Contribution of a Space-borne Backscatter Lidar to Earth Radiation Budget and Surface Flux Climatology

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Abstract. The importance of a space-borne backscatter lidar for profiling the vertical structure of clouds, aerosols layers and planetary boundary layer has been demonstated by the LITE mission in September 1994. It follows that new missions dedicated to Earth radiation should implement an instrumental payload for complementary observations by active (lidar, radar) and passive sensors. Such a goal is discussed in terms of an observational strategy aiming at an improvement in the determination of the vertical heating rate in presence of clouds and aerosols, and better surface flux analysis. First, results are shown on the retrieval of cloud climatology by lidar and radiometer using simulated data. These data are generated for one month using the LMD Global Circulation Model. A significant improvement in the retrieved large scale cloud climatology is obtained using a space based lidar. A combination of lidar and IR radiometric measurements is of prime importance for cloud structure analysis at the mesoscale using airborne sensors, and a possible extension at the global scale is discussed. A discussion on aerosols and Planetary Boundary Layer (PBL) is finally given in terms of parameters that a spaceborne lidar could provide for improving surface flux determination.

1. Introduction

The vertical distribution of atmospheric heating rate and energy budget at the surface are among the most critical parameters to understand the climate system. They are closely interrelated through the spatial and vertical distribution of clouds. The vertical cloud distribution in the atmosphere has a large impact on the heating rate and surface energy budget [1]. It is presently poorly determined, due to spatial and temporal cloud variability and limitations in present-day observational capabilities [1, 2]. On the other side, the boundary layer dynamics controls surface energy budget, low cloud formation and vertical redistribution of moisture through exchange processes and convection. Until now, the accuracy on determinations of both the radiative forcing and surface fluxes over the ocean is questionable for only sparse observations are made on the vertical and at the surface. At the present, the radiative fluxes at the top of the atmosphere are the only observation provided at the global scale from space. An accurate retrieval of the vertical distribution of clouds and a more precise determination of surface turbulent heat fluxes thus appears as a key issue. As far as clouds are concerned, a precise determination of their optical and microphysical properties as a function of altitude is required [1, 2]. The implementation of a backscatter lidar on an space platform providing a valuable information on the aerosol and cloud vertical structure would bring new informations on the cloud dynamics and radiation processes, as well as on boundary layer structure. The sensitivity and the capability of such lidar measurements have been recently emphasized by the results obtained from the LITE mission [3], especially to detect multilayered cloud structure. Such a system would have a large impact on the determination of cloud climatology [1, 2]. The objective of the present paper is to discuss last results in this domain in terms of complementarity of lidar measurements with current passive observations for improving the heating rate and energy budget determination.

2. Spaceborne Lidar Detection Performance

Daytime lidar operation is required to monitor the diurnal cycle of clouds and surface energy forcing, especially in the tropics. However it brings drastic technical constraints and calls for a compromise between single shot signal to noise ratio (SNR) and horizontal resolution. This is driven by system performance (energy, detection filter bandwith, telescope size, ...) and platform motion. This needs to be analyzed in terms of detection capability imposed by the scientific objectives. For cloud climatology, the cloud fraction as a function of cloud type, derived from the cloud top height determination, is a critical parameter to be retrieved in a climatological sense [1]. A first analysis [4] has been performed which is presented in the following paragraph.

3. Cloud Climatology Analysis at the Global Scale

A cloud data base has been developed for the month of July 1987 with the LMD-GCM to assess the performance of both a spaceborne backscatter lidar and radiometers with respect to the retrieval of large scale cloudiness [4]. Each model grid (constant surface about 1.5 10^5 km^2) is supposed to be representatively sampled by the lidar.

3.1 Methodology

The original model cloudiness in each grid has been splitted into smaller colums considering two overlap schemes : 1) high and middle clouds cover low clouds as completely as possible, 2) cloud layers are randomly distributed on the vertical. Each column is assumed to be uniformly filled in the horizontal. In the two cases, the multi-layered cloud structure is kept for all sub-grid columns. Low cloud layers in a vertical column may thus not be detected if dense cloud are present above, introducing a bias in the retrieved cloud vertical distribution and estimated radiative heating. The data analysis considers a new cloud data set every 3 hours. These sets are analyzed by lidar and/or radiometry before an averaging of the observations over a month. Two lidar detection schemes have been used. An ideal lidar system is considered first, and cloud layer top is detected provided the optical thickness above the cloud is smaller than 3. The actual number of lidar shots to achieve a sufficient SNR is not taken into account. The second scheme is based on an estimate of a practical signal to noise ratio at each level averaged over each single column. SNR can be shown to be proportional to the cloud extinction coefficient for daytime measurements. It is assumed here that clouds are detected if the averaged signal to noise ratio in a sub-column layer is SNR > 4. SNR in each cloud layer is computed, in a first approximation, as a function of cloud optical depth, geometrical thickness, number of lidar shots in a given column (which depends on its area) and transmission through upper layers. The optical depth is computed from prognostic variables of the model namely the liquid/ice water content and particle effective radius. In order to compare the retrieved cloudiness by radiometry to the model cloudiness we have implemented an algorithm very similar to the one used for ISCCP [5]. In a first step an upward infrared radiance is computed as diagnostics in each sub-column, and consistently with the cloud layer overlap assumption. In a second step these radiances are analyzed. When a column is declared as cloudy, one layer only of cloudiness is allocated, and cloud-top temperature is retrieved assuming that the cloud is a blackbody source. A constant cloud particle size distribution is assumed (r_e =10 μm), and a correction is allowed for optical depth using visible radiance information. In this case, the cloud-top pressure determined from IR measurements only is adjusted according to cloud opacity.

3.2 Results

The cloud fraction retrieved at large scale using an idealized and SNR limited lidar systems has been compared in average to the initial cloud fraction (GCM) for both random and maximal overlap scheme. From the results, one can see that the introduction of a SNR limitation in the lidar observations leads to significant differences in the upper layer detection. While all upper level cloud layers are detected by an ideal system, the detection efficiency is about 70% for an SNR limited lidar for both cirrus clouds and low level clouds.

The results obtained for radiometry show that when using an IR channel only, errors in altitude retrieval occur, leading to smaller cloud fractions at high levels. The correction performed with visible channel information improves the distribution in upper levels, and most clouds are set to their true altitude level. The retrieved average cloud fraction is in this case 50 to 60% of the

input data from the model. It is to be noticed that, with the vertical cloud distribution used in the simulations, the detection of low clouds is satisfactorily performed by lidar.
Both results obtained with random and maximal overlap schemes show that a high performance backscatter lidar would provide with an improved cloud climatology at the global scale. The cloud top altitude and the cloud fraction are however not the only parameters to be retrieved for an accurate radiation budget analysis.

4. Additional Measurement Requirements

In order to better retrieve the radiative impact of clouds and aerosols, the vertical distributions of liquid water and effective radius are key parameters to be determined [1, 2]. Assuming a statistical relationship can be used between liquid water content and particle effective radius, it corresponds to a constraint on extinction coefficient and optical thickness. The accuracy on the determination of such parameters at the global scale depends on the cloud type and on the observational procedure. Single shot lidar observations are typically performed at the micro-scale (about 100 m). Such a scale is representative of turbulent motions. It is thus possible to assume that a fairly good lidar pixel homogeneity is achieved, even in a broken dense cloud field. A statistical analysis at the mesoscale is then necessary to retrieve the average properties of any cloud type, before it can be extended at the global scale.

4.1 Dense Cloud case

For low and middle (dense) clouds, the detection of cloud top altitude from space is made easier by an increasing liquid water content with height. The detection of cloud is then linked to the identification of a signal peak out of the background noise. This is in turn related to the single shot signal to noise ratio (SNR). A SNR value greater than 20 can be obtained for dense clouds and surface return, for transmited energies of 100 mJ or more and a telescope diameter of 60 cm or larger, the other parameters being optimized. This allows the detection of such clouds even in the presence of cirrus clouds above on a single shot basis. For optical depths greater than 3, the cloud base and the optical thickness cannot be determined using a standard signal analysis. This may however be achievable through the analysis of multiple scattering signal [6]. This would require a specific optical design of the detection system.

4.2 Cirrus Cloud Distribution

Frequent optically thin cirrus cloud are observed. Analyses of lidar and radiometric measurements at the mesoscale have shown that their occurrence follows an exponential distribution for thin cirrus with an average optical thickness smaller than 0.5 [2]. Such high clouds have a significant radiative impact when their average optical thickness is greater than 0.1 [2]. In this case, and in order to retrieve the cloud optical thickness to within 50% it can be shown that a minimal SNR of 5 is required below the cloud. This can be achieved using the surface return or the dense cloud return underneath. In the case of several semi-transparent layers an additional information is needed. It can be provided by IR radiometry still with the help of lidar surface return. In this case it is important that coincident measurements are made at the same scale, due to the large variability of cirrus optical properties (this also applies to other broken cloud fields).

4.3 Discussion

Selecting a 60 cm diameter telescope and a 100 mJ laser source operating at 1.064 μm, it can be shown that clusters of a few tens of shots are required, when aiming at detecting cirrus clouds with an average extinction coefficient as low as 2.10^{-4} m^{-1}. Assuming the properties of clouds are not varying on average for the observed area, both lidar and IR radiometry informations can be combined to retrieve spatial and vertical distributions of structural and optical properties. The objective is to work on an elementary area of the order of 10x10 to 30x30 km^2 [2,5], corresponding to the size of a few geostationnary satellite pixels. This analysis at the mesoscale should lead to the development of a statistical data base. It would be further improved by

combining informations obtained by both the geostationnary satellite and the orbiter on several elementary areas.
The extension to a representative average at the mesoscale may however be complicated by the occurrence of multi-level clouds and their organisation (as in the case of roll vortices in the PBL or cirrus bands for example). To take advantage of a simplified non-scanning lidar system, a high resolution IR/Vis imager may be thus more suited than a radiometer.

5. Boundary layer height and surface fluxes
The PBL top height corresponds to the altitude of lower clouds, which is a critical parameter for the surface energy budget. It is an important parameter in the analysis of the PBL dynamics as it provides with a constraint on its development [7]. Over the oceans, far from the coasts, a coarse horizontal resolution (about 50 to 100 km) is adapted to the analysis of the evolution of the average PBL height. Using additional remotely sensed meteorological parameters above the PBL and at the surface, a PBL model could thus be used to infer turbulent surface fluxes [2, 7, 8]. It is to be noticed that surface wind strength is routinely derived from scatterometer observations but this parameter could also be obtained from the sea surface backscattered lidar signal over clear air pixels [2].

6. Conclusion
The implementation of a spaceborne backscatter lidar is of prime importance for improving our knowledge on cloud climatology. Lidar measurements should however be combined with passive observations for accurate radiation budget analyses. Aiming at measurements of the vertical distribution of cloud optical thickness, a high resolution infrared radiometer (or better IR/Vis imager) could provide with the required complementarity to analyse the cloud radiative impact at the mesoscale. A better extension to the global scale should thus be achieved through a better coupling with geostationnary observations. Additional information on the aerosol distribution during continental outbreaks and on the turbulent surface fluxes should also be obtained.

7. Aknowledgements
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8. References
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CONTRIBUTION OF A SPACEBORNE BACKSCATTER LIDAR TO EARTH RADIATION BUDGET AND SURFACE FLUX CLIMATOLOGY

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FRANCE

OBJECTIVE OF THE STUDY : ASSESS SPACEBORNE CONTRIBUTION WITH RESPECT TO PRESENT QUESTIONS ON CLIMATE

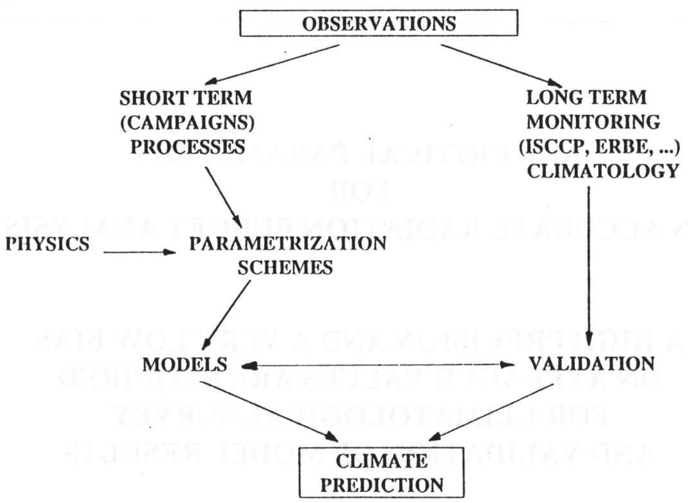
FRAME : WORLD CLIMATE RESEARCH PROGRAMME
(ISCCP, GEWEX, CLIVAR, ...)

MONITORING AND STUDY OF CLIMATE FORCING AND FEEDBACKS

UNDERSTAND PROCESSES RESPONSIBLE FOR CLIMATE VARIABILITY

CLIMATE PREDICTION

STRATEGY



Cloud parameters unadequately parameterized in General Circulation Models.

Cloud geometry:
-cloud vertical extension is not predicted (= to model layer)
-assumptions concerning cloud layer overlapping are simplistic

Cloud water content:
- model predict a condensed water content: almost impossible to validate at present (microwave retrievals are uncalibrated)

- the phase (ice/liquid) is of utmost importance and predicted through simple temperature criteria

Size of cloud meteors
- depends on microphysical properties: the effective radius is of utmost importance

Importance of **predicting** those parameters (not diagnosing them): implies determination of the right **processes** leading to those parameters

CLOUD FRACTION
CLOUD HEIGHT
OPTICAL THICKNESS

ARE CRITICAL PARAMETERS FOR AN ACCURATE RADIATION BUDGET ANALYSIS

A HIGH PRECISION AND A VERY LOW BIAS ON AVERAGED VALUES ARE REQUIRED FOR CLIMATOLOGICAL SURVEY AND VALIDATION OF MODEL RESULTS

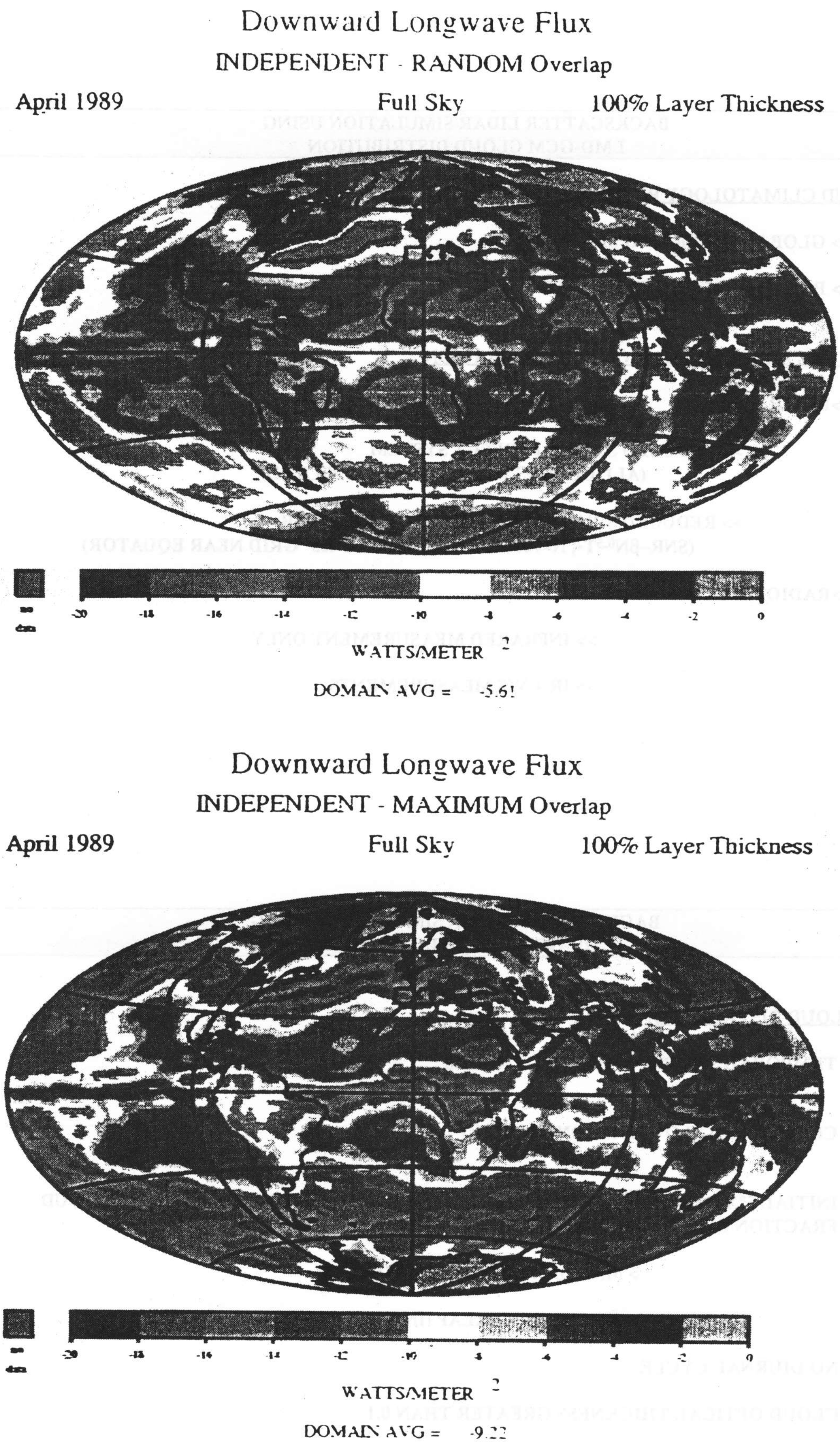


Figure 8c. The difference in the downward longwave flux at the surface for different cloud overlap assumptions shown in Fig. 8*a* (Charlock et al., 1994).

BACKSCATTER LIDAR SIMULATION USING LMD-GCM CLOUD DISTRIBUTION

CLOUD CLIMATOLOGY RETRIEVED BY

> GLOBAL OBSERVING SATELLITE

> POLAR ORBITING SATELLITE

DAYTIME LIDAR AND RADIOMETRY OPERATION

>LIDAR

>> REDUCED SWATH PERFECT SYSTEM
(ALL CLOUDS WITH $\delta(Z\text{-}\infty)<3$ DETECTED)

>> REDUCED SWATH SNR LIMITED SYSTEM (SNR>4)
($SNR \sim \beta N^{0.5} T^2$, N=7000 SHOTS OVER A 5°X5° GRID NEAR EQUATOR)

>RADIOMETRY

>> INFRARED MEASUREMENT ONLY

>> IR + VIS MEASUREMENTS

BACKSCATTER LIDAR SIMULATION USING LMD-GCM CLOUD DISTRIBUTION

4D CLOUD DISTRIBUTION :

TEMPORAL SAMPLING : EVERY 3 HOURS

CLIMATOLOGY OVER 1 MONTH (JULY)

INITIAL 5°X5° GRID SPLIT INTO SUBCOLUMNS ACCORDING TO 2 VERTICAL CLOUD FRACTION DISTRIBUTION HYPOTHESES

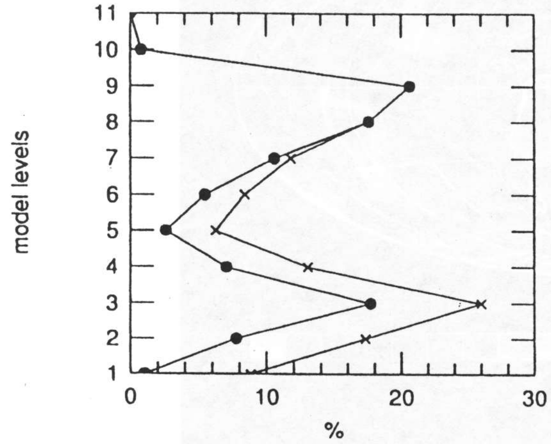
> MAXIMUM OVERLAP (TROPICS)

> RANDOM OVERLAP (INDEPENDENT LAYERS)

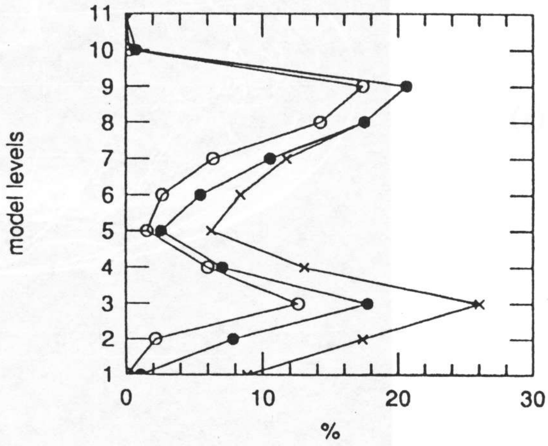
NO DIURNAL CYCLE

CLOUD OPTICAL THICKNESS GREATER THAN 0.1

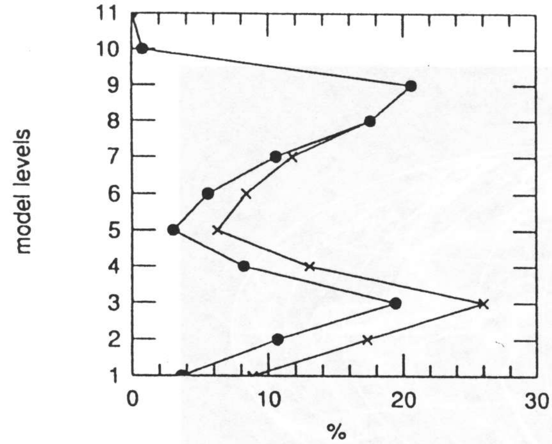
4D CLOUD FRACTION RETRIEVAL



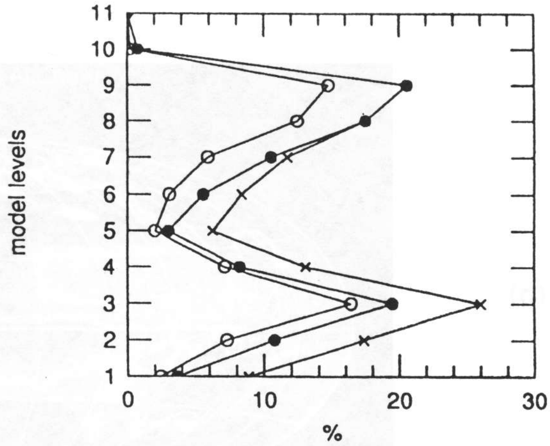
(a) Globe (lidar)



(b) Orbitography (lidar)



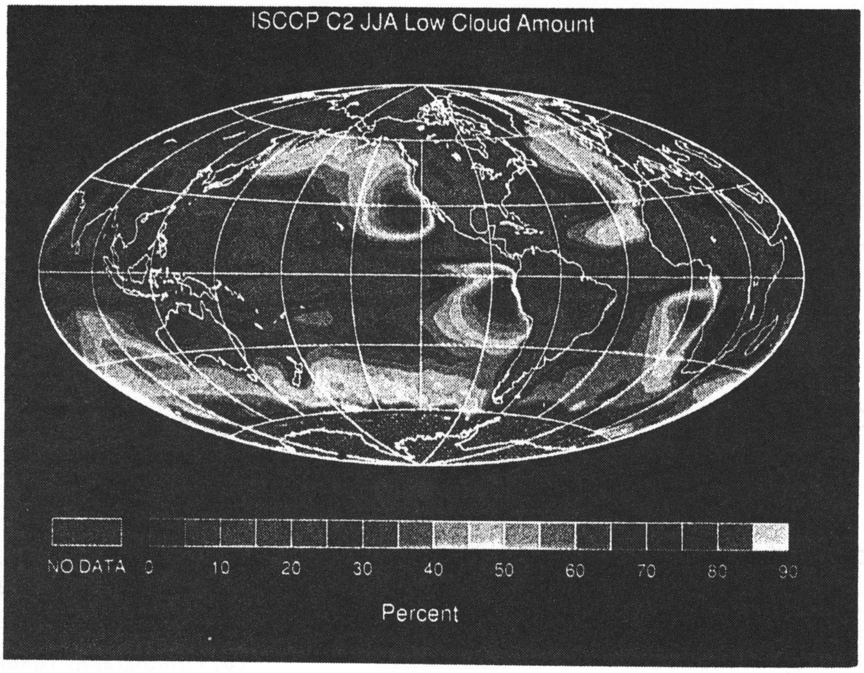
(c) Globe (lidar)



(d) Orbitography (lidar)

Comparison of lidar retrieved and modelled cloud fraction for global observations (left) and observations reduced to the SBL swath (right). Upper figures are given for maximal overlap and lower curves are for random overlap (× model, • perfect lidar, o SNR limited lidar).

(a)



(b)

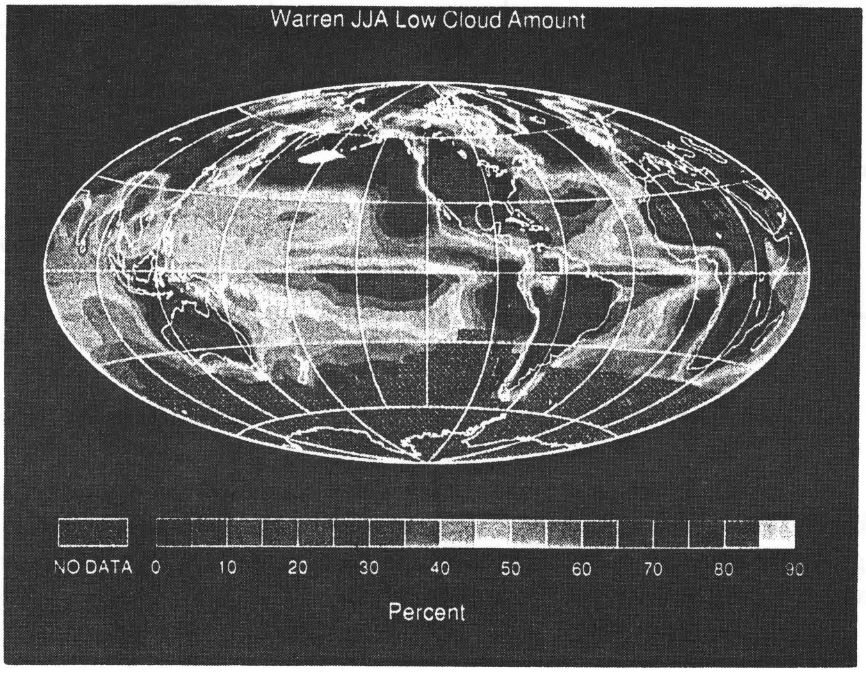
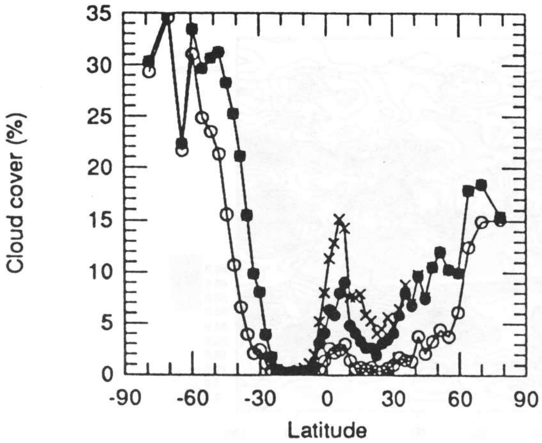
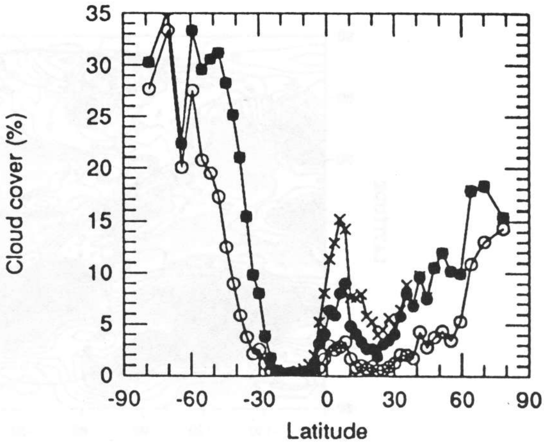


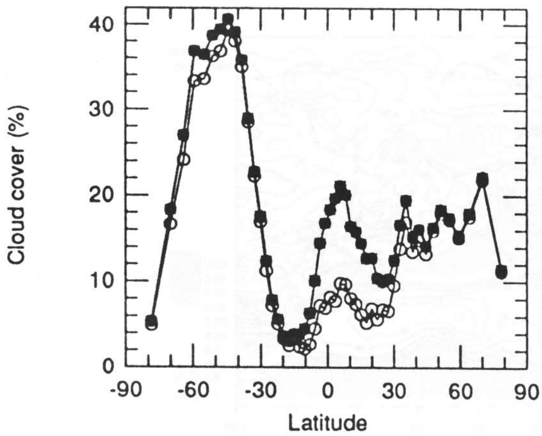
Figure 3. The JJA climatologies of low cloud amount from (*a*) ISCCP and (*b*) from the Warren surface climatology (personal communication, S.A. Klein, University of Washington, 1993).



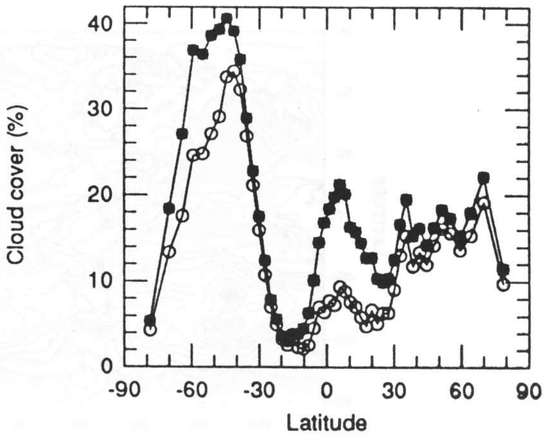
(a) Level 7 (6800 m, lidar, maxi)



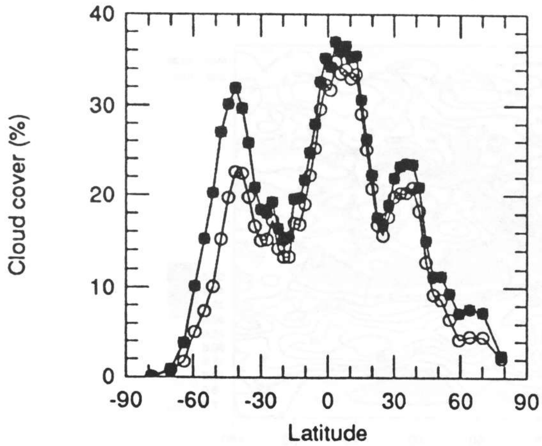
(b) Level 7 (6800 m, lidar, random)



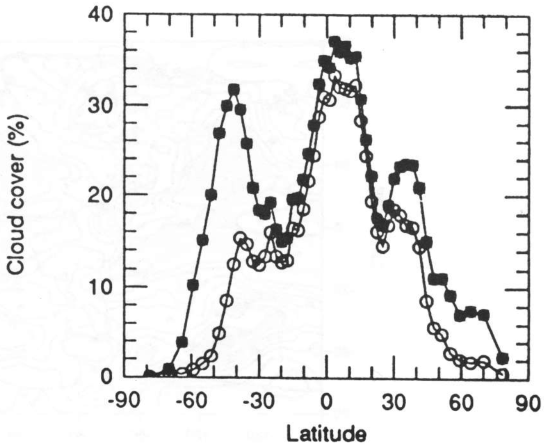
(c) Level 8 (9800 m, lidar, maxi)



(d) Level 8 (9800 m, lidar, random)

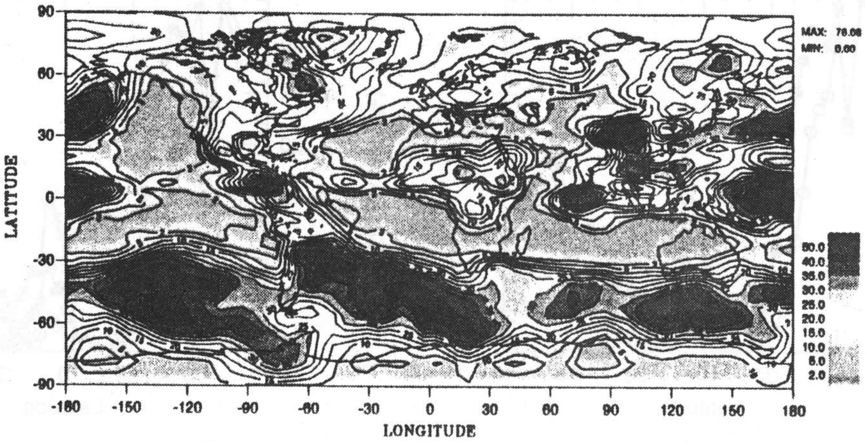


(e) Level 9 (13600 m, lidar, maxi)

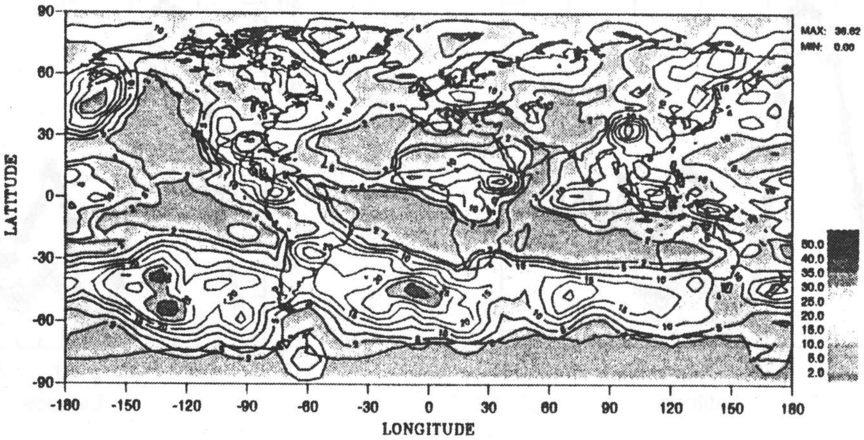


(f) Level 9 (13600 m, lidar, random)

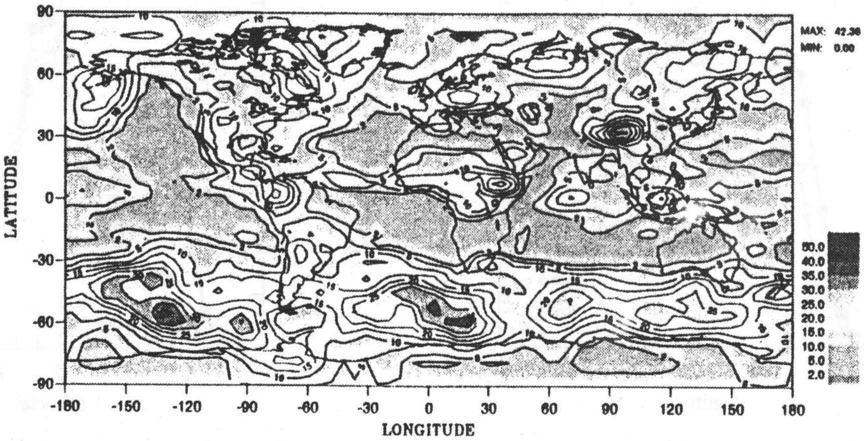
Mean zonal cloud fraction retrieved by lidar as a function of latitude at different levels for maximal overlap (left) and random overlap (right) (× model, • perfect lidar, o SNR limited lidar).



(a) Model

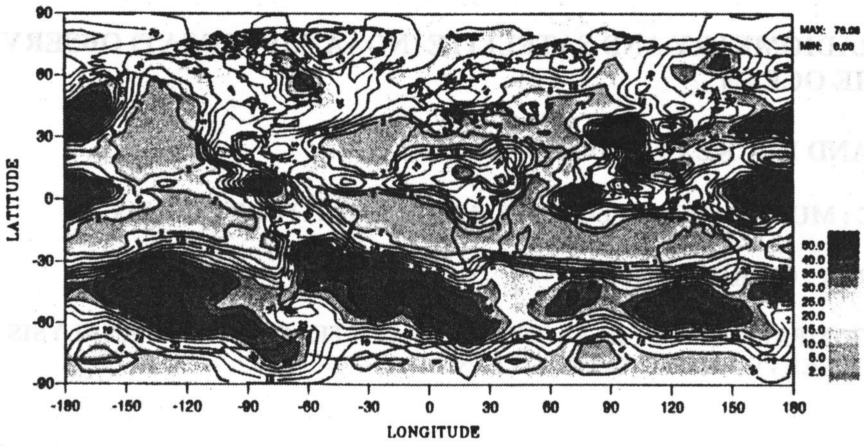


(b) ISCCP, IR only

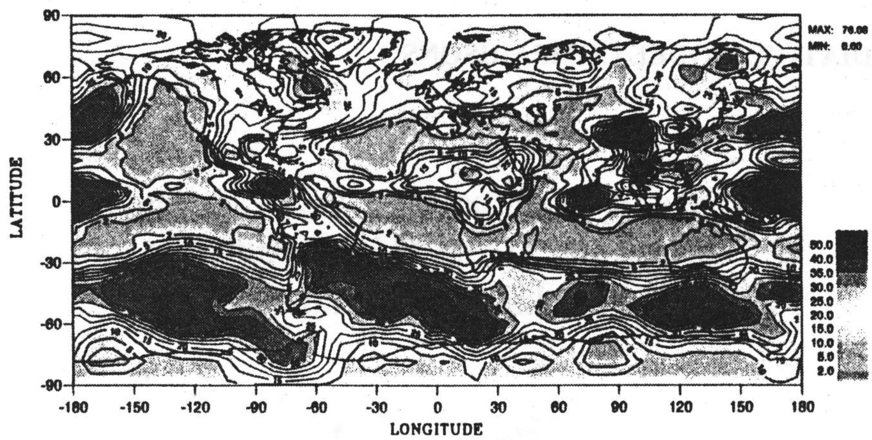


(c) ISCCP, IR + VIS radiometry

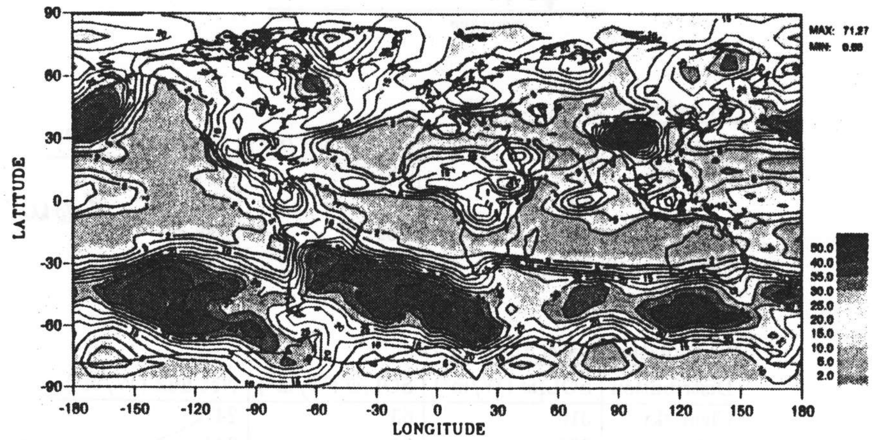
Cloud cover simulated at model level 8 (9800 m), using maximum overlap (orbitography).



(a) Model



(b) ISCCP, IR only



(c) ISCCP, IR + VIS radiometry

Cloud cover simulated at model level 8 (9800 m), using maximum overlap (orbitography).

MESOSCALE ANALYSIS OF CLOUD PROPERTIES

LIDAR, RADIOMETRY AND SATELLITE (NOAA, METEOSAT) OBSERVATIONS OVER THE OCEAN

♥ ELAC AND EUCREX CAMPAIGNS

ELAC : MULTILAYERED LOW AND MIDDLE ALTITUDE CLOUDS

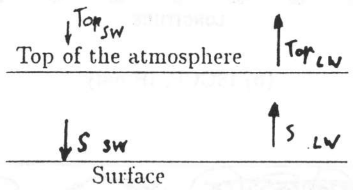
EUCREX : CIRRUS CLOUDS

COMPARISONS OF IR ALONG AIRCRAFT TRACK AND 2D ANALYSIS AS OBSERVED FROM SATELLITE (NOAA)

VERTICAL CLOUD STRUCTURE ANALYSIS (A/C LIDAR)	|	**FULL**
	|	**3D CLOUD**
COINCIDENT IR RADIANCE MEASUREMENT (A/C RADIOMETRY)	|	**MODEL**

♠ 1D RADIATIVE MODEL COMPARISONS

Sensitivity of radiation fluxes at the surface and at the TOA for different optical thickness (τ) of high clouds.



Net radiative flux at the TOA

Distribution	TOP$_{sw}$ (W/m^2)	TOP$_{lw}$ (W/m^2)	Net flux (W/m^2)
Clear sky	408	281	127
τ=0.1	405	276	130
τ=0.3	400	262	138
τ=0.5	395	250	145

↑ 10 W.m^{-2}

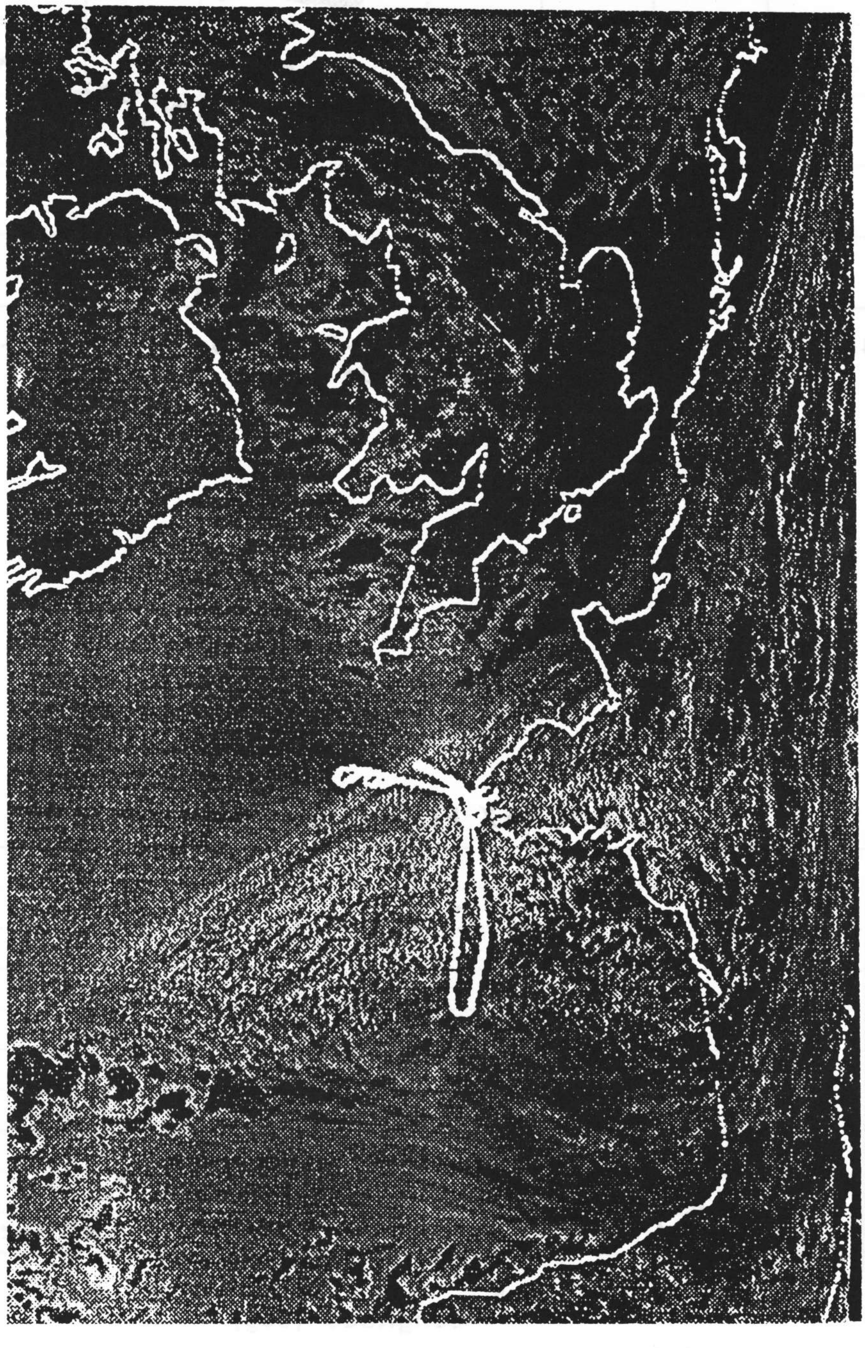
Net radiative flux at the Surface

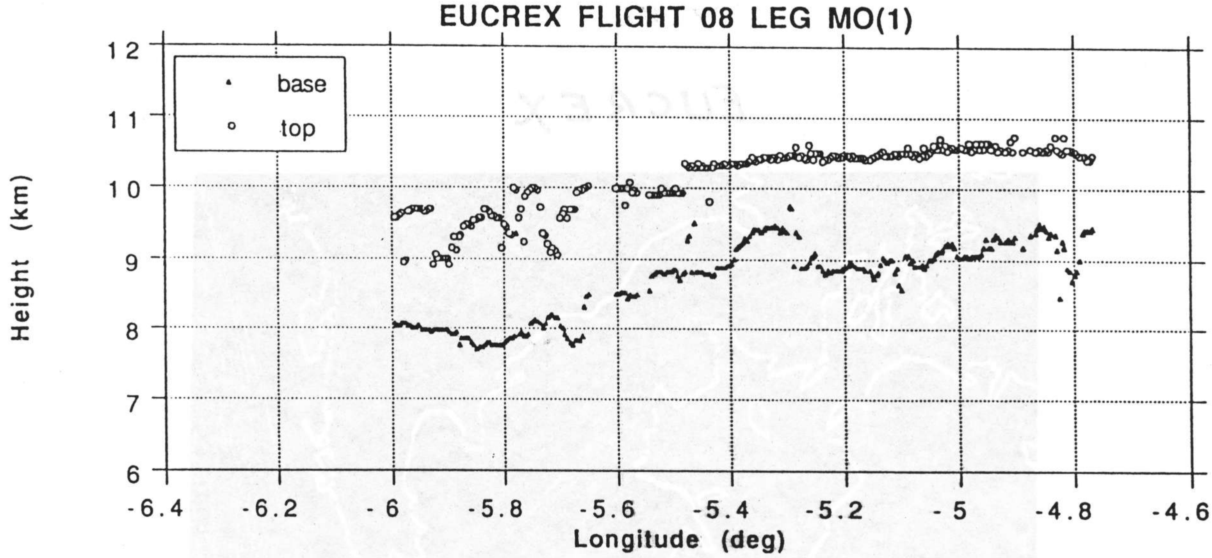
Distribution	SOL$_{sw}$ (W/m^2)	SOL$_{lw}$ (W/m^2)	Net flux (W/m^2)
Clear sky	310	63	247
τ=0.1	306	62	244
τ=0.3	301	61	240
τ=0.5	296	59	237

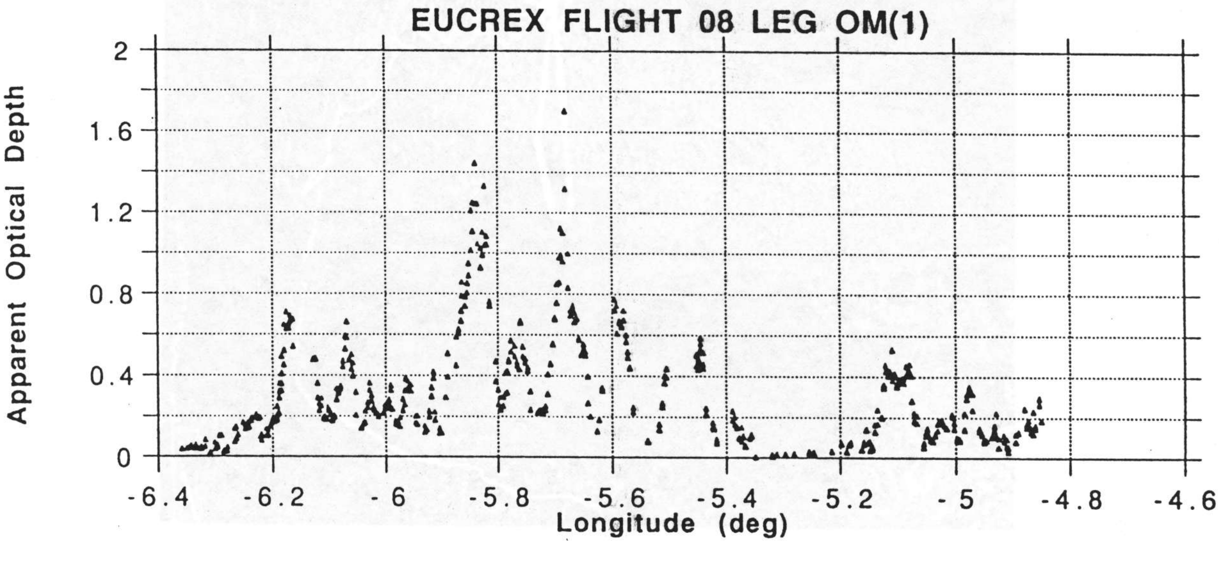
↓ 10 W.m^{-2}

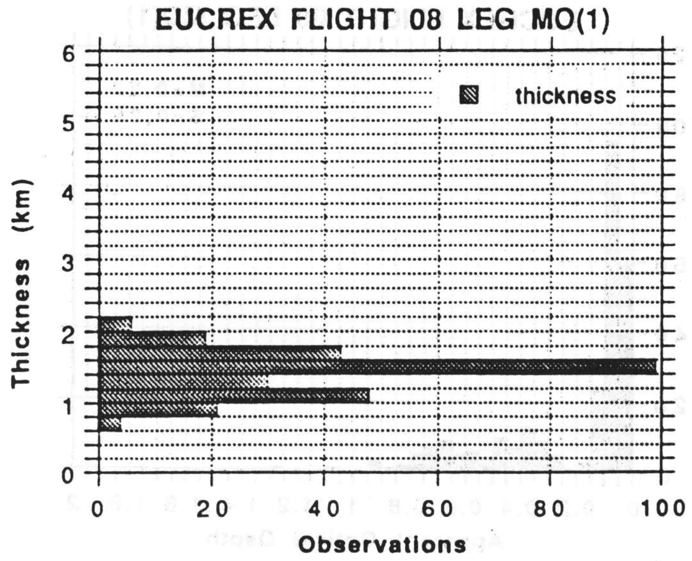
WE MUST DETECT CLOUDS WITH $\tau > 0.1$

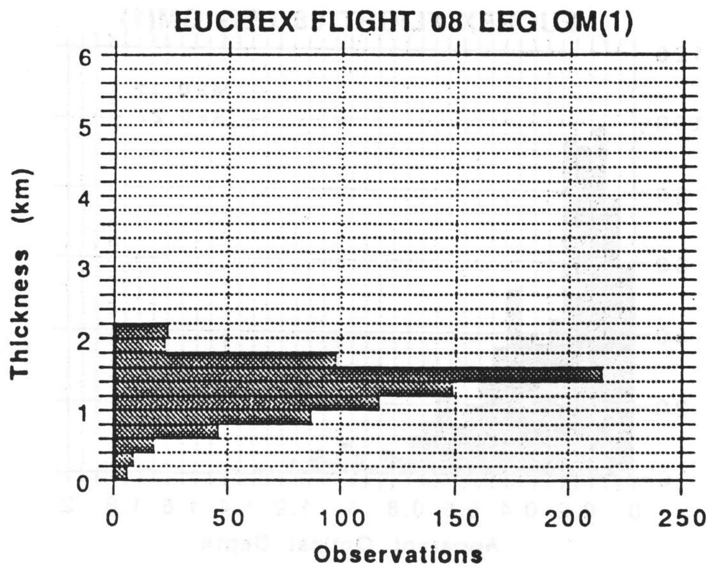
EUCREX

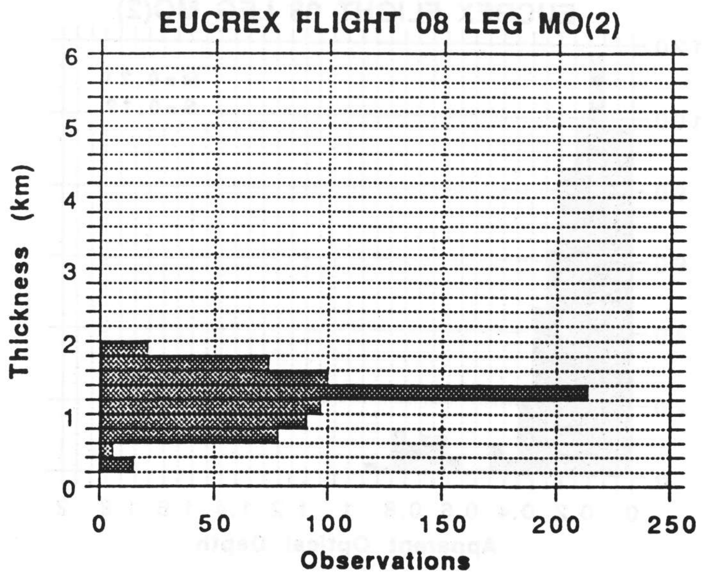


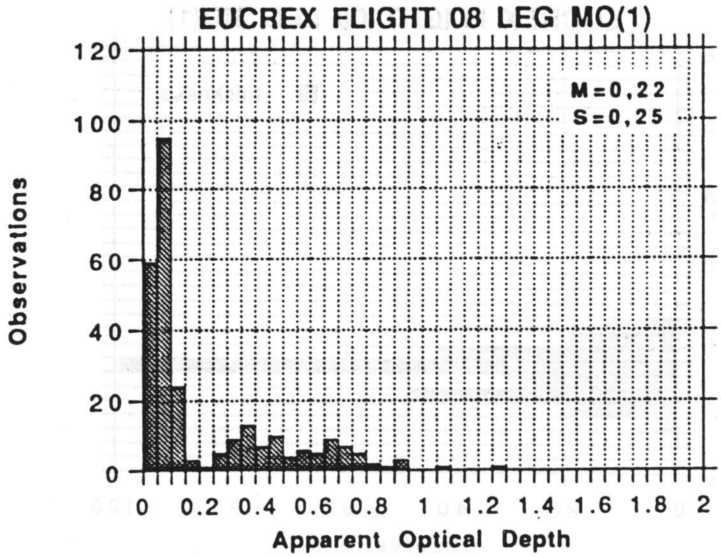

EUCREX FLIGHT 08 LEG MO(1)
base
top
Height (km)
12
11
10
9
8
7
6
-6.4
-6.2
-6
-5.8
-5.6
-5.4
-5.2
-5
-4.8
-4.6
Longitude (deg)

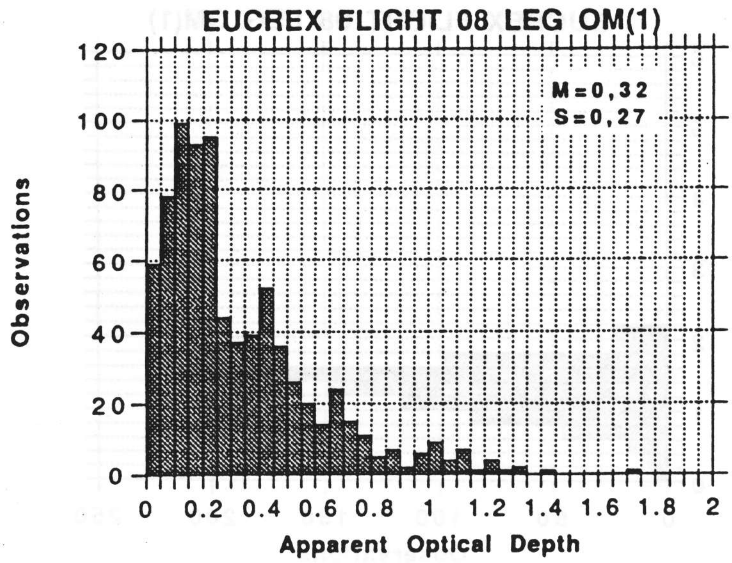

EUCREX FLIGHT 08 LEG OM(1)
Apparent Optical Depth
2
1.6
1.2
0.8
0.4
0
-6.4
-6.2
-6
-5.8
-5.6
-5.4
-5.2
-5
-4.8
-4.6
Longitude (deg)

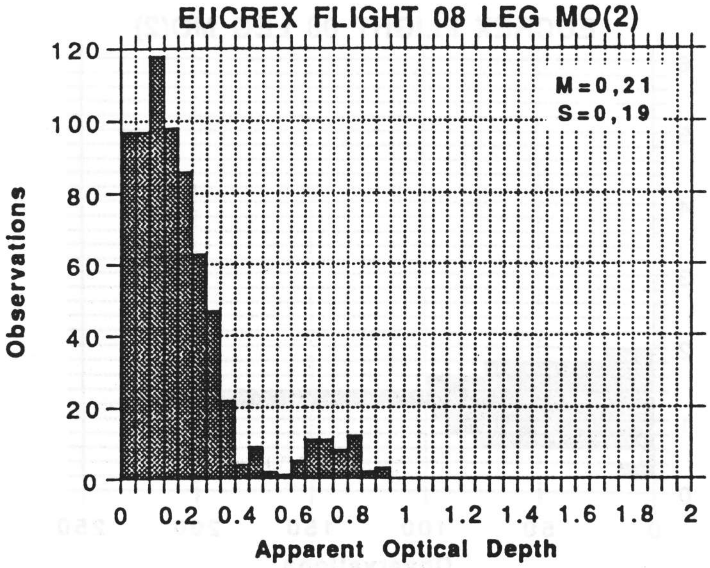

EUCREX FLIGHT 08 LEG MO(1)
thickness
Thickness (km)
0
1
2
3
4
5
6
0
20
40
60
80
100
Observations


EUCREX FLIGHT 08 LEG OM(1)
Thickness (km)
0
1
2
3
4
5
6
0
50
100
150
200
250
Observations

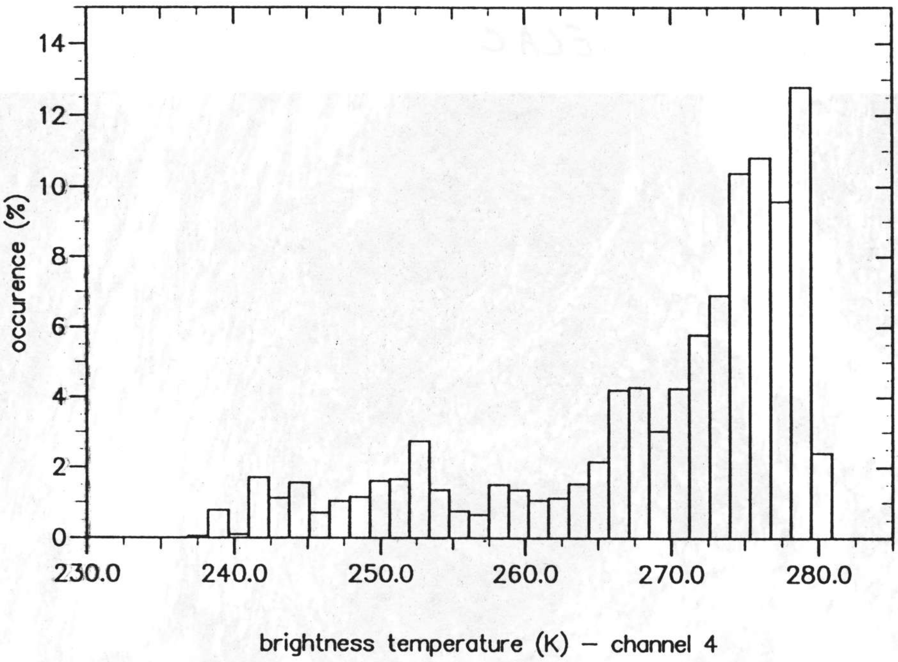

EUCREX FLIGHT 08 LEG MO(2)
Thickness (km)
0
1
2
3
4
5
6
0
50
100
150
200
250
Observations


EUCREX FLIGHT 08 LEG MO(1)
M=0,22
S=0,25
Observations
120
100
80
60
40
20
0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Apparent Optical Depth

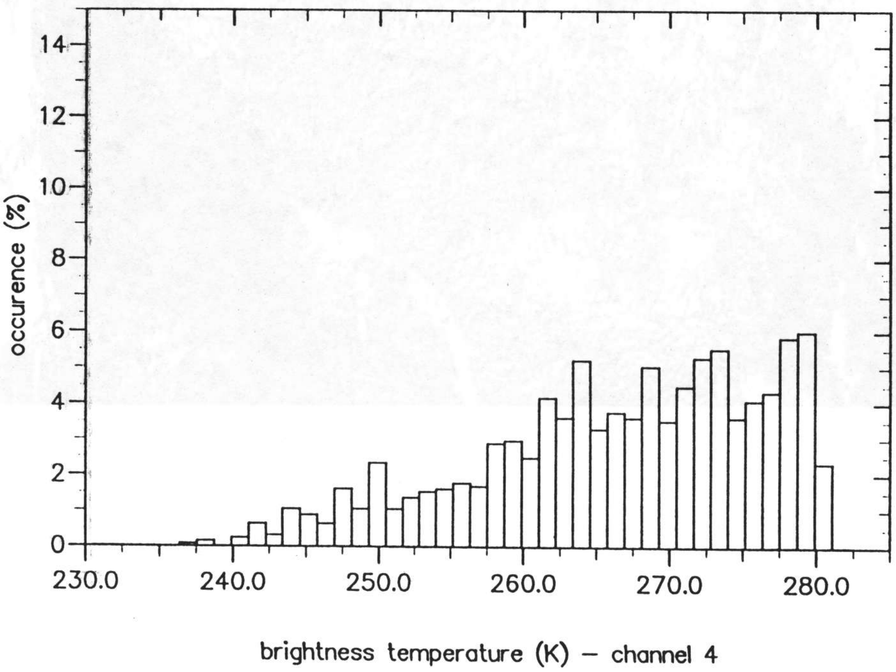

EUCREX FLIGHT 08 LEG OM(1)
M=0,32
S=0,27
Observations
120
100
80
60
40
20
0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Apparent Optical Depth


EUCREX FLIGHT 08 LEG MO(2)
M=0,21
S=0,19
Observations
120
100
80
60
40
20
0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Apparent Optical Depth

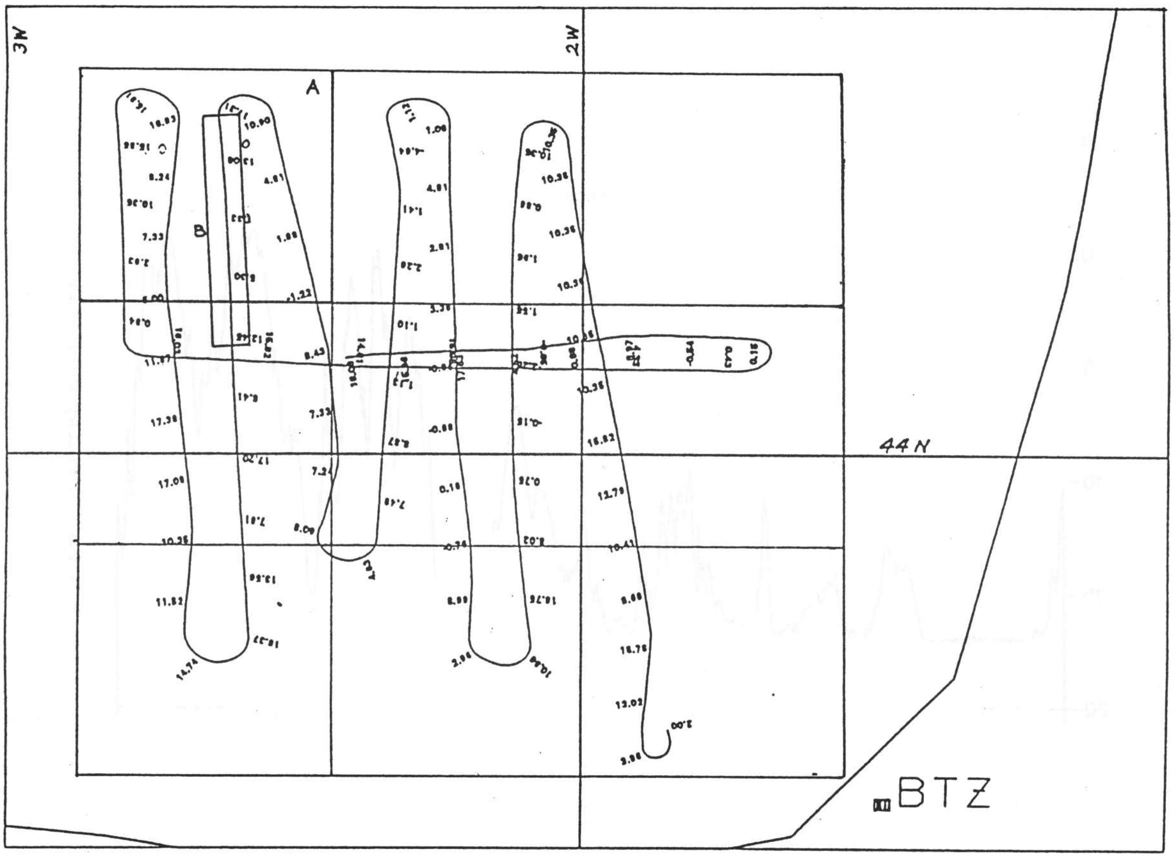
EUCREX – FLIGHT 08 – pattern O–M

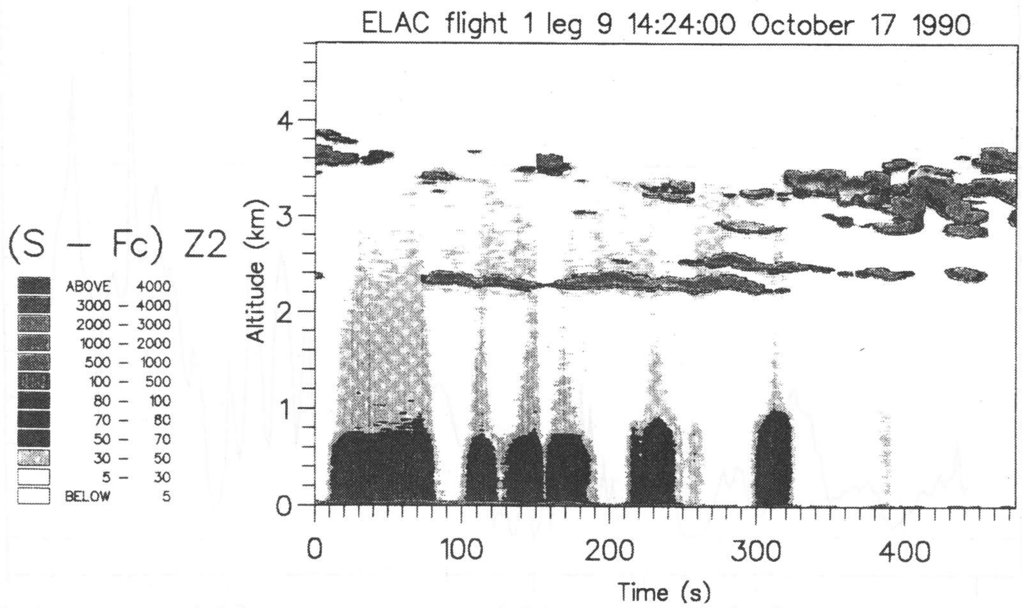


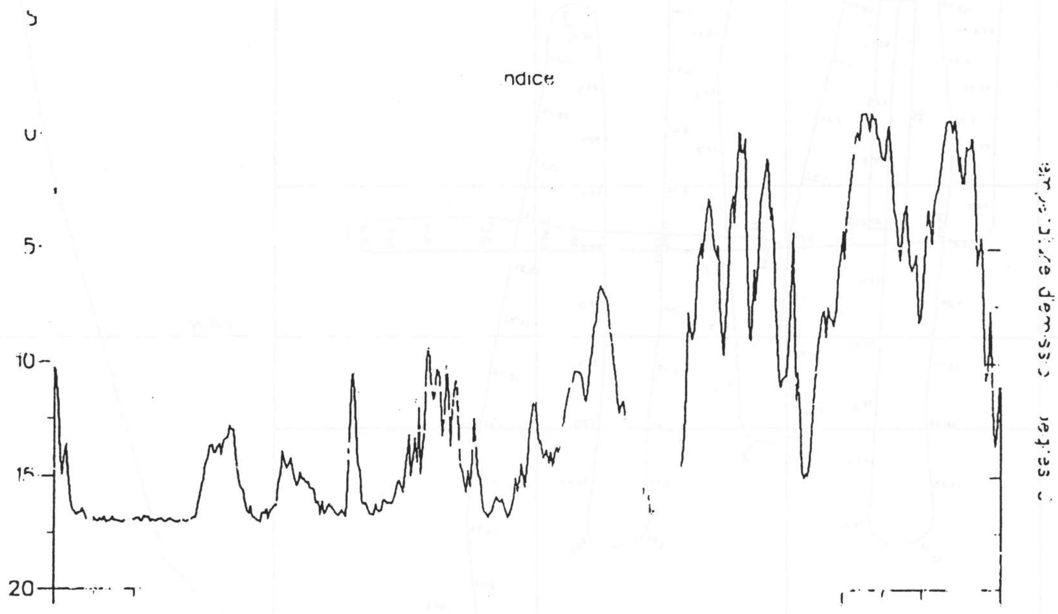
EUCREX flight 08 – pattern O–M – (square)



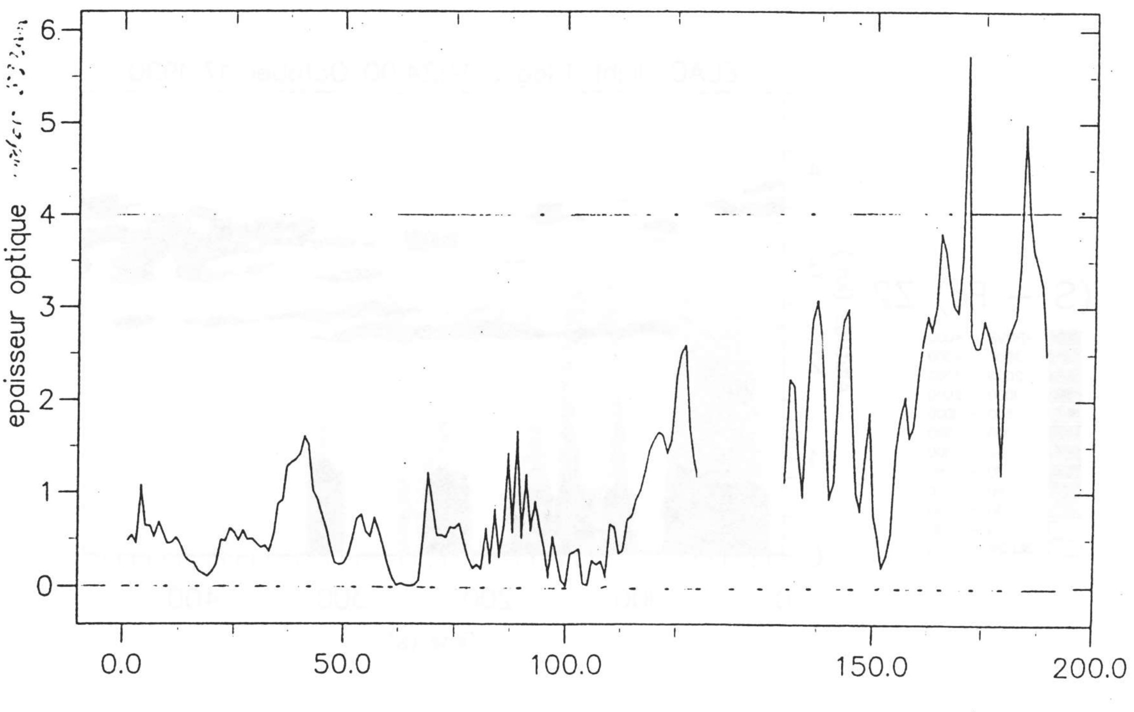
ELAC

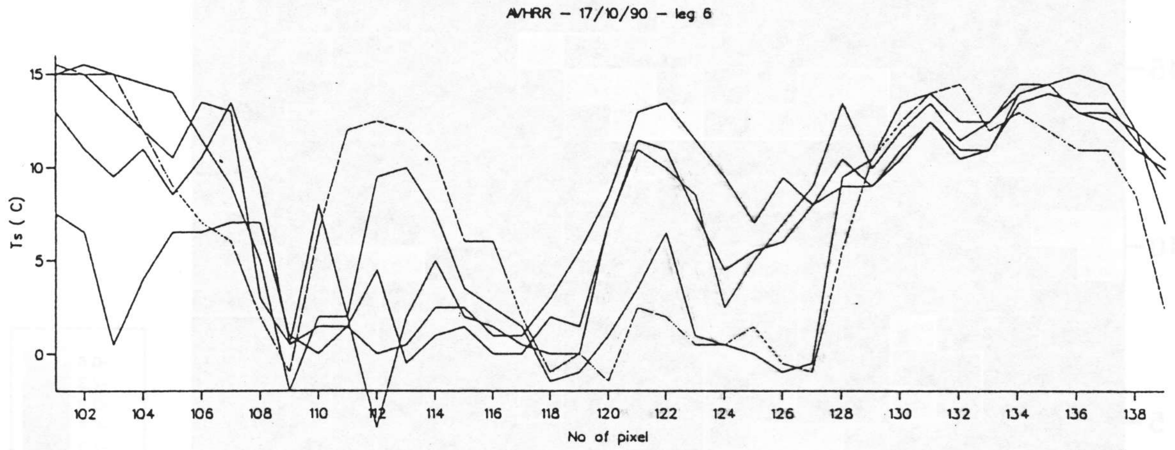

3W
2W
A
B
44 N
BTZ

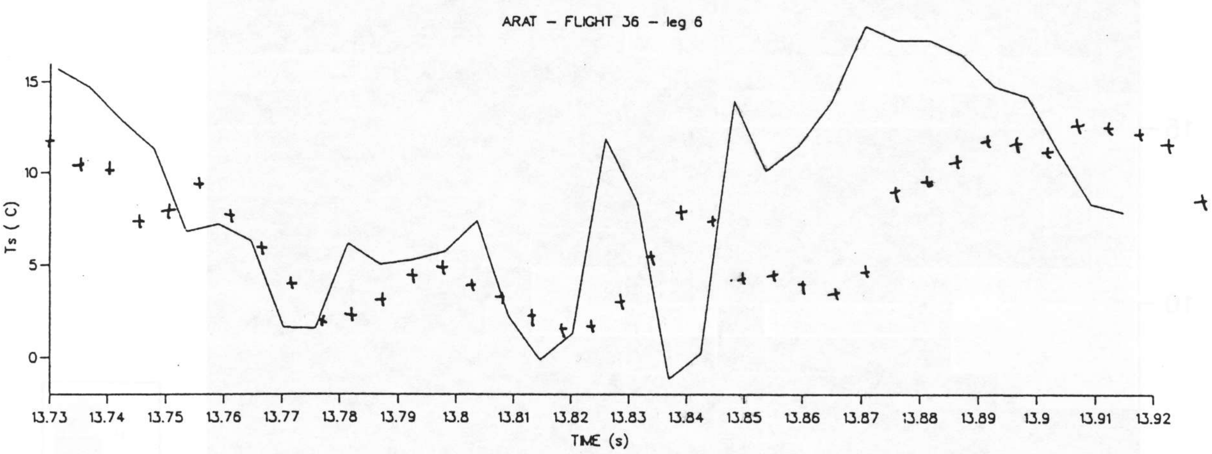

ELAC flight 1 leg 9 14:24:00 October 17 1990
(S − Fc) Z2
ABOVE 4000
3000 − 4000
2000 − 3000
1000 − 2000
500 − 1000
100 − 500
80 − 100
70 − 80
50 − 70
30 − 50
5 − 30
BELOW 5
Altitude (km)
Time (s)



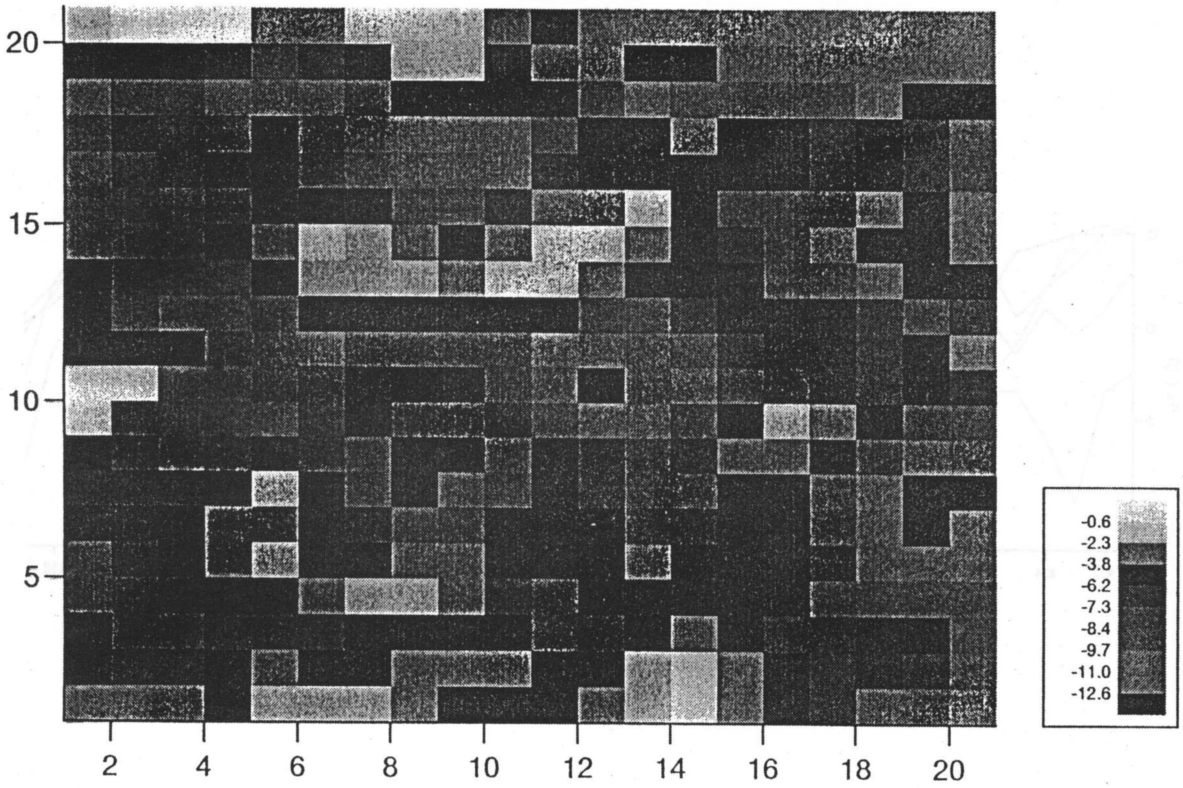
ELAC VOL36 leg9 14:24:21–14:31:58



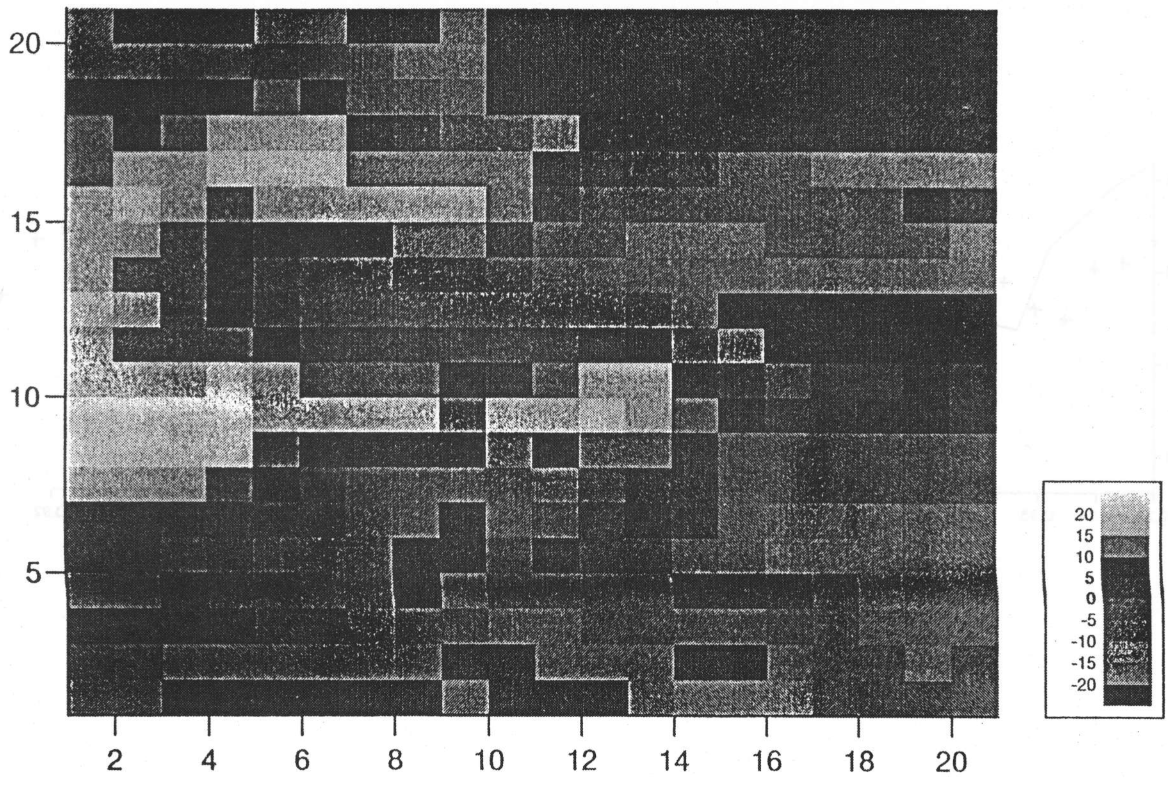

AVHRR – 17/10/90 – leg 6
Ts (C)
No of pixel
15
10
5
0
102
104
106
108
110
112
114
116
118
120
122
124
126
128
130
132
134
136
138

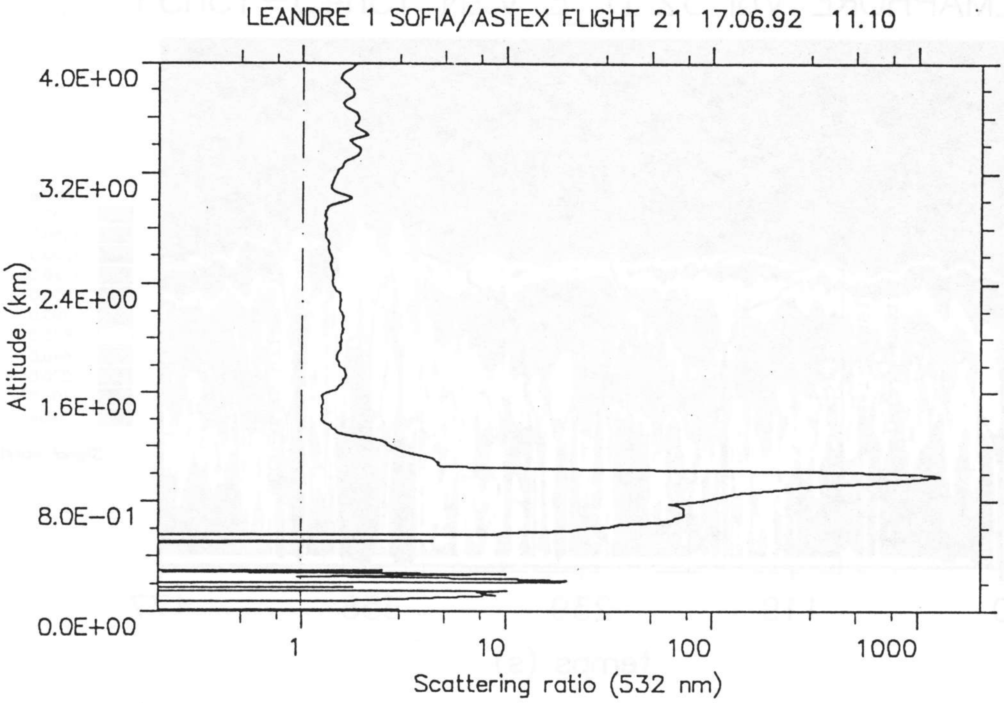

ARAT – FLIGHT 36 – leg 6
Ts (C)
TIME (s)
15
10
5
0
13.73
13.74
13.75
13.76
13.77
13.78
13.79
13.8
13.81
13.82
13.83
13.84
13.85
13.86
13.87
13.88
13.89
13.9
13.91
13.92

shortwave irradiance (meteosat - model) (W.m-2)



longwave irradiance (meteosat - model) (W.m-2)





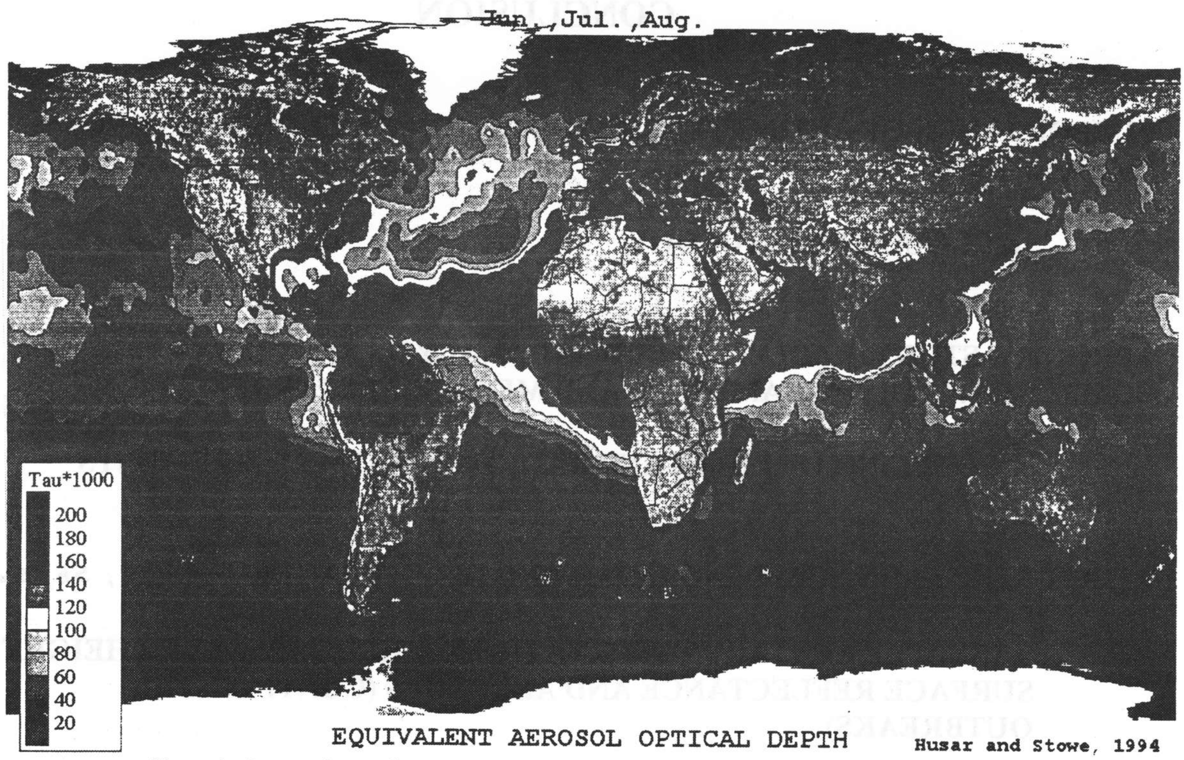
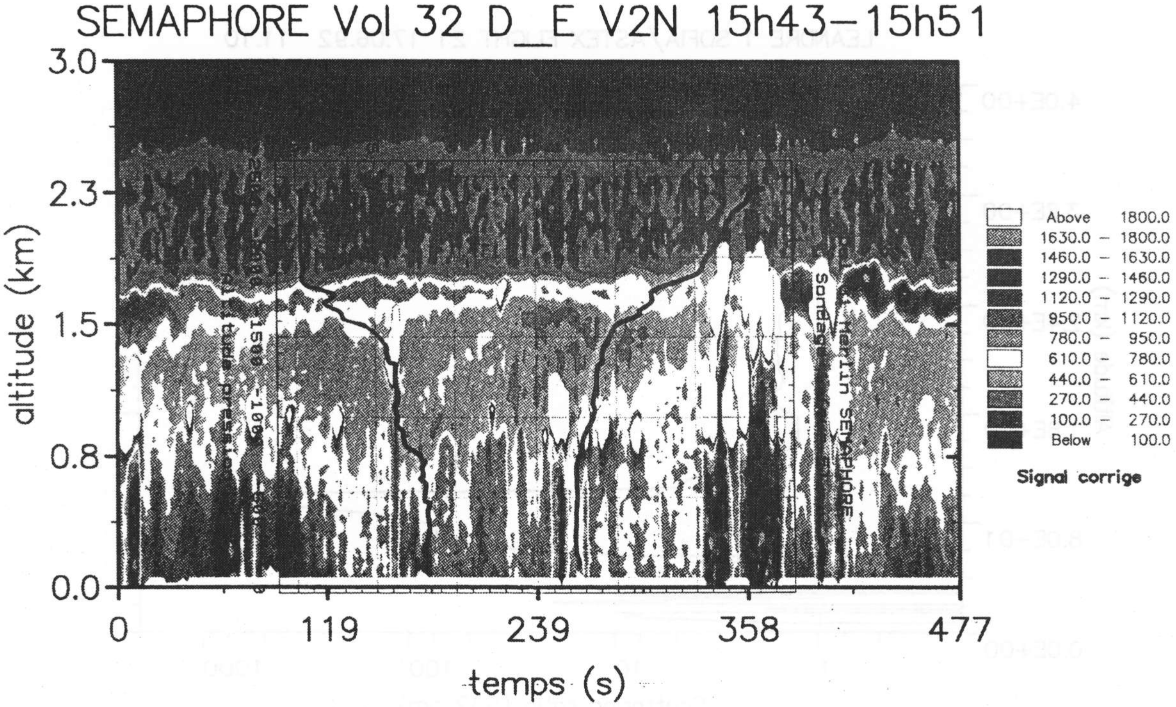


Figure 1. Seasonal map of aerosol backscattering derived from NOAA/AVHRR satellite data over the ocean [Husar and Stowe, http://capita.wustl.edu/CAPITA/CapitaReports/TropoAerosol/trop2.html]



CONCLUSION

♥IMPORTANCE OF ALTIMETRIC INFORMATION ON CLOUD HAS BEEN EMPHASIZED

♠ CLOUD CLIMATOLOGY

♥PROCESS STUDY, RADIATION BUDGET ANALYSIS REQUIRES COMPLEMENTARY PARAMETERS AND MESO-SCALE INFORMATION

♠ COUPLING OF LIDAR AND RADIOMETRIC MEASUREMENTS

♥FIRST STEP : NON-SCANNING LIDAR AND IR IMAGER → Ci, St, Sa

♠ COMPLEMENTARY OBSERVATIONS BOUNDARY LAYER HEIGHT, SURFACE REFLECTANCE AND AEROSOLS (CONTINENTAL OUTBREAKS)