AEROSOL INFLUENCE ON CLOUD OPTICAL DEPTH AND ALBEDO OVER THE NORTH ATLANTIC SHOWN BY SATELLITE MEASUREMENTS AND CHEMICAL TRANSPORT MODELING

Stephen E. Schwartz and Carmen M. Benkovitz

BROOKHAVEN NATIONAL LABORATORY

Harshvardhan

PURDUE UNIVERSITY

Photooxidants, Particles, and Haze across the Arctic and North Atlantic: Transport Observations and Models

Lamont-Doherty Earth Observatory, Palisades, New York
June 12-15, 2001

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)

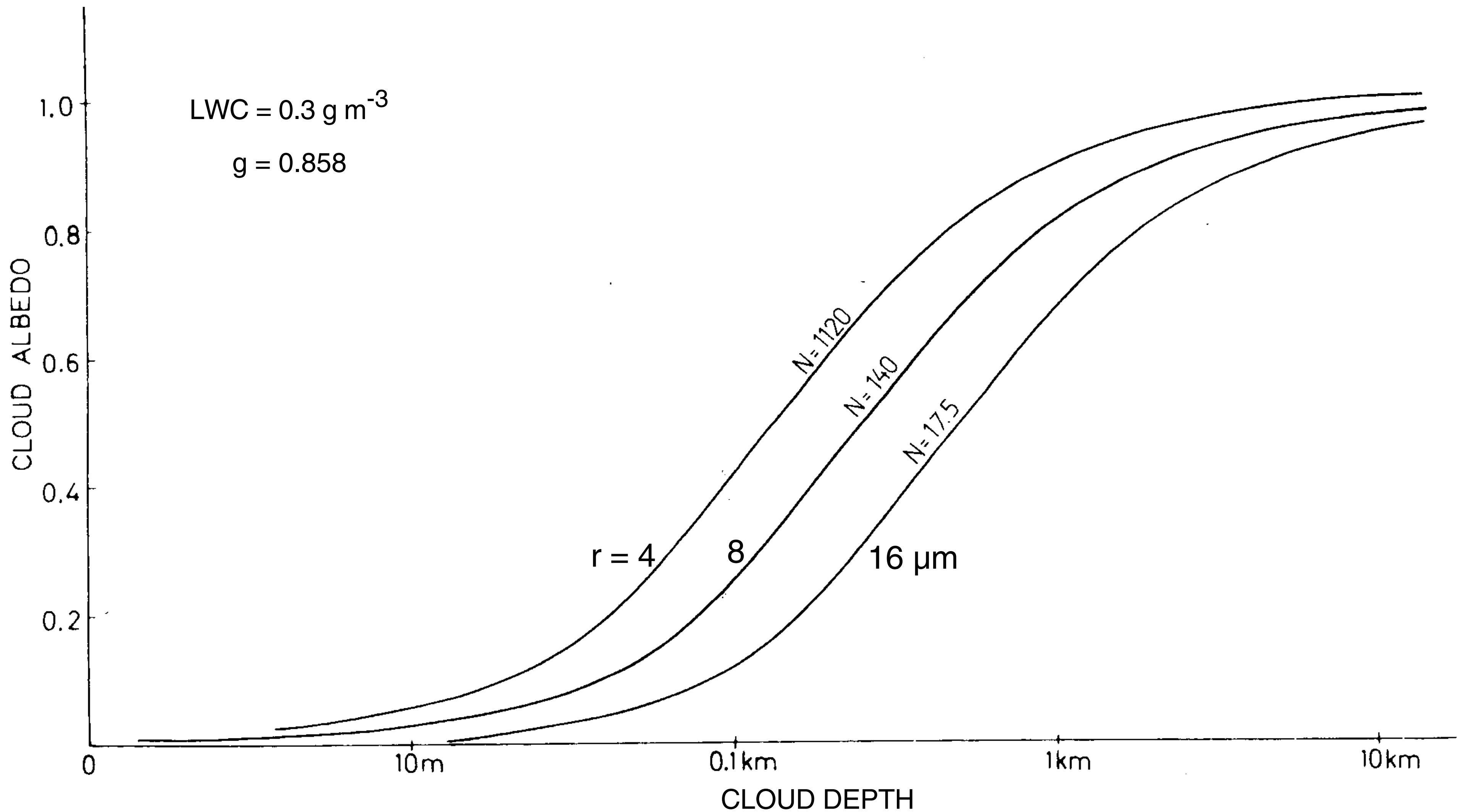
More droplets -- Enhanced cloud lifetime (Albrecht)

Semi-Direct Effect

Absorbing aerosol heats air and evaporates clouds

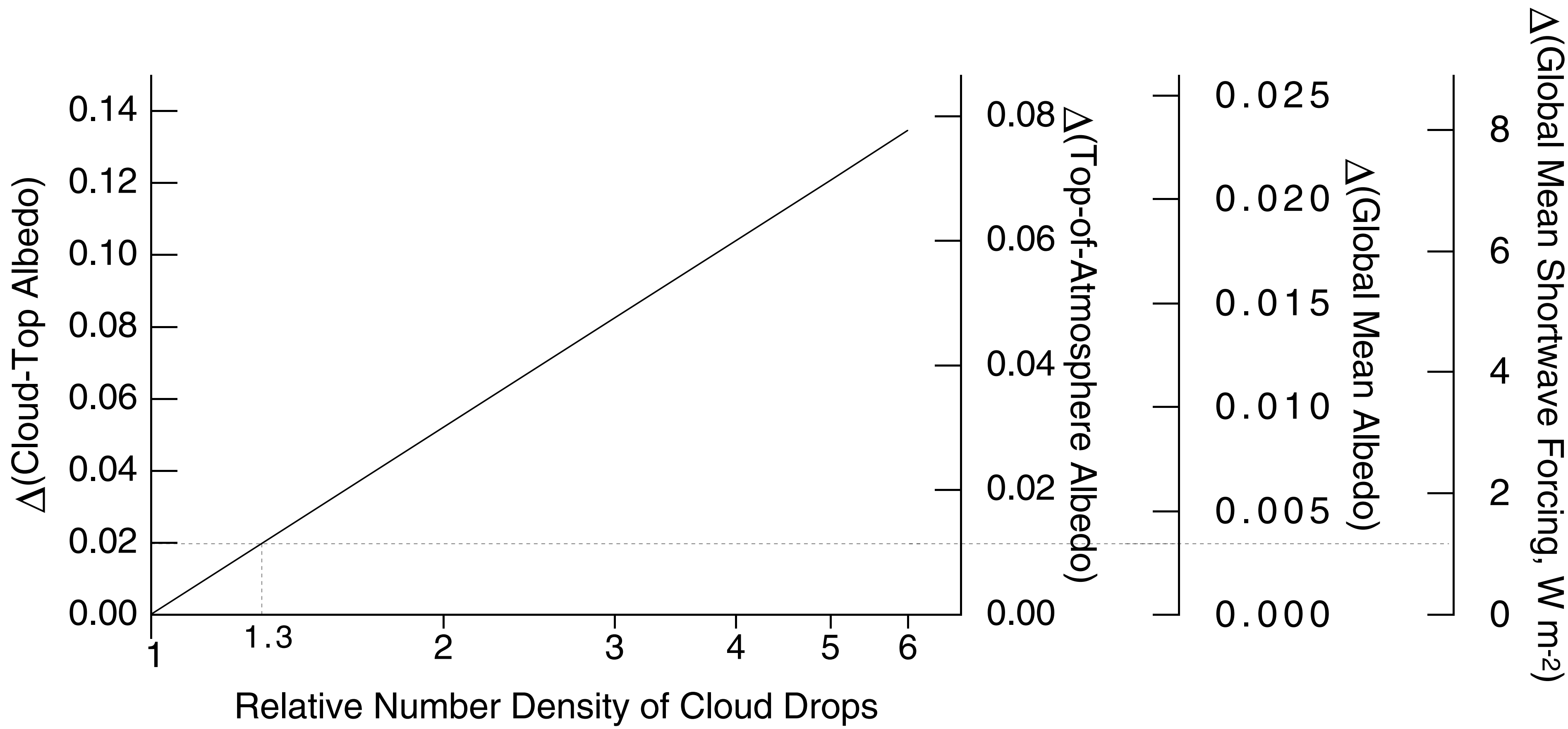
DEPENDENCE OF CLOUD ALBEDO ON CLOUD DEPTH

Influence of Cloud Drop Radius and Concentration



Twomey, *Atmospheric Aerosols*, 1977

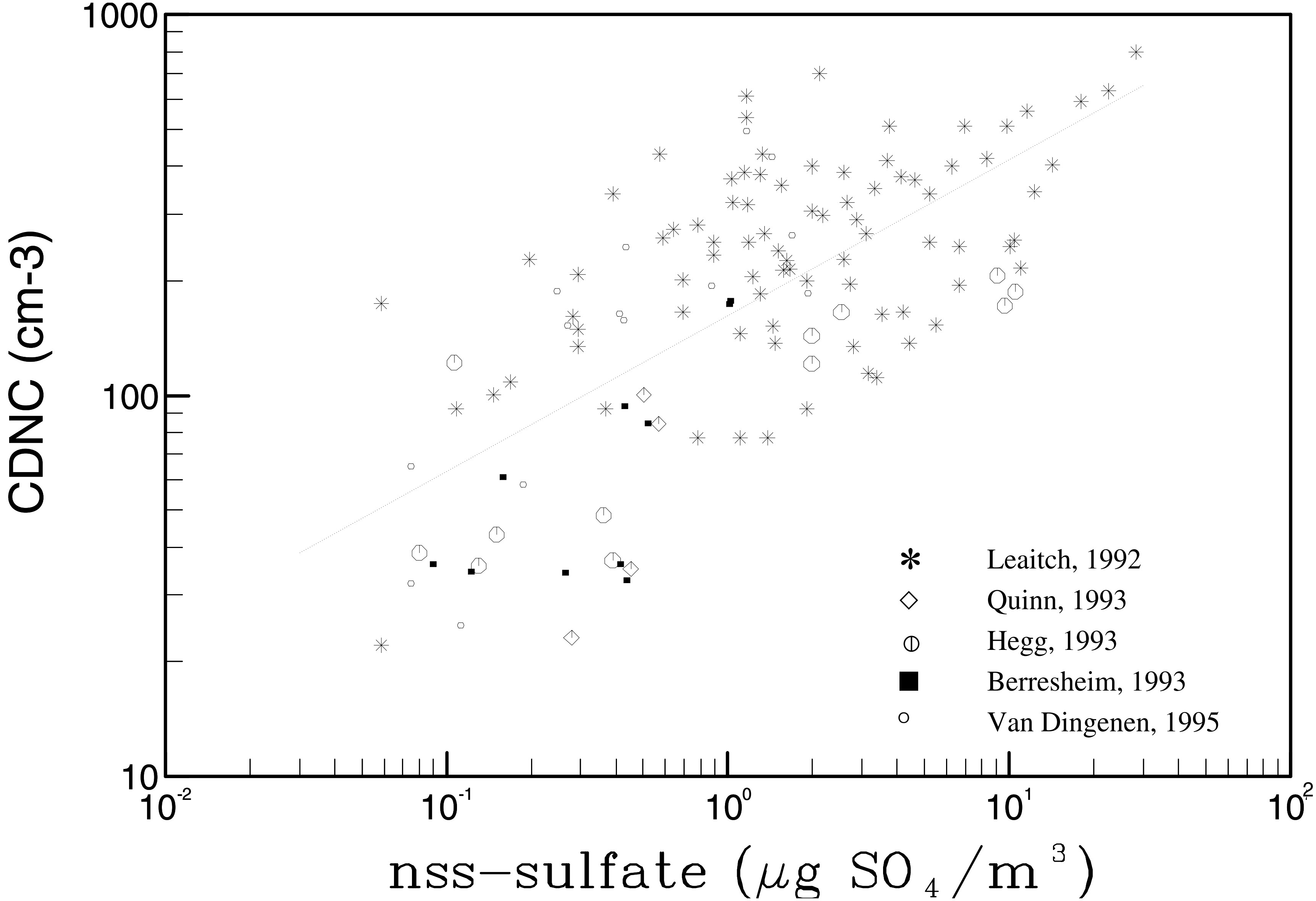
SENSITIVITY OF ALBEDO AND FORCING TO CLOUD DROP CONCENTRATION



Schwartz and Slingo (1996)

CLOUD DROPLET NUMBER CONCENTRATION

Dependence on Non-Seasalt Sulfate



Boucher and Lohmann, 1995

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.

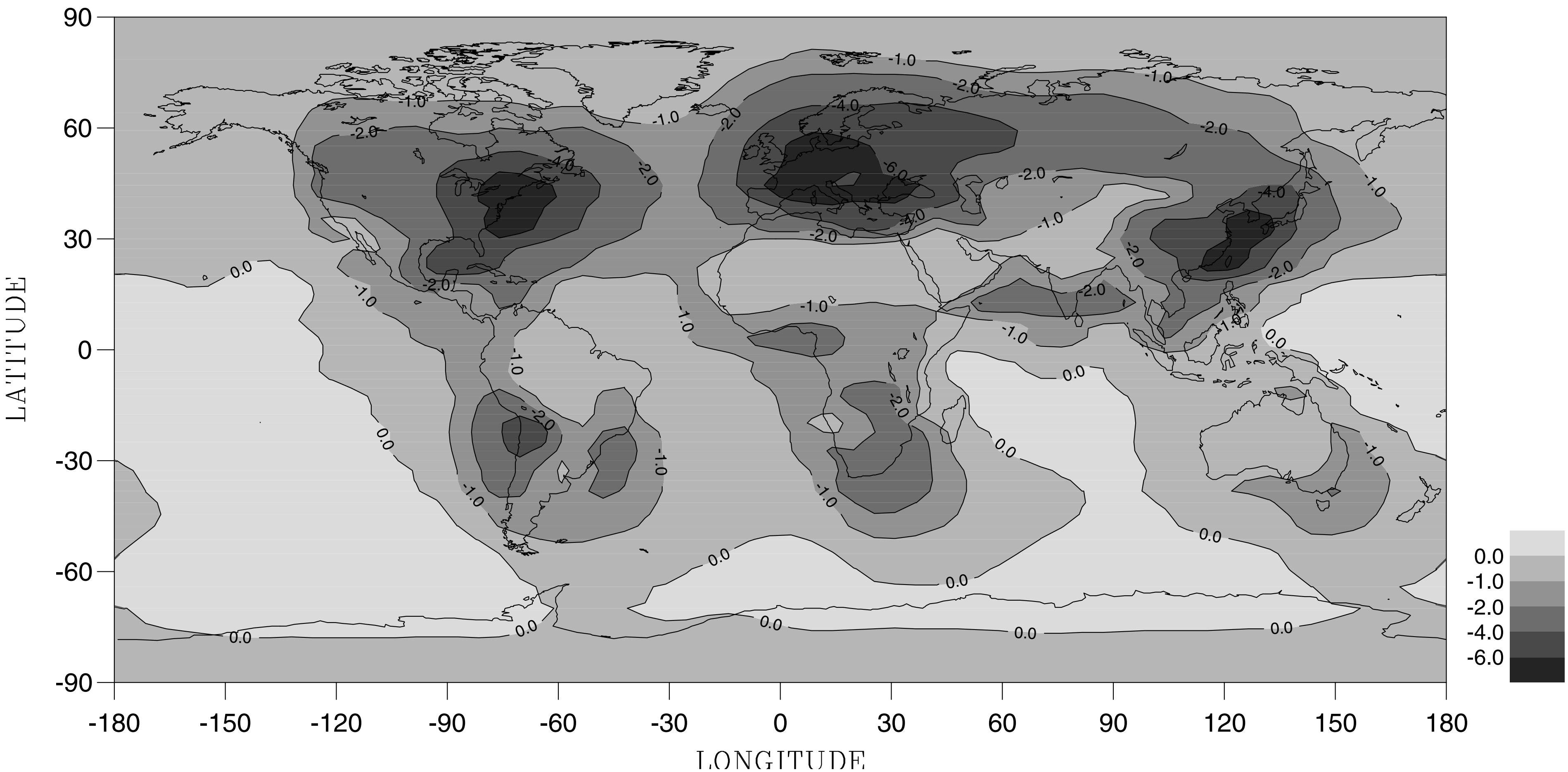
The great uncertainty about this indirect aerosol climate forcing presents a severe handicap both for the interpretation of past climate change and for future assessments of climate changes.

CLIMATE CHANGE SCIENCE

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

INDIRECT FORCING OF SULFATE AEROSOL

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

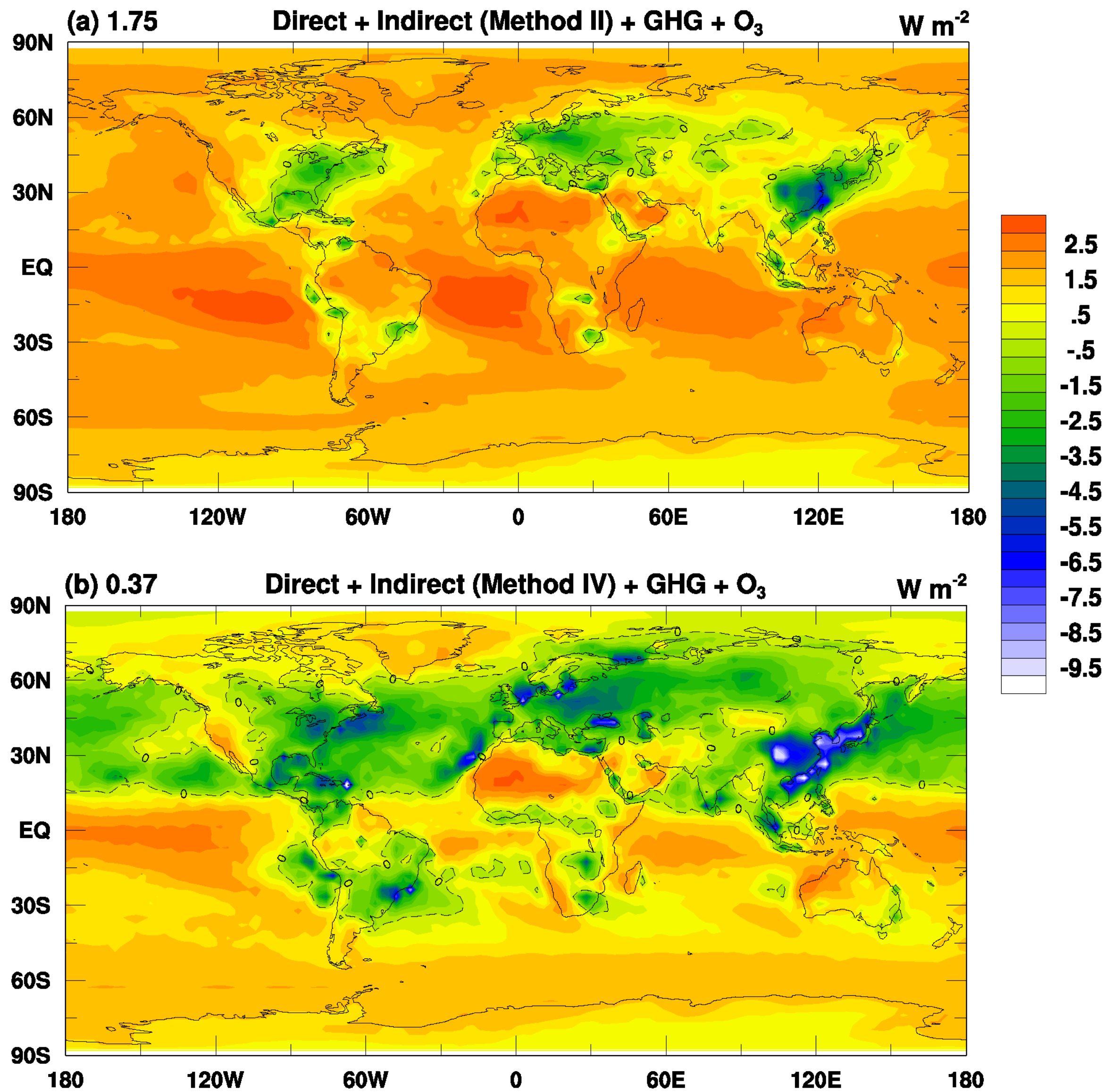


LMD model; Boucher and Lohmann, 1995

SHORTWAVE FORCING, ANNUAL AVERAGE

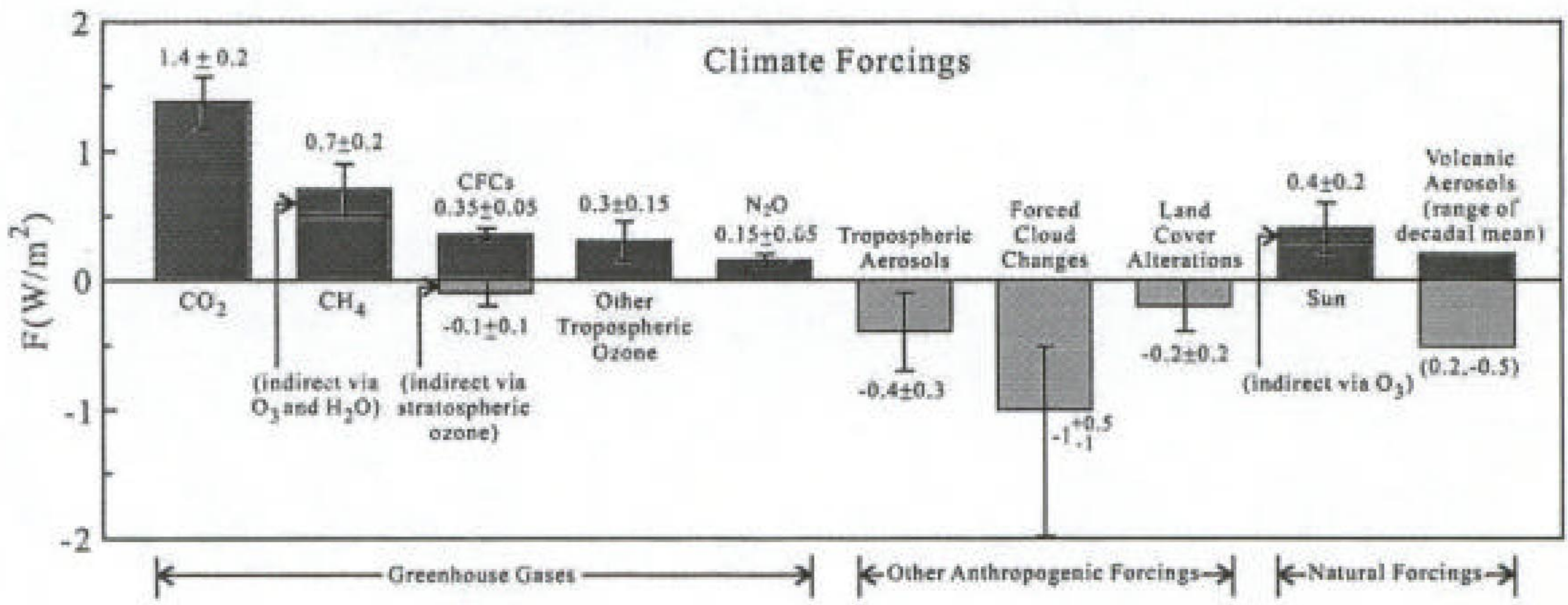
GHG's + O_3 + Sulfate (Direct and Indirect)

Two Formulations of Cloud Droplet Concentration



Kiehl et al., JGR, 2000

CLIMATE FORCING COMPONENTS OVER THE INDUSTRIAL PERIOD



CLIMATE CHANGE SCIENCE

AN ANALYSIS OF SOME KEY QUESTIONS

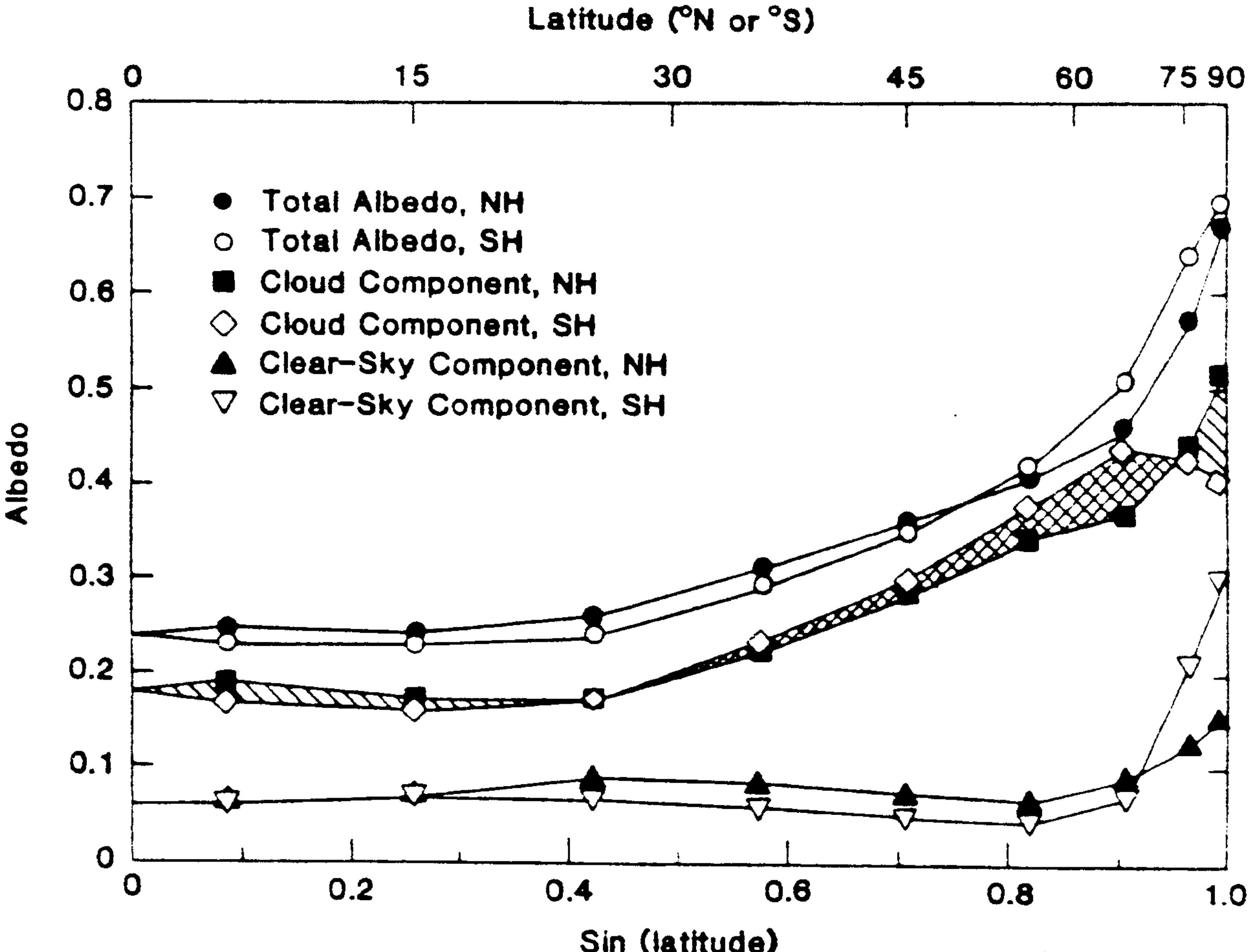
Committee on the Science of Climate Change

National Research Council

June 6, 2001

INTERHEMISPHERIC COMPARISON OF ALBEDO COMPONENTS

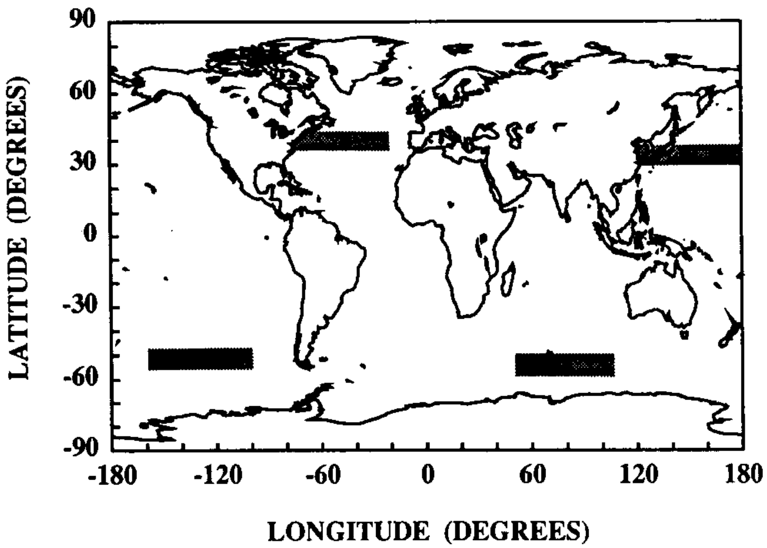
Data from Nimbus 4

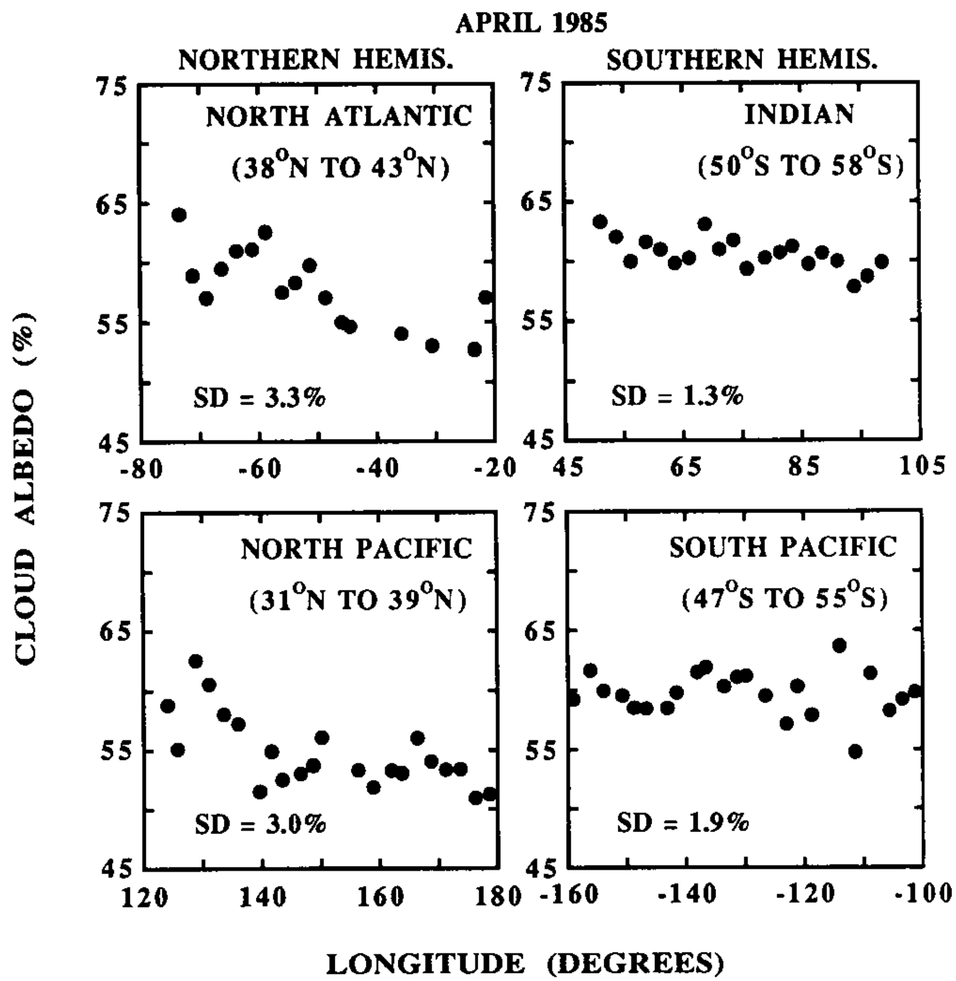


Schwartz (1989)

LONGITUDE DEPENDENCE OF CLOUD ALBEDO

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

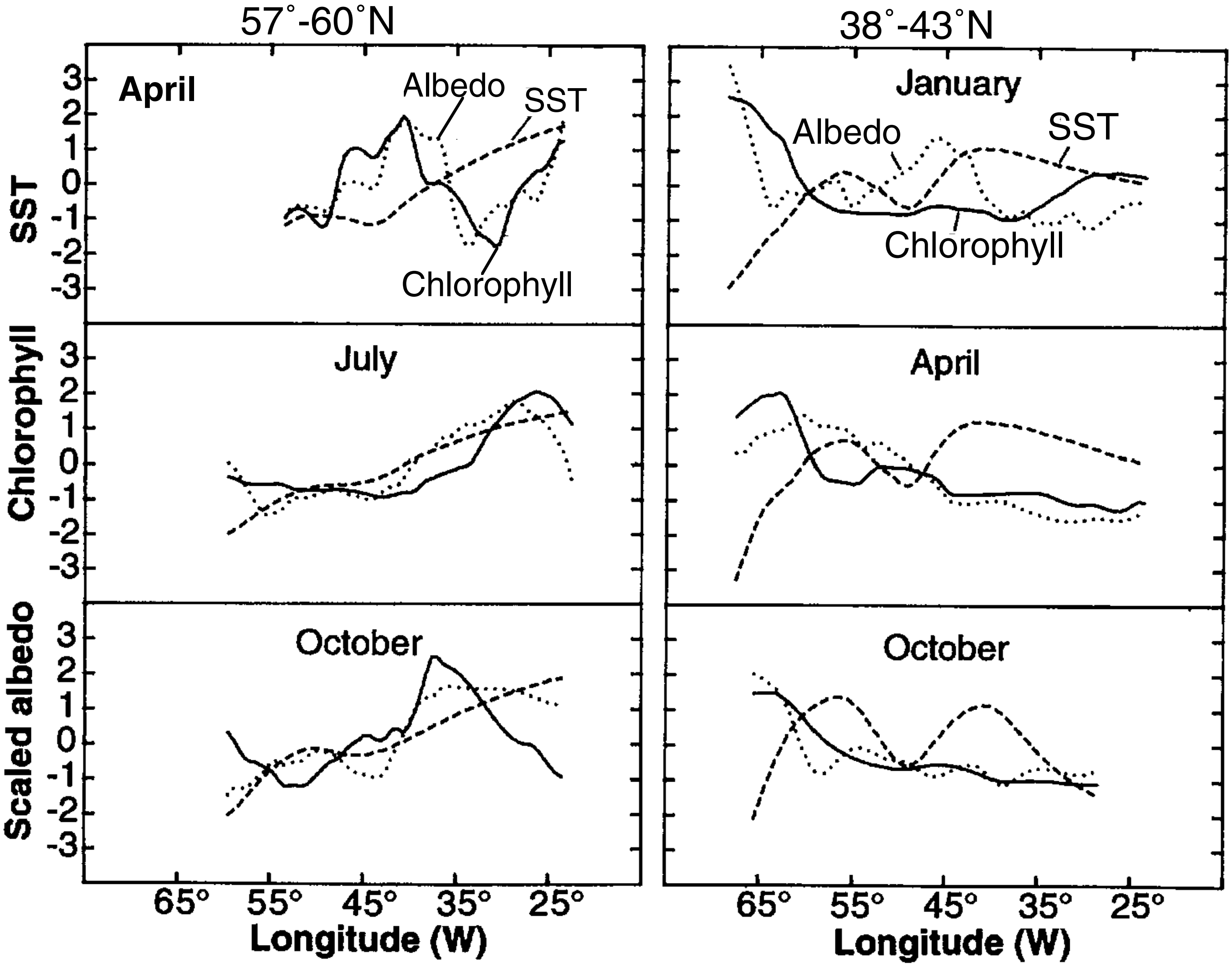




Kim and Cess, JGR, 1994

LONGITUDE DEPENDENCE OF CLOUD ALBEDO

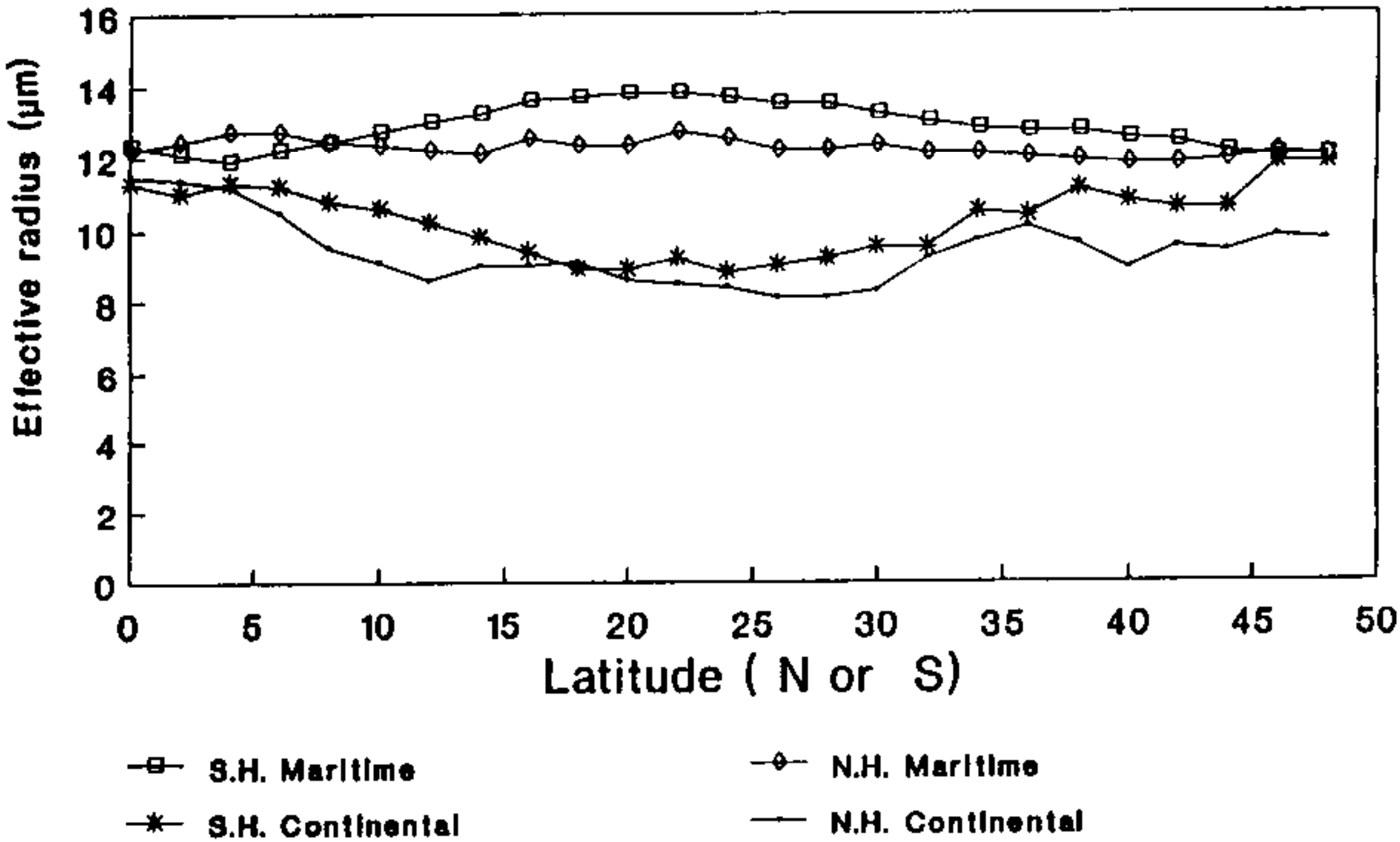
Test for Anthropogenic Influence in North Atlantic



Falkowski, Kim, Kolber, Wilson, Wirick and Cess, Science (1992)

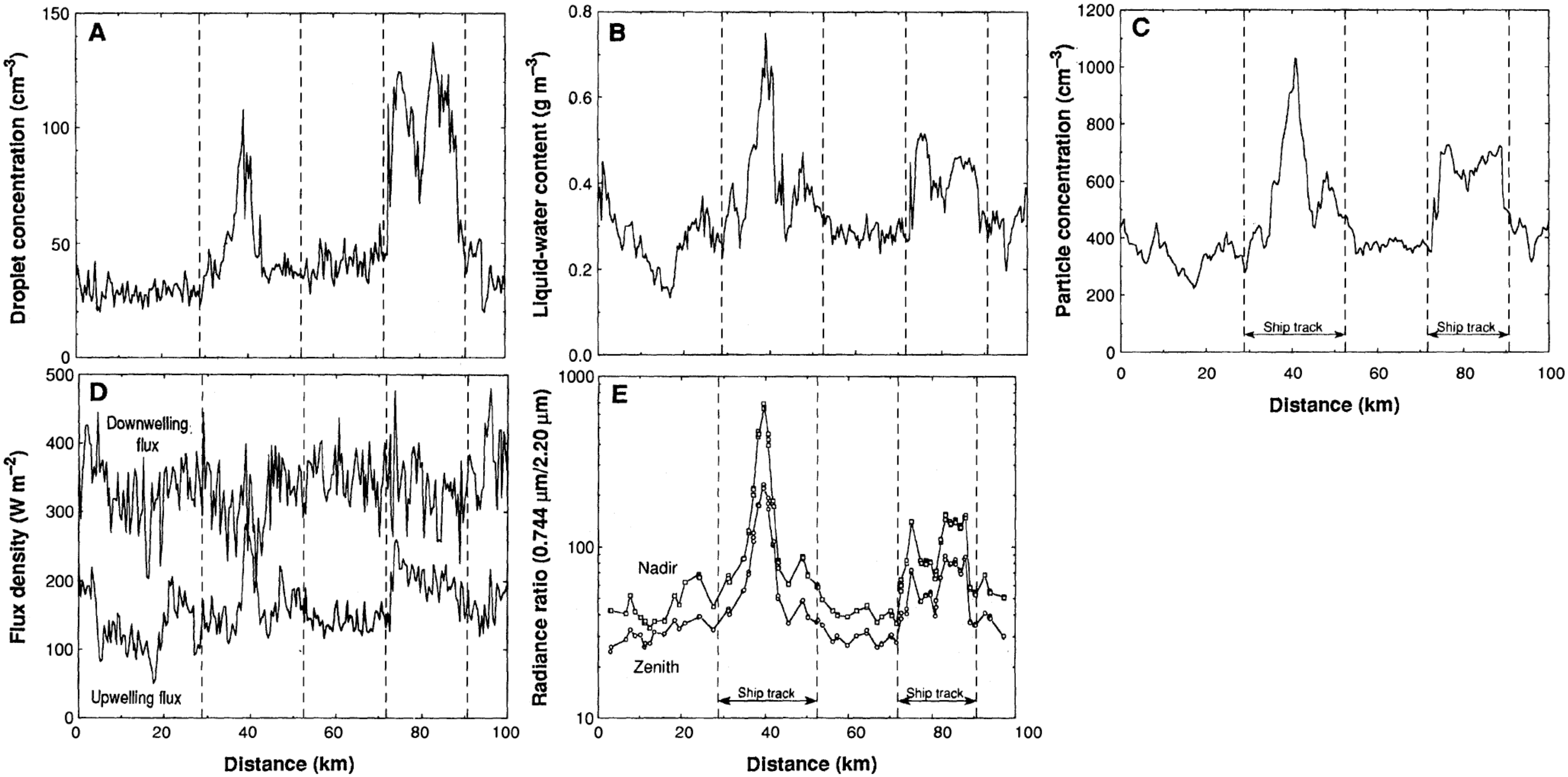
LATITUDE DEPENDENCE OF CLOUD DROP RADIUS

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



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

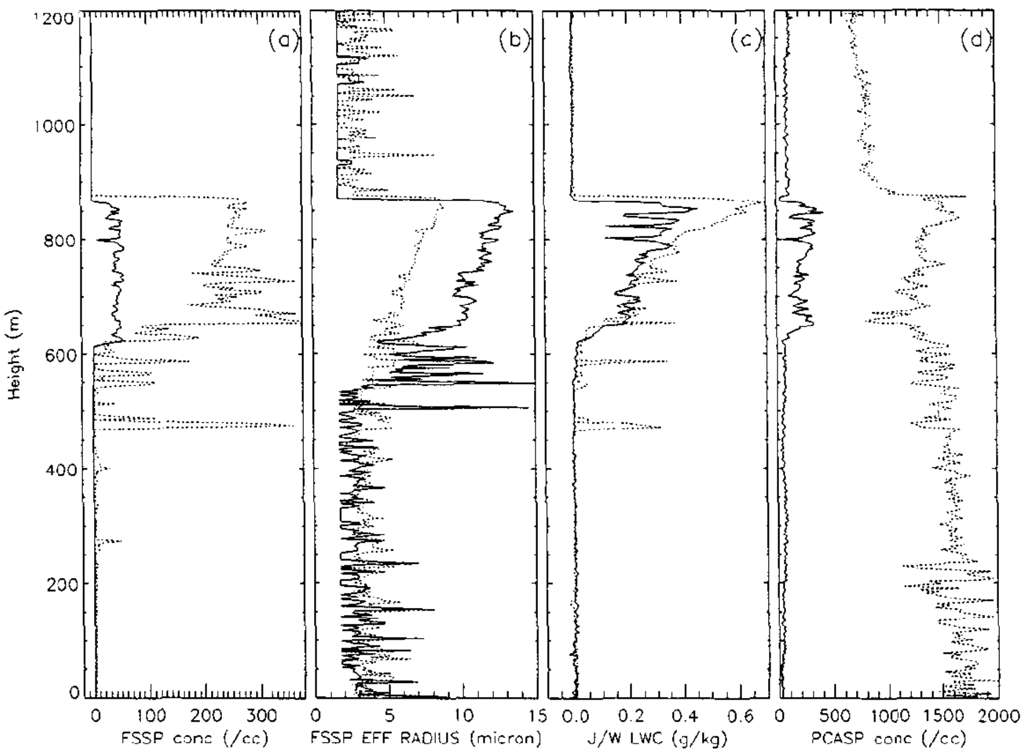
MICROPHYSICAL AND RADIATIVE PROPERTIES OF SHIP TRACKS IN CLOUDS

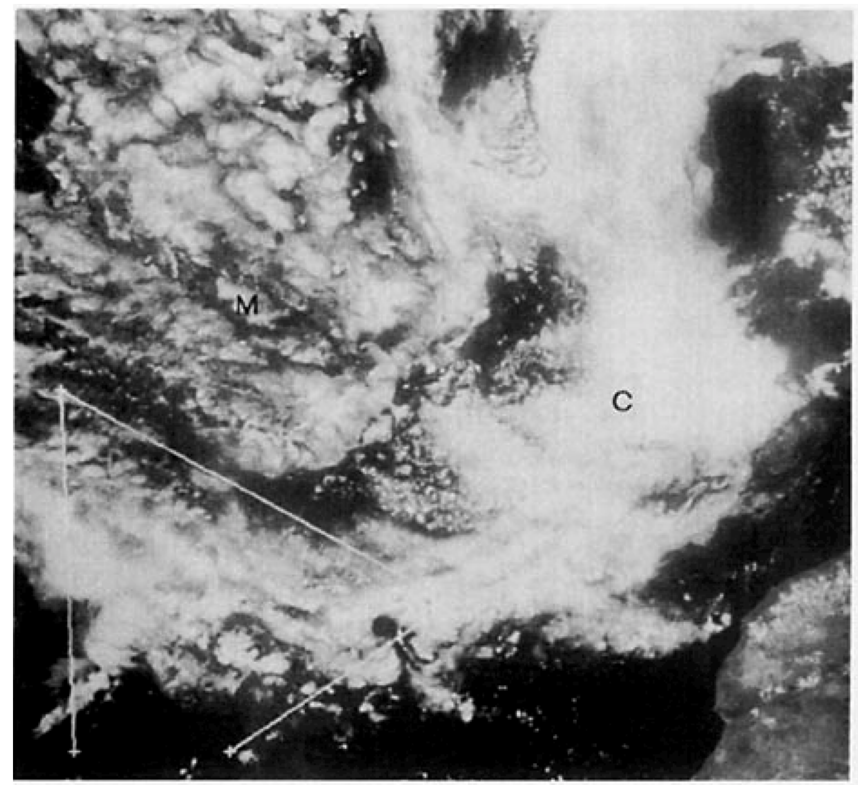


Radke, Coakley & King, Science, 1989

CLOUD MICROPHYSICAL PROPERTIES AND SATELLITE VISIBLE RADIANCE

ASTEX, Northeast Atlantic, June, 1992





Albrecht et al., BAMS, 1995

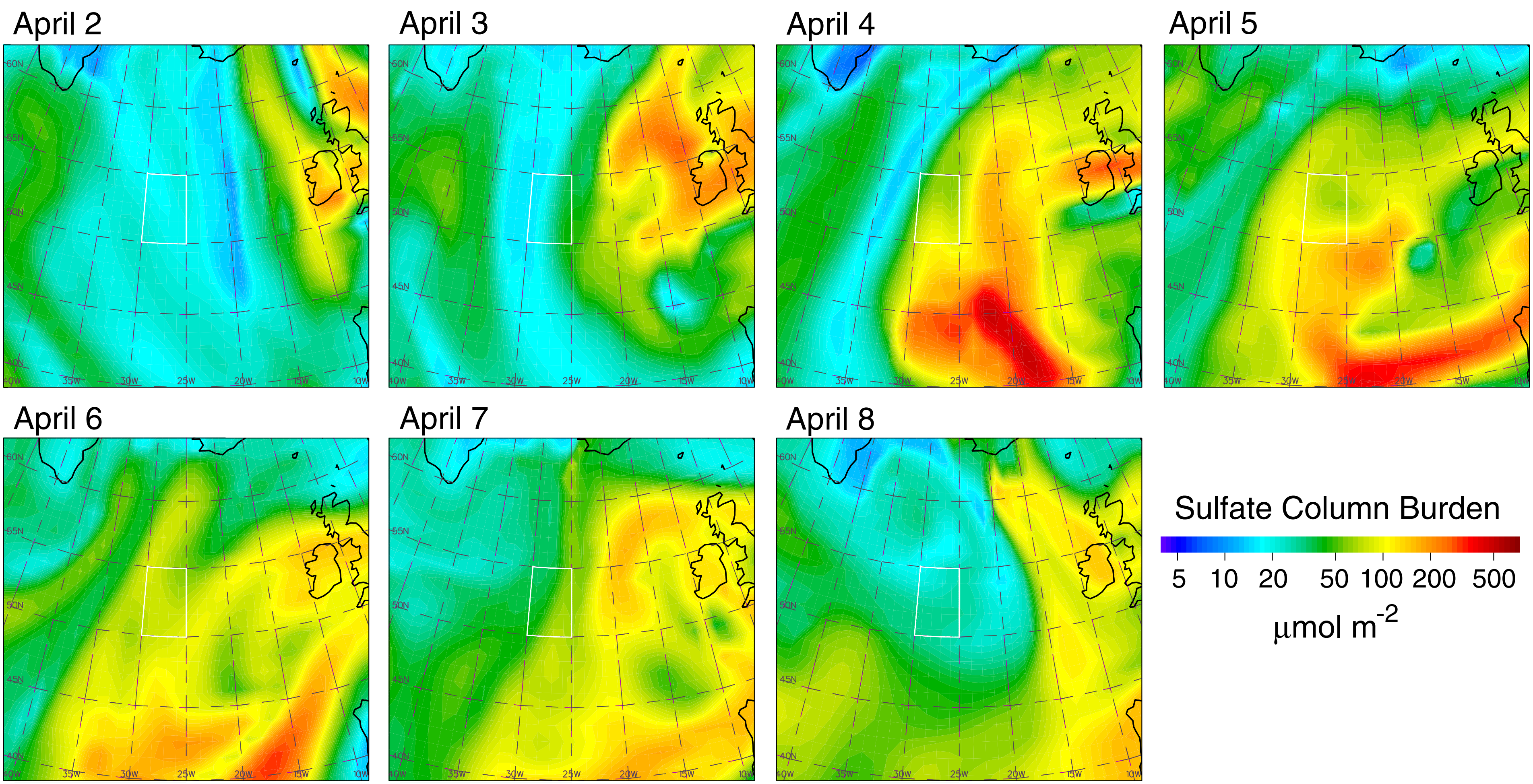
THIS STUDY

- Uses a chemical transport and transformation model to identify a situation where a strong aerosol influence on cloud albedo might be expected.
- Examines for this signal in satellite data.
- Finds a strong signal in cloud drop radius.
- Does ***not*** find an immediate strong signal in cloud albedo: ***Why?***
- Offers an explanation and extracts the signal of a strong perturbation in cloud albedo.

MODELED SULFATE COLUMN BURDEN

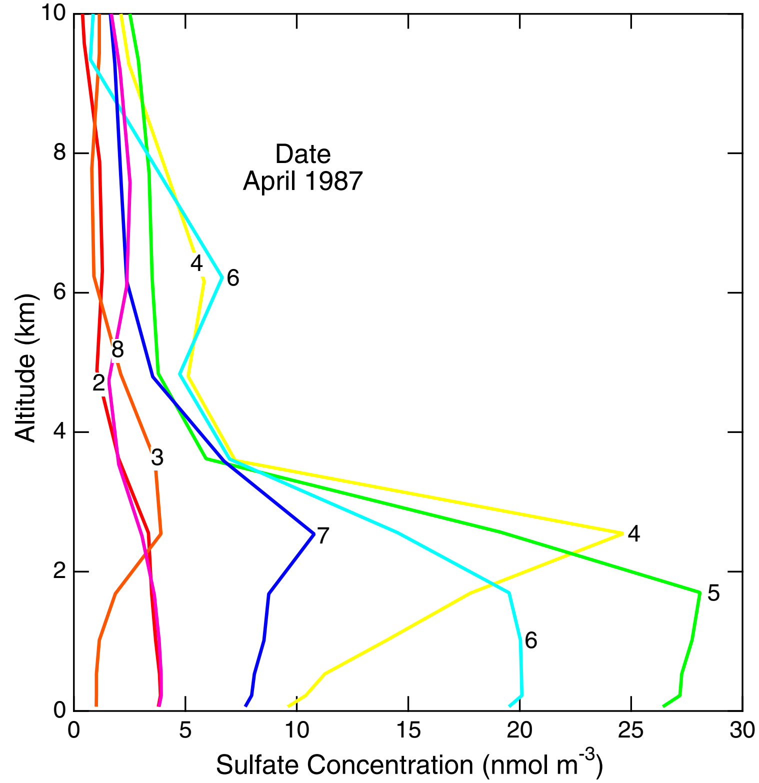
$$\int [SO_4^{2-}]\,dz$$

April 2-8, 1987

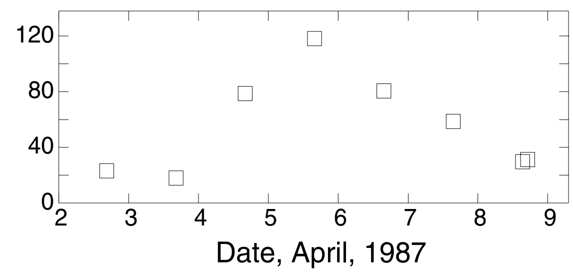


MODELED SULFATE CONCENTRATION PROFILE AND COLUMN BURDEN ($\int [SO_4^{2-}]dz$)

25°-30°W, 50°-55°N, April 2-8, 1987

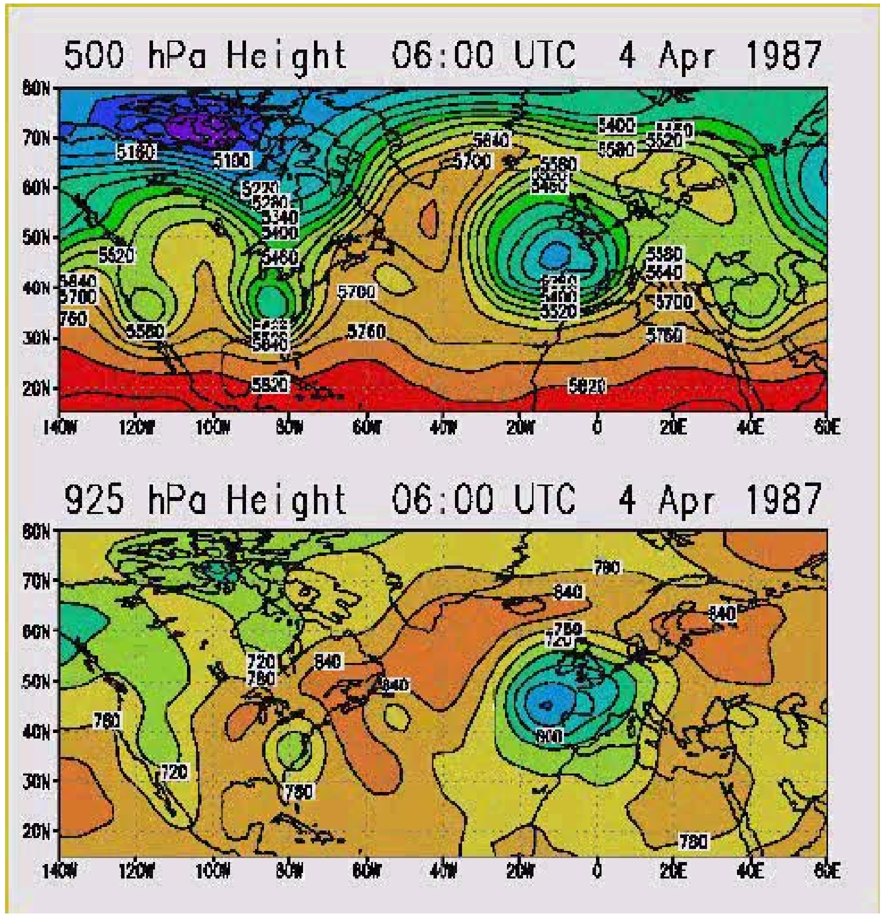


Sulfate, µmol m-2



SYNOPTIC METEOROLOGY

Height of surfaces of constant pressure

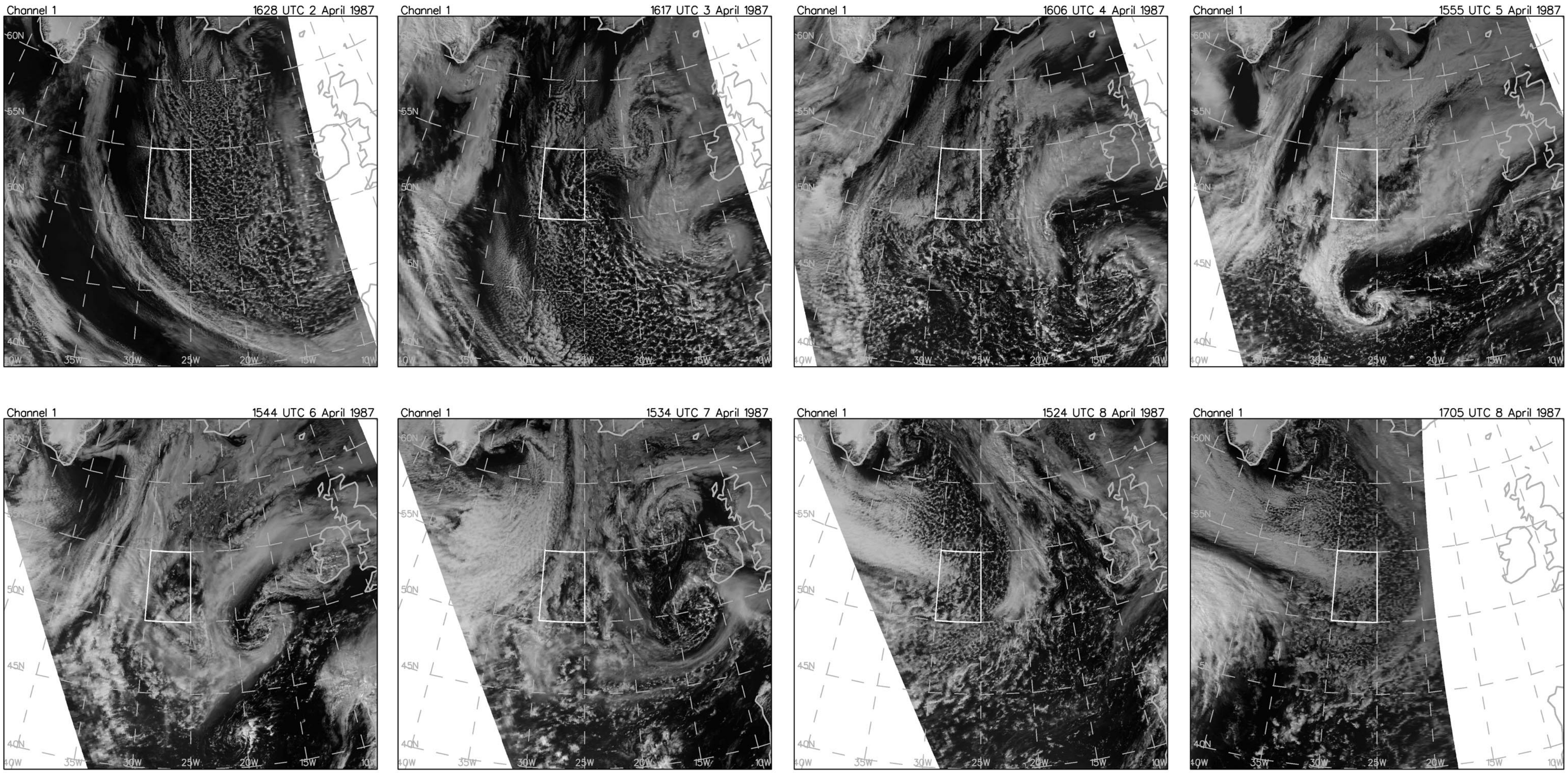


Benkovitz, Miller, Schwartz & Kwon, *G*[3], in press, 2001

- Note cut-off low-pressure system -- vertically aligned low pressure.
- Persistent low-pressure system transports material from northern European continent and Britain to northwest North Atlantic.

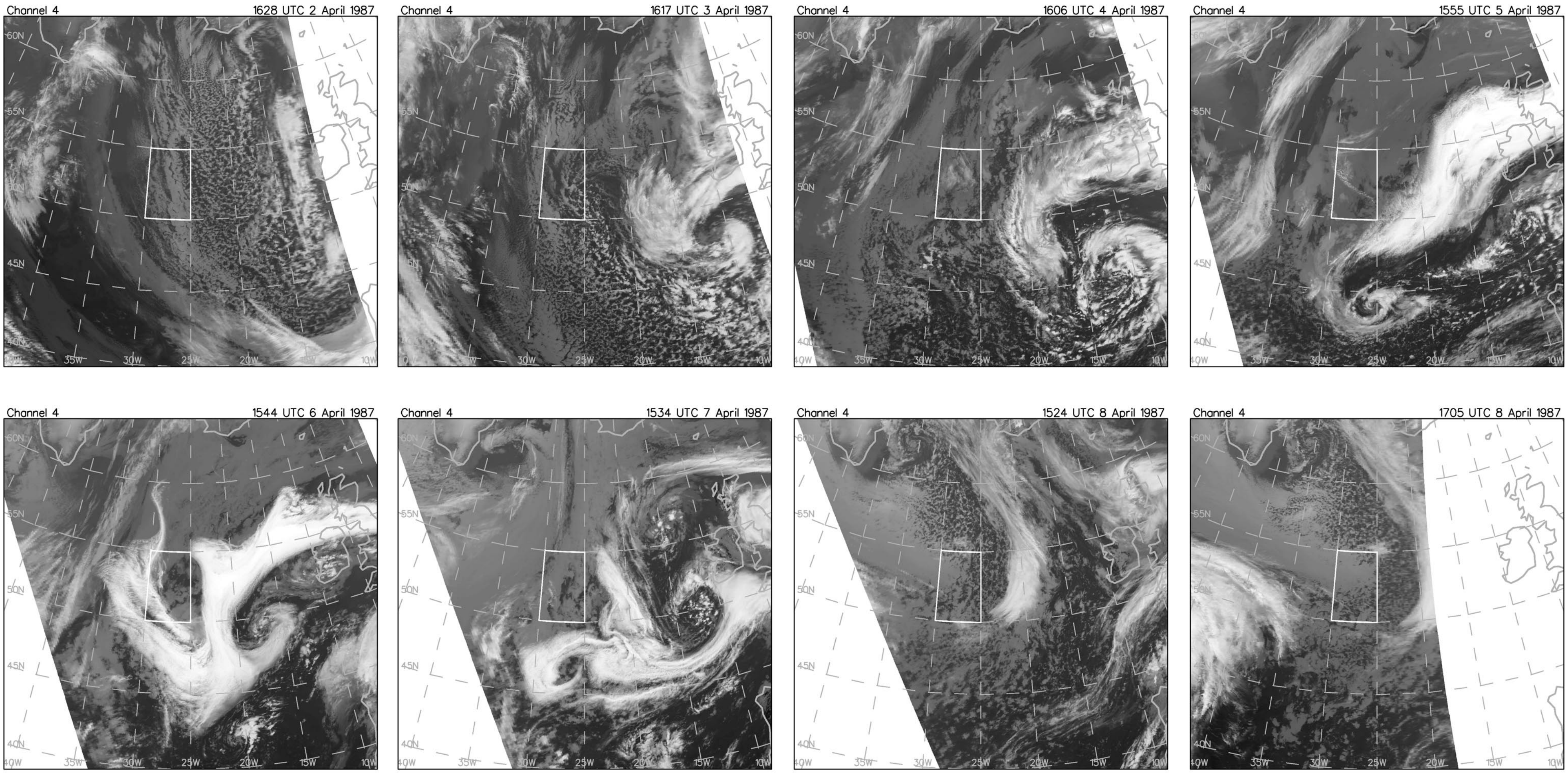
AVHRR IMAGES APRIL 2-8, 1987

Channel 1, Visible, 0.58-0.68 µm



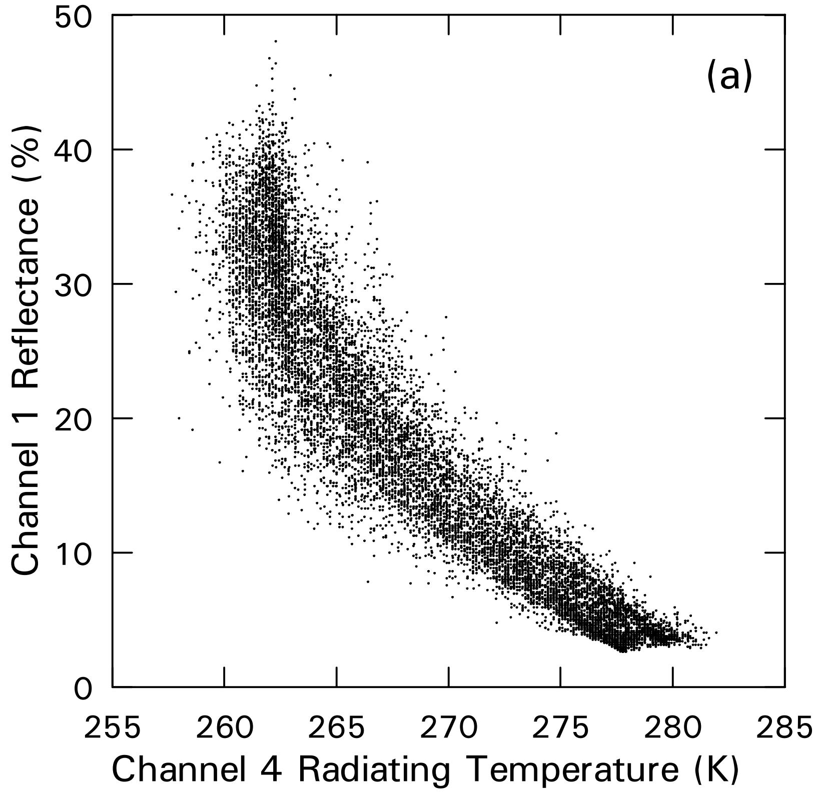
AVHRR IMAGES APRIL 2-8, 1987

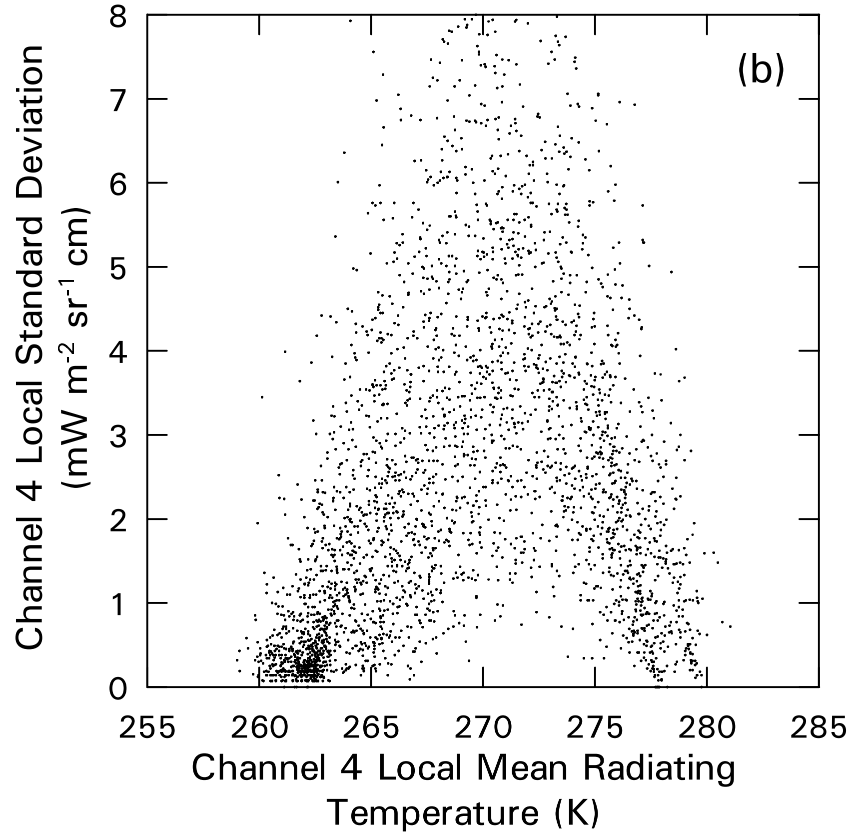
Channel 4, Thermal IR, 10.3-11.3 μm



AVHRR DATA
Screening for Spatial Coherence

April 2, 1987 50-55N/25-30W 1628 UTC

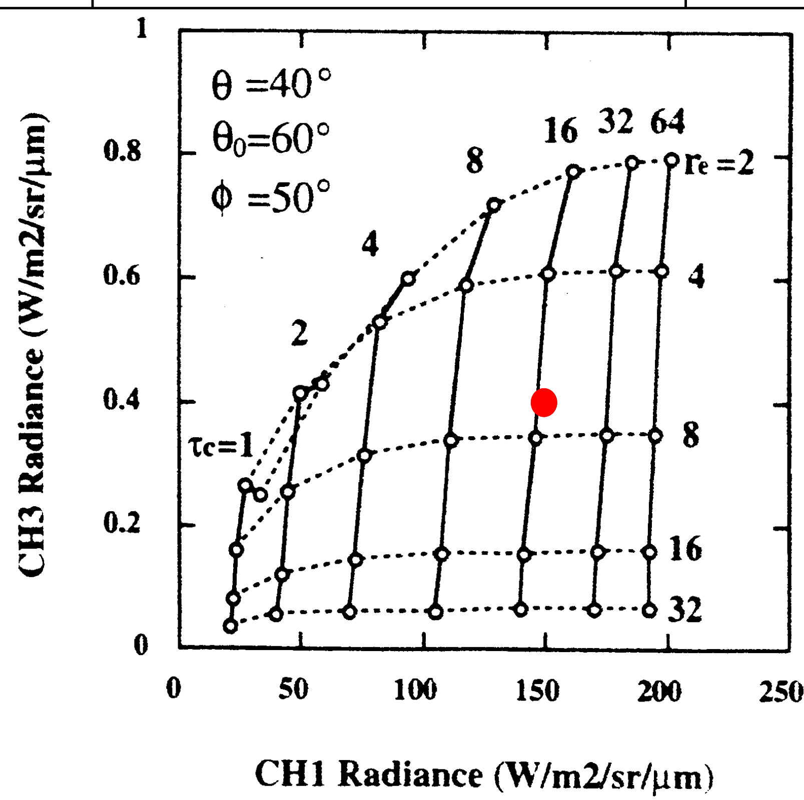




Harshvardhan, Schwartz, Benkovitz & Guo, J. Atmos. Sci, submitted, 2000

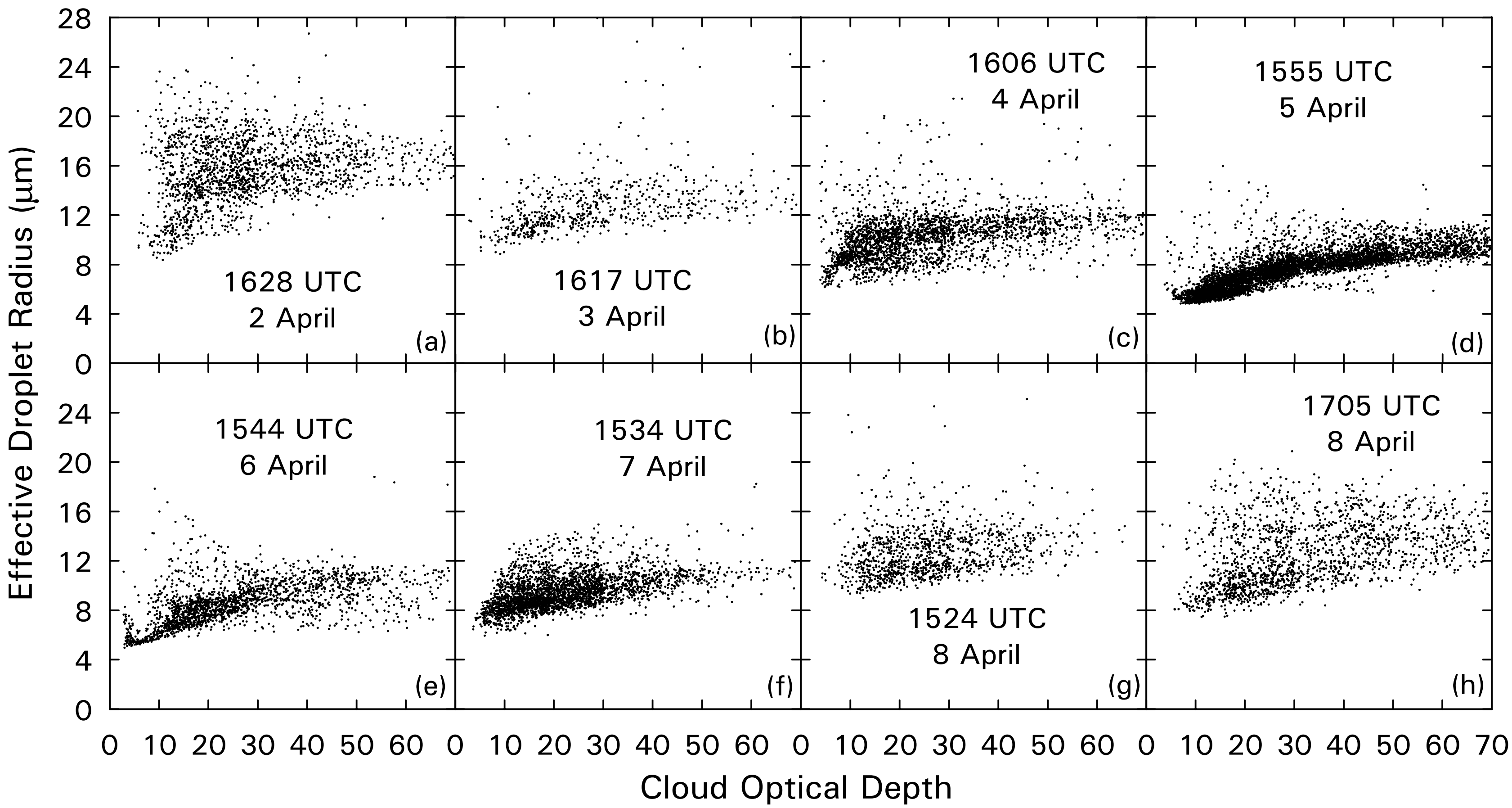
DETERMINING CLOUD OPTICAL THICKNESS AND EFFECTIVE DROP RADIUS FROM SATELLITE RADIANCE MEASUREMENTS

IN	LOOK-UP TABLE	OUT
Visible and IR radiance Channel 1 (0.58-0.68 μm) Channel 3 (3.6-3.9 μm)	Based on Radiative Transfer Calculations $f(\theta_0, \theta, \phi)$ →	Cloud optical thickness (0.63 μm) τ_c Effective radius $r_e = \mu_3/\mu_2$



Nakajima and Nakajima, J. Atmos. Sci. (1995)

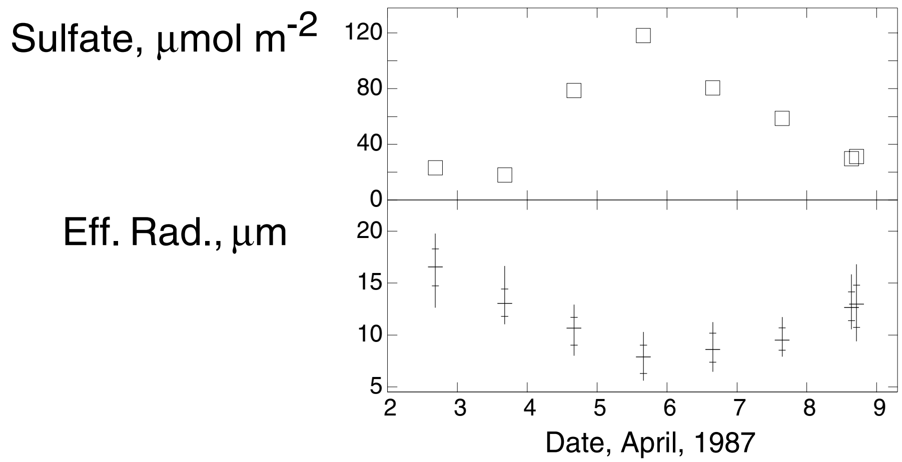
EFFECTIVE RADIUS VS. CLOUD OPTICAL DEPTH
AVHRR Data: 50-55°N, 25-30°W, 2-8 April, 1987



Harshvardhan, Schwartz, Benkovitz & Guo, J. Atmos. Sci., submitted, 2000

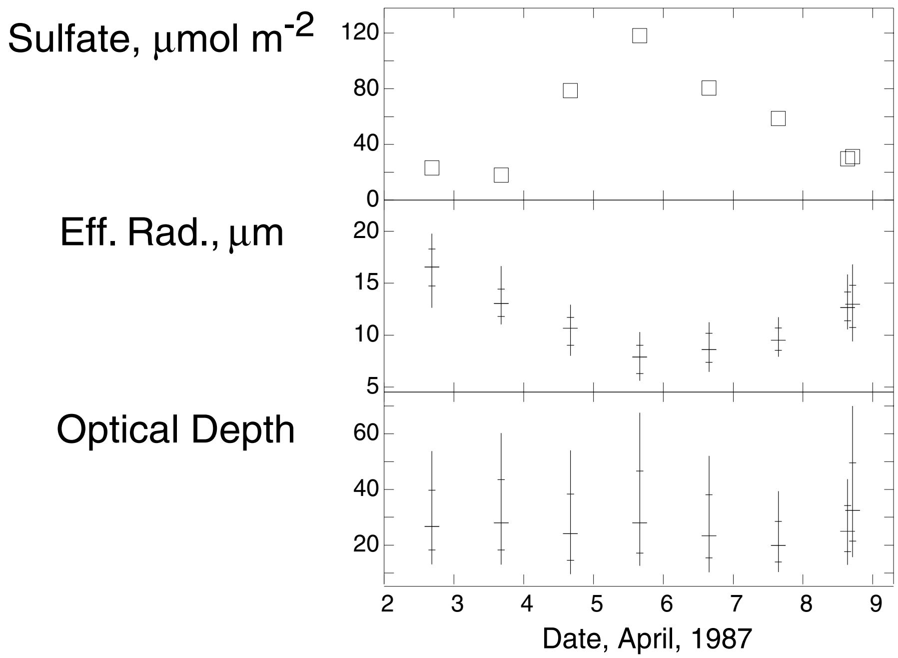
SULFATE COLUMN BURDEN AND CLOUD DROP EFFECTIVE RADIUS

25°-30°W, 50°-55°N, April 2-8, 1987



SULFATE COLUMN BURDEN, CLOUD DROP EFFECTIVE RADIUS, AND CLOUD OPTICAL DEPTH

25°-30°W, 50°-55°N, April 2-8, 1987



DERIVED MICROPHYSICAL QUANTITIES

Primary measured quantities:

Effective radius at top of cloud r_e

Cloud optical depth τ_c

Derived quantities:

Liquid water path $W = \dfrac{2\rho_w \tau_c \overline{r_e}}{3}$

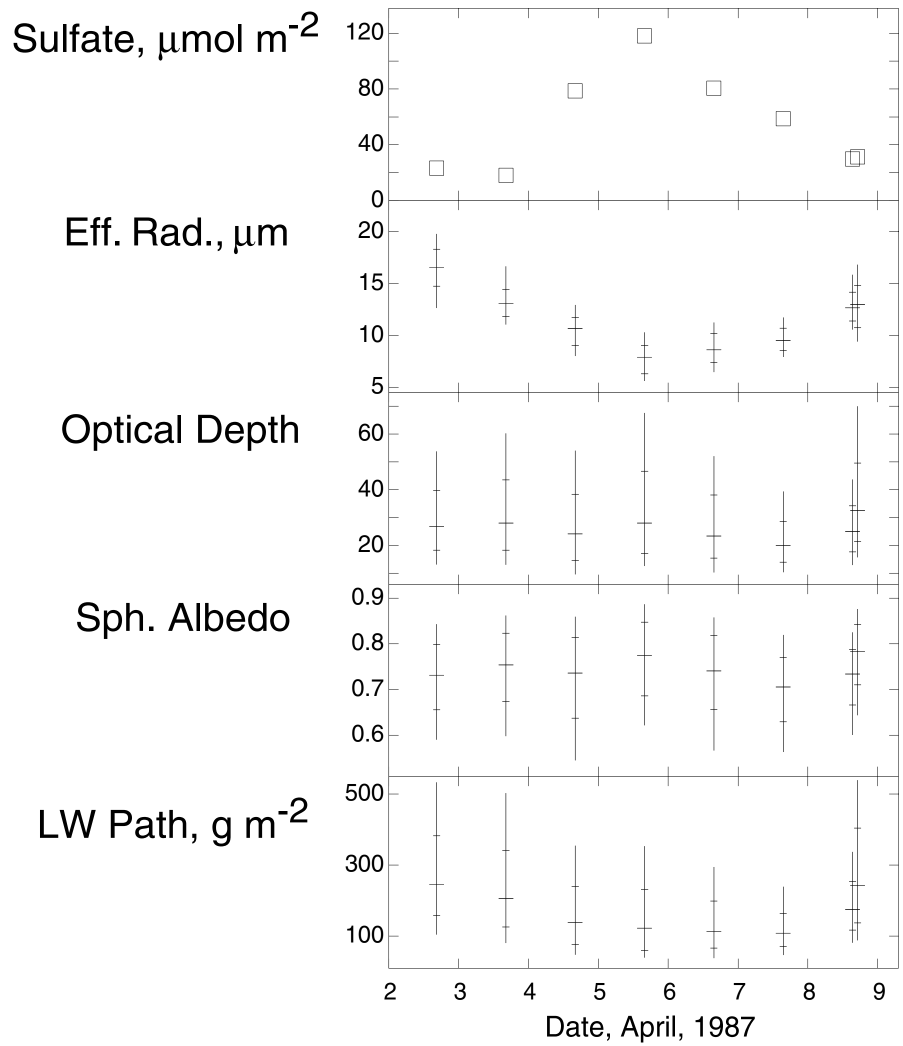
where $\overline{r_e}$ is mean drop radius in cloud, taken as $(5/6)r_e$, and

Cloud spherical albedo $\alpha_{\text{sph}} \approx \dfrac{\tau_\text{c}(1-g)+0.097}{\tau_\text{c}(1-g)+1.43}$

where g is asymmetry parameter ranging from 0.834 for $r_e = 6$ μm to 0.872 for $r_e = 19$ μm.

CLOUD PROPERTIES AND SULFATE COLUMN BURDEN

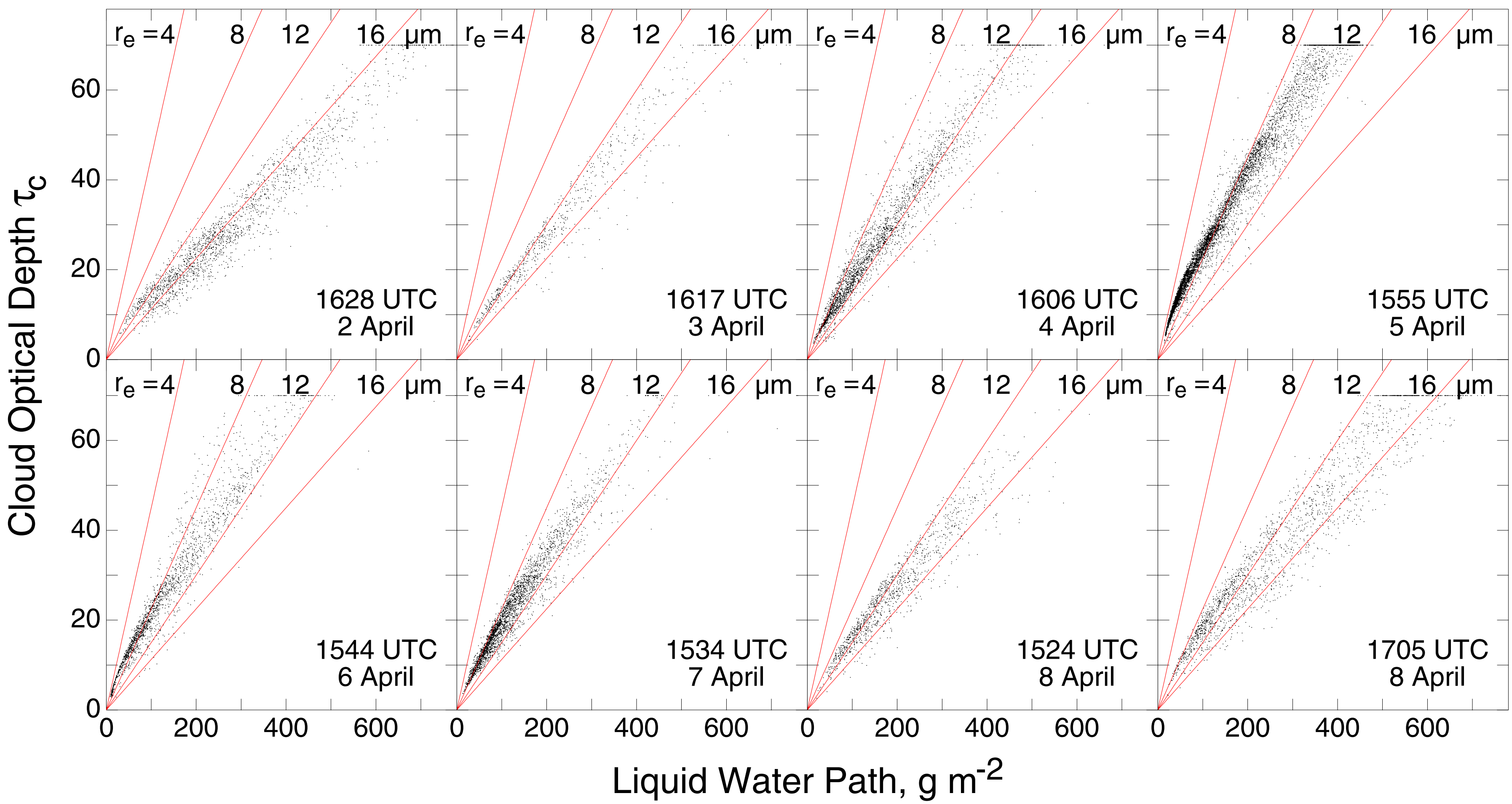
25°-30°W, 50°-55°N, April 2-8, 1987



CLOUD OPTICAL DEPTH

Dependence on Liquid Water Path

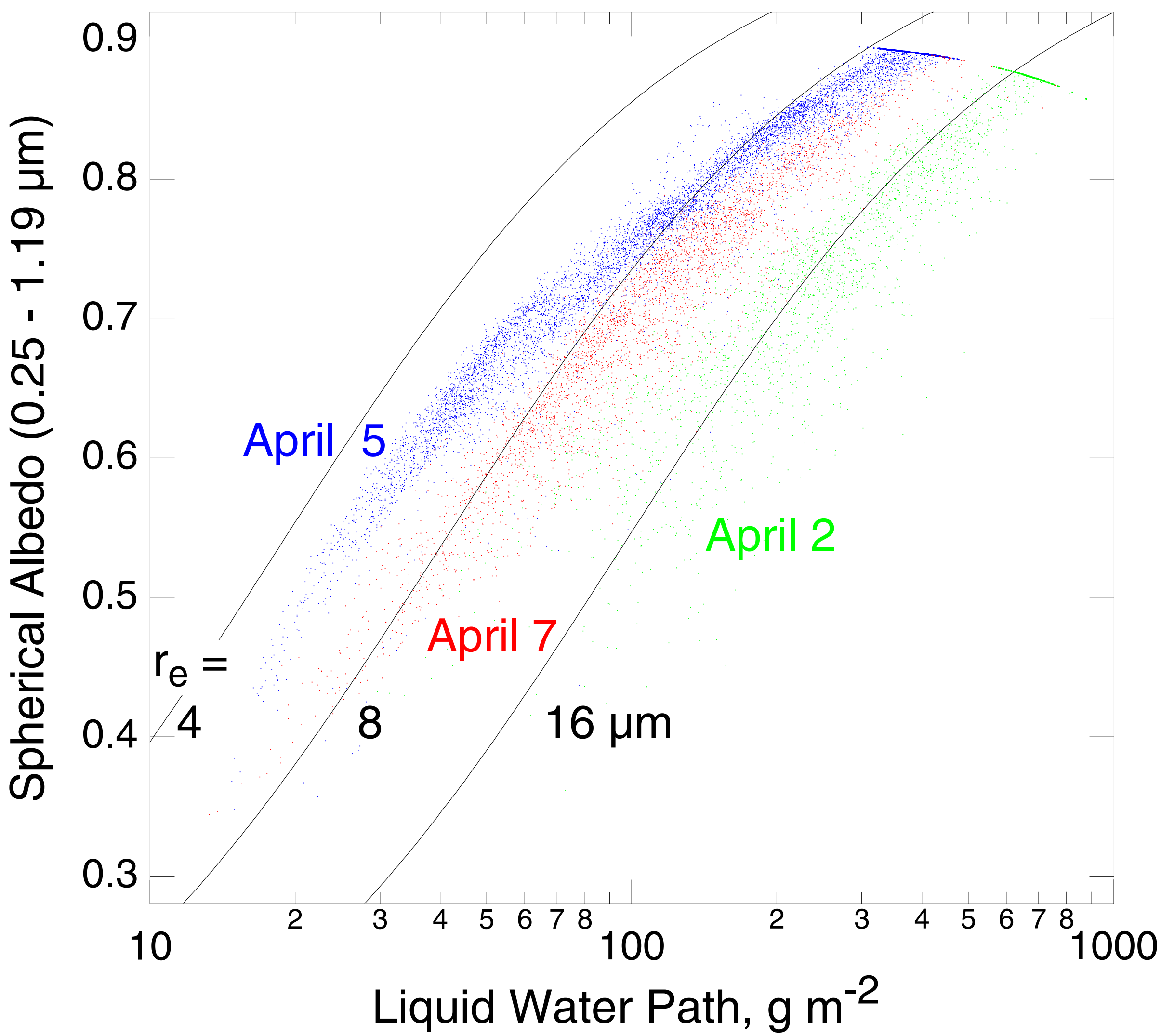
25°-30°W, 50°-55°N   April 2-8, 1987



CLOUD-TOP ALBEDO

Dependence on Liquid Water Path

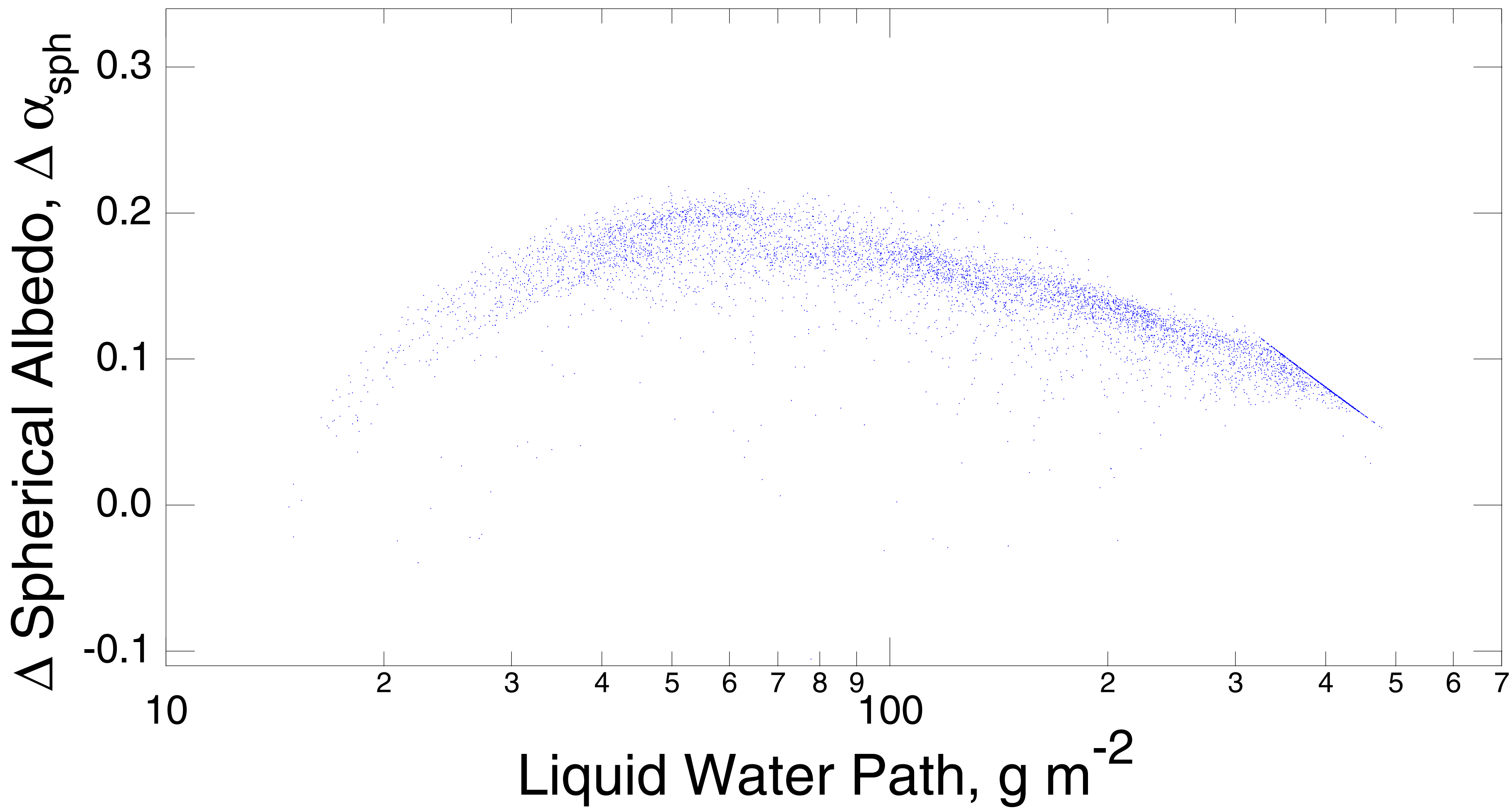
25°-30°W, 50°-55°N April 2, 5 and 7,1987



CLOUD-TOP ALBEDO DIFFERENCE

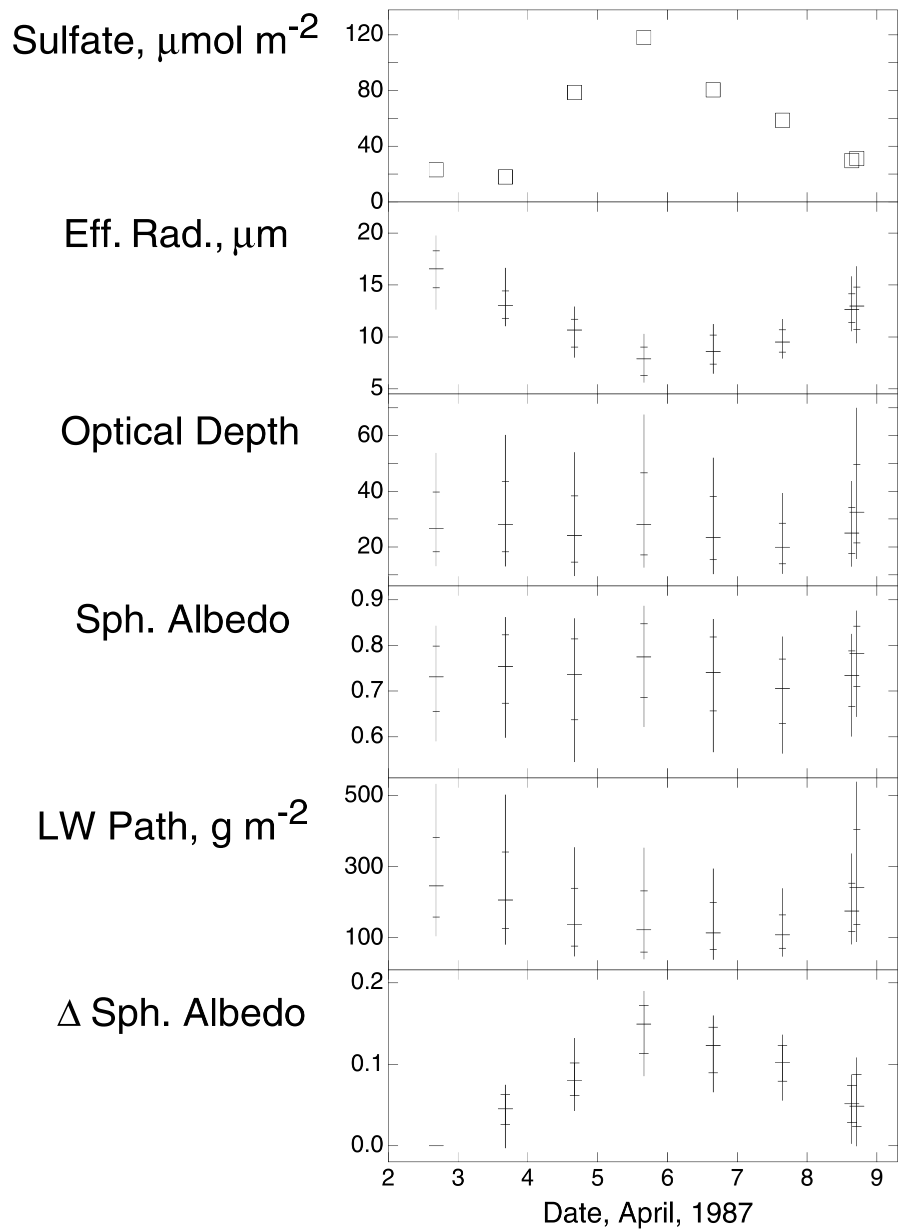
April 5 relative to April 2, 1987

Evaluated for LWP of April 5 Data



CLOUD PROPERTIES AND SULFATE COLUMN BURDEN

25°-30°W, 50°-55°N, April 2-8, 1987



CONCLUSIONS

- Demonstrated ability to relate satellite-derived cloud microphysical properties to modeled aerosol loading.
- Cloud-drop effective radius is strongly correlated with modeled sulfate loading.
- Lack of evident correlation of cloud optical thickness and spherical albedo with modeled sulfate is attributed to variation in liquid water path.
- Plotting optical thickness or spherical albedo *vs*. LWP allows dependence on LWP to be accounted for.
- When LWP variation is accounted for, clouds on high sulfate days exhibit marked enhancement in spherical albedo.
- This approach takes advantage of variable LWP and aerosol loading to identify and quantify the enhancement in spherical albedo due to aerosols.
- This approach may be broadly applicable to examining aerosol influences on cloud microphysical properties and radiative forcing.