Utility of Spaceborne Lidar Data for Cloud Studies in Climate Research

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The application of spaceborne cloud lidar is discussed in relation to the effect of ice clouds on Earth's Radiation Budget (ERB) and on atmospheric and surface radiative heating. The key science questions highlighted include: .

- What is the impact of the cloud and aerosol optical properties on radiation reflected and emitted to space and the particular peculiarities of ice clouds and aerosol to the ERB?

- What is the effect of the distribution of cloud on the water budget of the middle-to-upper troposphere and what is the relevance of this budget to climate?

- What are the possible roles of the radiative properties of clouds and aerosol on climate and climate feedback?

The utility of spaceborne lidar for addressing these science issues will be described. Among the most relevant issues addressed are:

- Backscatter ambiguity - the need to convert lidar backscatter to information relevant to the science questions highlighted above is described and some examples as to how this might be achieved will be discussed.

- The space-time requirements imposed by a single satellite carrying a lidar will be described and the kinds of biases on radiative budget properties expected by this sampling will be highlighted.

SPACEBORNE LIDAR IN CLIMATE RESEARCH

Graeme L. Stephens
Int. workshop on space borne lidar, 1995

1. Cloud - aerosol climate forcing
2. Cirrus and aerosol
3. Scene identification and cloud contamination
4. Time space sampling and biases
5. Summary

BACKSCATTER AMBIGUITY

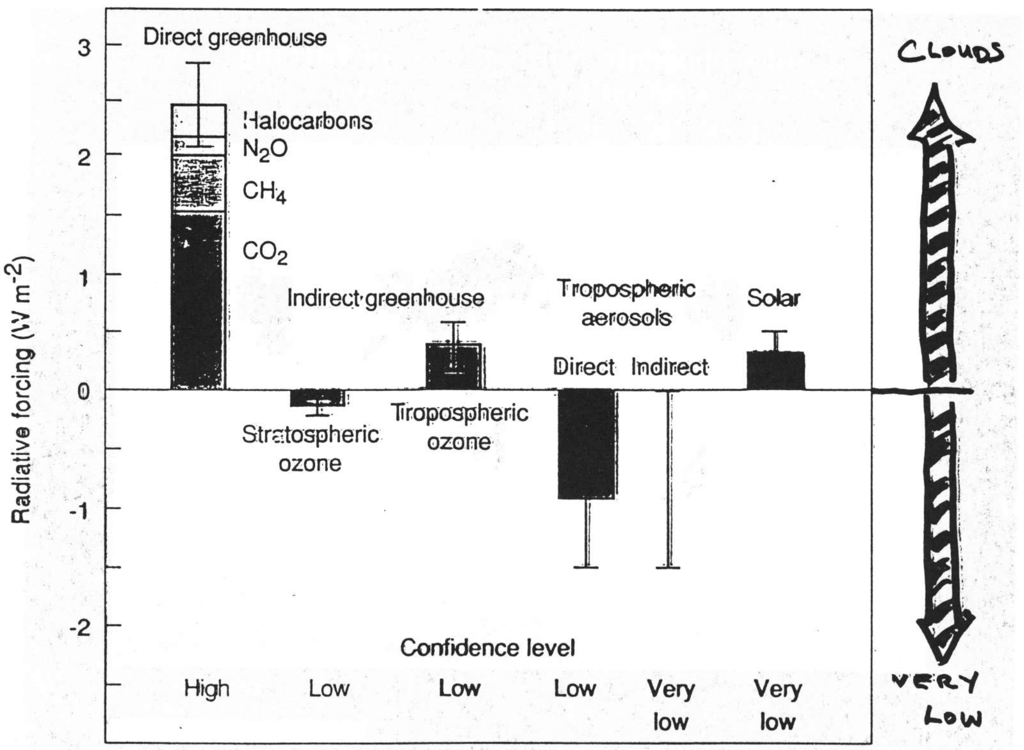
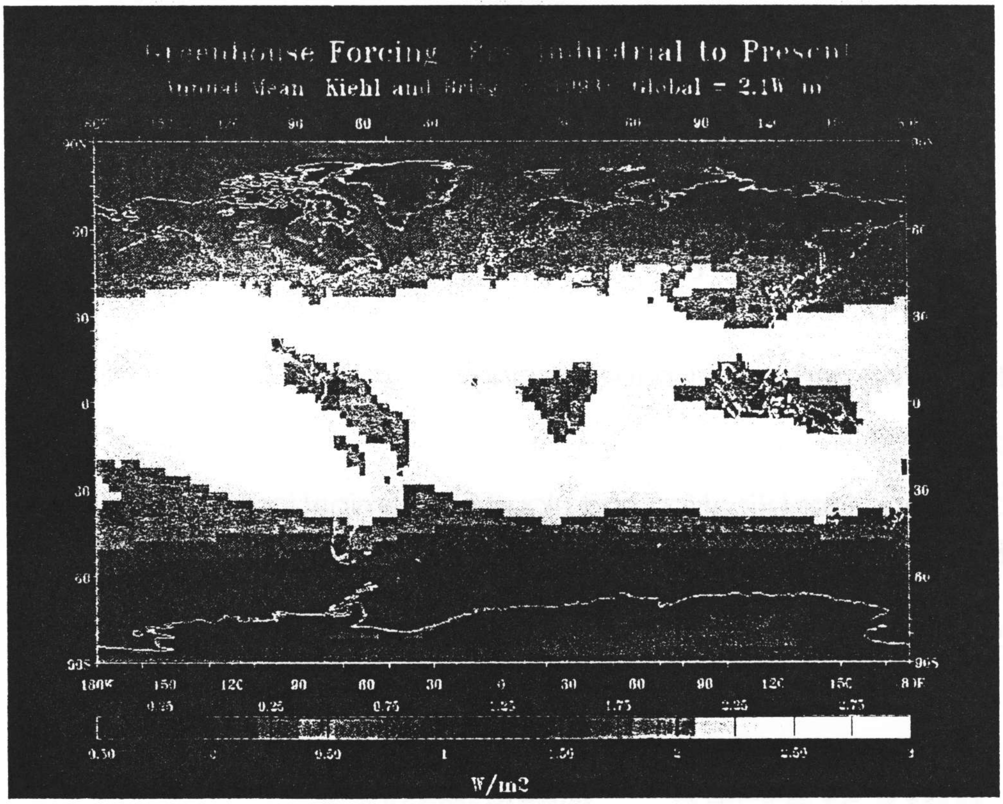
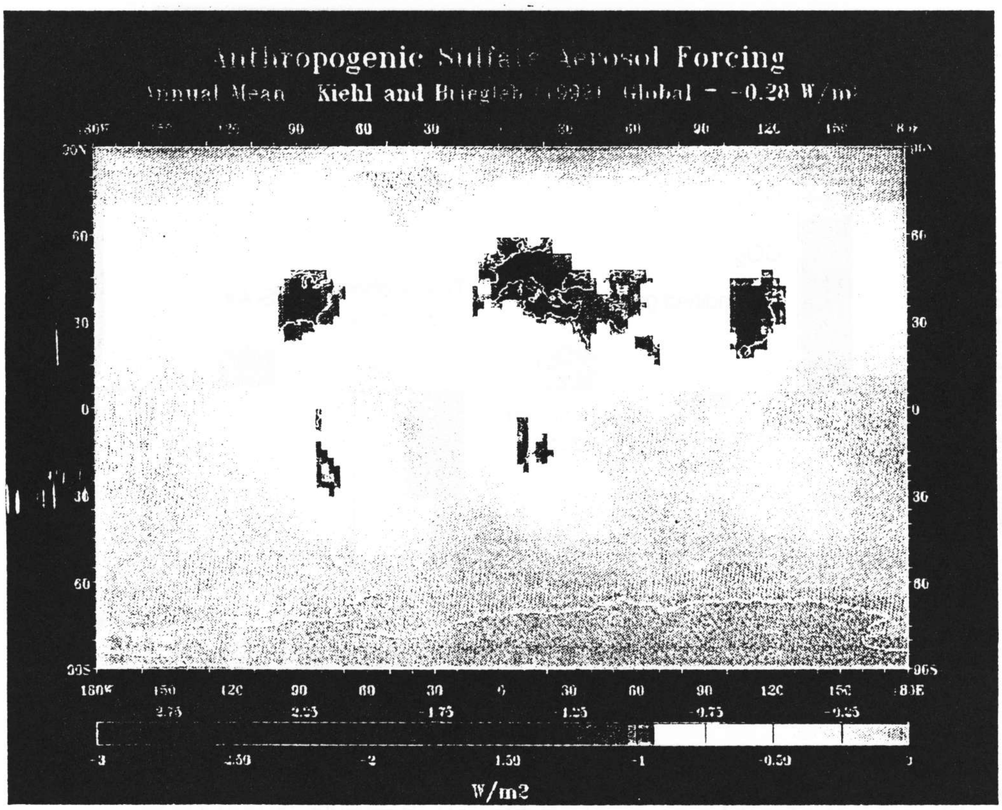


Figure 3. *Estimates of the globally averaged radiative forcing due to changes in greenhouse gases and aerosols from pre-industrial times to the present day and changes in solar variability from 1850 to the present day. The height of the bar indicates a mid-range estimate of the forcing whilst the lines show the possible range of values. An indication of relative confidence in the estimates is given below each bar. The contributions of individual greenhouse gases are indicated on the first bar for direct greenhouse gas forcing. The major indirect effects are a depletion of stratospheric ozone (caused by the CFCs and other halocarbons) and an increase in the concentration of tropospheric ozone. The negative values for aerosols should not necessarily be regarded as an offset against the greenhouse gas forcing because of doubts over the applicability of global mean radiative forcing in the case of non-homogeneously distributed species such as aerosols and ozone (see Section 1 and Section 7).*



K + B, 1993

Figure 4a



KIEHL + BRIEGLEB, 1993

Figure 2a

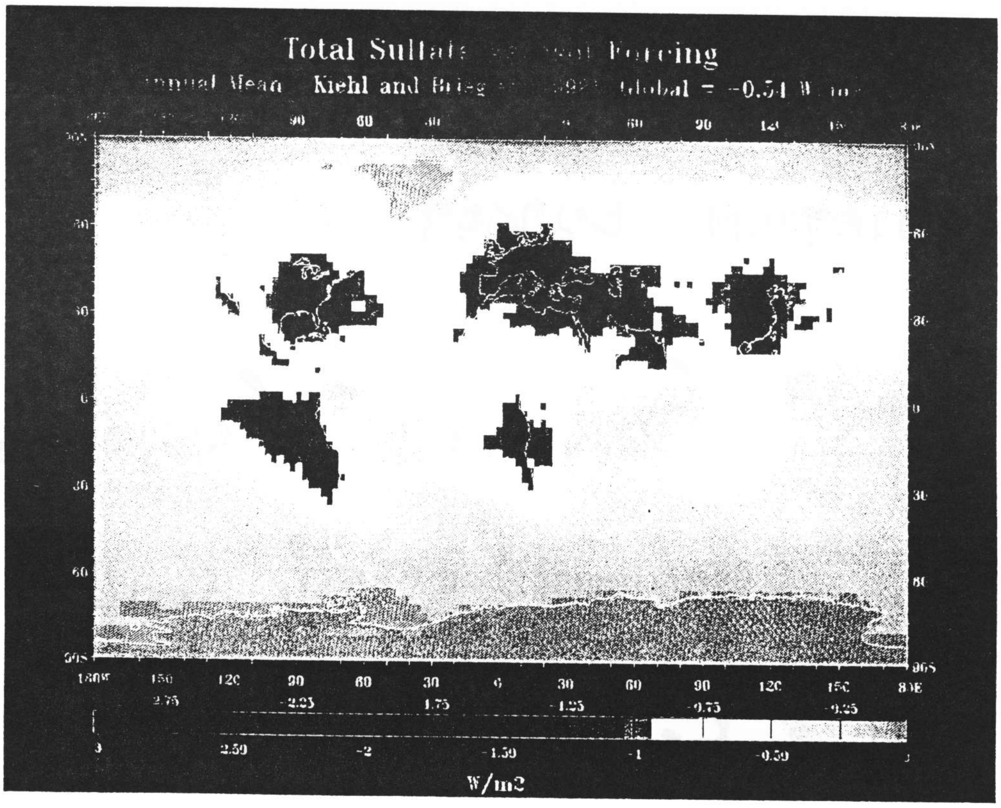


Figure 2b

K+B, 1993

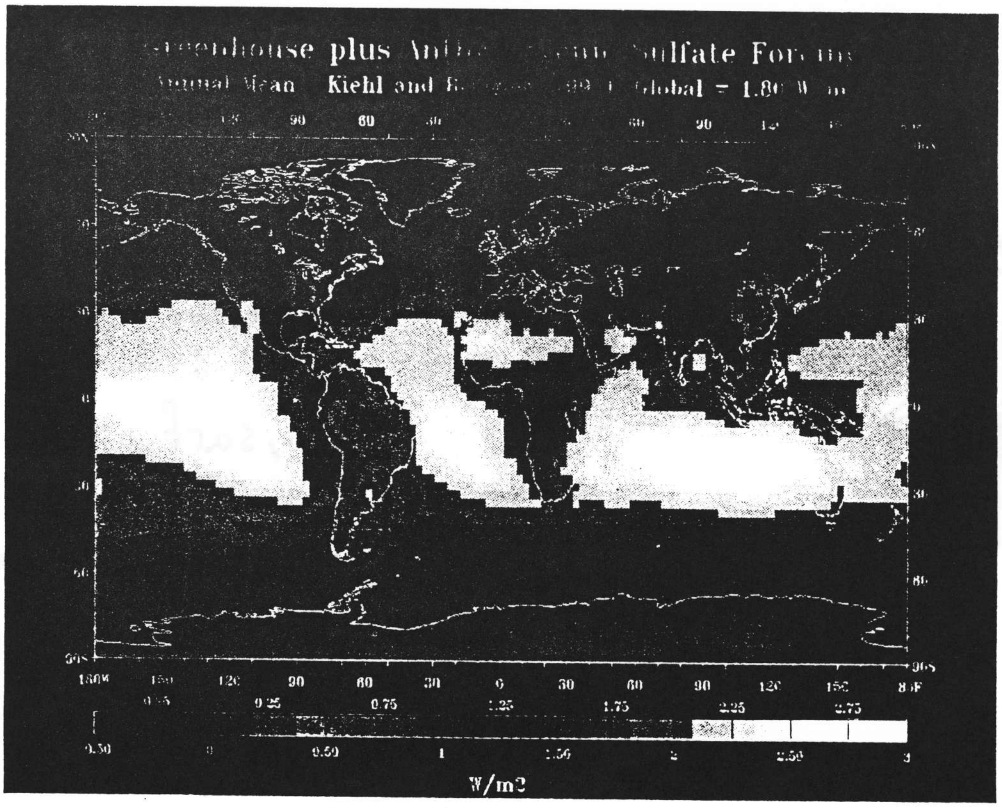


Figure 4b

K+B, 1993

CLOUD EFFECTS ON RADIATION BUDGET

$$C_{LW} = C_{LW,CLEAR} - C_{LW,CLOUD}$$

"GREENHOUSE" EFFECT, $C_{LW} > 0$

$$C_{SW} = C_{SW,CLR} - C_{SW,CLD}$$

"ALBEDO" EFFECT, $C_{SW} < 0$

$$C_{net} = C_{LW} + C_{SW} \lesseqgtr 0$$

- → ATMOSPHERE $C_{net,atm}$
- → SURFACE $C_{net,surf}$
- → TOTAL $C_{net} = C_{net,atm} + C_{net,surf}$

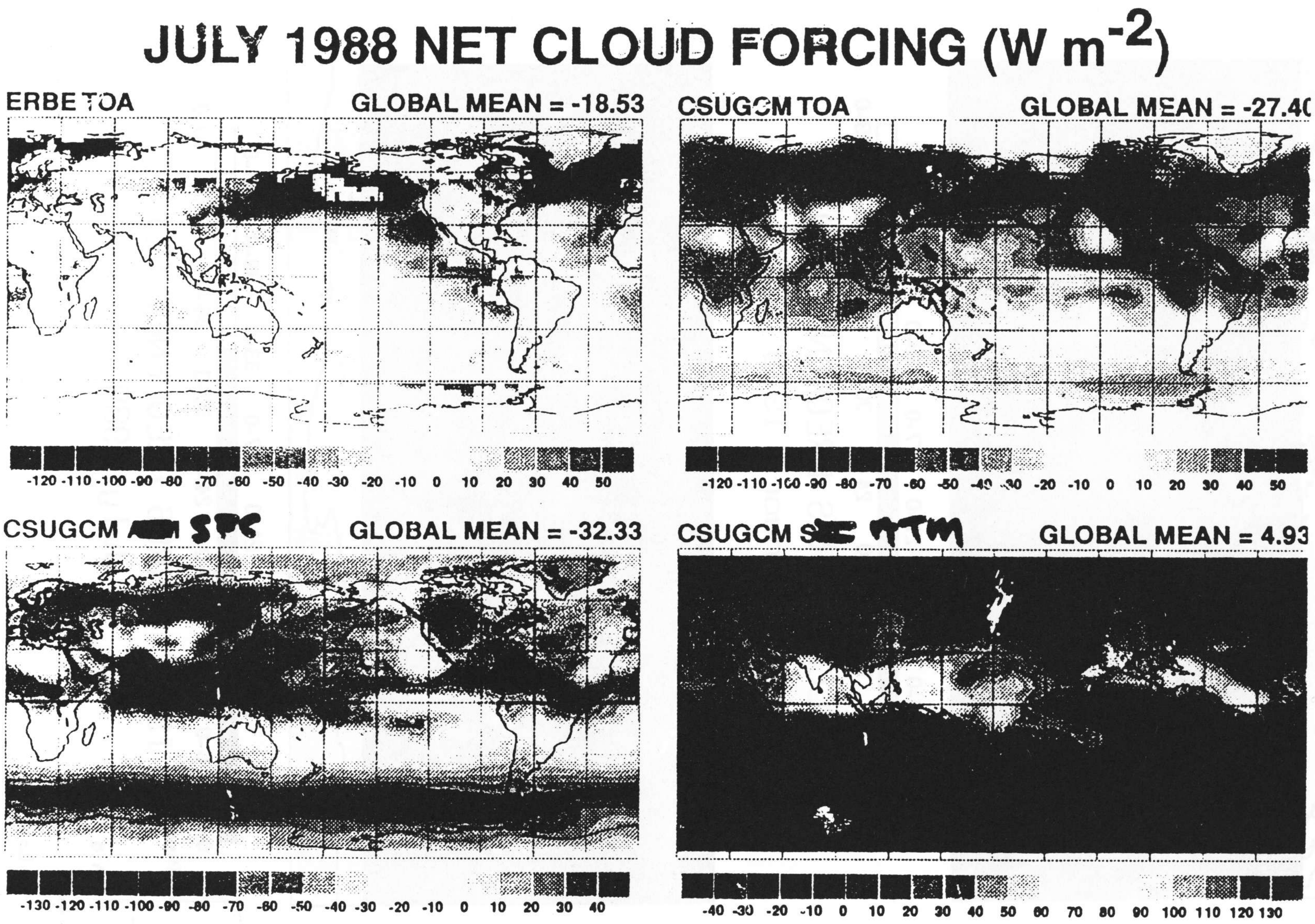
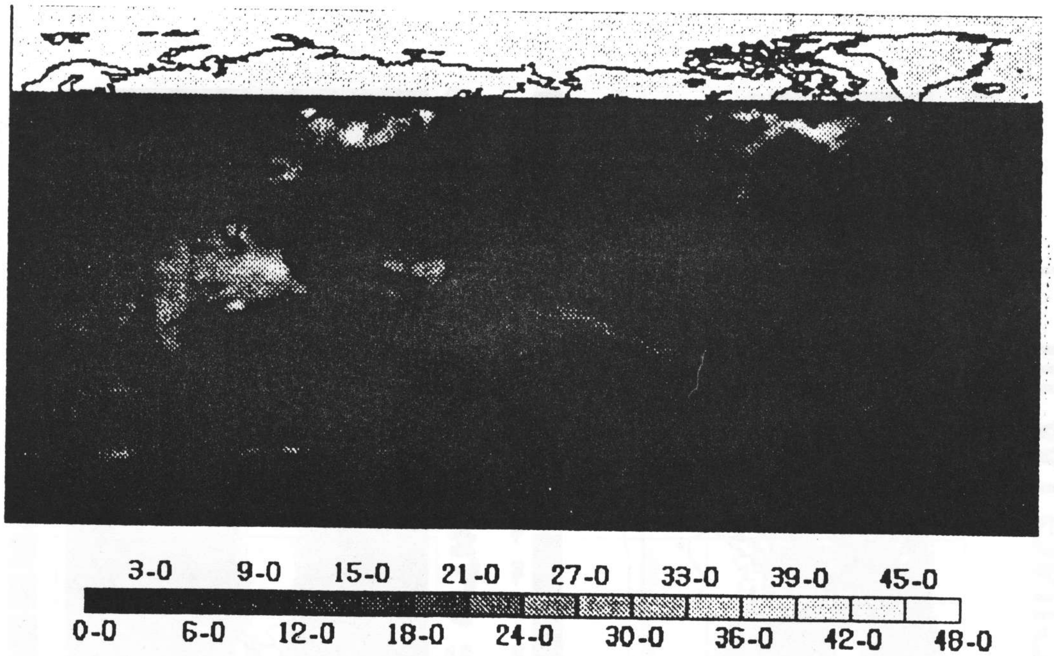


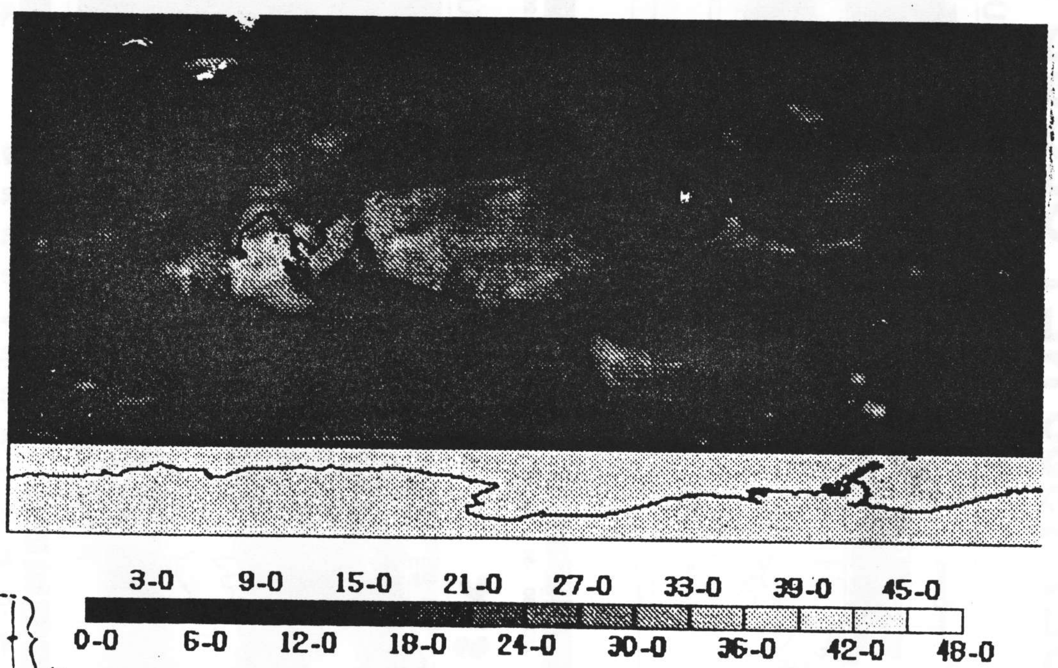
Fig. 1 NET CLOUD RADIATIVE FORCING

Top: Total cloud radiative forcing from ERBE and from the Colorado State University GCM.

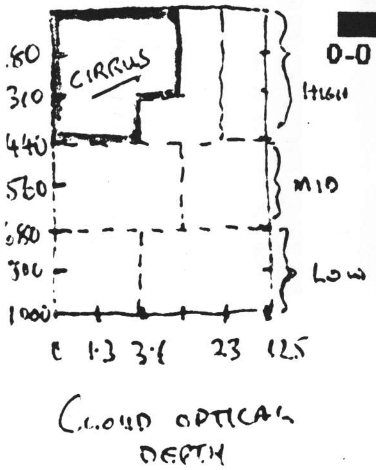
Bottom: Tropospheric (right) and surface (left) cloud radiative forcing from the CSU-GCM.

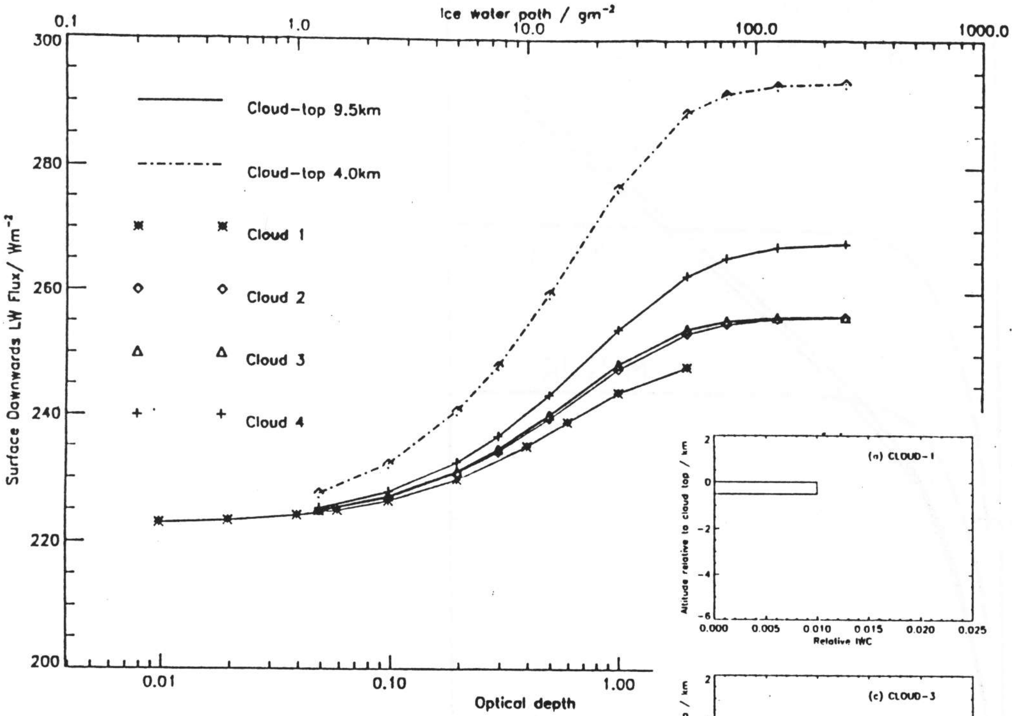


ISCCP CIRRUS FREQUENCY (%)
January 1989



ISCCP CIRRUS FREQUENCY (%)
July 1989





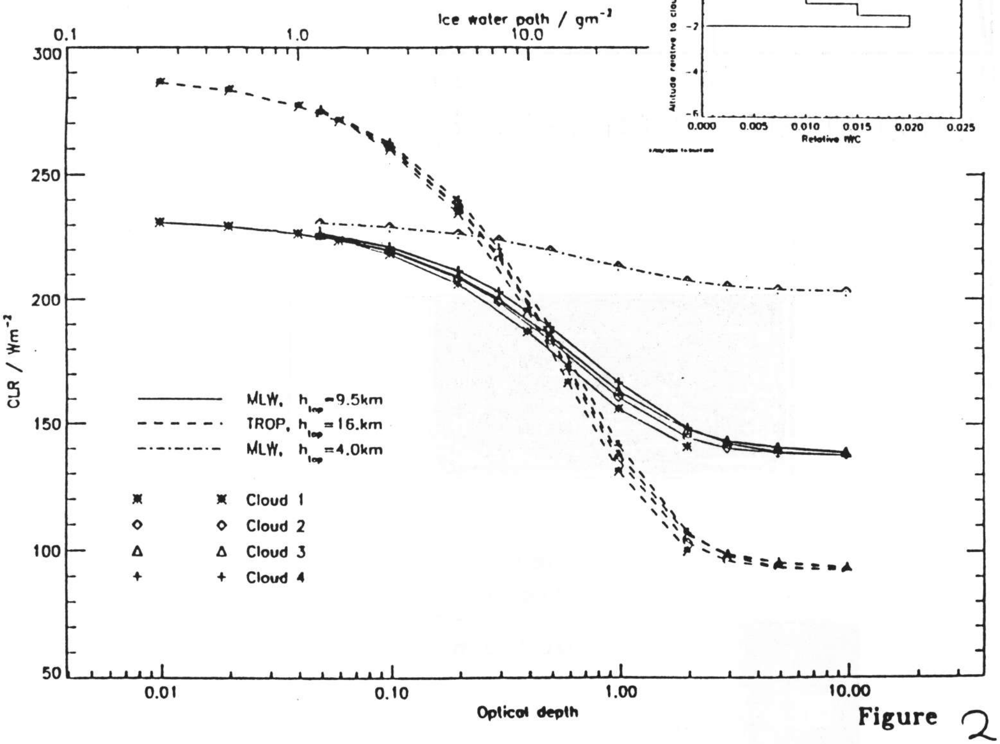


Figure 2

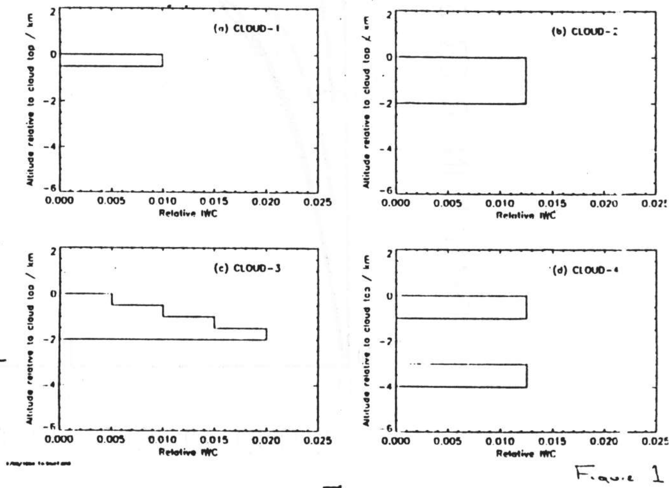
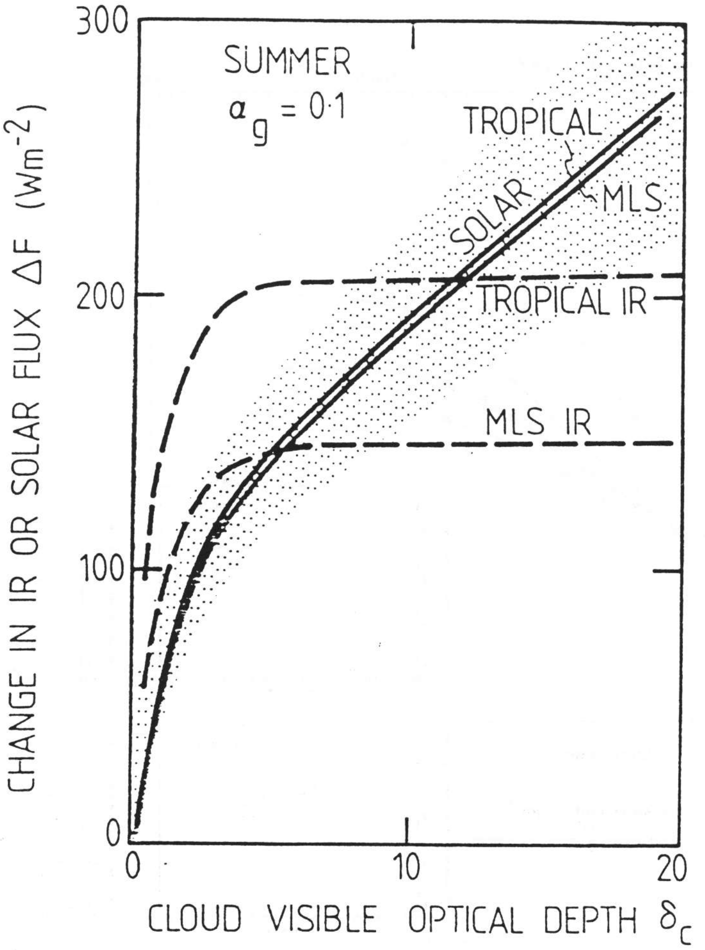
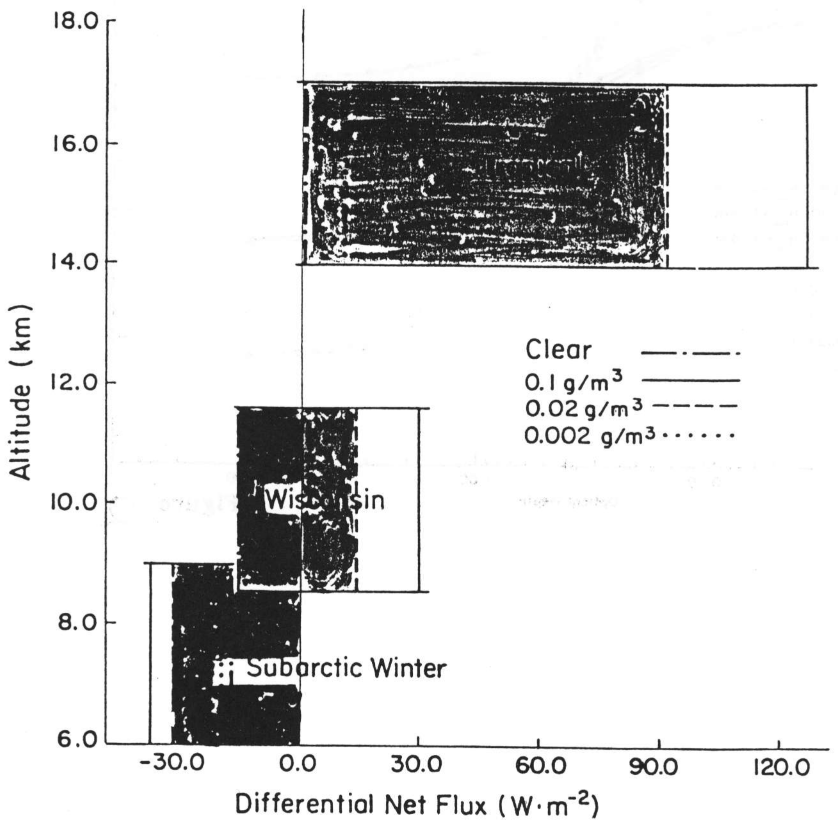


Figure 1

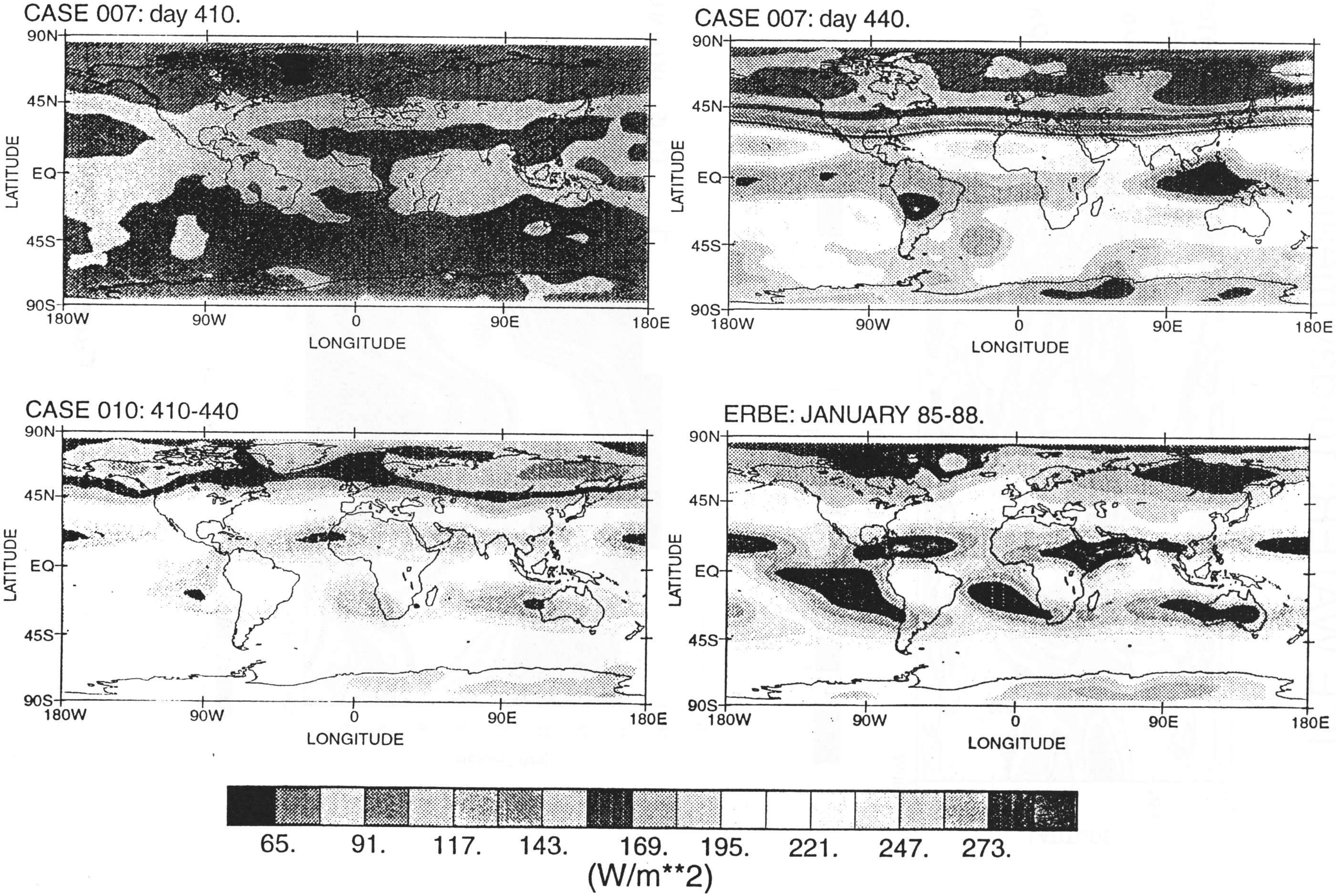




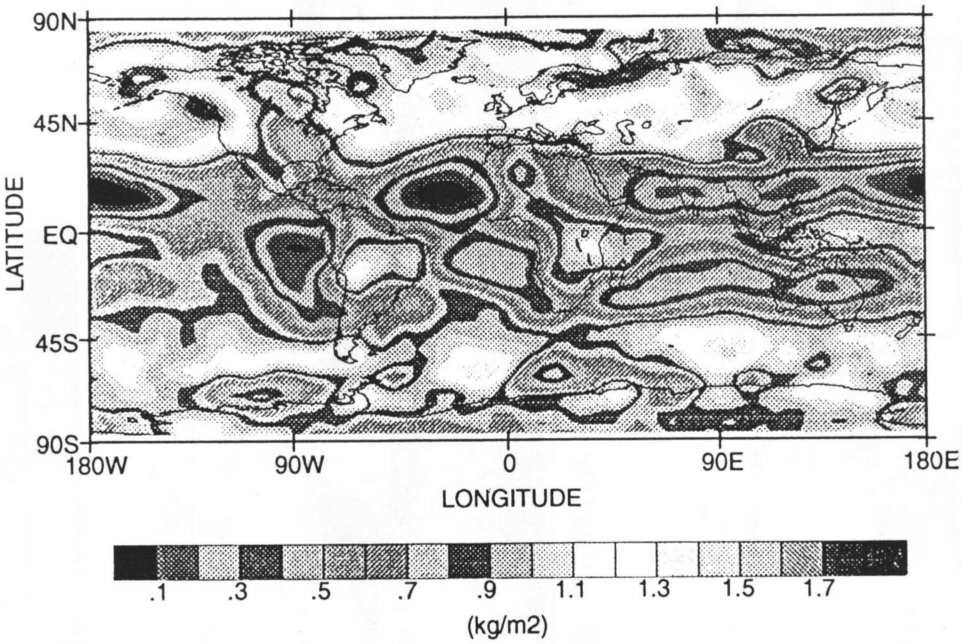
Stackhouse + Stephens

'ICE CATASTROPHE'

OUTGOING LONGWAVE RADIATION

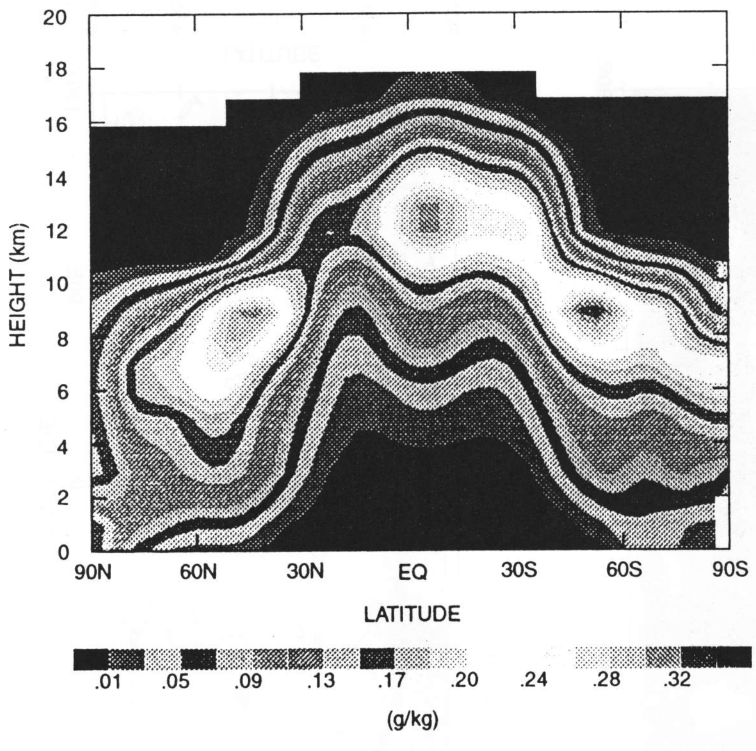


ICE WATER: 10-day mean



CLIMATE MODEL WITH CLOUD PHYSICS

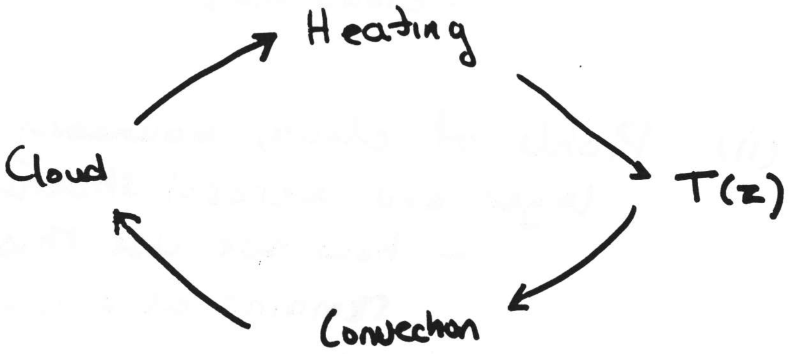
ICE PATH



ICE MIXING RATIO

FOWLER + RANDALL (1994)

Radiative heating – ice – convection feedback



Climate Issue

1. Aerosol Forcing

Major problem is that (direct) aerosol forcing occurs over landmasses. Passive (radiometric) methods as currently used lack sensitivity to determine aerosol of land surfaces.

2. Cloud Forcing

Cloud forcing is variable and depends on cloud type. They separate the column effects into a heating in the atmosphere and cooling at the surface. High cloud (cirrus) play an important role especially in tropical regions and contribute substantially to atmospheric heating (and probably to surface cooling).

- Heating by high ice clouds may play a key role in regulation of convection
- Low cloud radiatively cool

HOW CAN LIDAR CONTRIBUTE ??

Lidar by itself offers important information

(i) Scene identification / classification
- cloud bias

(ii) Profile of cloud, boundary layer and aerosol structure
- how we use this information remains as a matter of research
.
.
.
.

BUT with supporting measurements, lidar offers much more information

For example, it may be possible to

(i) retrieve profiles of extinction (of aerosol + thin cloud)

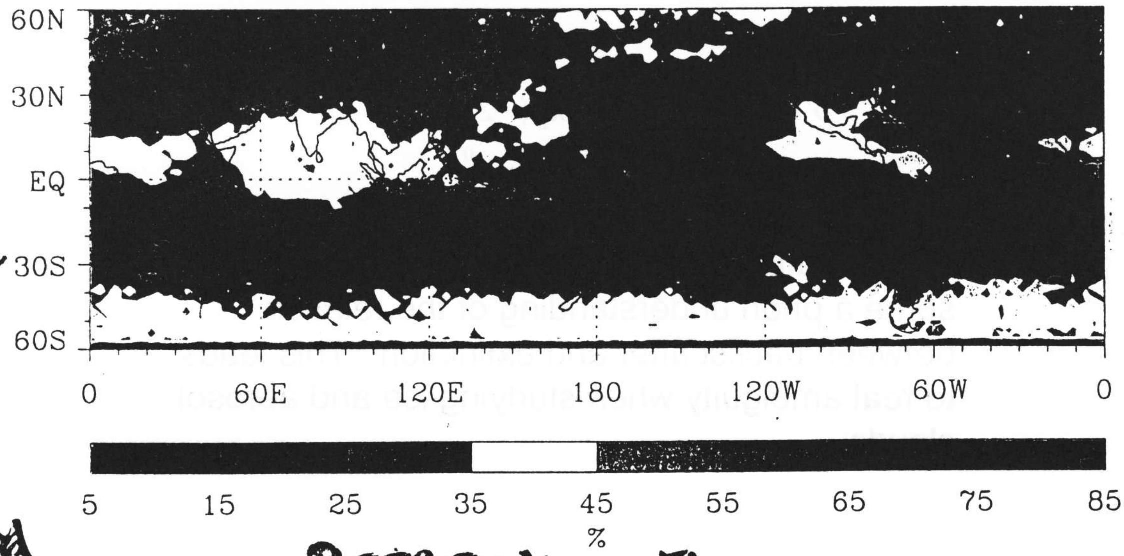
(ii) infer profiles of absorption

(iii) deduce other optical properties (scattering phase function ....)

MESSAGE careful choice of ancillary observations

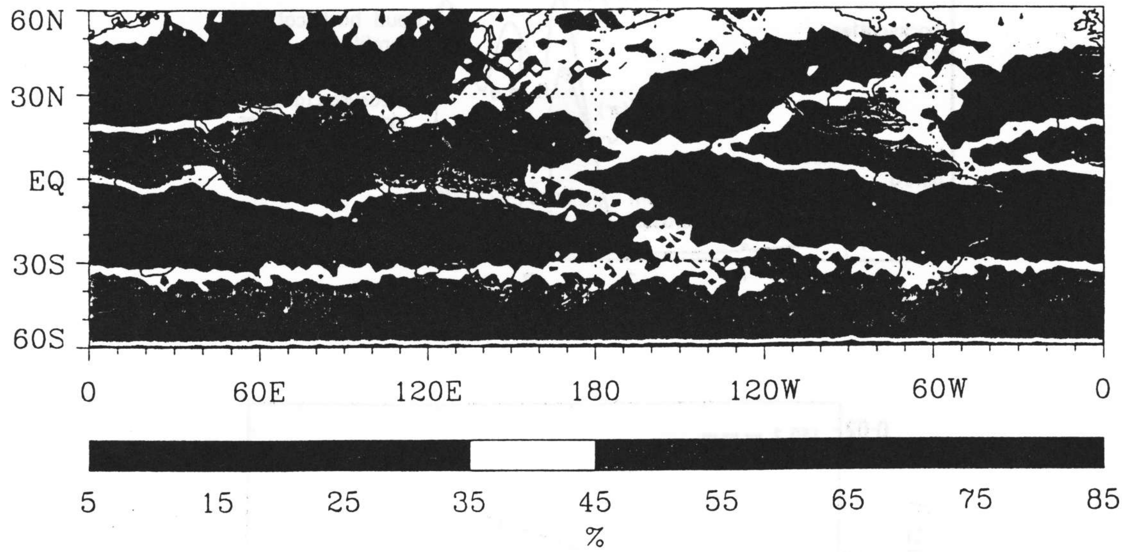
A 3K BIAS
(equivalent to → $\tau \approx 0{\cdot}2$)

Stephens UTH July 1988



FROM THIS RETRIEVAL OF UPPER TROPOSPHERE RELATIVE HUMIDITY (6.7μm) TO THIS

Soden UTH July 1988

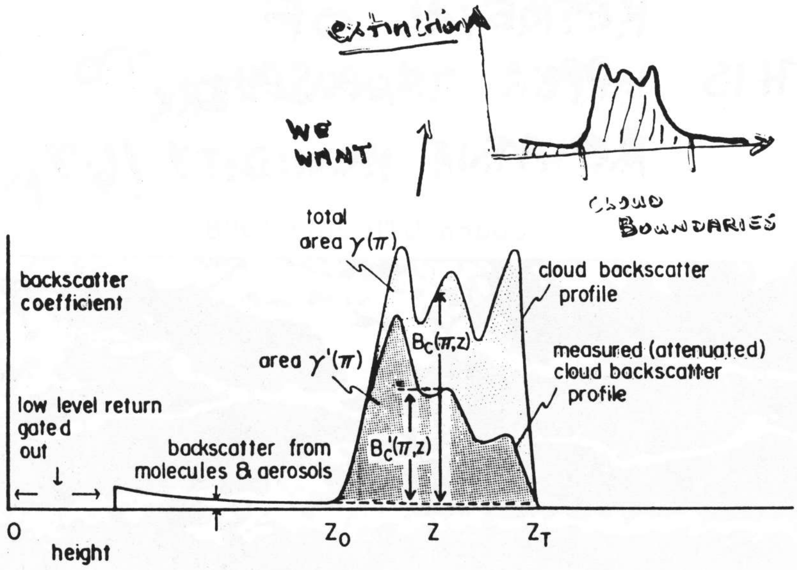


Backscatter ambiguity:

Lidar equation

$$p_r(R) = \frac{C}{R^2}\frac{h}{2}\frac{\beta}{4\pi}\exp(-2\int_0^R \sigma_{ext}(r')dr')$$

Interpretation in the form of extinction requires some a priori understanding of the relation between backscatter and extinction. This leads to real ambiguity when studying ice and aerosol clouds.



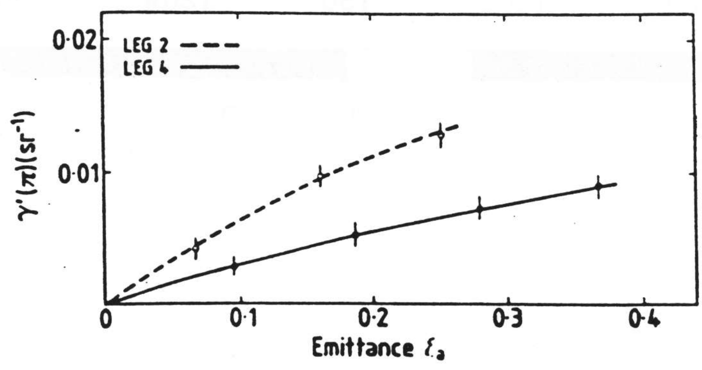


Fig. 13. Smoothed plots of $\gamma'(\pi)$ versus ε_a for flight legs 2 and 4. The lines are fits of (9) to the data.

REMOVING AMBIGUITY
(PLATT LIRAD METHOD)

Measured backscatter (multiple scattering: η)

$$\beta'(z) = \beta_c(z) \exp\left[-2\int \eta(z')\,\sigma_{ext}(z')\,dz'\right]$$

measured: $\beta'(z)$

retrieved: $\beta_c(z)$, $\sigma_{ext}(z')$

$$\gamma' = \int \beta'(z')\,dz' \approx \frac{k}{2\eta}\, 1 - \exp\left[-2\eta\tau\right]$$

Integrated backscatter (γ')

Backscatter to extinction (empirical)

$$k = \frac{\beta_c}{\sigma_{ext}}$$

'Measure' τ from emissivity (radiometric observations). Relate γ' to $\varepsilon(\tau)$ and fit provides $k/2\eta$ factor

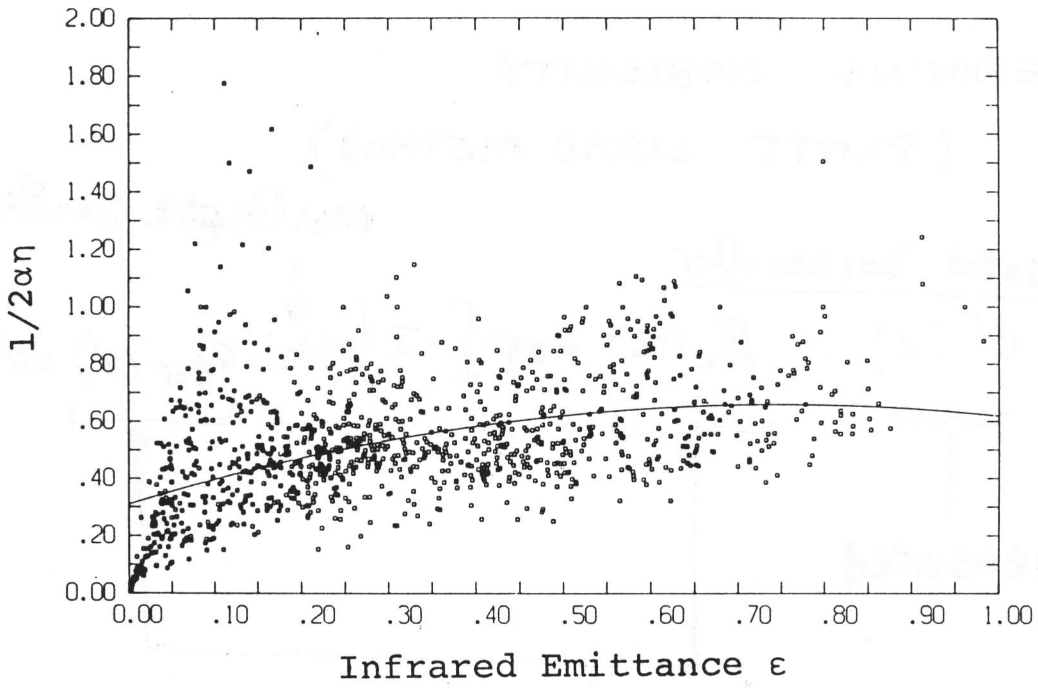


FIGURE 6. Plot of the quantity 1/(2αη) against infrared emittance ε.

Backscatter ambiguity

1. Backscatter to extinction

Profiles of extinction and absorption are needed.
Lidar offer profiles of backscatter.

2. Multiple scattering

Another source of ambiguity. Affects both optical property retrieval and ranging (profiling) through pulse elongation.

3. Supporting parameters

optical depth (via IR emittance or solar reflectivities)
photon path length (via spectral reflectance in Aband)
polarization
Doppler spectra
etc

5. Asynoptic Sampling (Salby + Callaghan, 1995)

- $O(x_1, t_1; x_2, t_2; \ldots$

Time mean

$$\bar{O}(x_k) = \frac{1}{N} \sum_{i=1}^{N} O(x_k, t_i)$$

- Reliability of time mean depends on N (and hence Δx)
- Reliability of time mean depends on reliability of sampled diurnal cycle (latter creates bias to $\bar{O}$).
- Latter in principle can eventually be obtained from individual precessing platform but in practice cannot be so as averaging more than a few months is contaminated by seasonal variations
- real solution is multiple platforms

To illustrate consider

$$\psi = T_0 - \hat{T}$$

T_0: threshold

$\hat{T}$: obs $= \begin{cases} T & T < T_0 \\ T_0 & T \geq T_0 \end{cases}$

$$\bar{\psi} = \frac{1}{N}\sum_{i=1}^{N}(T_0 - \hat{T}_i) = \frac{1}{N}\sum_{i=1}^{\hat{N}}(T_0 - \hat{T}_i)$$

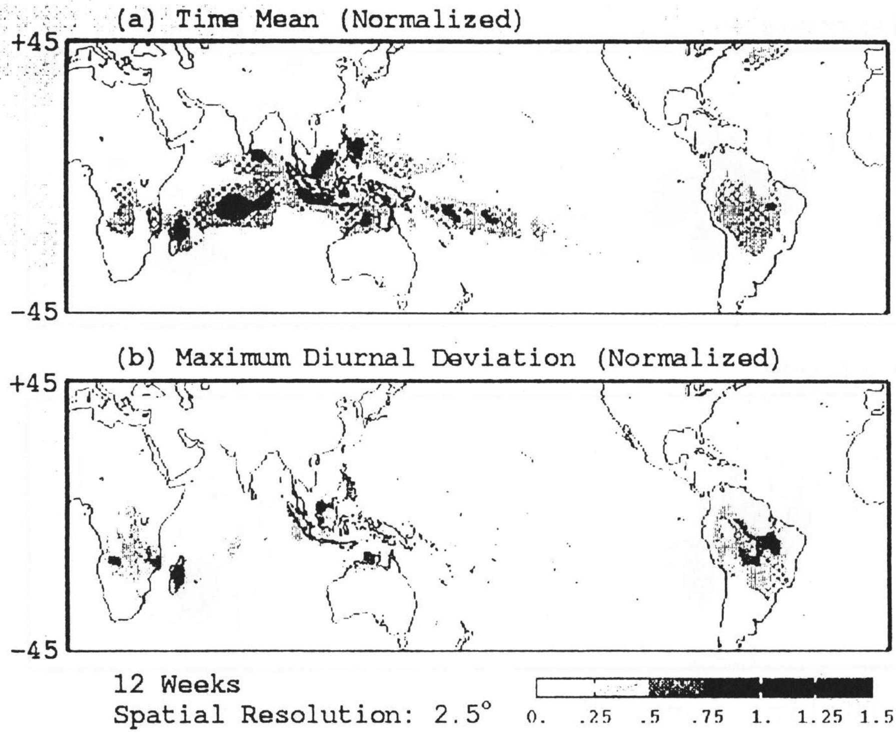
$$= \overline{\Delta T}\,\frac{\hat{N}}{N}, \quad \overline{\Delta T} = \frac{1}{\hat{N}}\sum_{i=1}^{\hat{N}} (T_0 - \hat{T}_i)$$

$$= \overline{\Delta T}\,\eta_{cold}$$

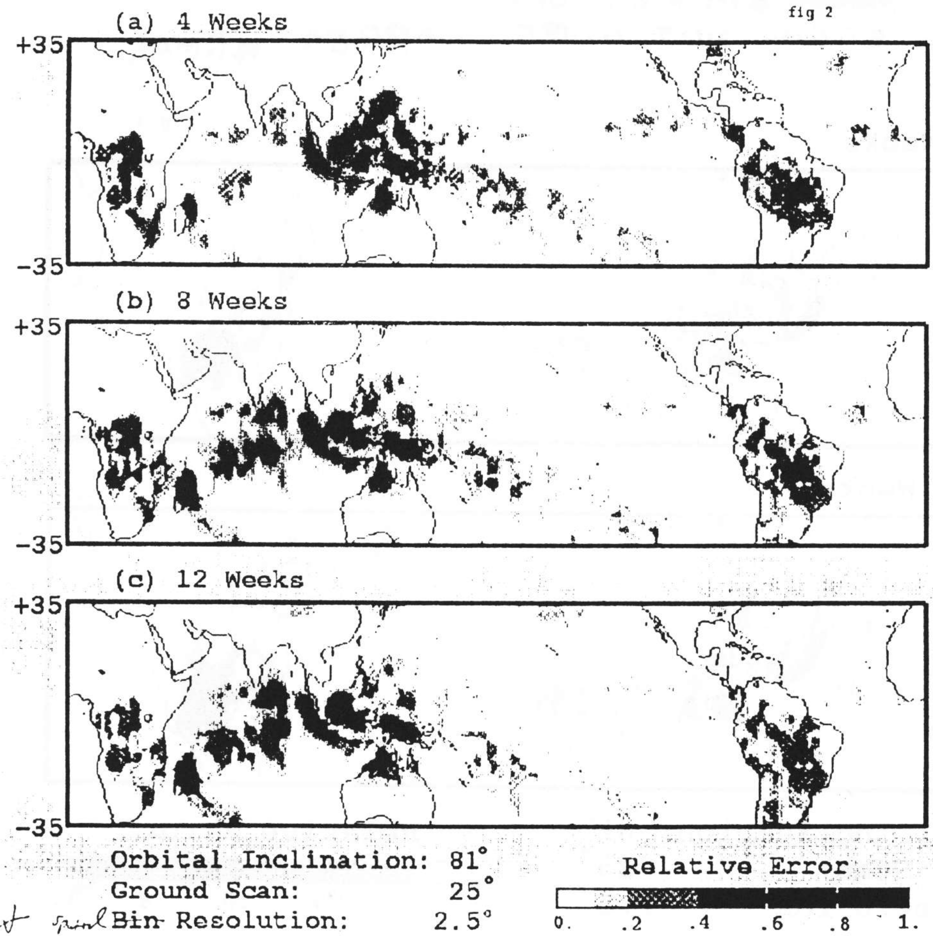
η_{cold}: fraction of cold cloud

Eg. $T_0 \sim 230K$, $\bar{\psi} \rightarrow$ precipitation (eg GPI)

- Use ISCCP 11μm data for T (3hr)
- Derive true $\bar{\psi}$, and deviation by diurnal cycle



"TRUE CLIMATOLOGY"

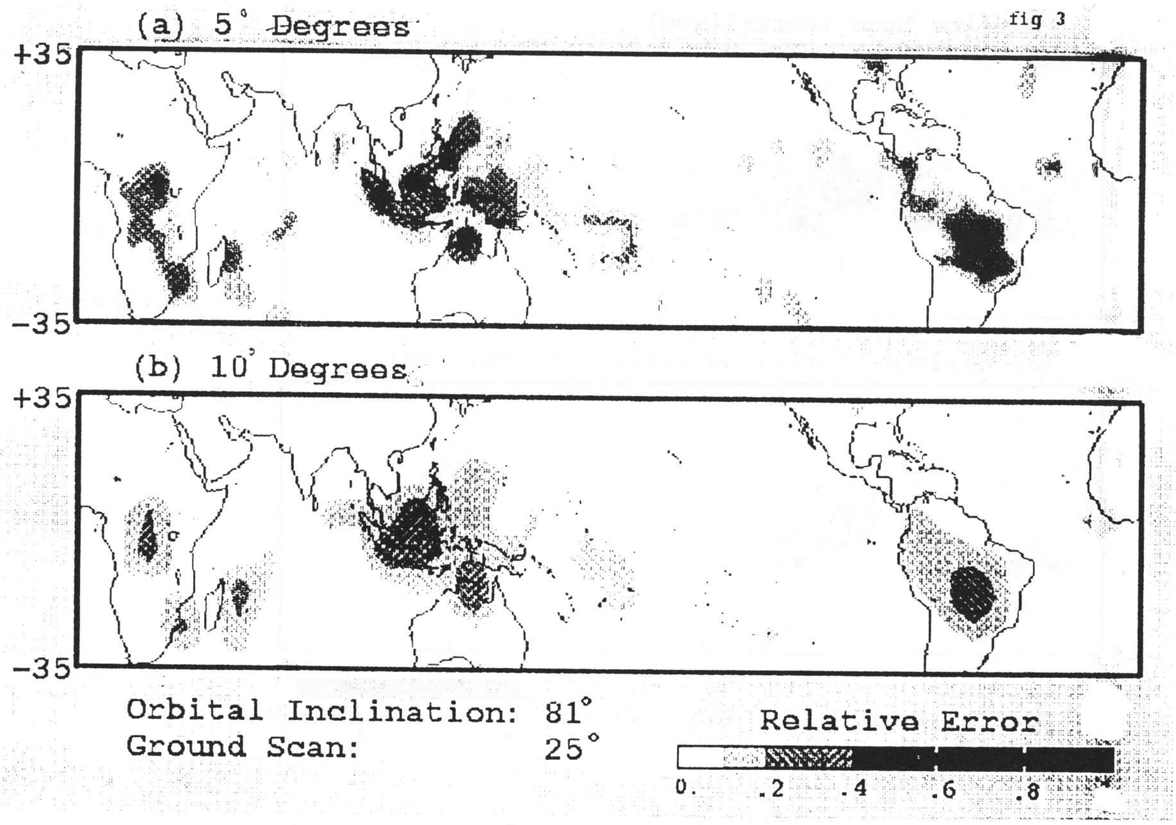


- DAY TIME ONLY
- INCREASING AVERAGE TIME ONLY HAS LITTLE EFFECT AS DIURNAL CYCLE REMAINS UNDERSAMPLED

POLAR ORBIT
SUN-SYN

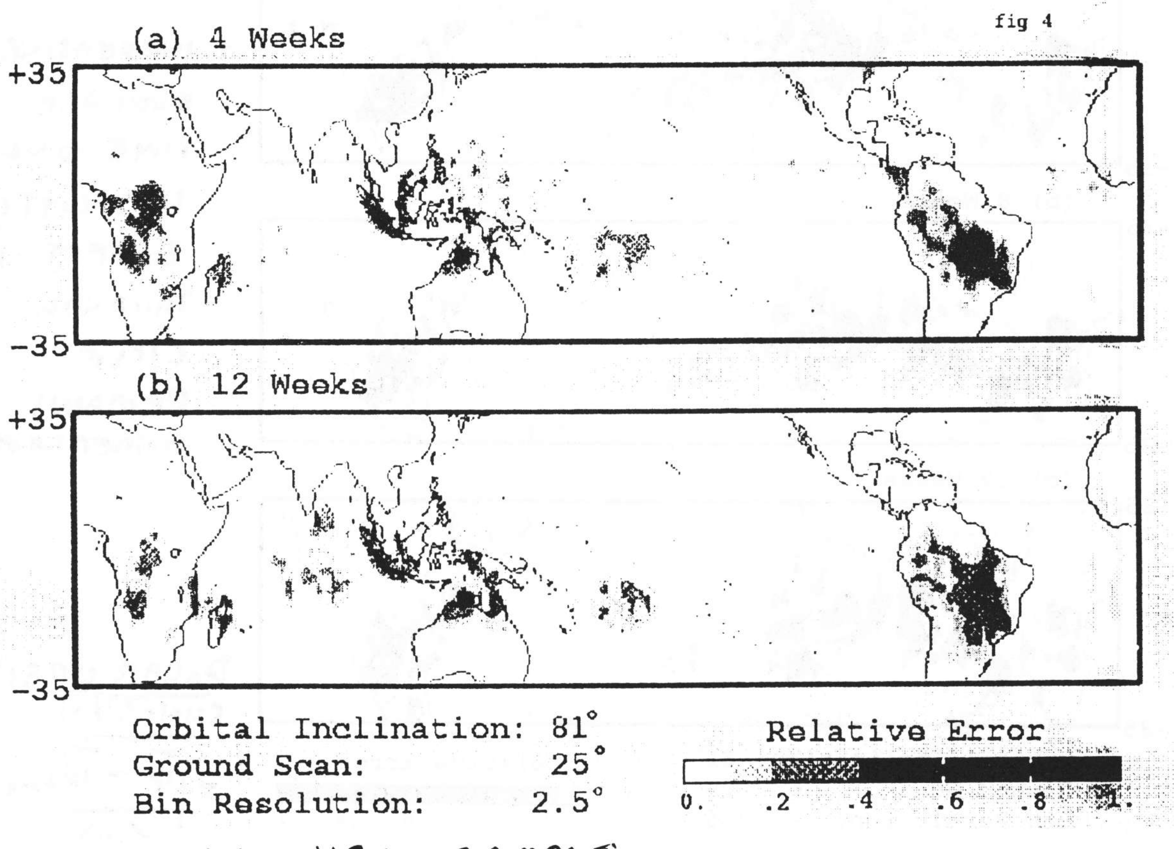
$= \left| \frac{\bar{\Psi} - \bar{\Psi}_{true}}{\bar{\Psi}_{true}} \right|$

fig 3



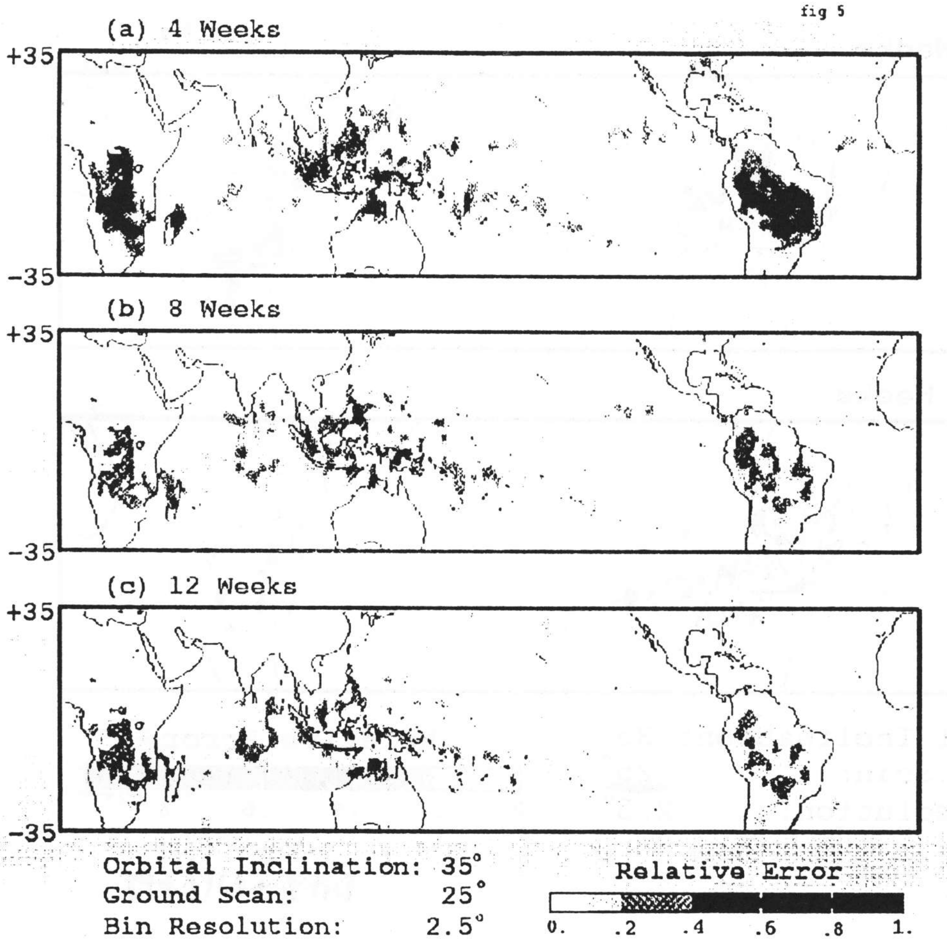
INCREASING ~~[struck]~~ BIN SIZE ONLY
SPREADS ERROR OUT OVER LARGER AREAS

fig 4



DAY + NIGHT SAMPLE

fig 5

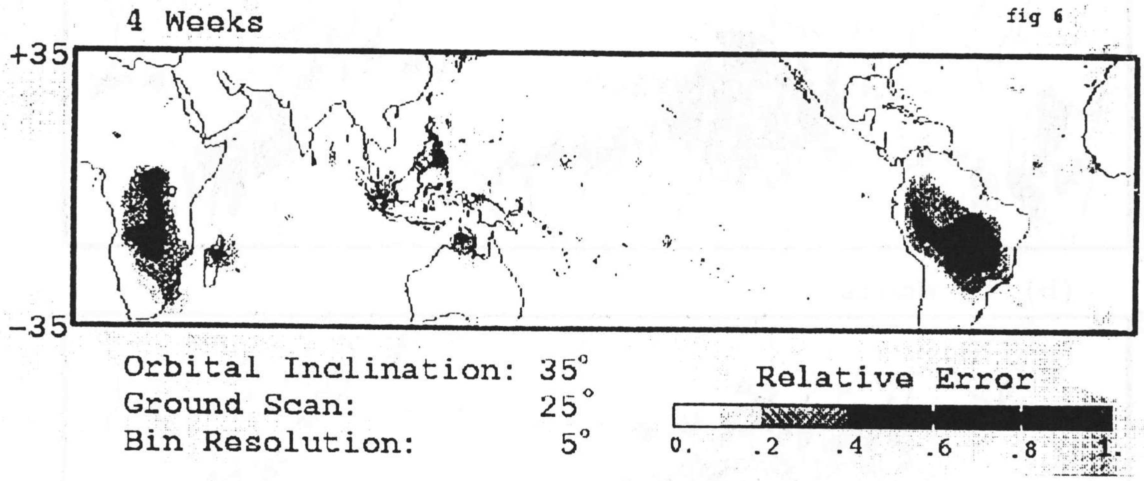


PRECESSING ORBIT (eg TRMM)

LENGTHENING DURATION OF AVERAGE LEADS TO SYSTEMATIC REDUCTION IN ERROR

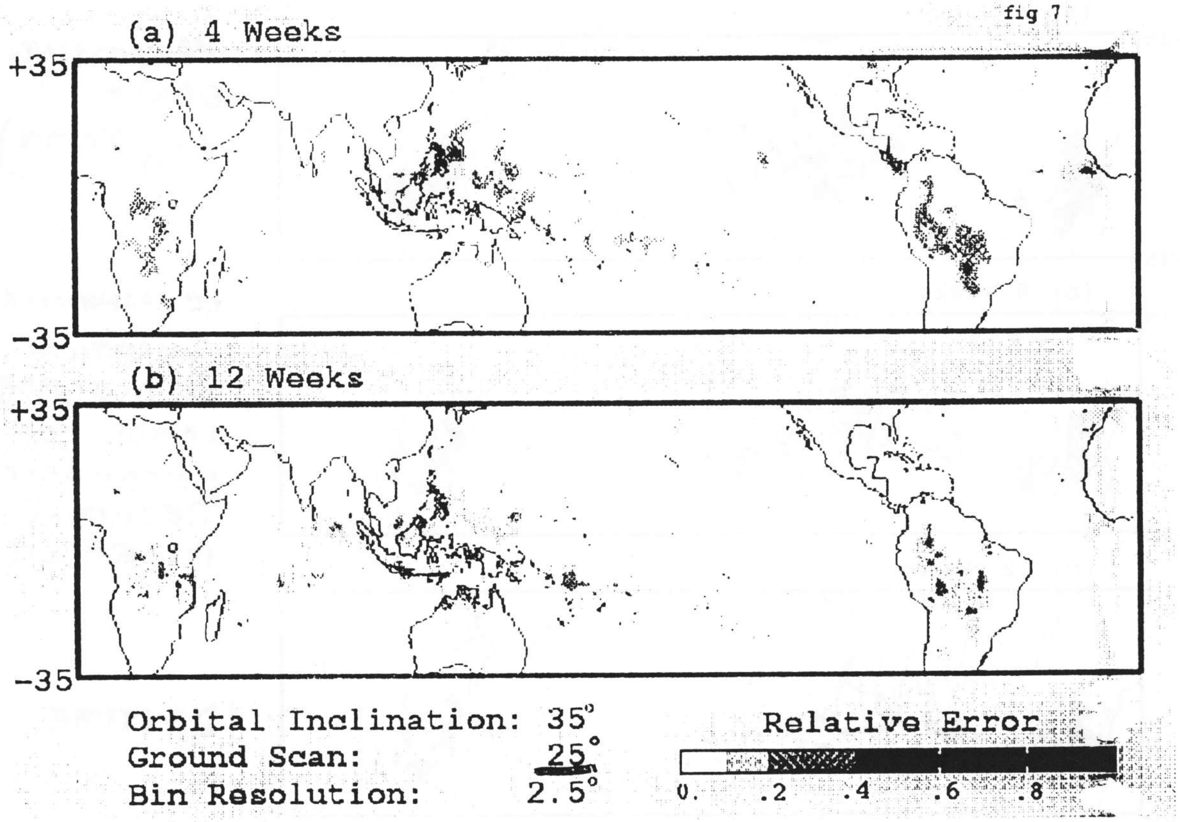
DAYTIME

fig 6



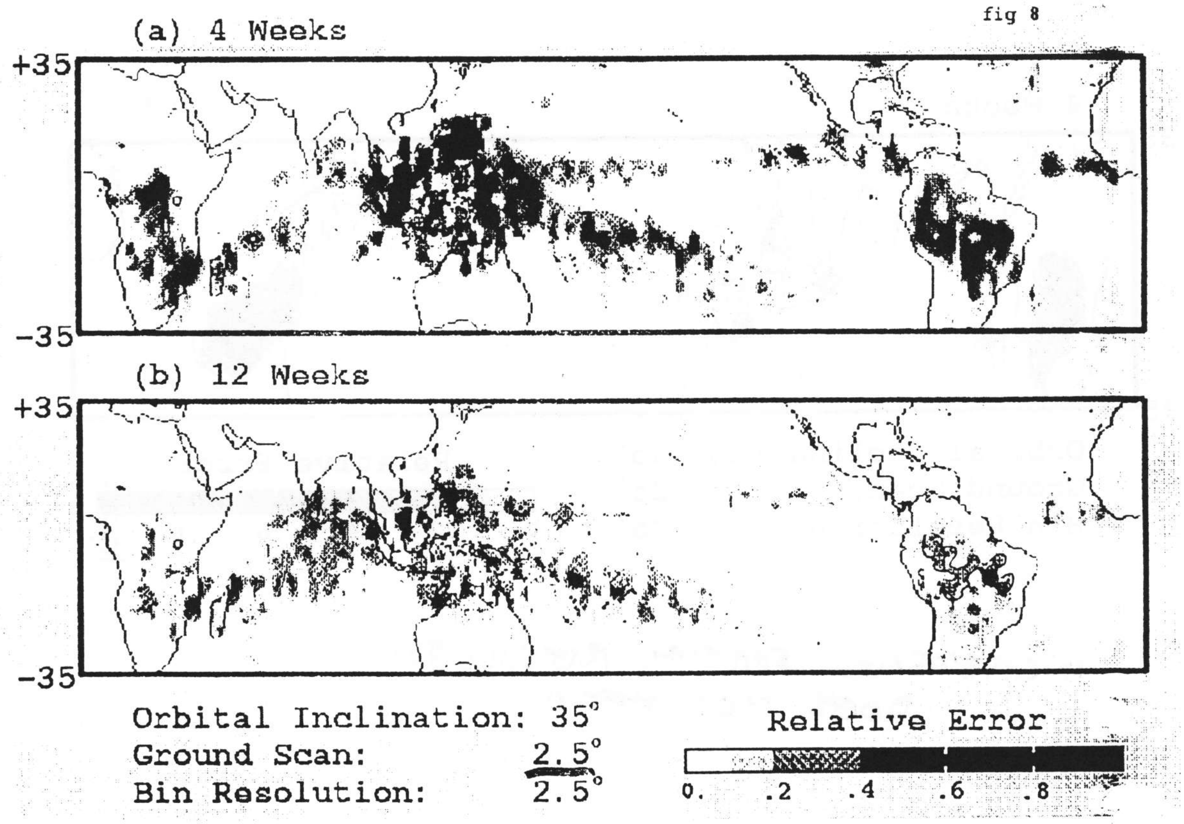
INCREASING SPATIAL RESOLUTION DOES NOT HELP

fig 7

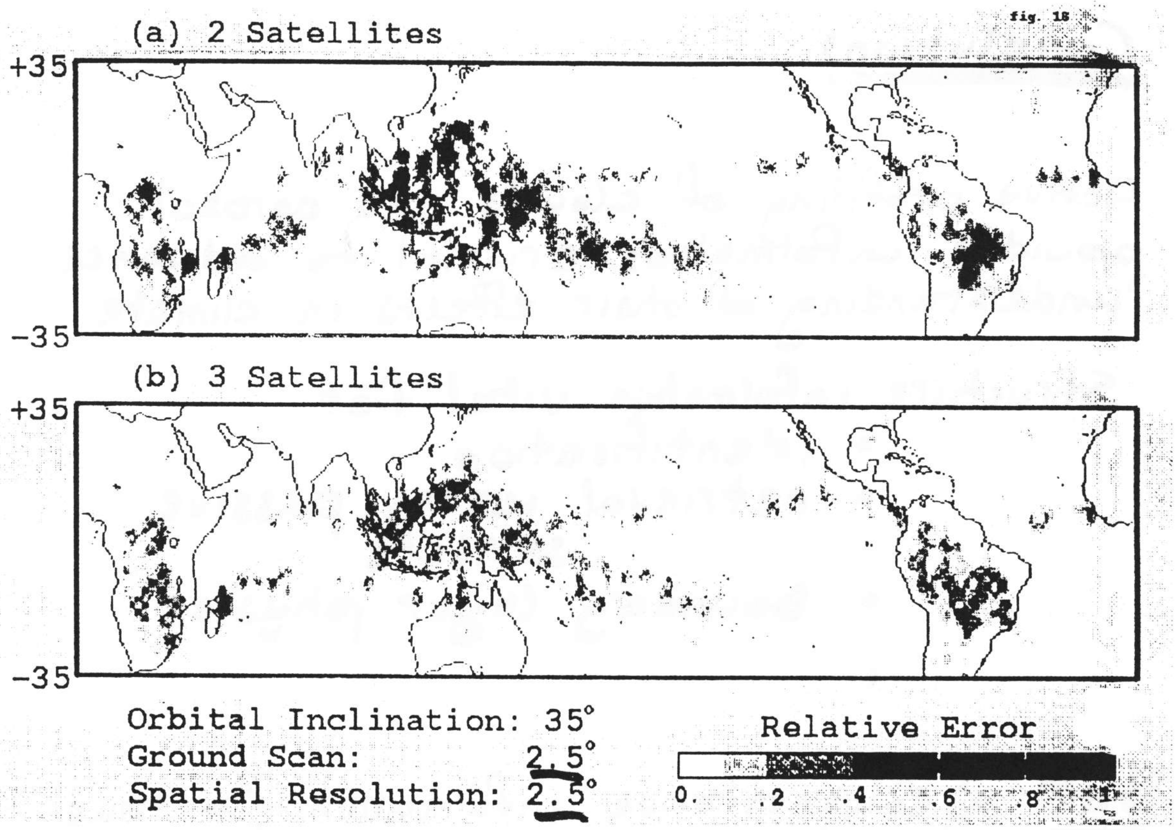


DAY + NIGHT

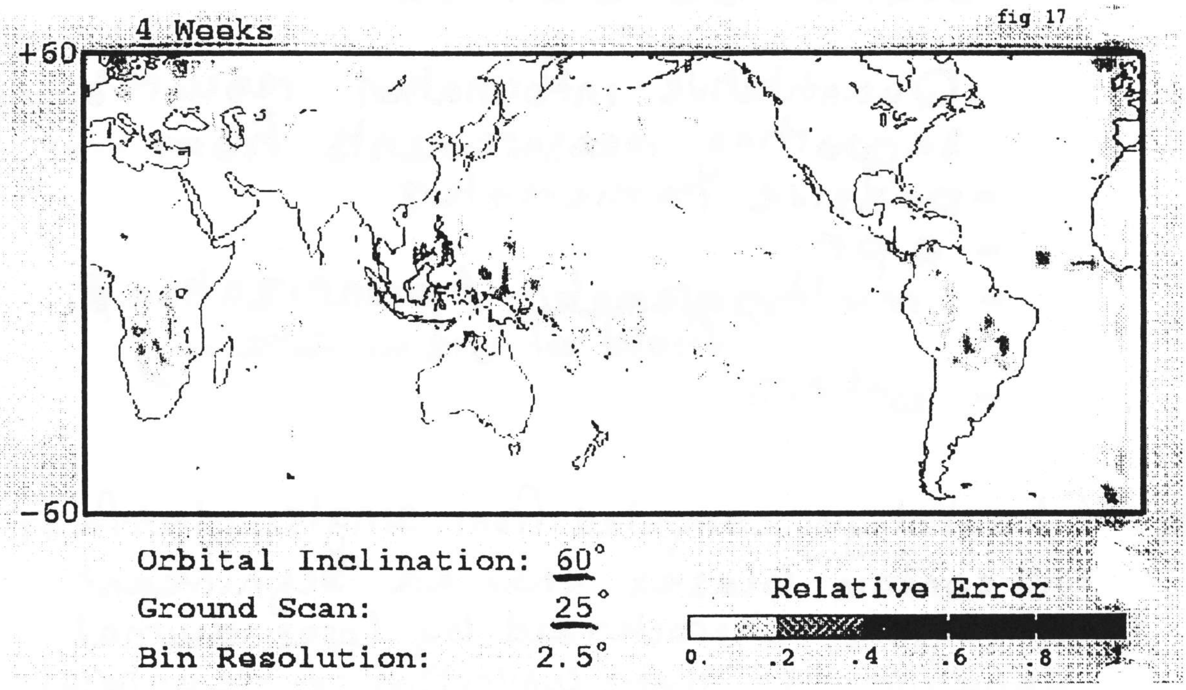
fig 8



DAY NIGHT
NARROW SCAN



4 weeks of averaging



TWO SATELLITES

Conclusions

Active profiling of clouds and aerosol provides information crucial to advance understanding of their effects in climate

Structure information vital for

- identification
- retrieval using passive sensors
- boundary layer physics
-

BUT a) Quantitative information (+ thus utility) on clouds and aerosol requires that ambiguities in back-scatter be clarified

Quantitative information requires supporting measurements from ....

- passive radiometers
- cpr
- multiparameter (polarization, field of view etc ...)
- others

(b) Climatology compiled from single platform will contain biases that are significant in regions characterized by large diurnal variation (eg deep convection of equatorial tropics).

MULTIPLE PLATFORMS WILL EVENTUALLY BE REQUIRED