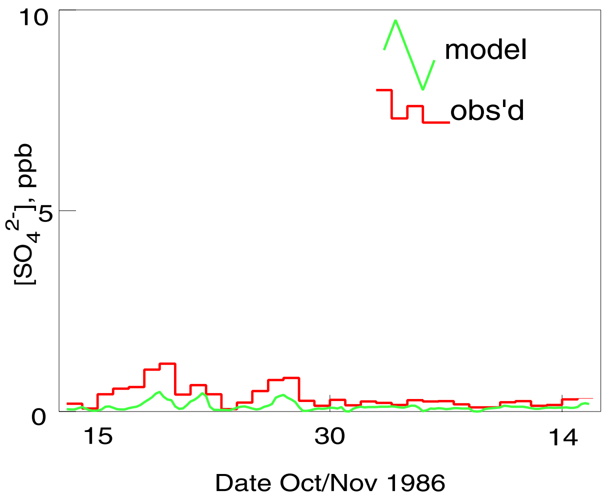


Brookhaven National Laboratory Chemical Transport Model

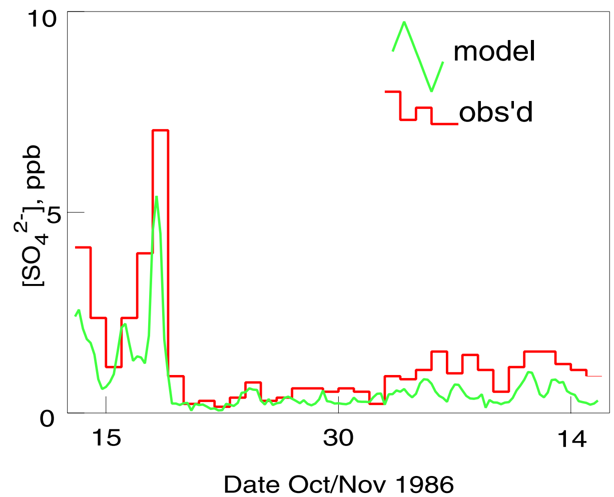
COMPARISON OF MODEL AND OBSERVATIONS

Comparisons for 24-hr sulfate mixing ratio at surface

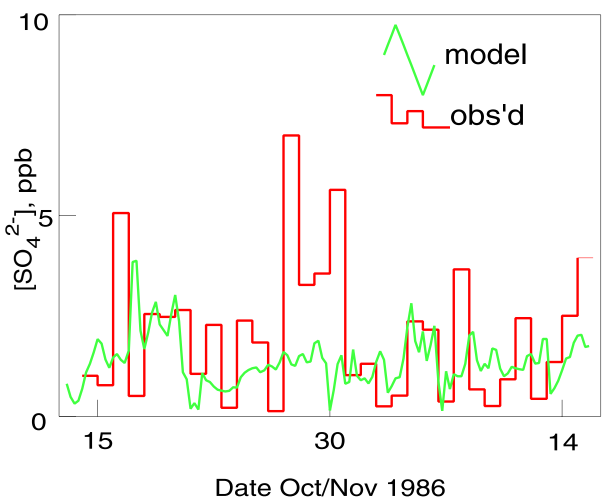
MANITOBA, CANADA



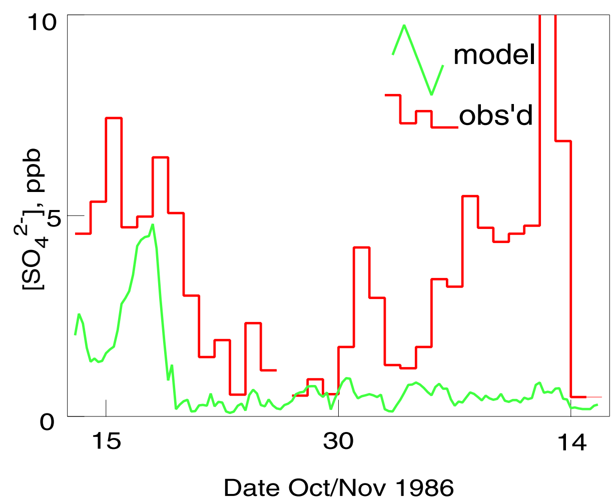
DEUSELBACH, GERMANY



JUNGFRAUJOCH, SWITZERLAND



JARCZEW, POLAND



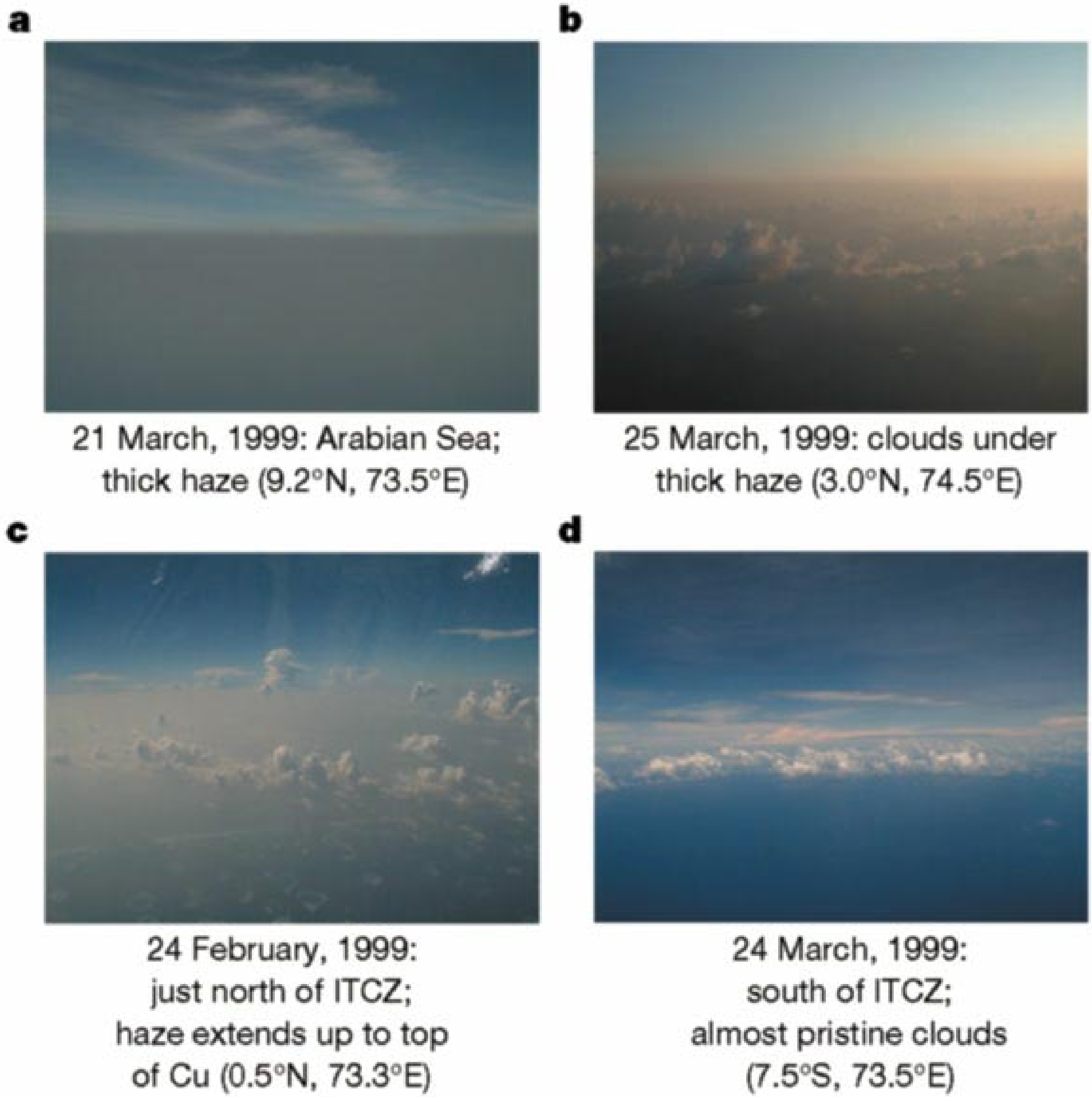
COMPARISON OF MODEL AND OBSERVATIONS

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

CLOUDS AND AEROSOLS DURING INDOEX PROJECT



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 (σ_{sp})
- Mass Concentration (C)
- Mass Scattering Efficiency (α)
- Aerosol Optical Depth (τ)
- Mean Upscatter Fraction ($\bar{\beta}$)
- Surface Reflectance (R)
- Cloud Fraction (A_c)
- Atmospheric Transmittance (T)
- Solar Constant (F_0)
- Change in Net TOA Flux (ΔF)

Global Average for ***Absorbing*** Aerosol

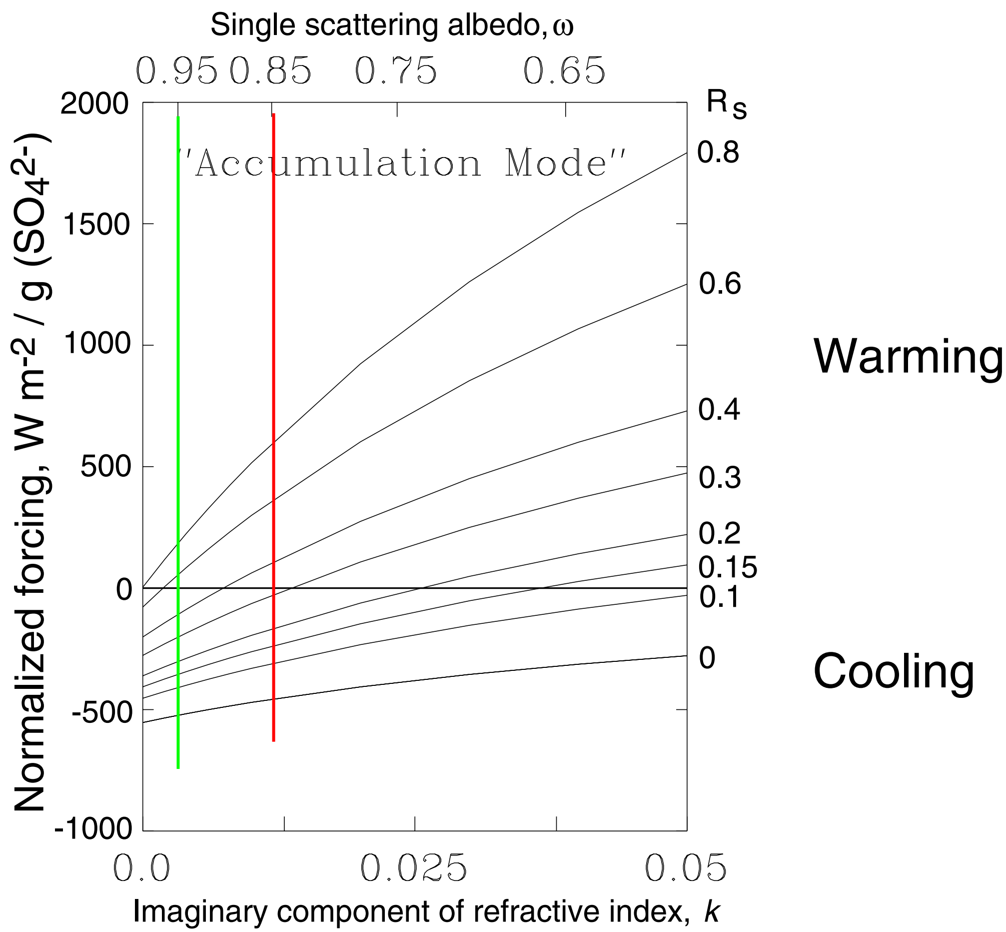
$$\Delta F = -\frac{1}{2} F_0 T^2 (1 - A_c)(1 - R)^2 \bar{\beta}\tau\omega \left\{ 1 - \frac{2R}{(1-R)^2} \frac{(1-\omega)}{\bar{\beta}\omega} \right\}$$

- Single Scattering Albedo (ω)

RADIATIVE FORCING OF ABSORBING AEROSOL

Sulfate with uniformly admixed absorber

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

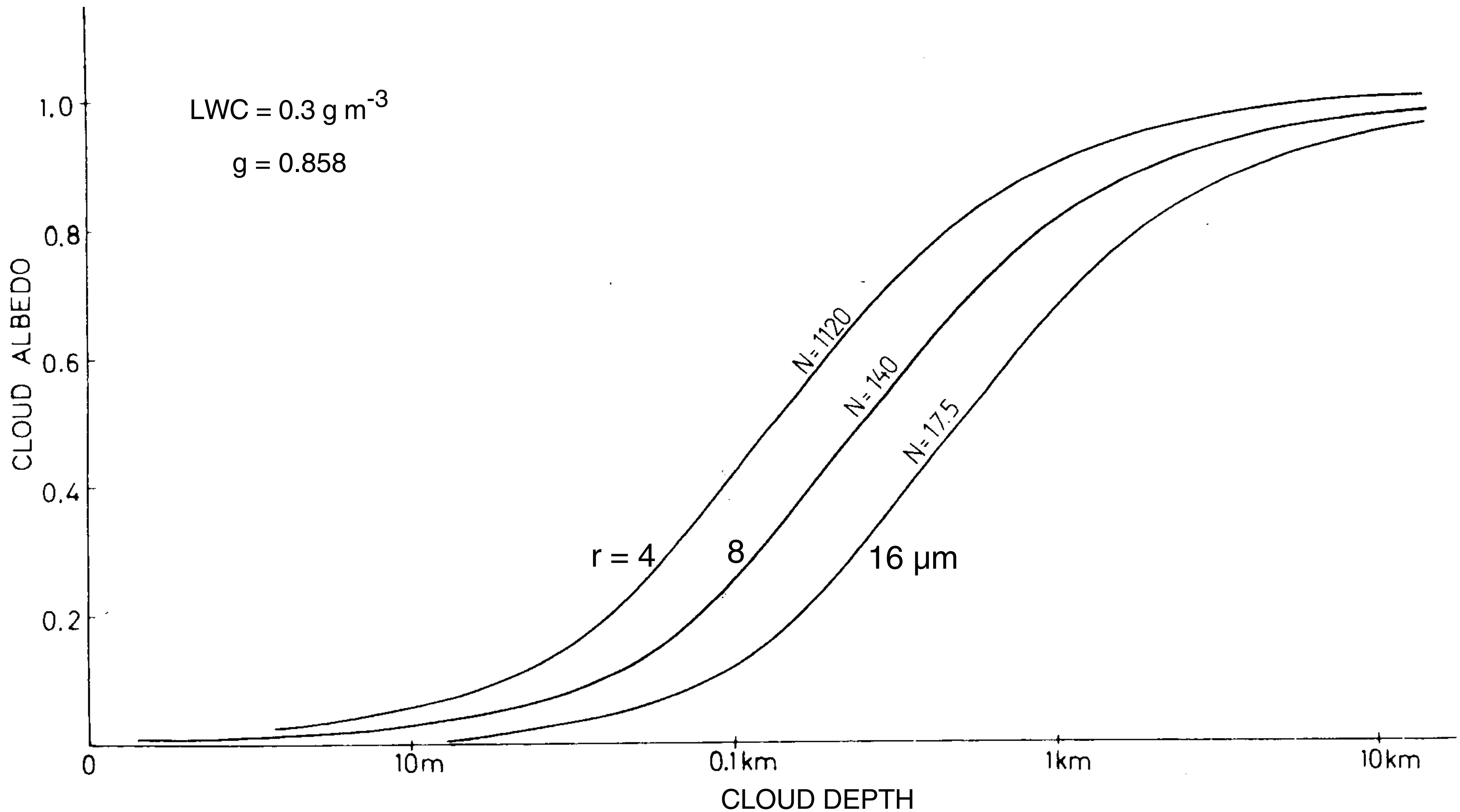


Compare to single scattering albedo w in north central Oklahoma, 0.92 ± 0.06 (one s.d.; 10,000 2-hour averages of 1-minute data).

INDIRECT EFFECT

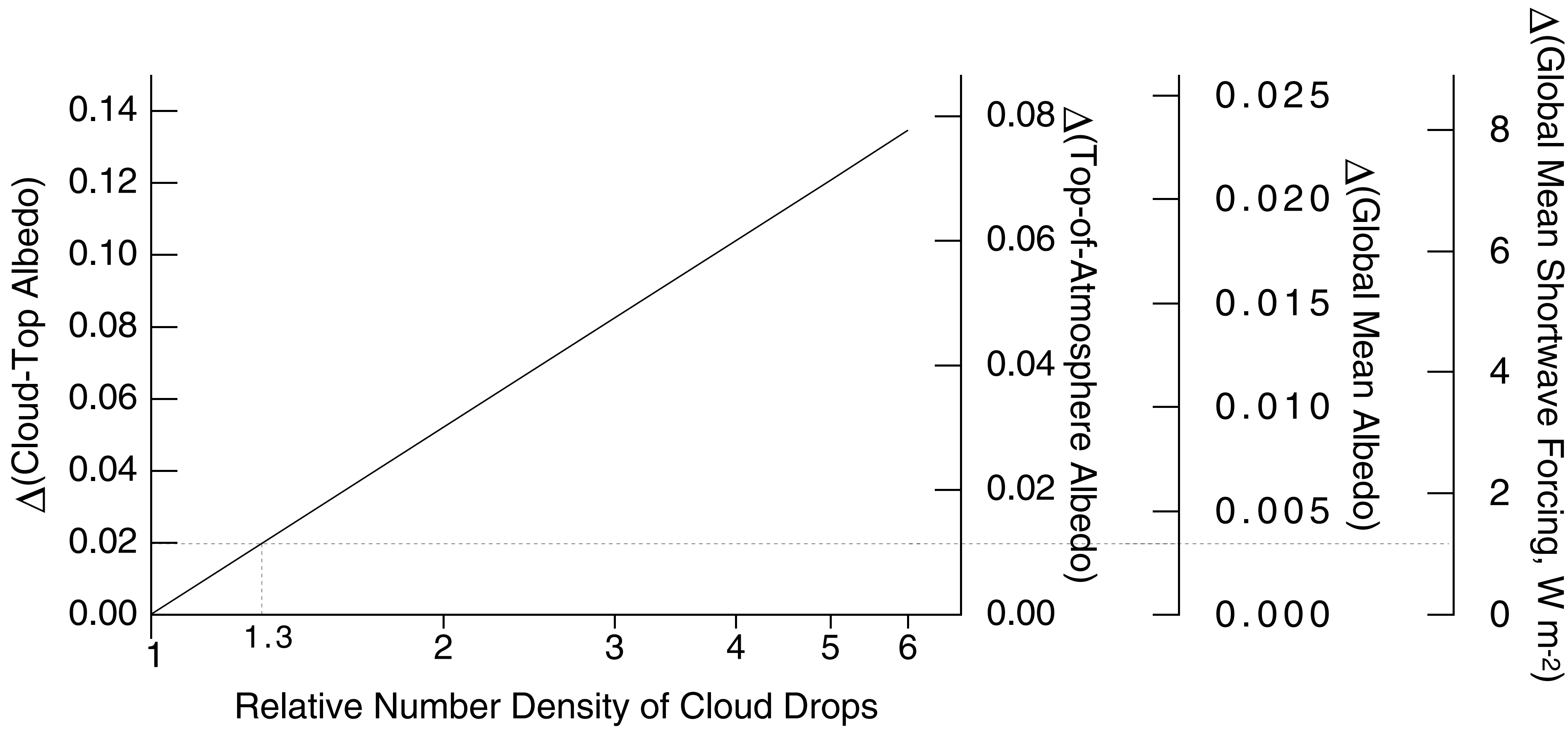
DEPENDENCE OF CLOUD ALBEDO ON CLOUD DEPTH

Influence of Cloud Drop Radius and Concentration



Twomey, *Atmospheric Aerosols*, 1977

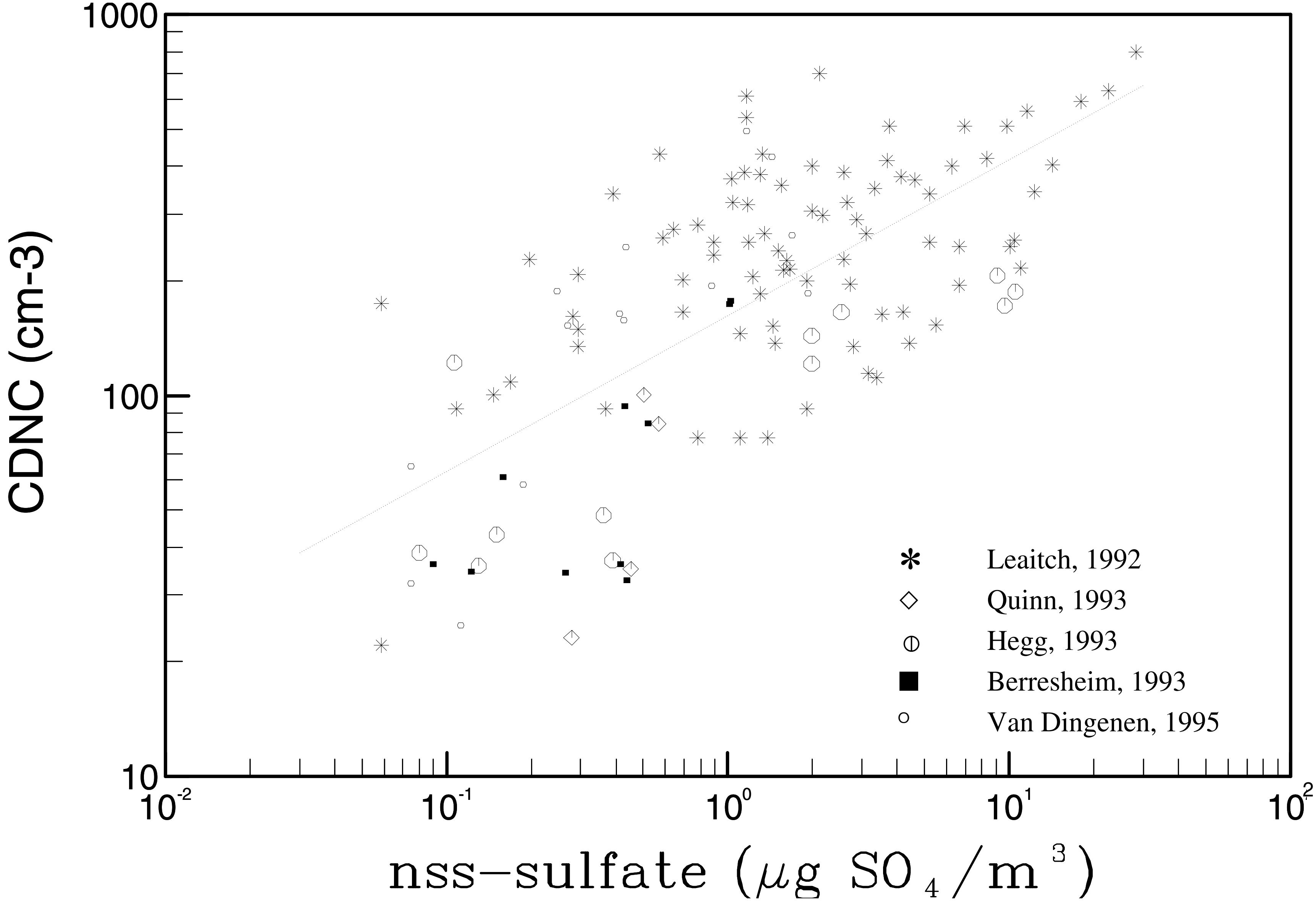
SENSITIVITY OF ALBEDO AND FORCING TO CLOUD DROP CONCENTRATION



Schwartz and Slingo (1996)

CLOUD DROPLET NUMBER CONCENTRATION

Dependence on Non-Seasalt Sulfate

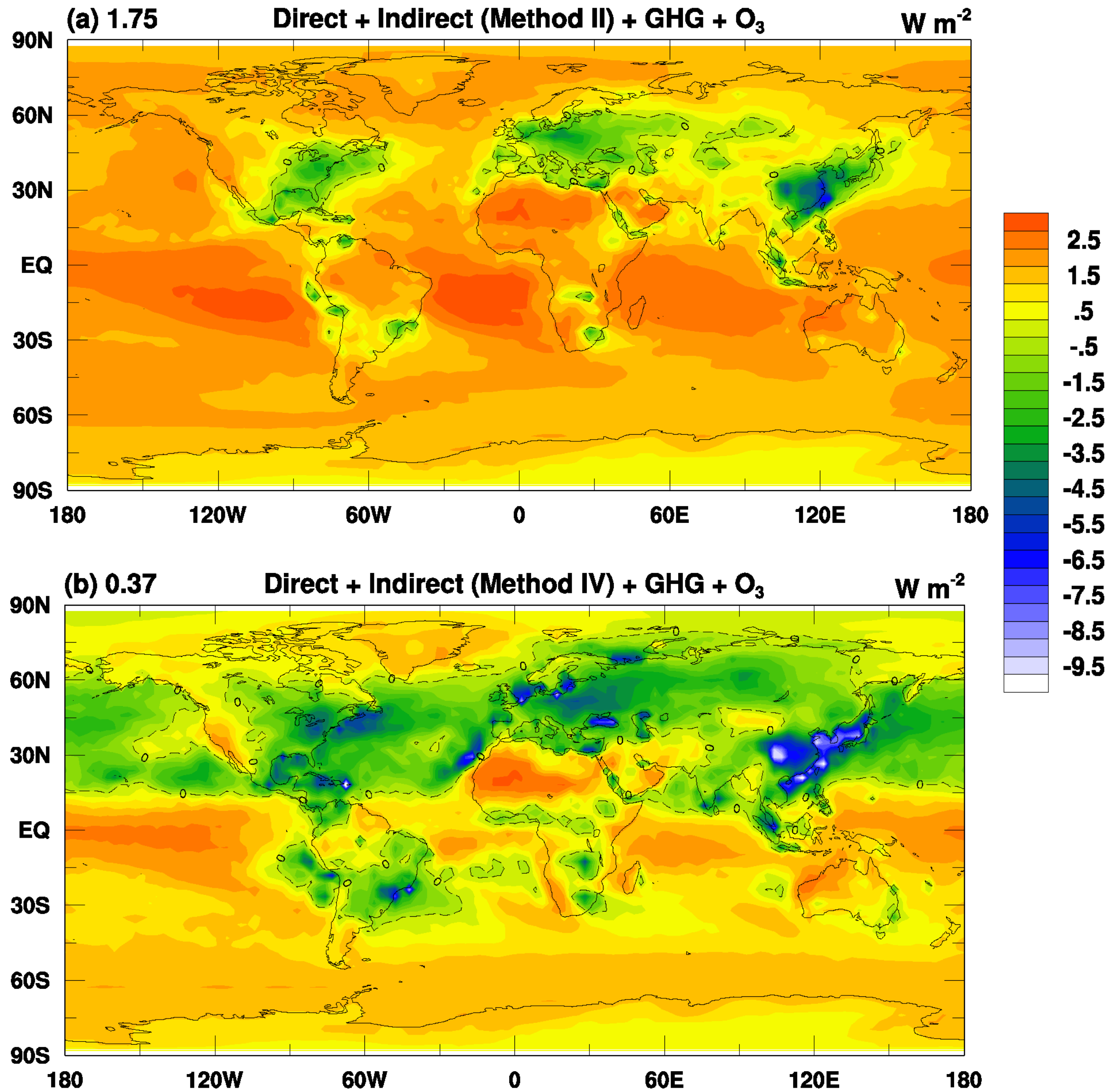


Boucher and Lohmann, 1995

SHORTWAVE FORCING, ANNUAL AVERAGE

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

Two Formulations of Cloud Droplet Concentration

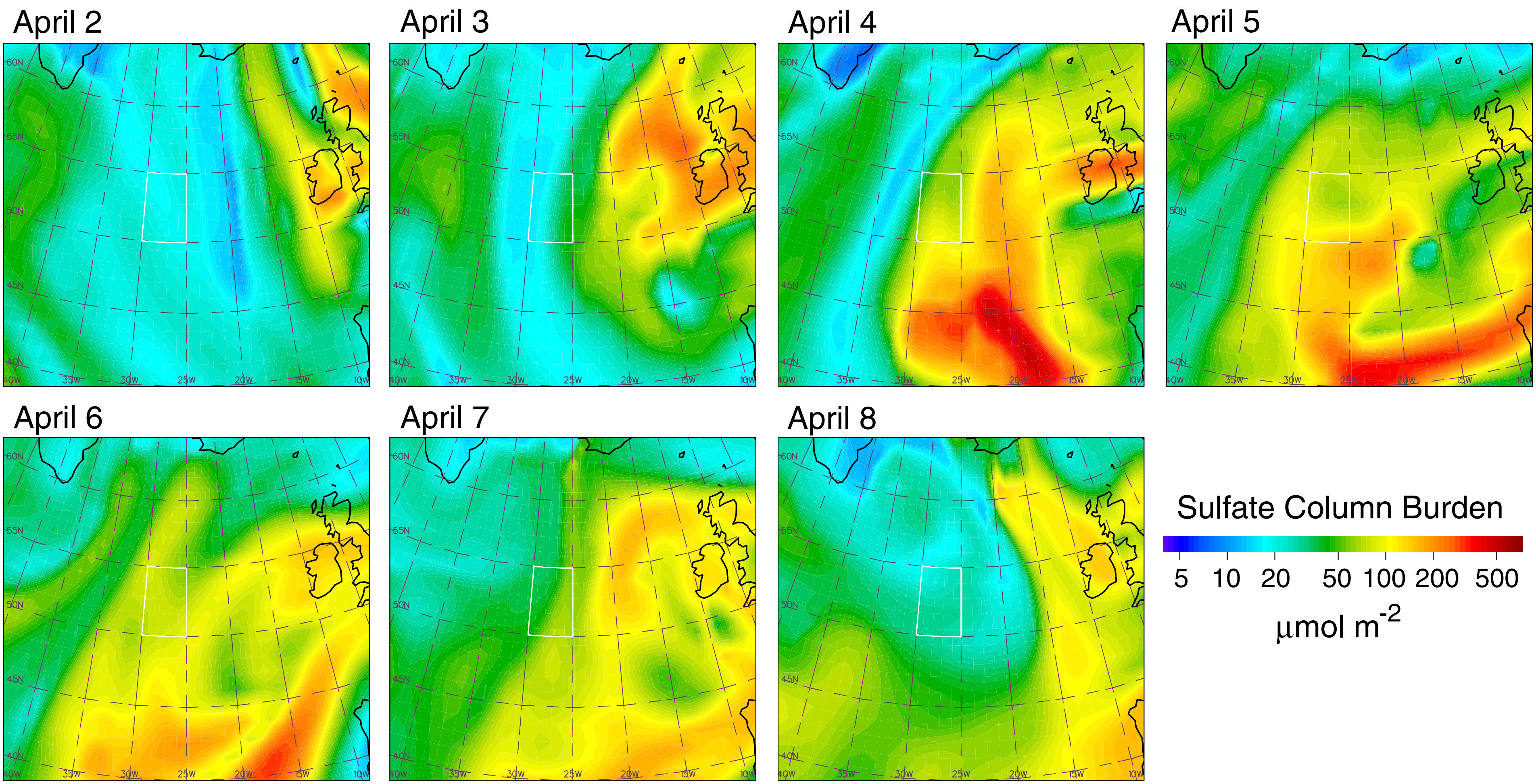


Kiehl et al., JGR, 2000

MODELED SULFATE COLUMN BURDEN

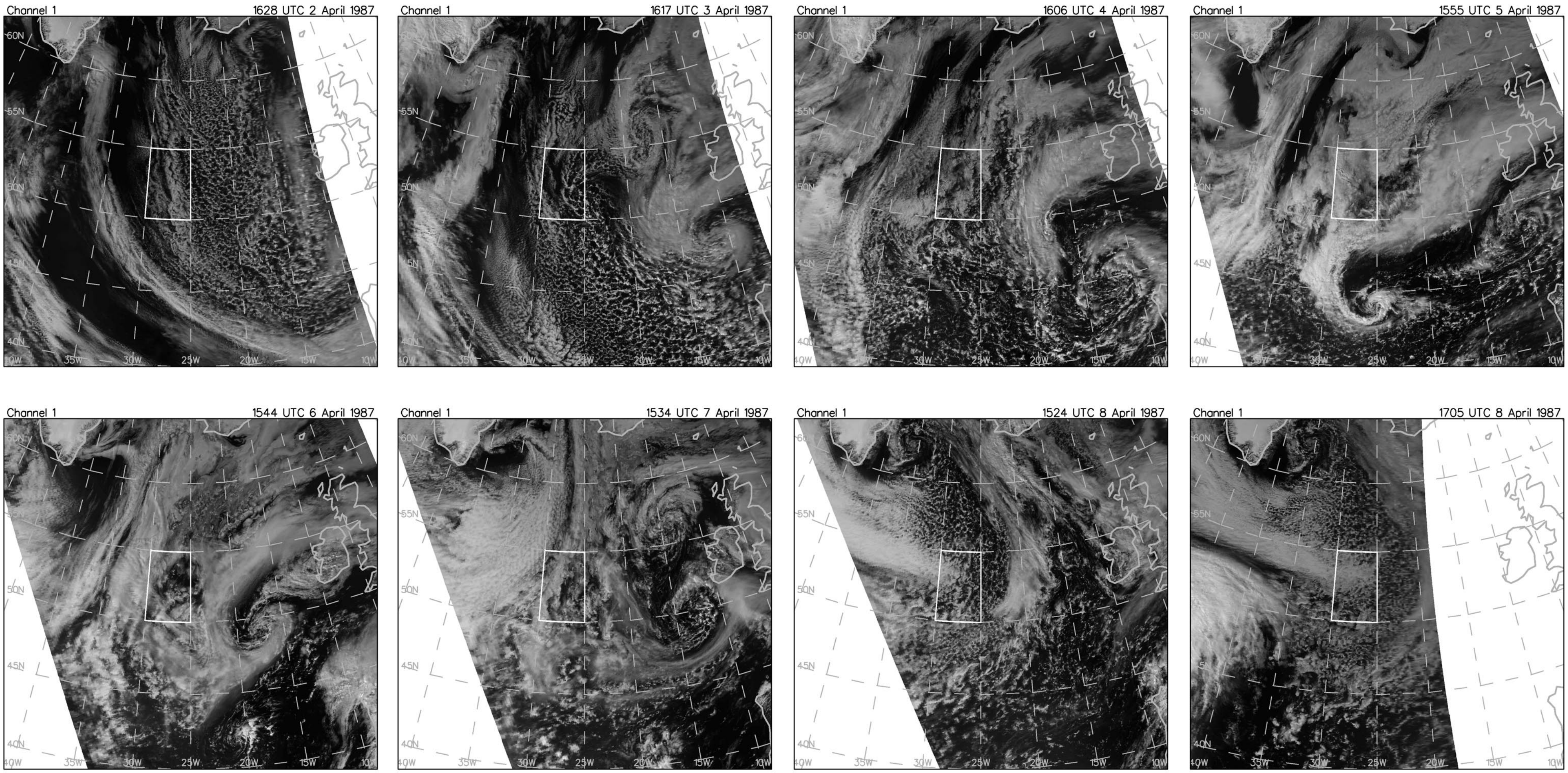
$$\int [SO_4^{2-}]dz$$

April 2-8, 1987



AVHRR IMAGES APRIL 2-8, 1987

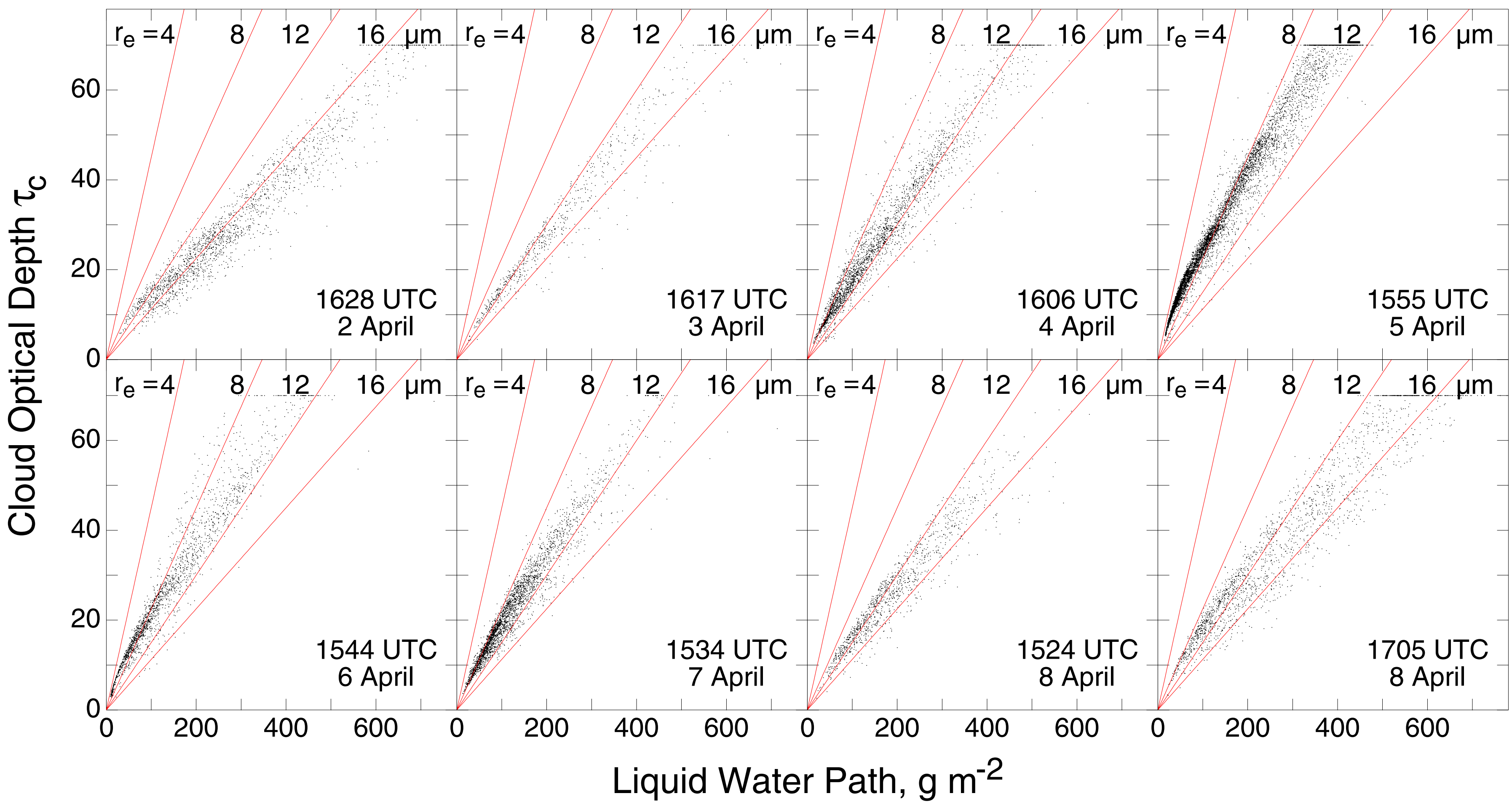
Channel 1, Visible, 0.58-0.68 µm



CLOUD OPTICAL DEPTH

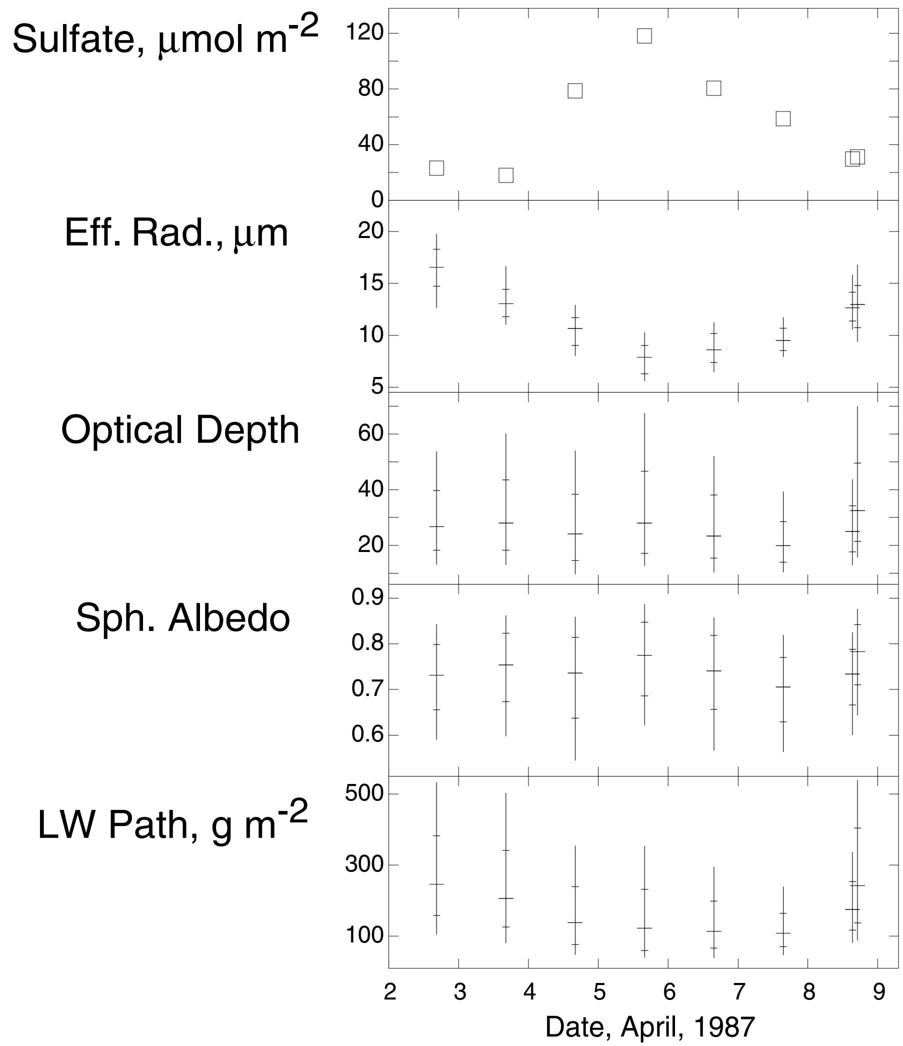
Dependence on Liquid Water Path

25°-30°W, 50°-55°N   April 2-8, 1987



CLOUD PROPERTIES AND SULFATE COLUMN BURDEN

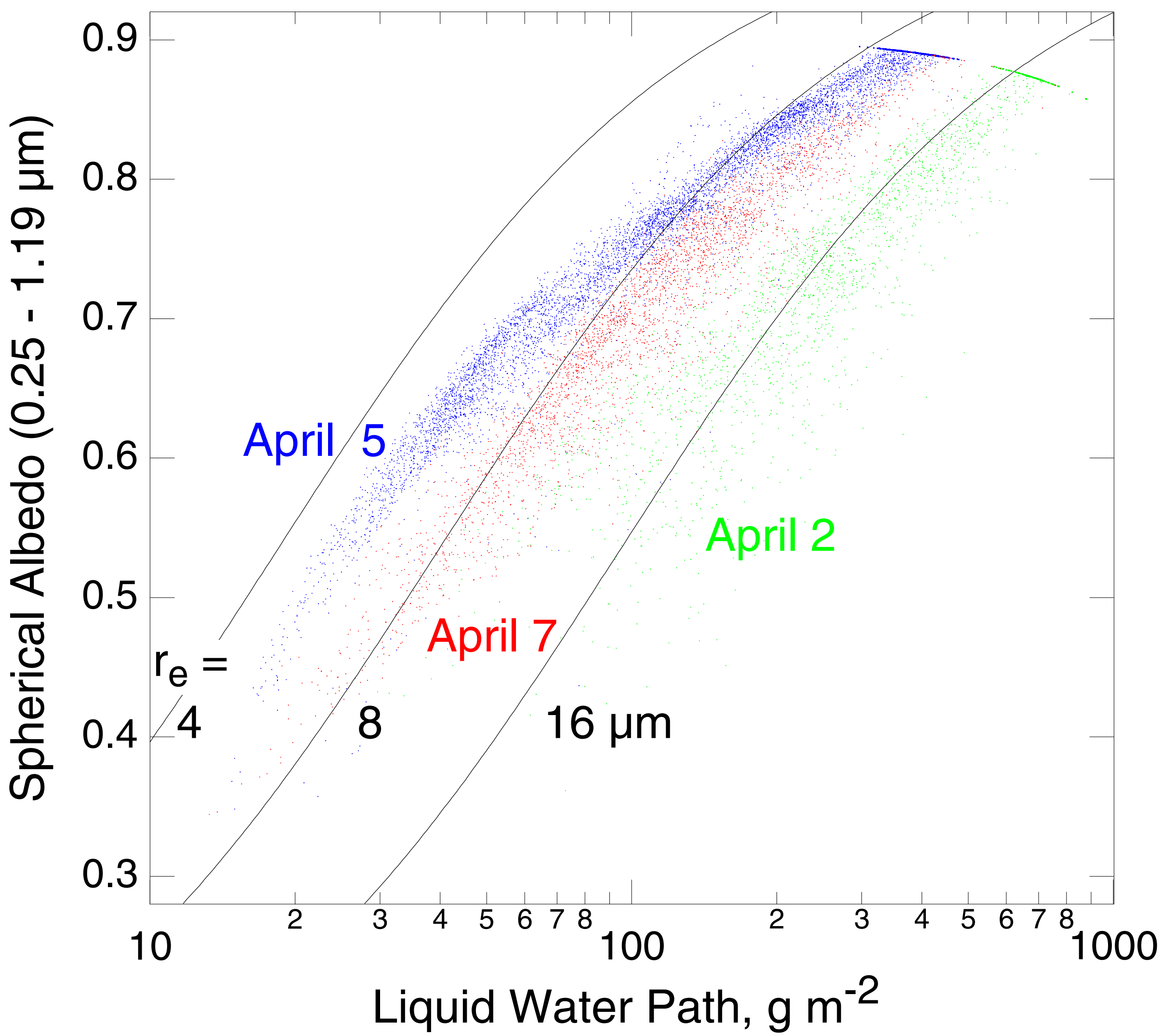
25°-30°W, 50°-55°N, April 2-8, 1987



CLOUD-TOP ALBEDO

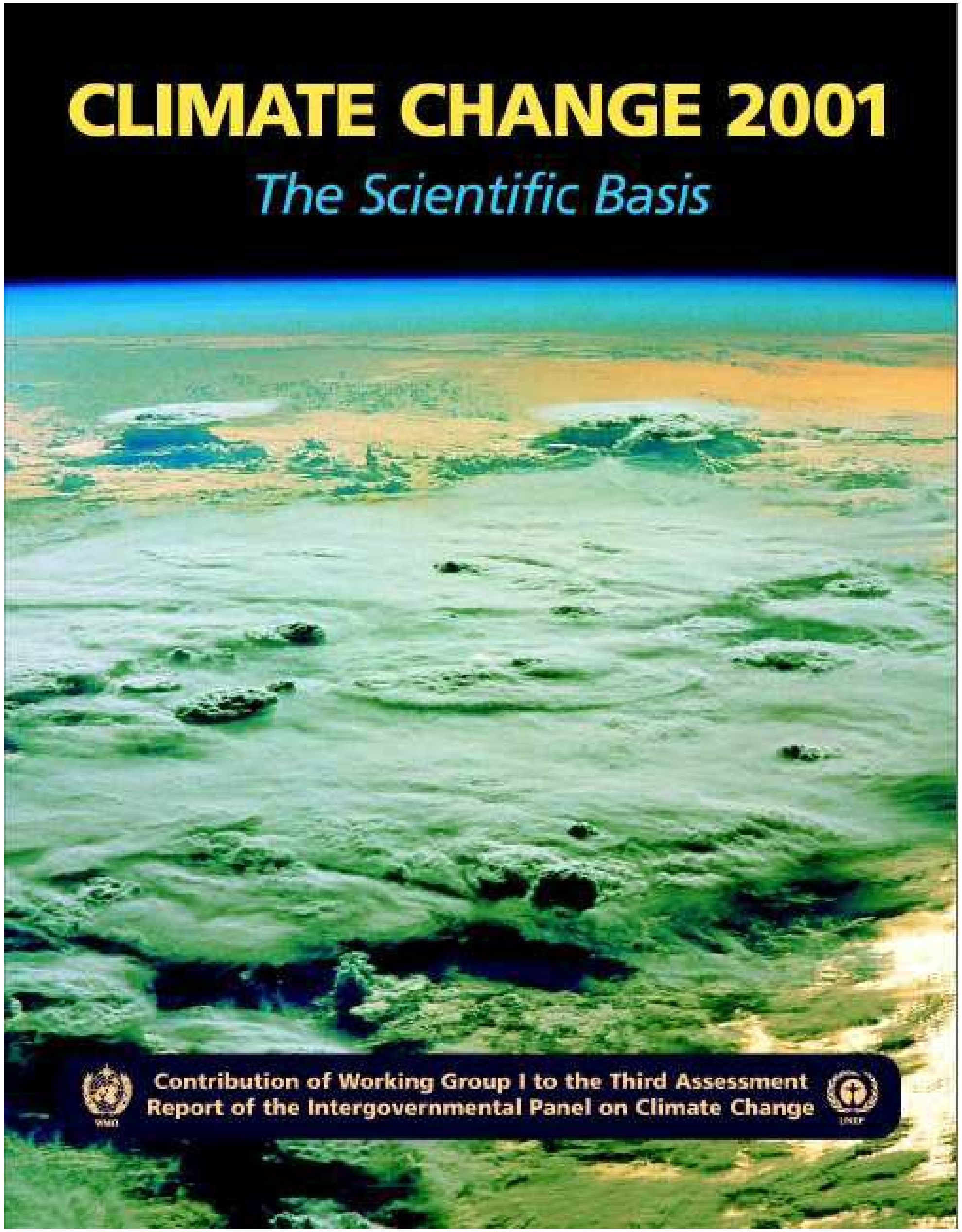
Dependence on Liquid Water Path

25°-30°W, 50°-55°N   April 2, 5 and 7,1987



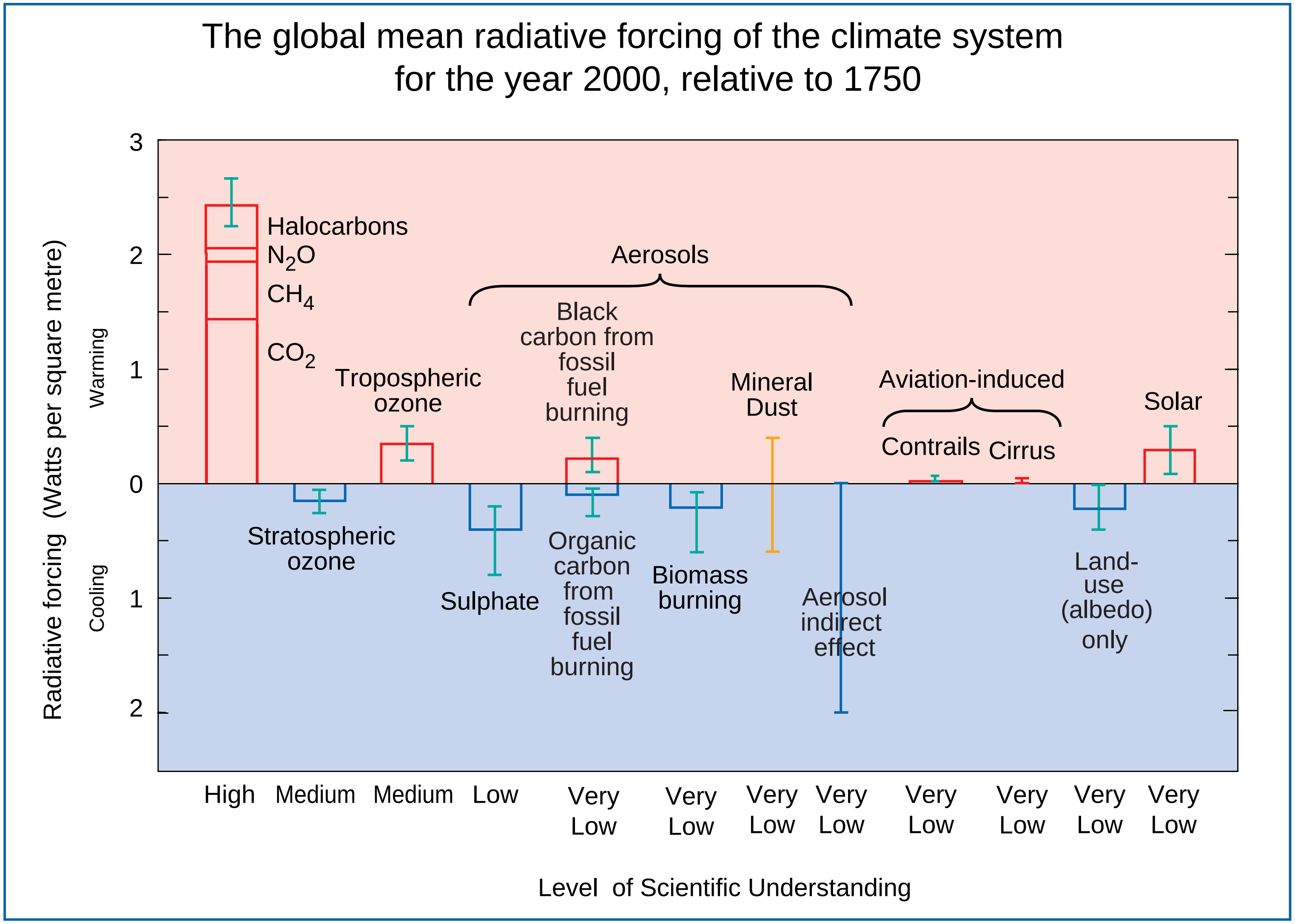
Schwartz, Harshvardhan & Benkovitz, PNAS, 2002

THE “BIBLE” OF CLIMATE CHANGE RESEARCH



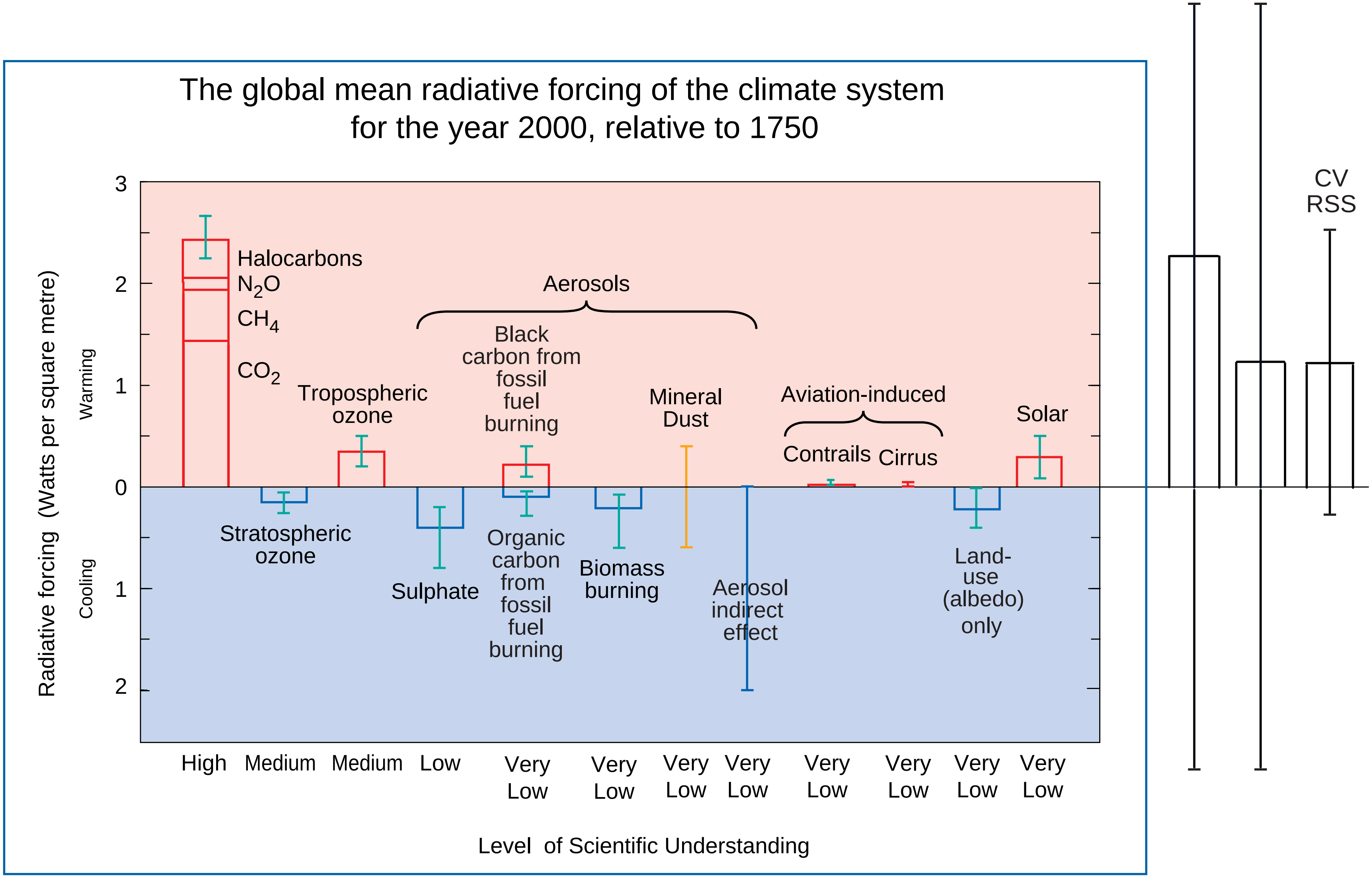
Cambridge University Press, 2001

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)

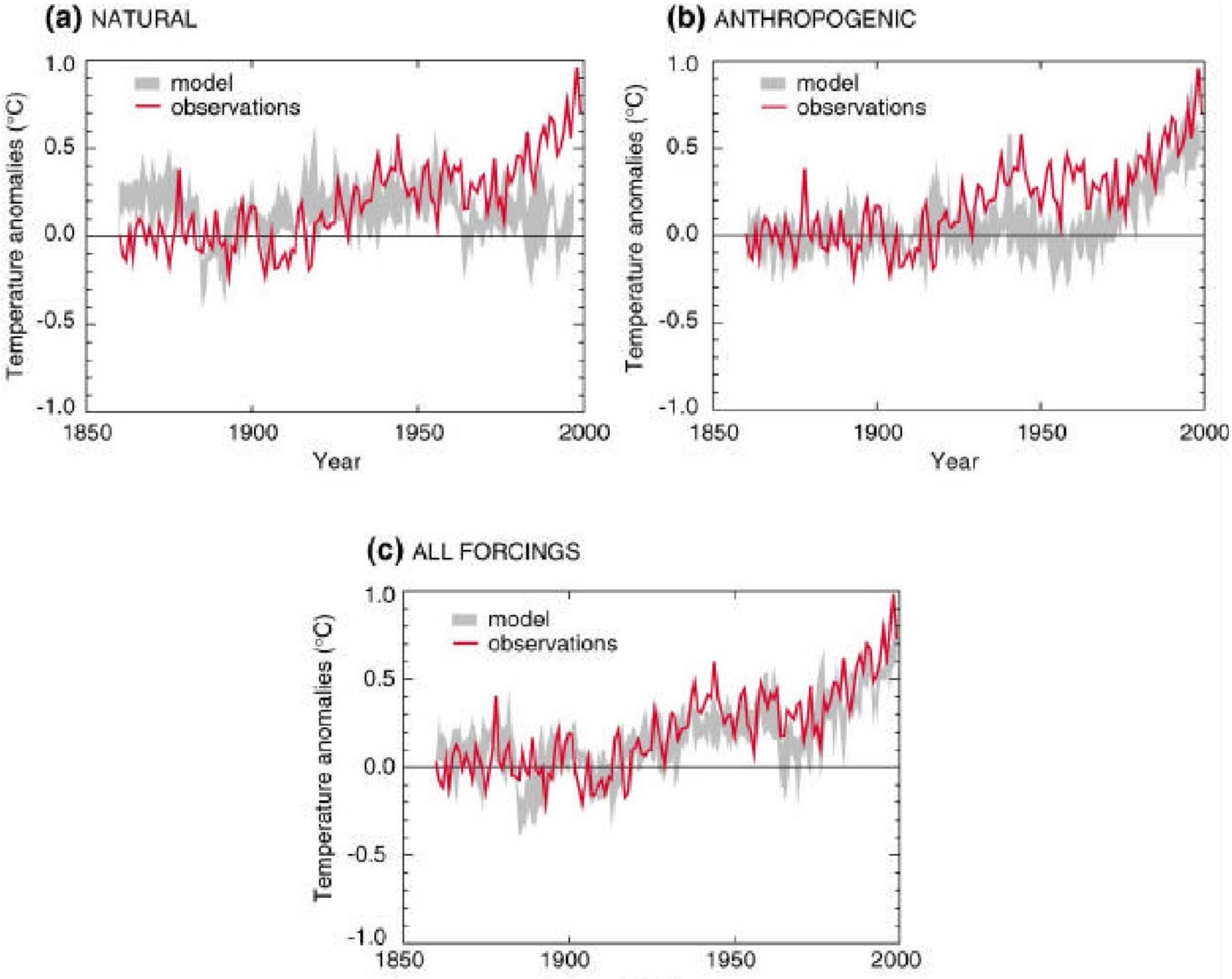


RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)

With totals and overall uncertainties by 3 approaches



IPCC-2001 COMPARISONS OF MEASURED AND MODELED SURFACE TEMPERATURE TRENDS

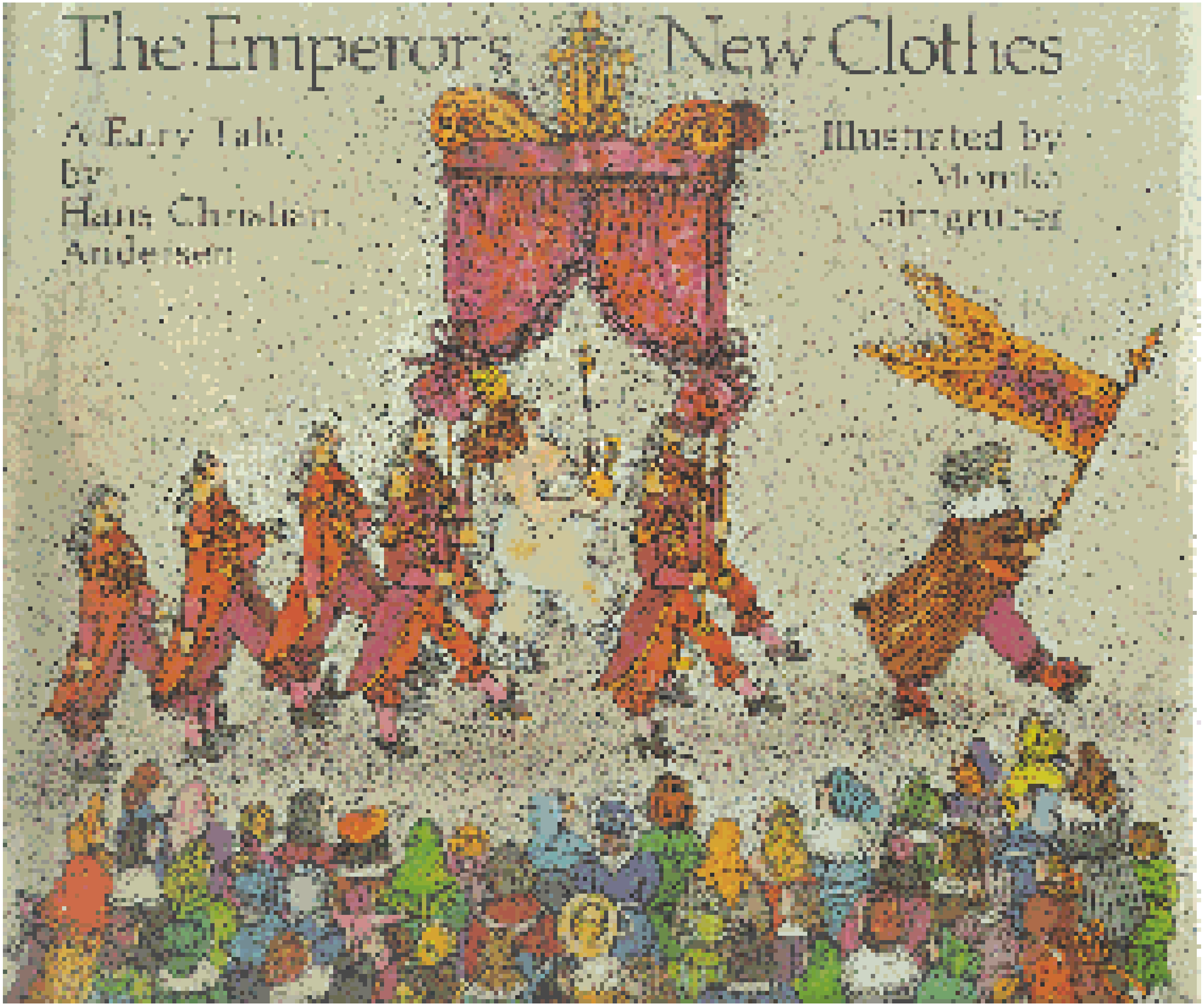


IPCC-2001 STATEMENT ON CONFIDENCE IN ABILITY OF MODELS TO PROJECT FUTURE CLIMATE

- ***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 (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
Laimgruber

THE PREMISES UNDERLYING ATTRIBUTION OF WARMING TO INCREMENTAL GREENHOUSE GASES

Attribution of this warming to radiative forcing by anthropogenic greenhouse gases (GHGs) rests on three interconnected premises:

1 Forcing over the industrial era is dominated by anthropogenic GHGs and thus is positive and of substantial magnitude.

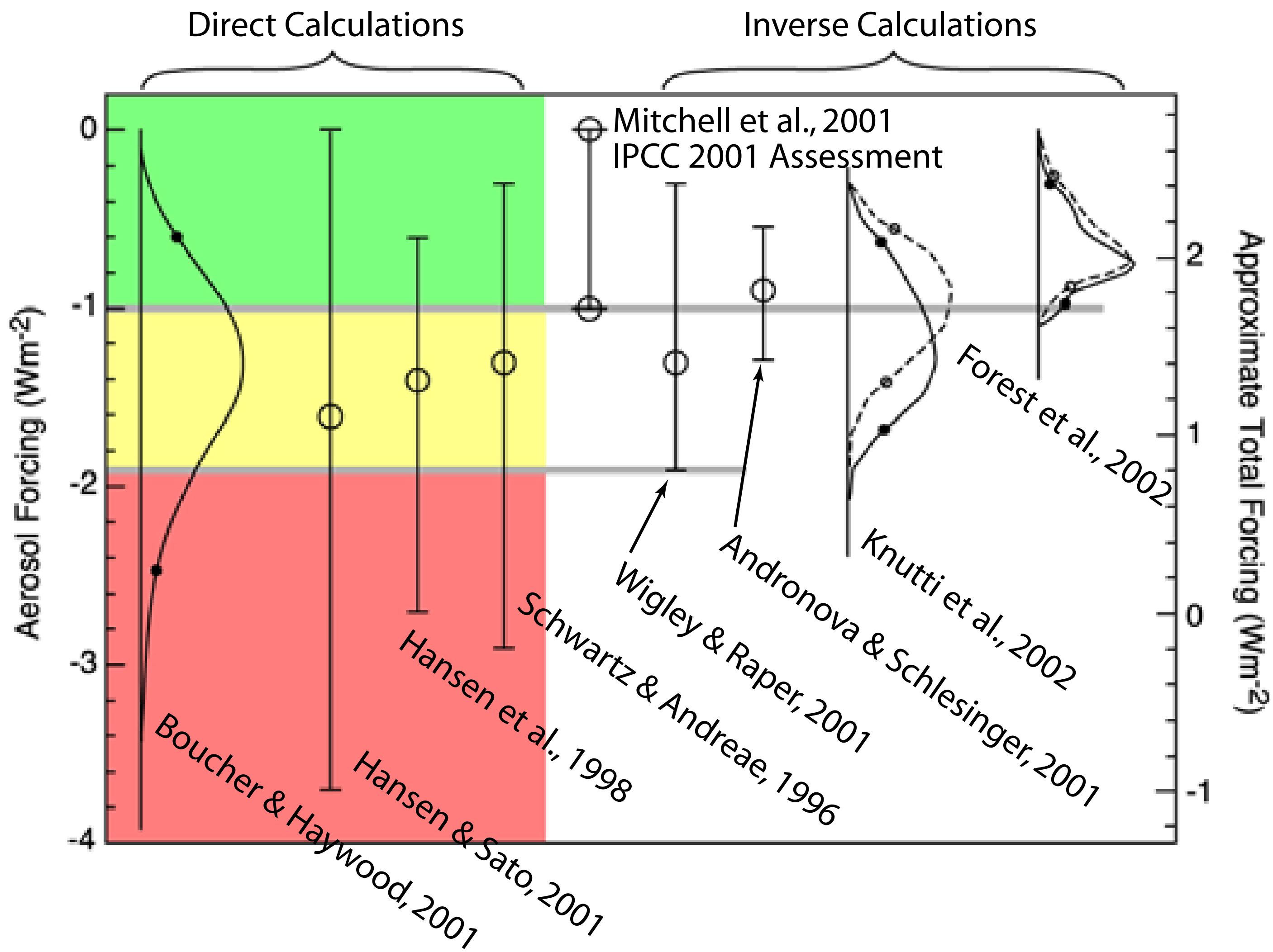
2 Global-mean surface temperature has increased over the industrial era by an amount that is outside the range of natural variability.

3 The magnitude and pattern of the observed temperature changes are consistent with current knowledge of the forcings and forcing/response relationships as embodied in climate models.

Confidence in the attribution of global warming to GHGs depends on the degree to which these three premises can be demonstrated.

Anderson, Charlson, Schwartz, Knutti, Boucher, Rodhe, Heintzenberg, in review, 2002

INCONSISTENCIES IN ESTIMATED AEROSOL AND TOTAL RADIATIVE FORCING OVER INDUSTRIAL PERIOD



Anderson, Charlson, Schwartz, Knutti, Boucher, Rodhe, Heintzenberg, in review, 2002

Aerosol forcing inferred from observed warming and modeled climate sensitivity is much less than directly estimated forcing.

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).

LOOKING TO THE FUTURE . . .

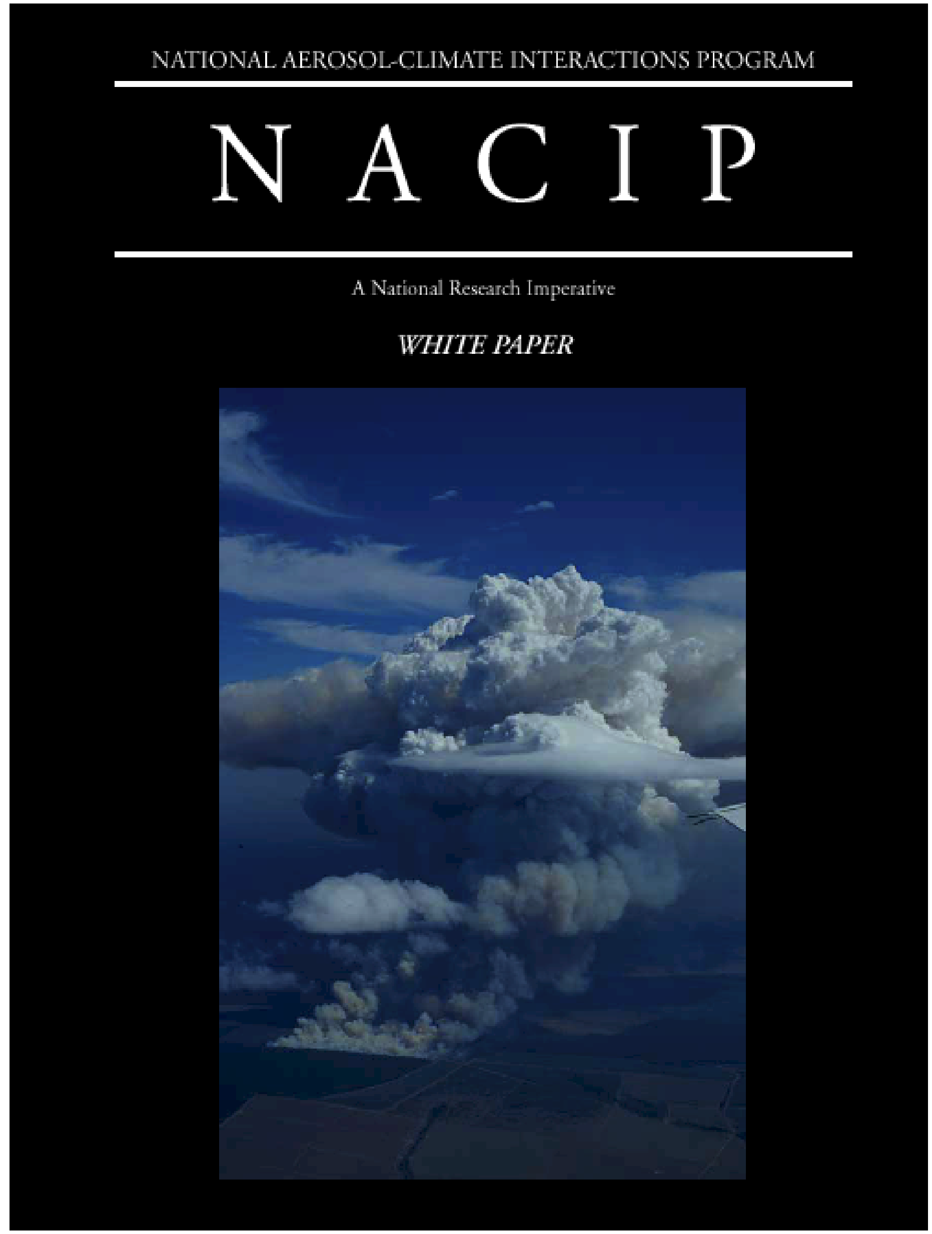

DOE/SC-0034

Tropospheric Aerosol Program

Program Plan

March 2001

U. S. Department of Energy
Office of Science
Office of Biological and Environmental Research
Environmental Sciences Division


NATIONAL AEROSOL-CLIMATE INTERACTIONS PROGRAM

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