The Interactions of Clouds and Radiation
: Retrieval of optimum parameters from space lidar and radiometry

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THE INTERACTIONS OF CLOUDS AND RADIATION: RETRIEVAL OF OPTIMUM PARAMETERS FROM SPACE LIDAR AND RADIOMETRY.

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1. *The effects of clouds on climate*

The global climate is determined by the net radiative flux at the top of the atmosphere. Two opposing tendencies cause the net radiative flux to change when in the presence of clouds. On the one hand, an increase in cloud amount reduces the infrared flux to space because the cloud temperature is lower than the earth's surface temperature. On the other hand an increase in cloud amount increases the solar flux back to space on account of the scattering properties of the cloud.

The opposite is true at the surface, where clouds increase the downcoming infrared flux, but reduce the solar flux. In the atmosphere itself, radiative divergences due to clouds tend to cause cooling near cloud top and heating near cloud base. Absorption of solar energy also causes a net heating.

We can illustrate the radiative tendency at the top of the atmosphere by a simple model (Platt, 1981). We define ΔF_I and ΔF_S as the changes in infrared and solar fluxes respectively over one day length for a change in cloud amount from zero to completely overcast. We illustrate these effects by a model of cirrus clouds in Figure 1. The radiative tendencies are plotted against cloud optical depth. Figure 1 shows that for typical cirrus of low optical depth, the net radiative tendency is a warming. As the optical depth increases, the tendency switches to cooling at an optical depth that depends on cloud height.

The diagram can also be applied to midlevel and low clouds. In those cases, the infrared tendency would be less, because of the smaller temperature differential with the surface. Therefore, for low clouds, the tendency is a cooling except for clouds of very low optical depth, and because the optical depths tend to be large, the cooling tendency is also large. The net change $\Delta F_n = \Delta F_S - \Delta F_I$ in flux has been investigated on a global scale, both from orbiting satellite radiance data and from numerical models. The general conclusion is that clouds have a net cooling effect on the present climate due to the dominance of the albedo effect in low and midlevel clouds – and in tropical cirrus of high optical depth. However, the uncertainty in these figures is still appreciable. This is illustrated by the net global fluxes obtained from Harrison *et al.*, (1990) and shown in Table 1.

The further question should then be asked: What would be the change in flux tendencies in the event of a climate change? Take, for argument's sake, the case of anthropogenic global warming, and consider the 'standard' case of a doubling in the concentration of CO_2 in the earth's atmosphere. If we neglect feedbacks the surface temperature warming is about 1.2°C. If we include water vapour feedback, that approximately doubles the warming because of the increase in atmospheric water vapour with temperature.

The equivalent feedbacks due to clouds are not quite that simple. On the assumption that either cloud amount or cloud optical depth, or both, increase, and that the increase is equal for all cloud types, we would expect a cooling tendency to counteract the predicted CO_2 and H_2O vapour warming. But numerical models indicate that this scenario is probably wrong. This is because the humidity increases are not equally spread. Stronger convection in some regions are predicted to cause a moister troposphere, whereas compensating downdrafts in other areas can cause a dessication in those regions. It is found, in fact, that many models show a positive feedback with increases in a CO_2-doubled temperature of as much as 5°C. The main reasons are an increase in high cloud amount and optical depth (a warming tendency) and a decrease in midlevel and low cloud amounts (also a warming tendency). However, some other models indicate a net negative feedback, with an overall warming reduced to less then 2°C. The differences in the results are due to the various cloud parameterisations employed (eg., Lee *et al.*, 1996).

It is thus evident, and in fact has been for a number of years, that further progress is required in our understanding and treatment of cloud processes. Several programs such as the Global Energy and Water Cycle Experiment (GEWEX), the Japanese Cloud and Climate Study (JAPACS), the Atmospheric Radiation Measurement Program (ARM) among others are now currently addressing this problem.

2. Observational requirements

The radiative effects of clouds are determined by the cloud albedo, or reflectance, to solar radiation and the cloud infrared emittance (e.g., Platt, 1981). What, then, are the parameters that are needed to determine these quantities, and how many of them can be determined by lidar?

The cloud albedo depends on cloud optical depth, cloud structure and inhomogeneity and to a lesser extent, on cloud height. The cloud albedo also depends on the cloud particle asymmetry parameter. The lidar can measure all of the above properties except the asymmetry parameter. The latter requires a knowledge of cloud particle type, size and phase. However, a measurement of the cloud reflectance, simultaneous to the lidar measurement of optical depth, will give information on this quantity. The dependence of solar reflectance on the infrared emittance of cirrus is shown in Figure 2 (Spinhirne *et al.*, 1996), where observations are compared with different cloud particle models.

It is also well known that the solar albedo of inhomogeneous and 'finite' clouds tends to be lower than for a stratified layer cloud of similar optical depth. Thus it is important again to measure the cloud reflectance along with the cloud structure and cloud topography.

The number of aerosols acting as Cloud Condensation Nuclei (CCN) can also effect the cloud albedo, particularly for boundary layer water clouds (Boers *et al*, 1996). Because of the generally much larger aerosol content in the Northern hemisphere the cloud albedoes are predicted to be higher. Therefore the associations of the albedo of low clouds with the local aerosol population is very important.

Measurement of the cloud solar reflectance simultaneous with lidar measurements of optical depth is obviously desirable. It would require the use of a visible radiometer in conjunction with the lidar. Measurement of the infrared emittance similarly requires an infrared spectral radiometer. Platt *et al.*, (1987) and Spinhirne *et al.*, (1996) have demonstrated the benefits of using an infrared radiometer simultaneously with groundbased lidar.
Thus, the utility of lidar to observe cloud climate parameters is enhanced considerably by simultaneous use of infrared and visible narrow-beam radiometers.

3. Lidar observations of clouds from Space

What observations of critical cloud-radiation parameters can be made with a space lidar. How would these complement other observations?

Lidar observations from space are illustrated here by results from the Lidar In-Space Technology Experiment (LITE) shown in Figure 3. Space lidar can obviously provide lidar backscatter profiles of clouds on a global basis. This is already a significant step forward. By contrast groundbased lidar can provide continuous temporal data at one point, although low water clouds can obscure higher level clouds. Thus, another advantage of space lidar is that it will encounter high cirrus clouds first, thus giving unambiguous data on cirrus global climatologies. Space lidar will also frequently penetrate high cirrus clouds to measure midlevel and boundary layer clouds beneath. This is also illustrated in Fig. 3. In this case, the most attenuating clouds are encountered last, which is opposite to the case of ground based lidar. Figure 3 further illustrates the details of cloud amount and structure that are obtainable from space lidar. The spatial patterns of cirrus, midlevel and boundary-layer cumulus clouds are illustrated very clearly.

The optical depth of high cirrus cloud can be measured directly by calculating the transmittance of laser radiation scattered by the molecular atmosphere below the cloud. This is illustrated in Fig. 4. The optical depth and extinction can also be retrieved by lidar backscatter inversion techniques (Platt, 1979, Young, 1995). The global distribution of the ice phase can be determined by measuring the linear depolarisation ratio. Recent studies have shown that the cloud ice content can also be related to the retrieved extinction coefficient (Platt, 1997). The optical depths of highly attenuating clouds might also be retrievable by utilising the multiple scattering process (e.g., Platt and Winker, 1995). (See also Figure 3). The integrated backscatter can be used to obtain information on cloud particle phase function (Platt *et al.*, 1987, Platt *et al.*, 1997).

As in the case of groundbased lidar, the inclusion of infrared and visible radiometers would allow the full calculation of the infrared emittance and the visible albedo.

Thus, the inclusion of infrared and visible radiometer channels parallel to the lidar axis is recommended.

4. Space lidar observations of aerosols

The climatic effects of aerosols are also very important, and critical to accurate climate predictions. The effect of aerosols on climate is predicted to be mainly an increase in the planetary albedo. Therefore aerosols have a cooling effect on the climate. Aerosol effects in the troposphere are quite regional, depending on local sources, although advection can spread the effects over considerable distances.

Some aerosols can, however, also absorb solar radiation. Carbonaceous aerosols, which are quite absorbing of solar radiation, are formed from biomass burning and industrial processes. Volcanic aerosols also have a detectable effect on climate.

Space lidar can detect the vertical structure of aerosols in great detail, as also shown in Fig. 3. Aerosol plumes can be traced over considerable distances using successive orbits.

Again, the inclusion of a visible radiometer with space lidar to measure aerosol reflectances would be very useful.

5. References

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Table 1. Net fluxes at the top of the atmosphere

	Longwave (wm^{-2})	Shortwave (wm^{-2})	Net (wm^{-2})
GCM's (Average)	39.9±9.5	- 57.3±8.8	- 17.4±10.7
ERBE	30.5	- 49.5	- 19

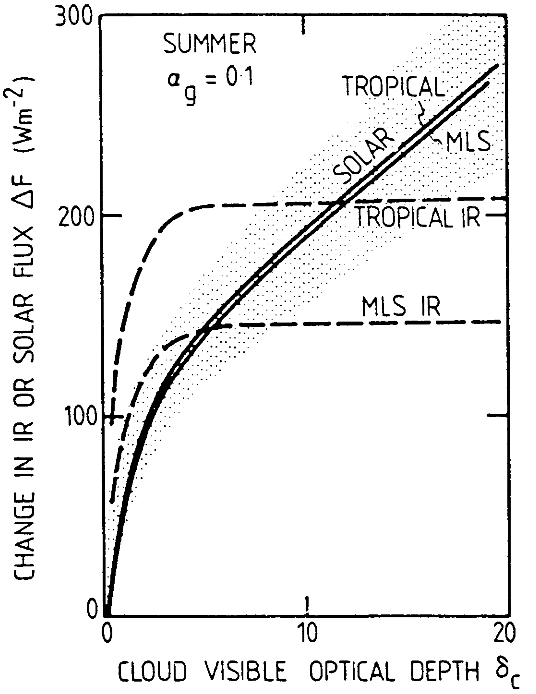


Figure 1. Solar and infrared flux changes at the top of the atmosphere.

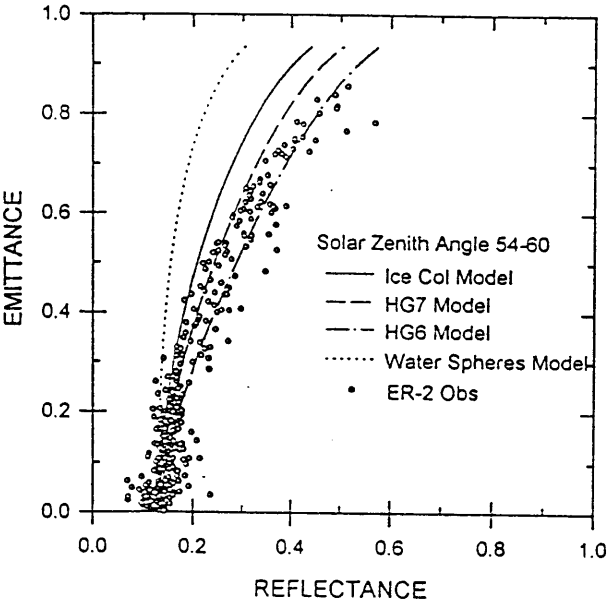


Figure 2. Aircraft radiometric observations of cloud solar flux and infrared emittance.

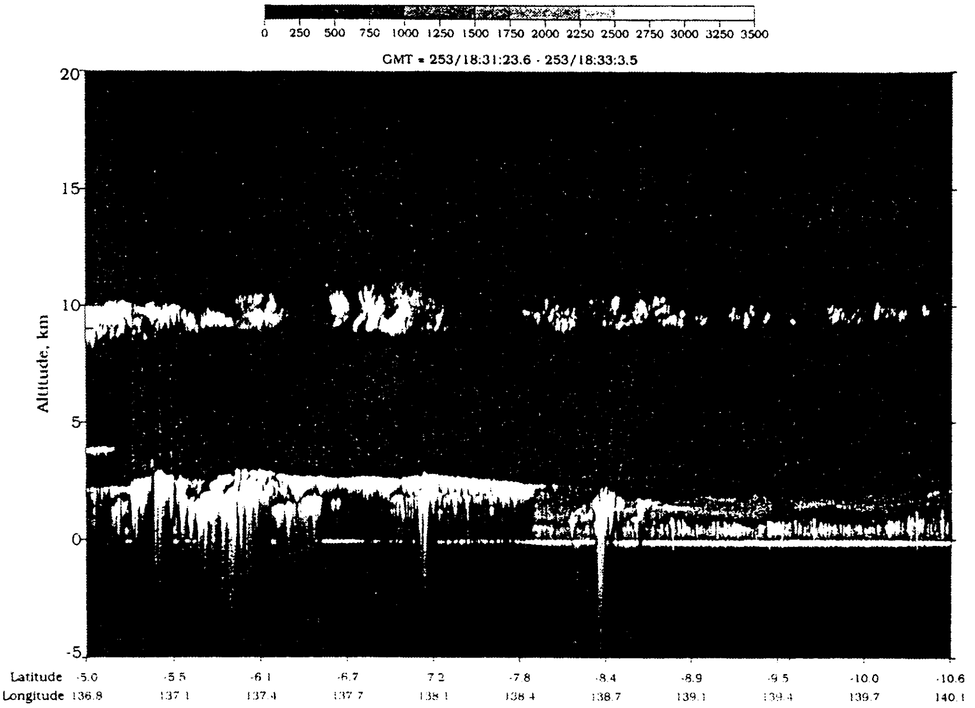


Figure 3. LITE image over the tropical west Pacific. Shown are cirrus, altocumulus, stratocumulus and. cumulus. The long tails on the low clouds are due to pulse stretching from multiple scattering.

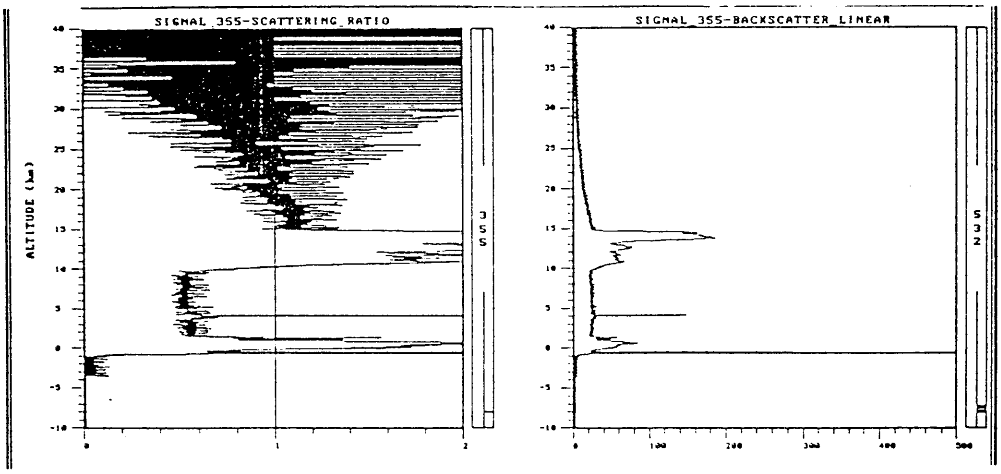
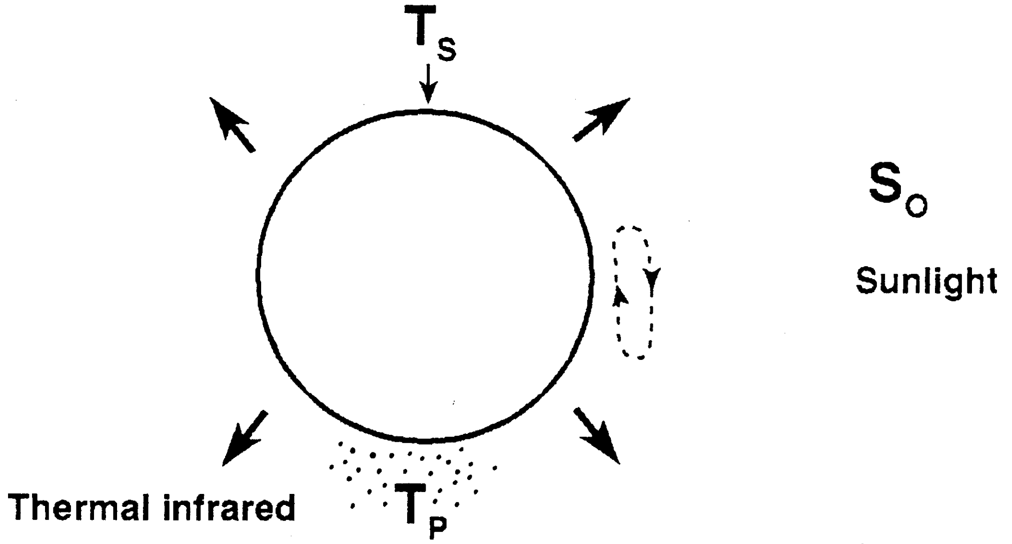


Figure 4. One LITE backscatter profile showing the linear backscatter (355 nm)and scattering ratio (532 nm). The reduction in scattering ratio below cloud base is proportional to the transmittance.

What determines our present climate?

Radiation balance of the planet earth



Mean planetary temperature $T_P = -18^\circ C$
Mean surface temperature $T_S = +15^\circ C$
Atmospheric gases (CO_2, H_2O, etc) increase in T_S
Clouds (on average) decrease T_S

CLOUDS AND CLIMATE

CLOUDS IN PRESENT CLIMATE

SOLAR REFLECTION - MORE RADIATION - COOLING
LOSS TO SPACE

INFRARED ABSORPTION, - ENHANCED - WARMING.
EMISSION GREENHOUSE

WHICH EFFECT "WINS"?

GLOBALLY, A NET COOLING - FACTOR OF 2 IN UNCERTAINTY

Net radiative fluxes at the top of the atmosphere.

	Longwave (wm^{-2})	Shortwave (wm^{-2})	Net (wm^{-2})
GCM's (Average)	39.9±9.5	- 57.3±8.8	-17.4±10.7
ERBE	30.5	- 49.5	- 19

GCM - General Circulation Model.

ERBE - Earth Radiation Budget Experiment.

CLIMATE CHANGE

HIGH CLOUDS - ENHANCED WARMING

LOW CLOUDS - ENHANCED COOLING

SUPPOSE:

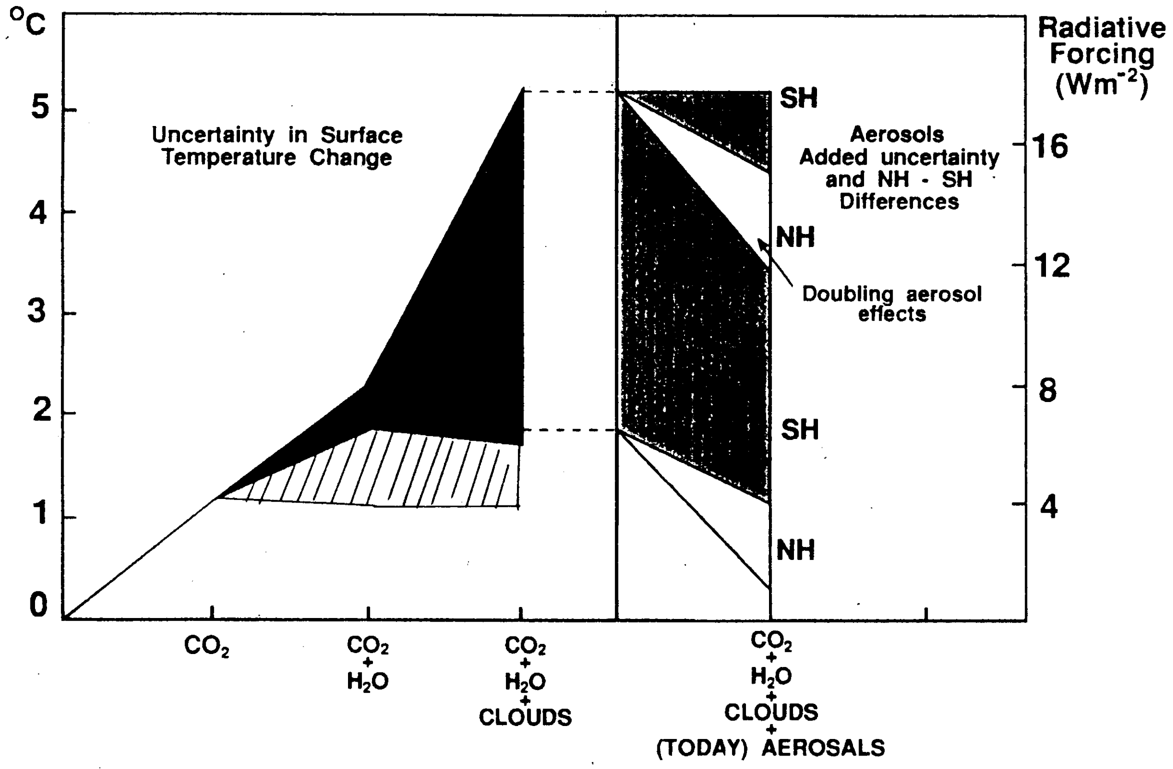
HIGH CLOUDS INCREASE (AMOUNT AND/OR OPTICAL DEPTH)

LOW CLOUDS DECREASE (AMOUNT AND/OR OPTICAL DEPTH)

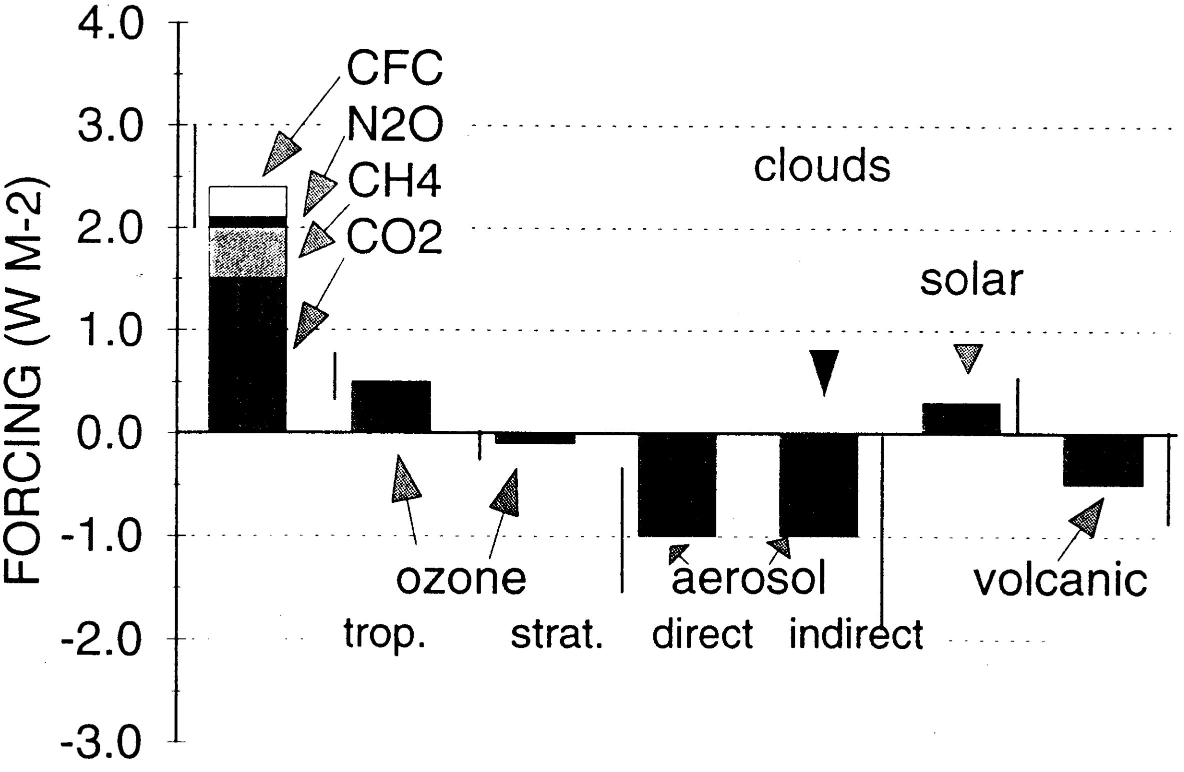
RESULT:

ENHANCED WARMING - POSITIVE FEEDBACK

GCM'S TEND TO GIVE THIS RESULT. ARE THEY RIGHT?



CO₂ doubling Simulations plus aerosol forcing



RADIATIVE FORCINGS

WHAT QUANTITIES DETERMINE THE CLOUD RADIATIVE INTERACTIONS, AND WHAT PARAMETERS DO WE NEED TO DETERMINE THESE QUANTITIES?

(i). *Solar albedo.*

- Optical depth
- Solar angle
- Cloud particle size and phase
- Cloud inhomogeneity or brokenness
- Asymmetry parameter - from cloud particle type and size.
- Cloud height and depth

(ii). *Solar absorption.*

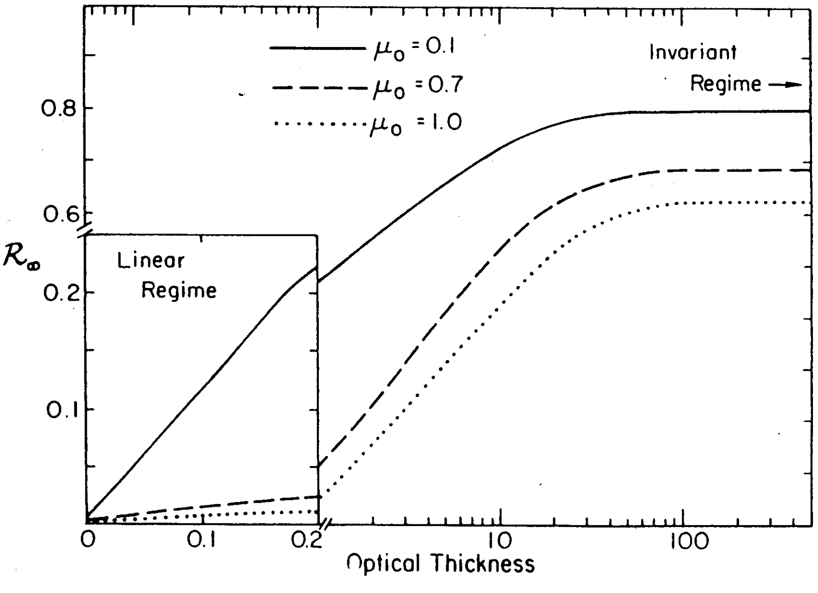
- Optical depth
- Particle size and crystal habit
- Solar angle
- Cloud phase
- Cloud brokenness

(iii). *Infrared emittance.*

- Optical depth
- Particle size and type
- Cloud brokenness
- Cloud height and depth

(iv). *Optical depth.*

- Liquid water path
- Particle size and type



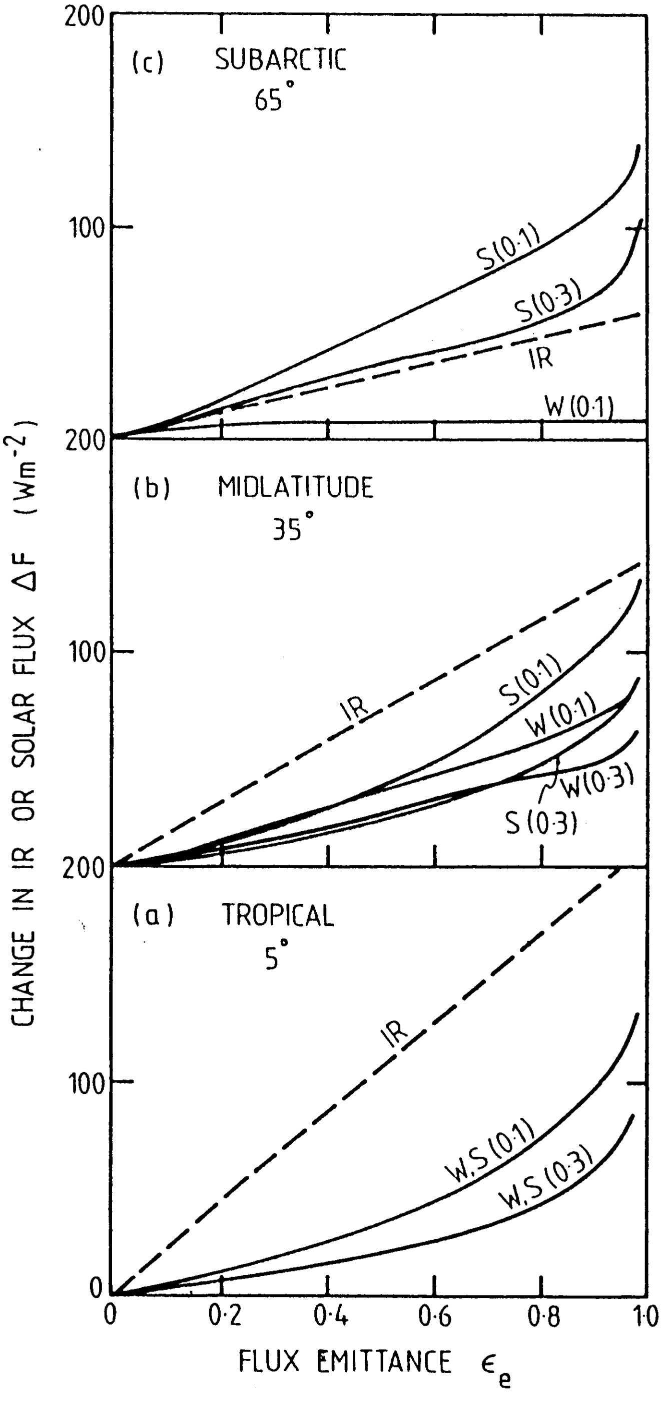
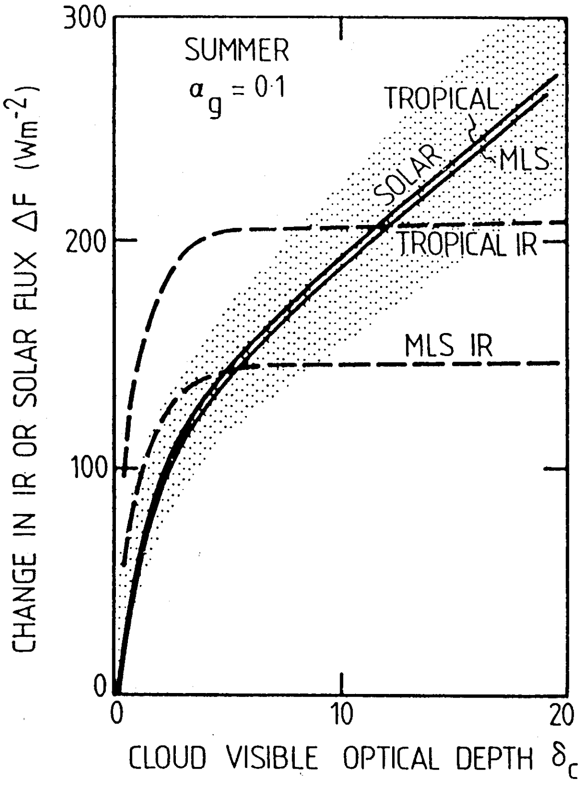


Figure 3. The solar (ΔF_s) and infrared (ΔF_I) flux changes at the top of the atmosphere for a unity change in cloud amount plotted against broadband flux emittance ε_e. S and W stand for summer and winter and figures in brackets indicate albedo a_g below the cloud. ΔF_s – full lines; ΔF_I – dashed lines.



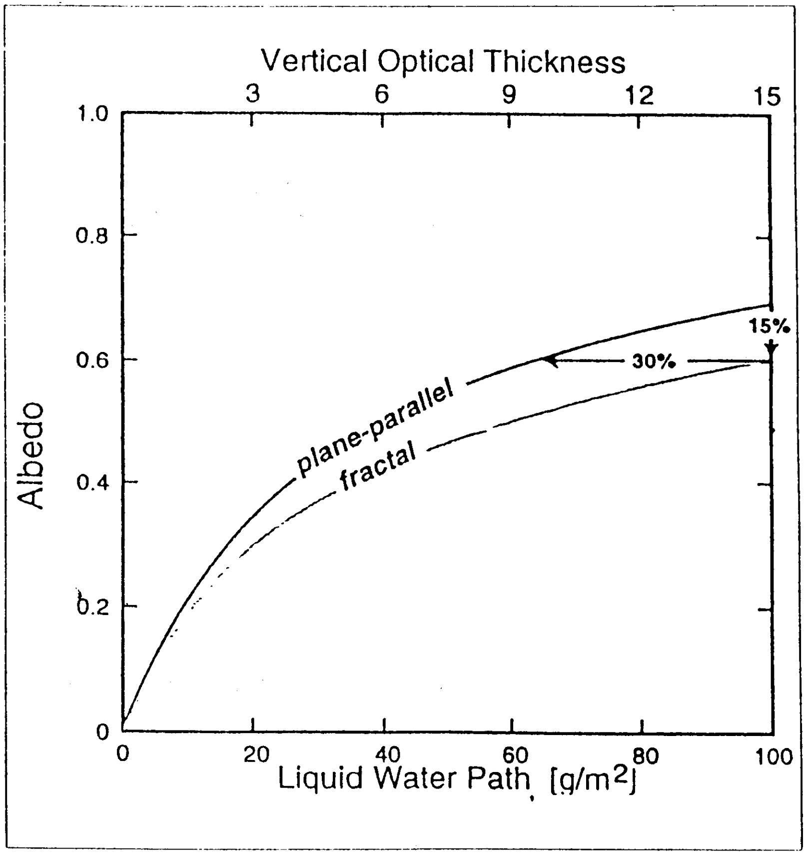


Figure 27.1: Dependence of albedo on optical thickness and liquid water path, for fractal and plane-parallel clouds

(Wiscombe, 1995)

WHAT QUANTITIES CAN LIDAR OBSERVE FROM THE SURFACE?

Lidar can observe cloud base height and depth and cloud visible extinction and optical depth of ice clouds. It can also measure the cloud phase. ***BUT:***

- ***THE ADDITION OF A NARROW BEAM IR SPECTRAL RADIOMETER ALLOWS AN INDEPENDENT OBSERVATION OF EMITTANCE - THE LIDAR/RADIOMETER OR LIRAD METHOD.***
- ***The LIRAD method also allows information on particle size and habit in ice clouds.***
- ***LIRAD allows retrieval of backscatter and extinction coefficient and optical depth of ice clouds.***

The presence of low attenuating clouds implies that some cirrus clouds are 'missed.'

WHAT ARE MEASURABLE QUANTITIES USING SURFACE REMOTE SENSING

OPTICAL DEPTH. (δ)

Visible:

$$\delta = \int_{Z_b}^{Z_t} \sigma(z)\, dz$$

We want to know profile of extinction coefficient, cloud base and top.

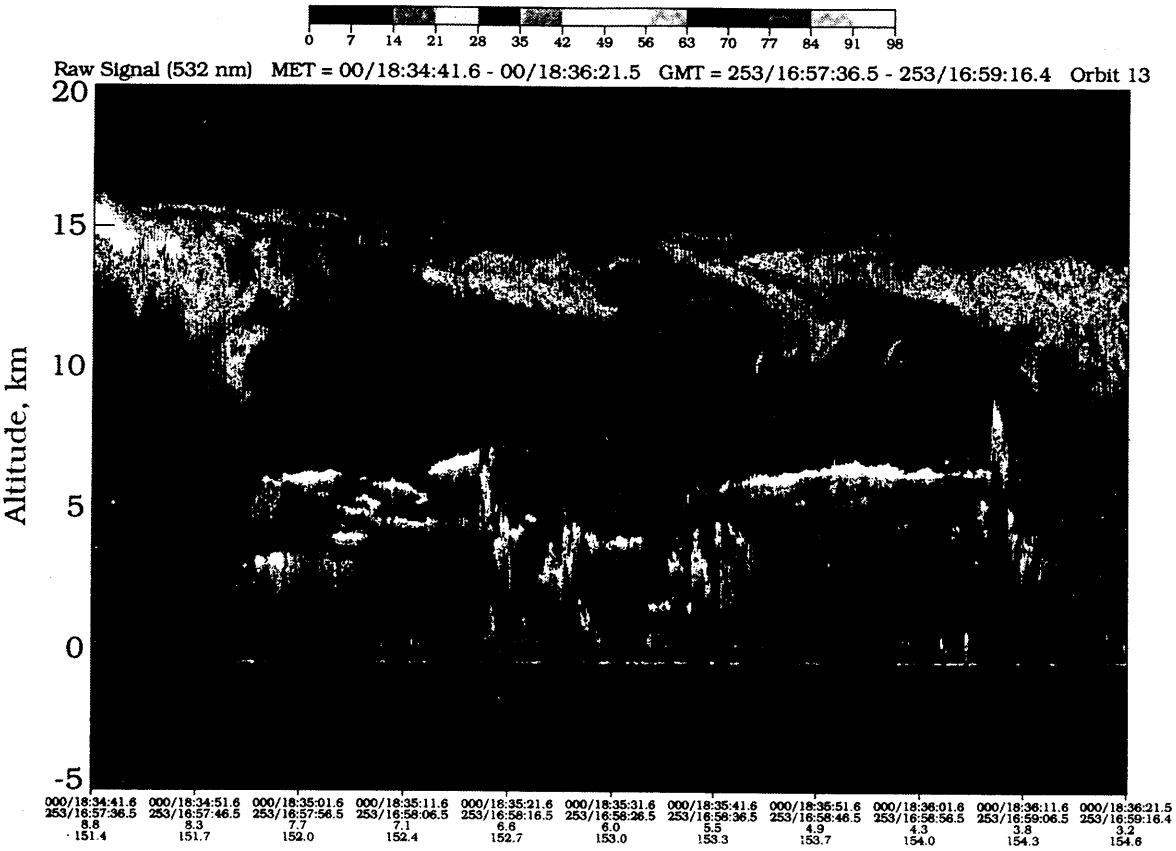
Infrared:

$$\delta_a = -ln\,(1-\varepsilon_a)$$

We want to know emittance ε_a.

SPACE LIDAR - WHAT ARE THE ADVANTAGES?

- Space lidar has a ‘top - down’ view of the atmosphere. Cirrus ice clouds are thus the first clouds encountered.
- *A three - dimensional cirrus cloud climatology can be generated.*
- The cirrus cloud top and base heights can be measured.
- *The cirrus cloud optical depths can be surveyed. This involves transmittance measurements through the cirrus using Rayleigh scattering from above and below the cloud.*
- Transmittance calculations are easier than from the surface because the Rayleigh scattering increases from cloud top to cloud base.
- *As the most transmissive clouds are encountered first, there is a high probability of transmission of the lidar pulse to clouds below. Thus multiple cloud layers can be studied.*
- There is little intervening atmosphere between high cirrus clouds and the space lidar to attenuate the signal.
- *A good global survey of cloud inhomogeneity can be generated.*
- A global survey of the presence of ice clouds can be generated using a depolarisation lidar.
- *The cloud ice content can be determined from the known relation between cloud extinction coefficient and ice water content (Platt, 1997).*
- Multiple scattering effects at space ranges a greater than at surface ranges. Whilst complicating the cloud extinction retrievals, such effects more than halve the attenuation in clouds.
- *Pulse stretching due to multiple scattering in dense clouds could assist with determination of the optical depths of such clouds.*



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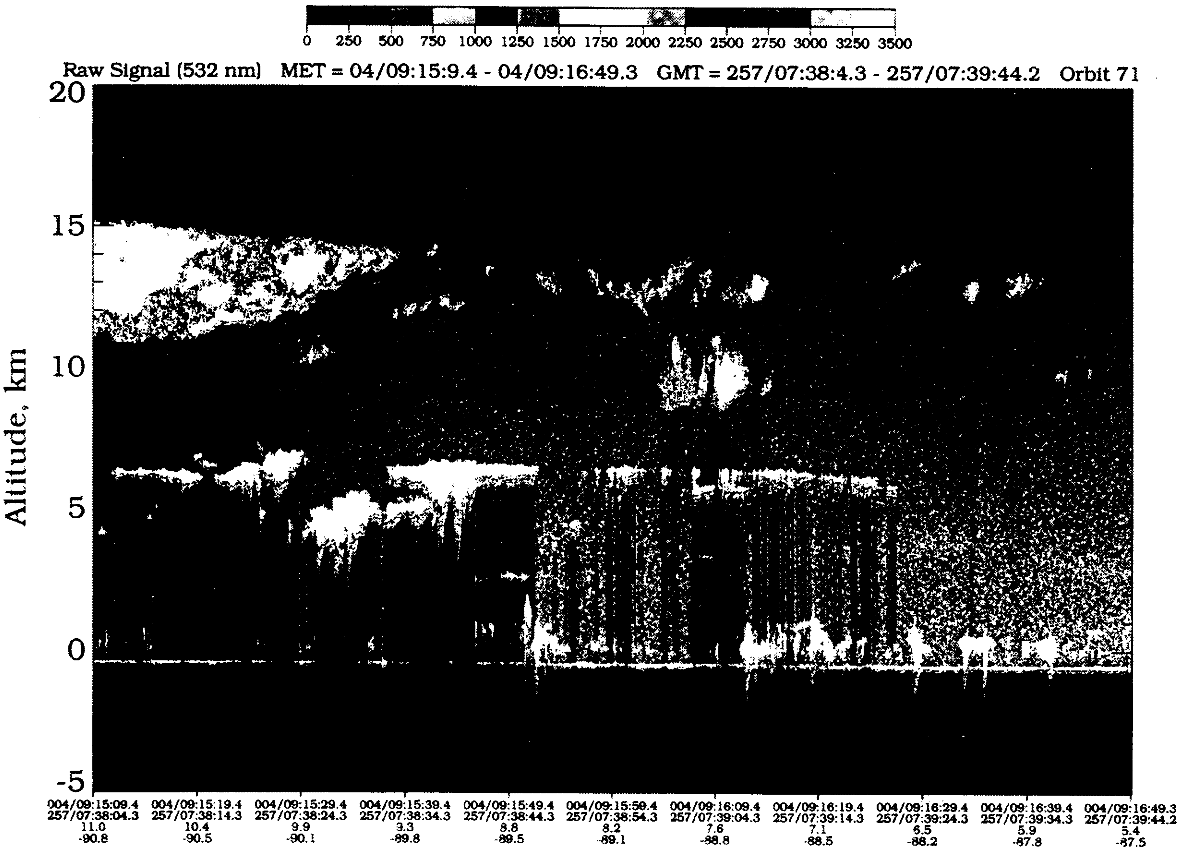

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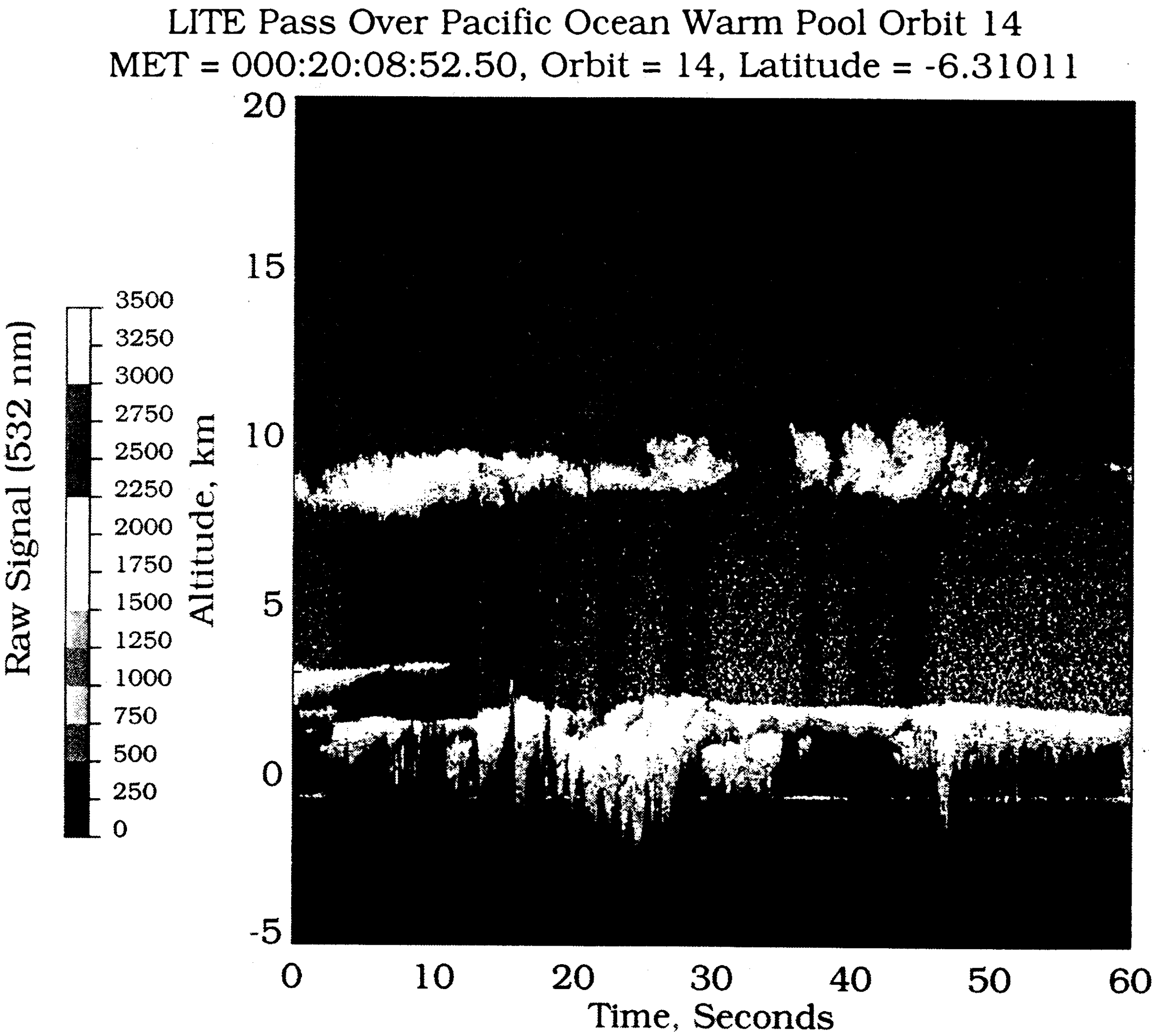
LITE Pass Over Pacific Ocean Warm Pool Orbit 14
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Raw Signal (532 nm)
3500
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1750
1500
1250
1000
750
500
250
0
Altitude, km
20
15
10
5
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-5
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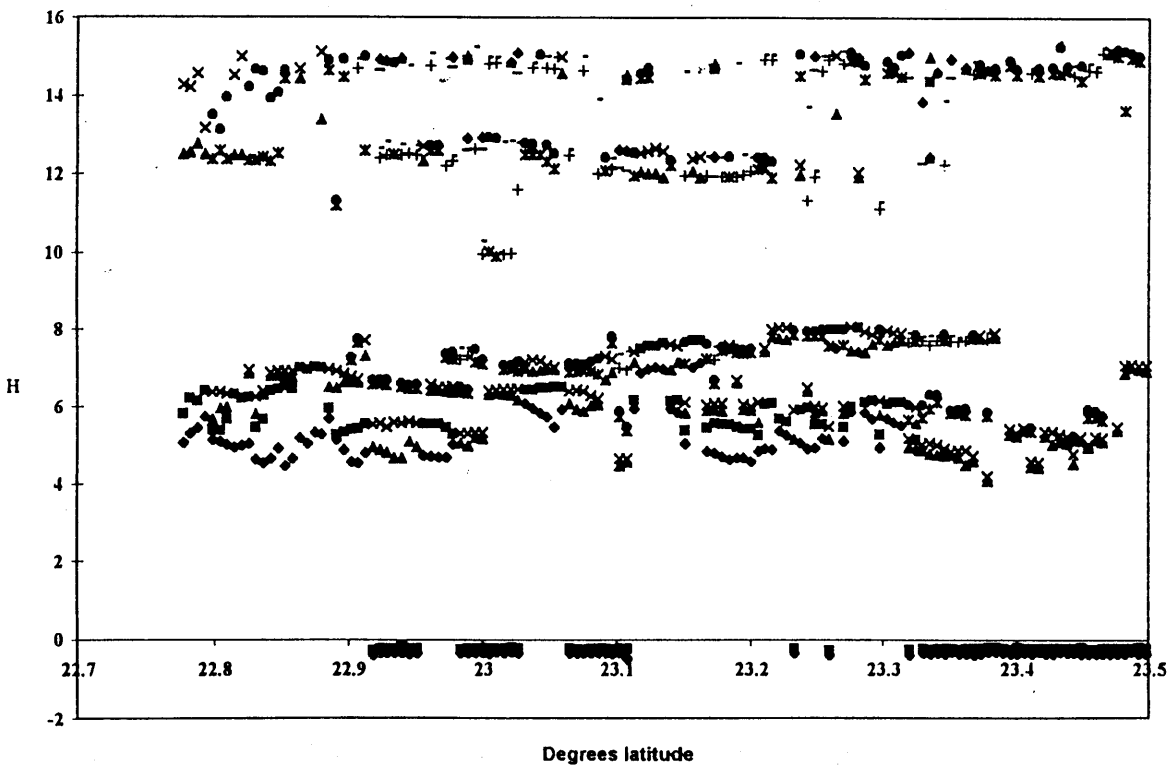
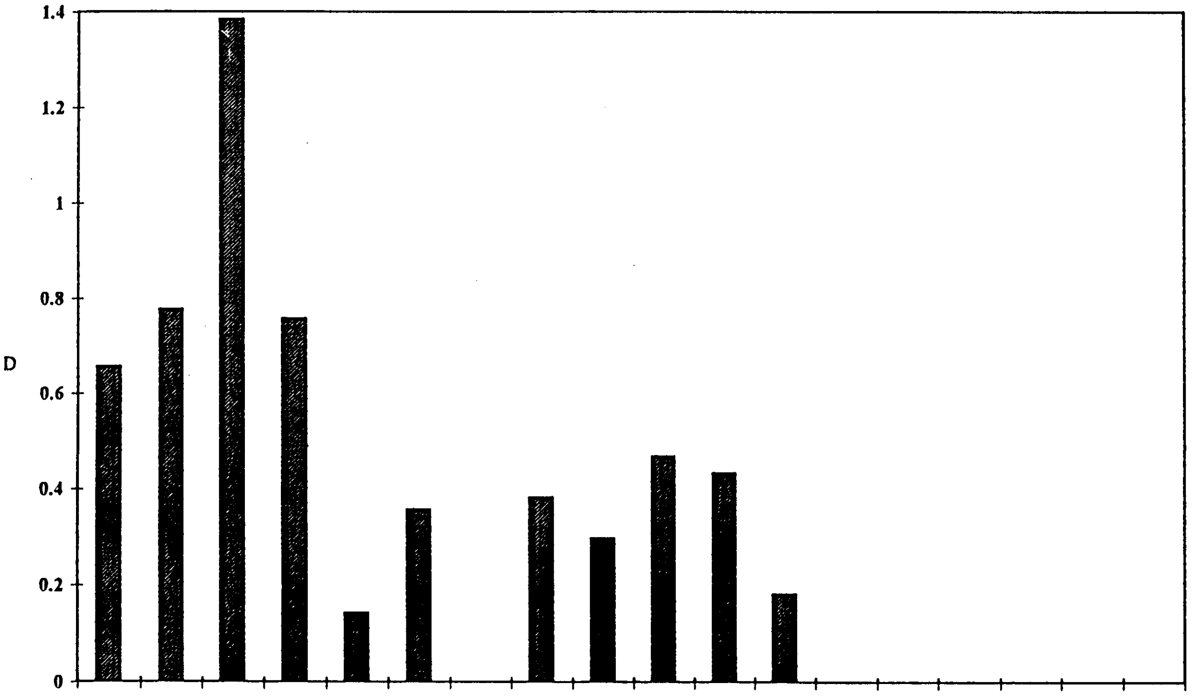
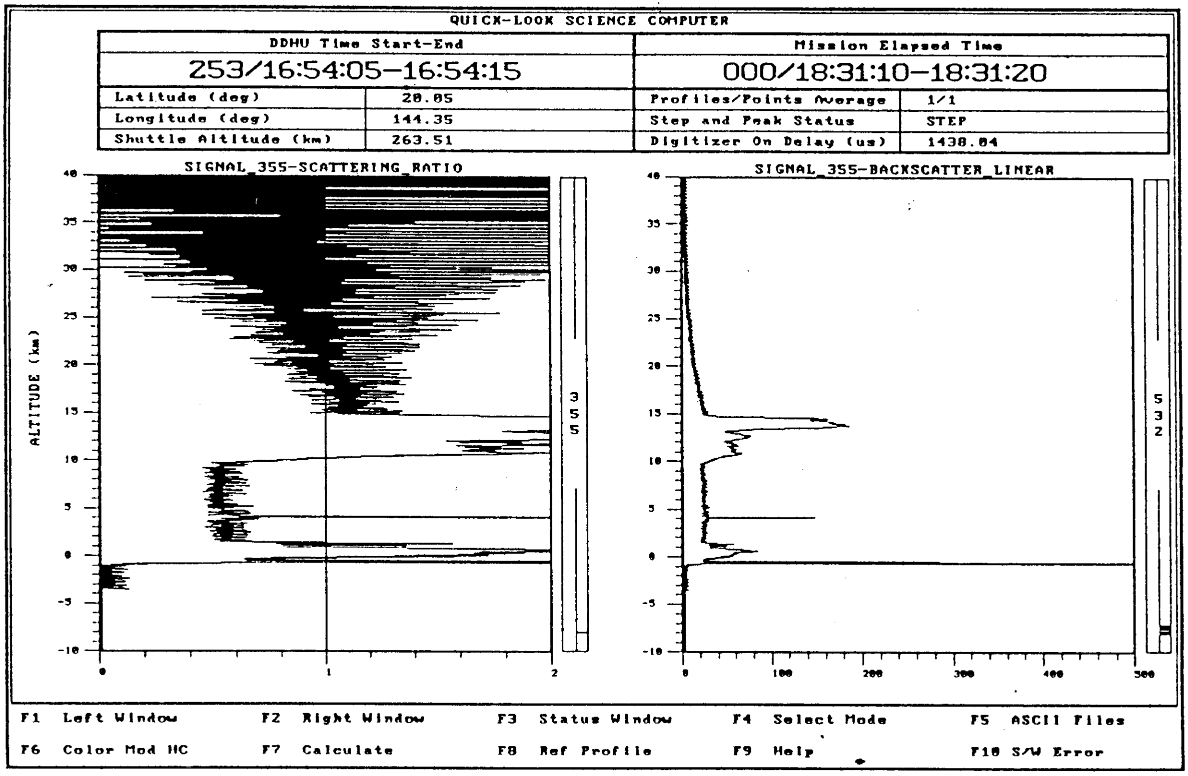
30
40
50
60
Time, Seconds

Cloud heights H km. Orbit 13. Tropical west Pacific.



Average cloud depth H km.Orbit 13. Latitude 22.8N to 23 N, Longitude 140E.





QUICK-LOOK SCIENCE COMPUTER

DDHU Time Start-End		Mission Elapsed Time	
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Longitude (deg)	144.35	Step and Peak Status	STEP
Shuttle Altitude (km)	263.51	Digitizer On Delay (us)	1438.84

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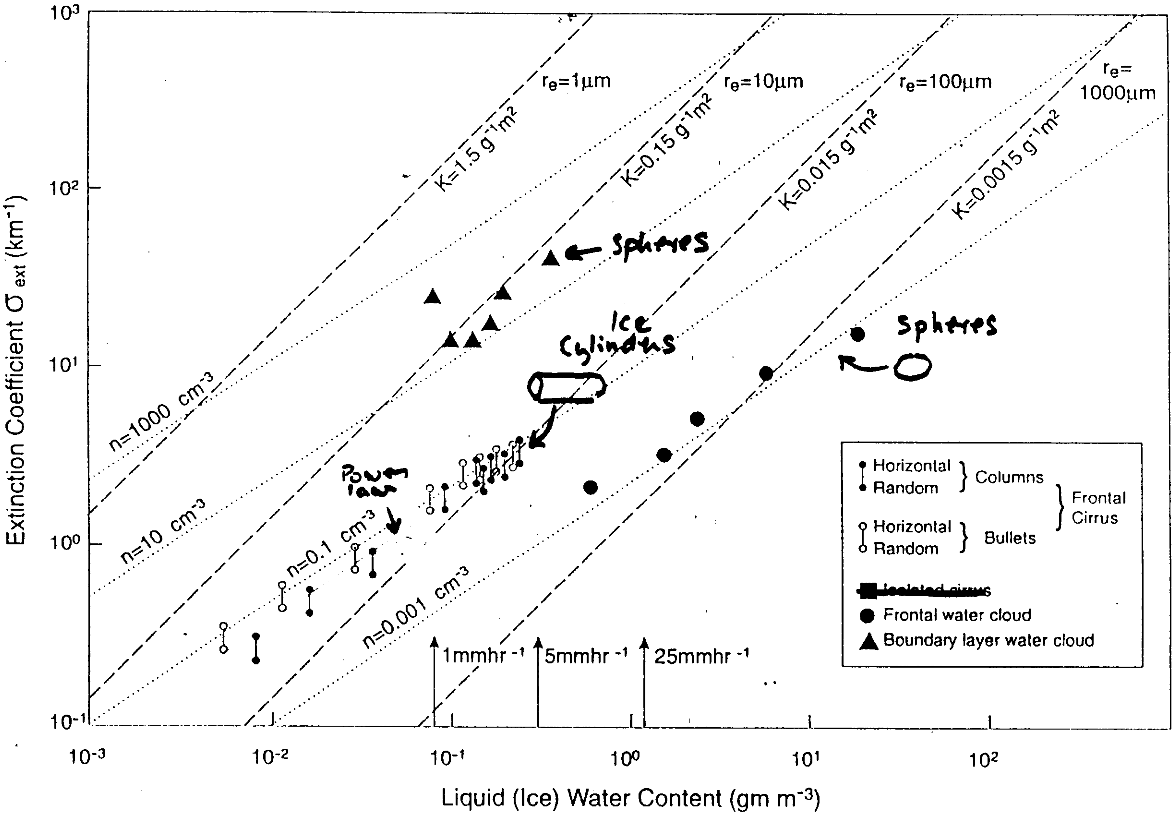
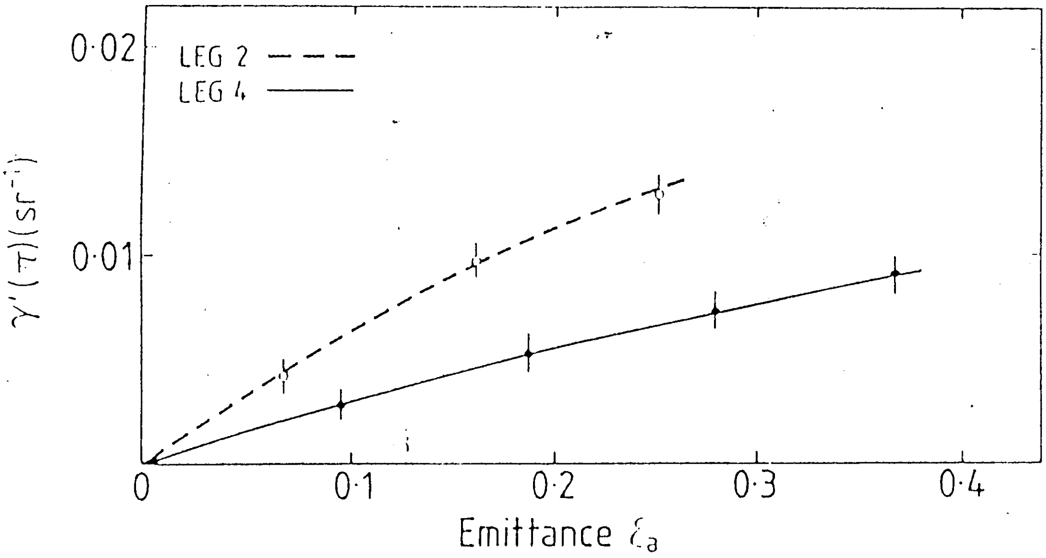
F6 Color Mod HC　F7 Calculate　F8 Ref Profile　F9 Help　F10 S/W Error



THE ADDITON OF IR AND VISIBLE RADIOMETERS WOULD ALSO ALLOW THE DETERMINATION OF CLOUD RADIATIVE PROPERTIES DIRECTLY WITHOUT A KNOWLEDGE OF CLOUD PHASE, PARTICLE SIZE OR TYPE OR CLOUD WATER CONTENT.

(However, some knowledge is still required of the spectral dependencies of optical depth).



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

THE ABOVE SHOWS THAT THERE ARE MANY ADVANTAGES TO SPACE LIDAR.

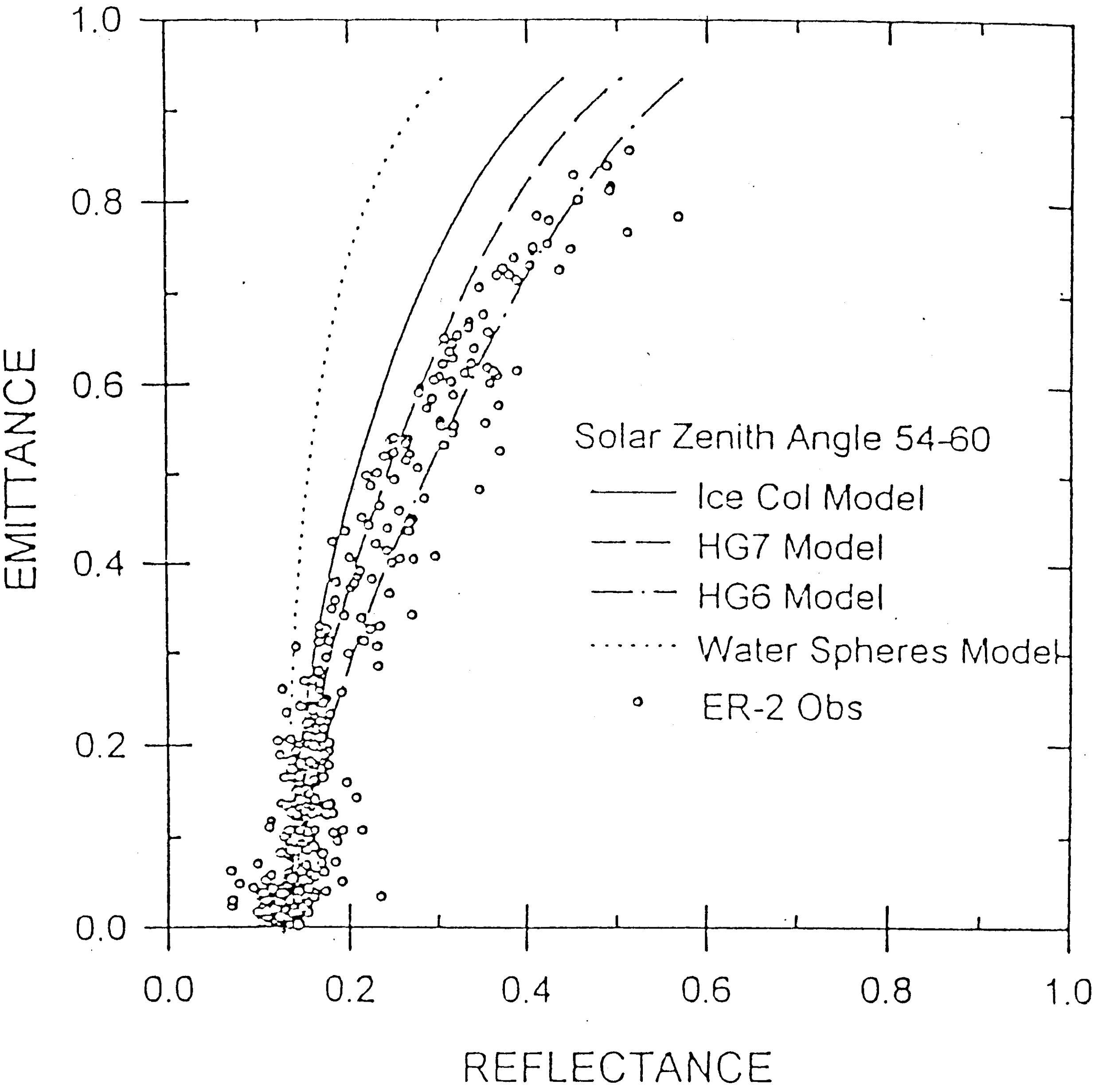
HOWEVER, TO OBTAIN ALL THE REQUIRED RADIATIVE PROPERTIES, WE STILL NEED THE ADDITION OF *RADIOMETRY* TO THE SPACE LIDAR SYSTEM.

- *Addition of a spectral narrow-beam **visible radiometer** will enable measurement of the cloud bidirectional reflectance, and thus **albedo.***

- *Addition of a spectral IR narrow-beam radiometer will enable measurement of cloud **emittance** and thus **optical depth**.*

(Additional requirements are measurement of cloudless albedo and cloudless surface temperature. Gaps in the cloud can be used to measure these).

Using the above observations, we can plot the albedo versus the IR emittance. This will give information on the asymmetry parameter and ice crystal habit in any ice clouds present. The albedo can also be related to observed cloud inhomogeneity.


1.0
0.8
0.6
0.4
0.2
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EMITTANCE
0.0
0.2
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0.6
0.8
1.0
REFLECTANCE
Solar Zenith Angle 54-60
Ice Col Model
HG7 Model
HG6 Model
Water Spheres Model
ER-2 Obs