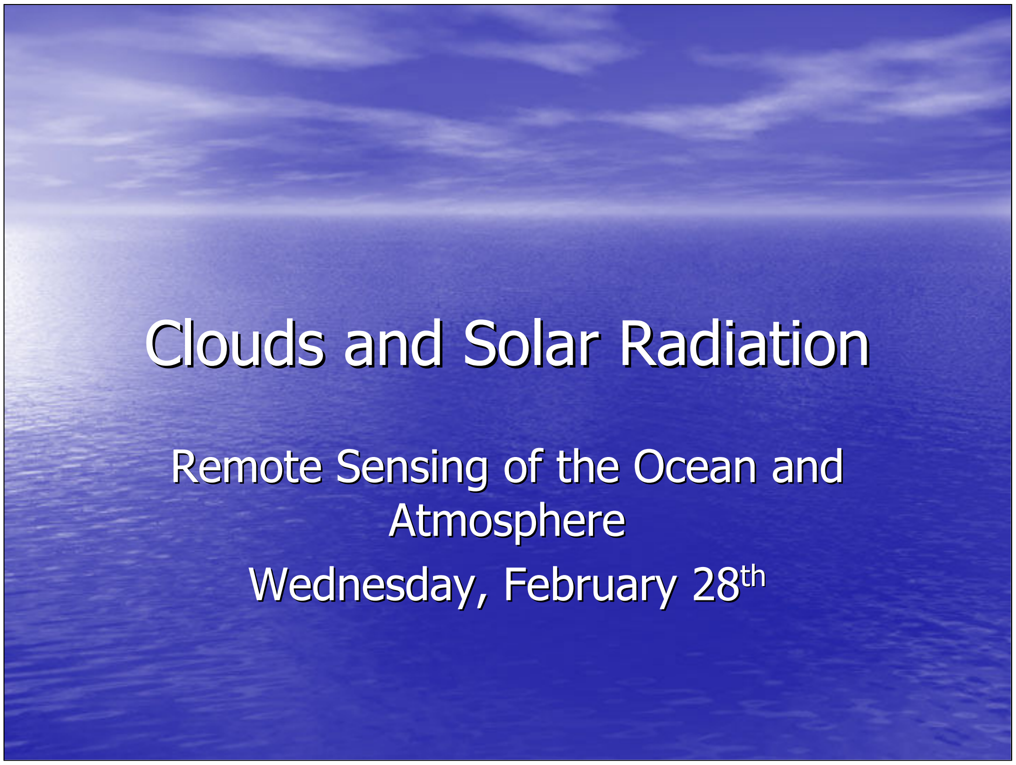
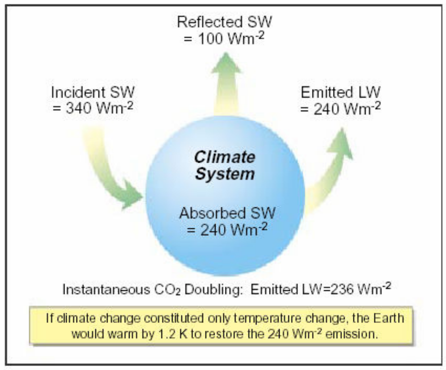


Most of these notes are taken from S. Q. Kidder & T. H. Vander Haar (1995)
Satellite Meteorology: An Introduction

Figure 2.7



Schematic illustration of the Earth's radiative energy balance and how a doubling of atmospheric carbon dioxide would perturb that balance *(Wielicki et al. 1995. Reproduced with permission from the American Meteorological Society).*

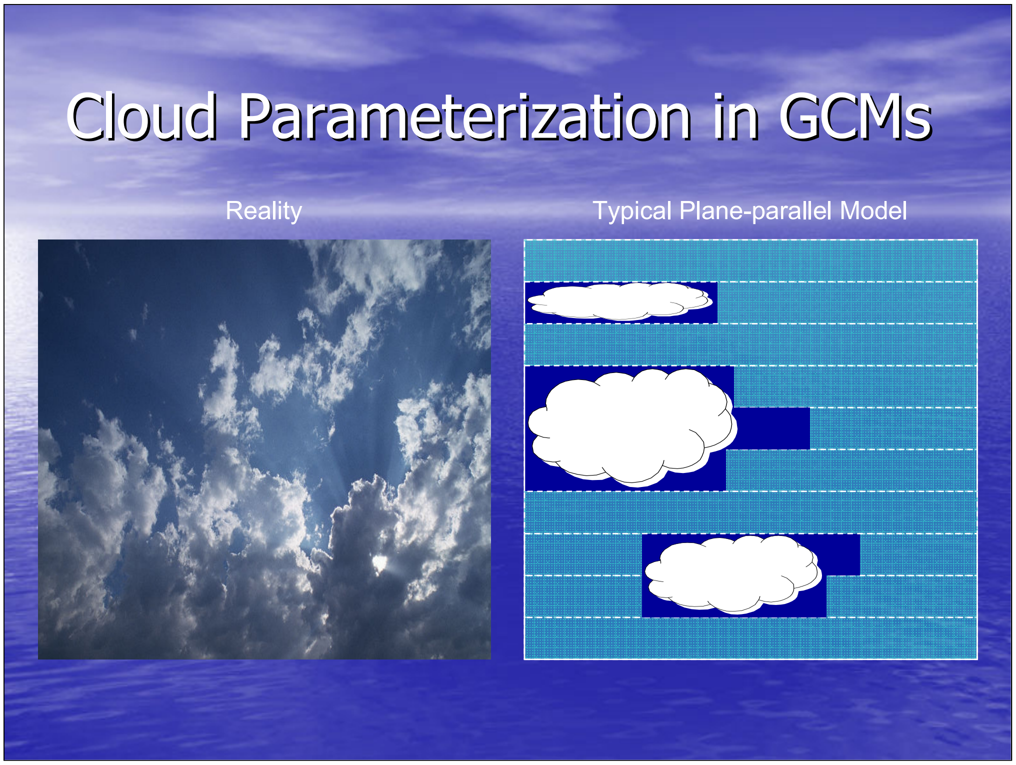
Table 2.3

	Average Conditions	Cloud-Free Conditions	Cloud Radiative Forcing
OLR	235	266	31
Absorbed Solar	239	288	–49
Net Radiation	4	22	–18

Global-annual-average conditions of top-of-atmosphere fluxes for average conditions, for clear-sky conditions, and cloud radiative forcing estimated from ERBE *(Harrison et al. 1992).* Units are Wm^{-2}.

The temperature near the surface of the Earth is in thermodynamic equilibrium when the absorption of radiant energy from the sun is in approximate balance with the emission of radiant energy to space by the planet. The amount of available solar energy absorbed by the Earth depends on its reflectivity, which is strongly dependent on the fractional coverage and optical properties of clouds in the atmosphere. Clouds cover roughly half the earth. They are a major factor in determining the radiation budget of the earth, and they play crucial, if not fully understood roles in modulating climate.

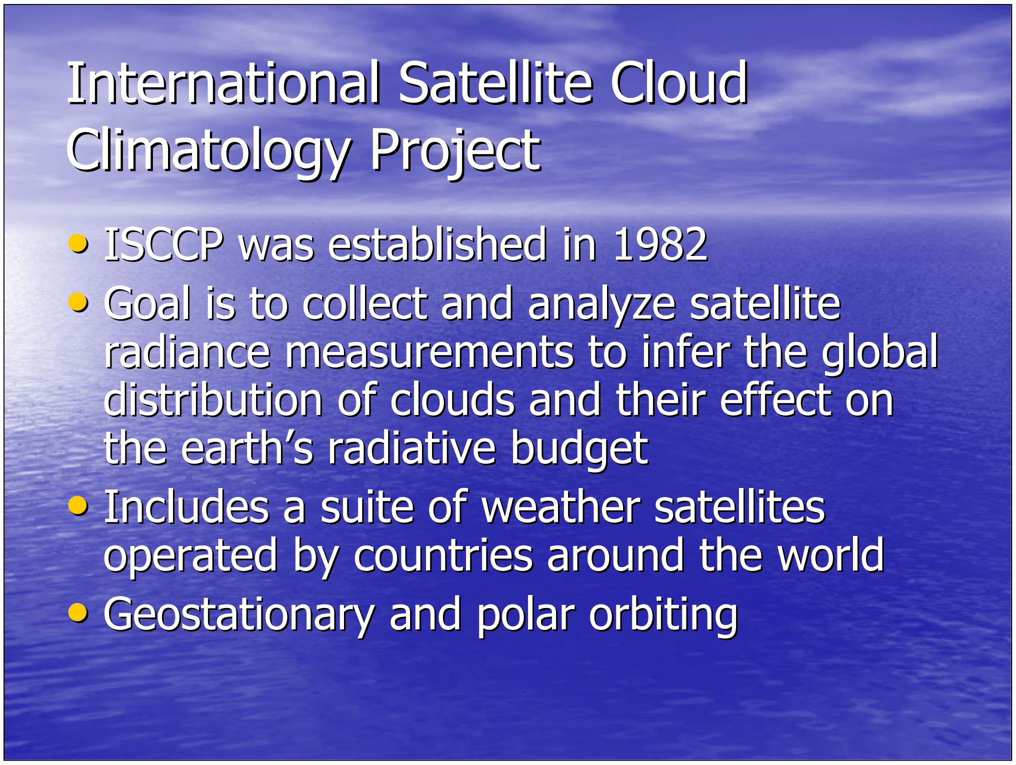
The influence of clouds on the radiation balance of the Earth was estimated by ERBE (ERBE; Ramanathan et al. 1989; Harrison et al. 1990). These estimates revealed that if clouds were suddenly removed, and nothing else changed, the absorbed solar radiation would increase by about 50 Wm-2 and the emitted longwave radiation would increase by about 30 Wm-2, yielding a net positive change in the energy balance of the Earth of about 20 Wm-2.



The uncertainty posed by cloud-radiative feedback to climate has been widely recognized as a key problem in climate prediction.

Estimating the radiative effects of clouds and retrieving cloud properties from space both require a detailed understanding of the scattering and absorption properties of clouds.

Important problems remain in the directional scattering of solar radiation by realistic clouds, overlap of cloud fragments, and perhaps even in the basic absorption properties of cloudy atmospheres.



The ISCCP of the World Climate Research Program (WCRP) (Rossow and Schiffer 1991) has striven to provide estimates of cloud areas, cloud top heights, and cloud visible optical thickness based on an analysis of operational narrowband meteorological imagers.

A nearly-global record of cloud observations by surface observers is available from surface weather observations (Warren et al. 1986, 1988). These data provide a longer record than that available from satellite observations, and also provide a wealth of information about the morphology of cloud systems observed over the Earth. The bottom-up view of surface observers is complementary to the top-down view from satellites. The cloud typing based on human visual observations of clouds provides valuable information on cloud genesis mechanisms and associated atmospheric structure. On the other hand, surface observations of clouds do not provide the quantitative information on radiative effects, drop size and phase, and cloud top structure that are recoverable from satellite-based observations.

Observations of clouds by surface remote sensing and aircraft instrumentation are necessary to investigate mesoscale and microscale aspects of cloud development and interaction with the large-scale environment.

The ISCCP attempts to take advantage of the visible and infrared information available from operational meteorological satellites to construct a climatology and time series of the abundance

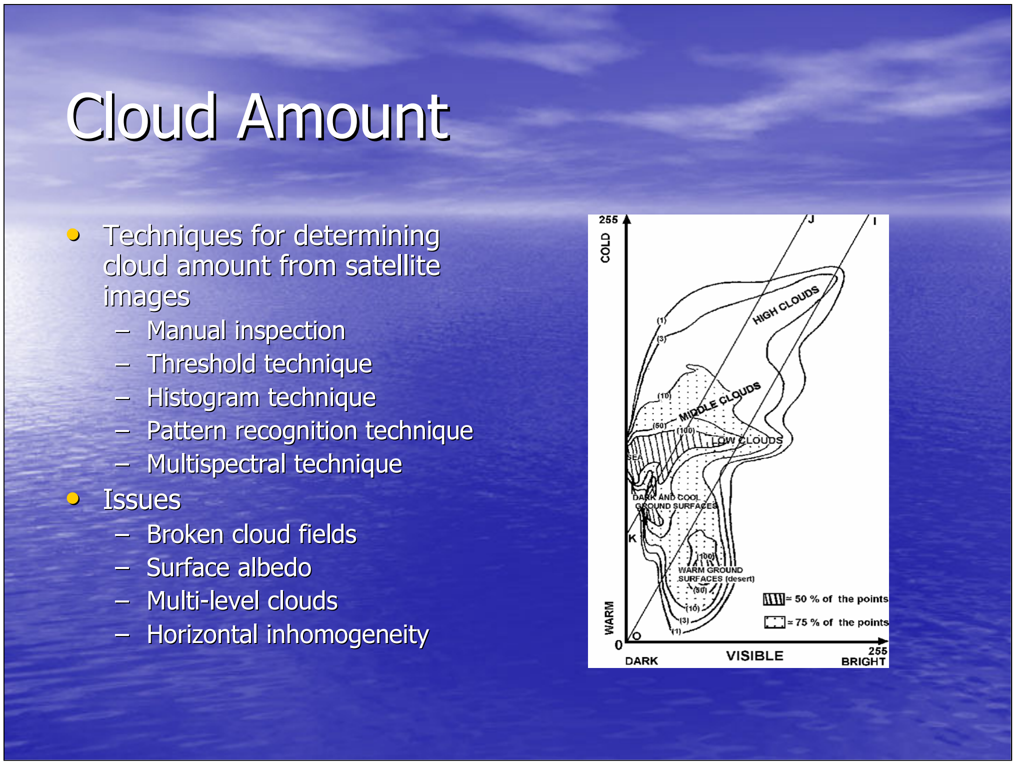
of clouds with optical depth and cloud top pressures paired into 35 categories, in three-hour intervals of time. These data are extremely valuable in characterizing global cloud coverage and type in a variety of other studies.

The goal of the International Satellite Cloud Climatology Program (ISCCP) is to collect global visible and 11 micron satellite data from polar and geostationary satellites and to process them into a cloud climatology. The data collection began in 1983 and is still going. To keep the data manageable, the satellite data is sampled at 30-km and 3-hr resolution.

There are four steps to the ISCCP algorithm. The first is to construct a map of the clear sky radiance. This step rests on the assumption that temporal and spatial variations of the clear sky is small compared to those caused by clouds. The next step is to apply a threshold to detect clouds. The thresholds are not absolute values, but consist of increments above the clear-sky values. There is both a temperature threshold (IR) and a reflectance threshold (visible). Then radiative transfer techniques are used to determine cloud properties such as cloud-top temperature and cloud optical depth. Finally, the data are histogrammed in terms of cloud type, which is determined by cloud top pressure and cloud optical depth.

Cloud properties

- Cloud amount
- Visible optical depth
- Cloud top pressure



Threshold technique - A visible (or infrared) brightness temperature threshold is set so that if a pixel is brighter (or colder) than the threshold, the pixel is assumed to be cloud covered. The fractional area covered with cloud is simply the ratio of the number of cloud pixels to the total number of pixels.

Two problems: (1) clouds are smaller than the satellite scan-spot (pixel with

(2) how do you set the threshold? Of the two, setting the threshold is the chief difficulty.

(2) If the threshold is nearly at *Lcld* (emitted by the cloud), only completely cloudy pixels will be classified as cloud, partly cloudy pixels will be classified as clear and the cloud amount will be underestimated.

A less biased estimate is to set two thresholds – one at nearly *Lclr* (radiance of the scene without cloud) and the other at *Lcld* (radiance of the scene if the cloud were black). Pixels that are in between the two thresholds are counted as 50% cloud cover.

Histogram technique - Histogram techniques are an alternative to threshold techniques. The idea is that a histogram of pixels in an area will show clusters of pixels that represent cloud or surface types. The histograms have as many dimensions as number of channels of data.

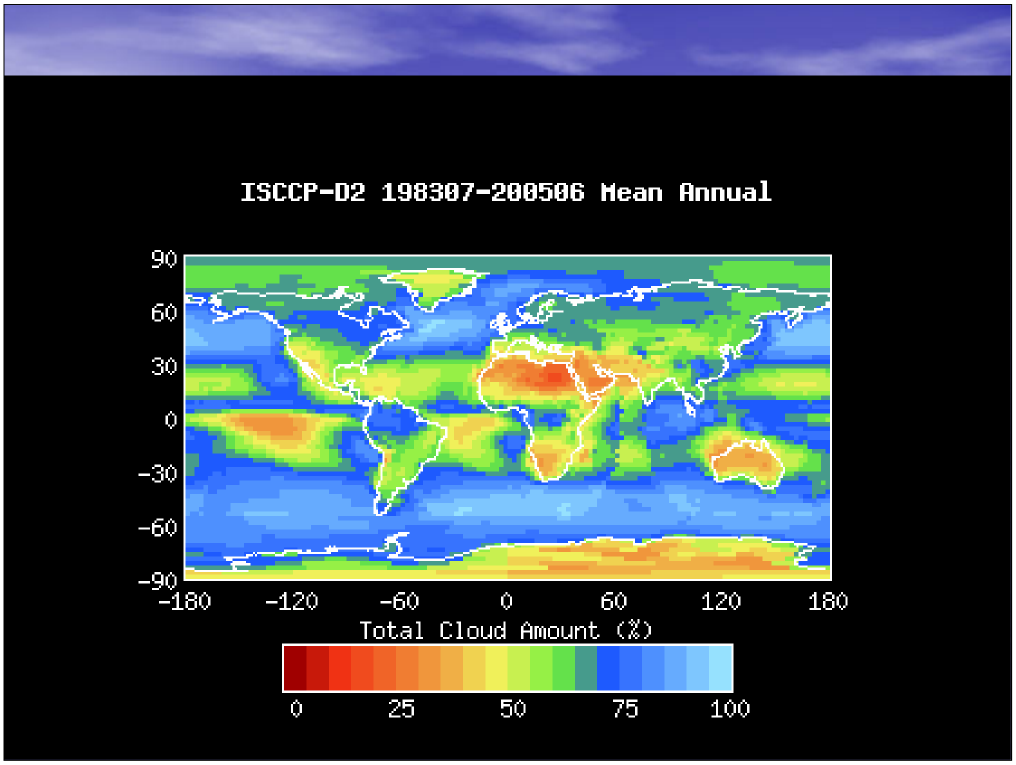
Pattern recognition - tried to classify arrays of pixels in a manner similar to how a person might perform such a classification. A person might look at an area of a satellite image of clouds over the ocean. If the area were uniform and bright, the analyst would say it is cloudy. If it were uniform and dark, the analyst would say it was clear. A simple pattern recognition algorithm might use the mean and standard deviation of the pixels in the area to do this. For example, uniform areas would have low standard deviation, whereas partly cloudy scenes would have high standard deviations. Cloud scenes would have high mean brightness while clear (ocean) ones would have low mean brightness.

Problems:

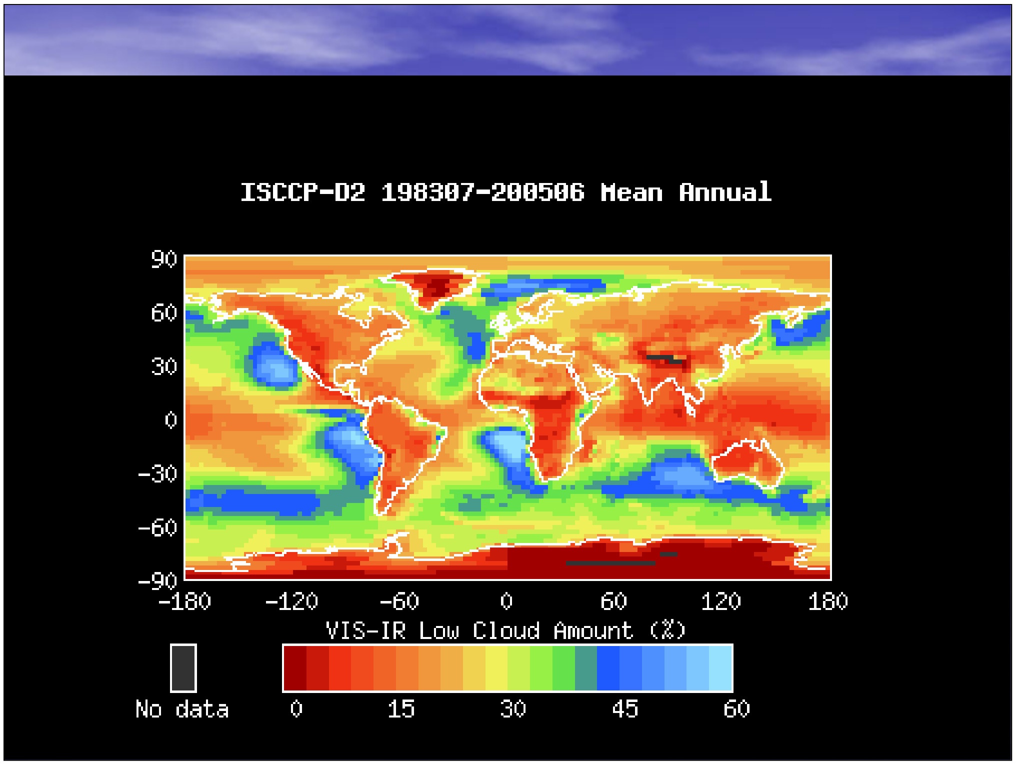
Broken cloud fields – broken clouds interact, for non-nadir viewing satallite sees cloud tops and sides – sometimes broken clouds escape detection

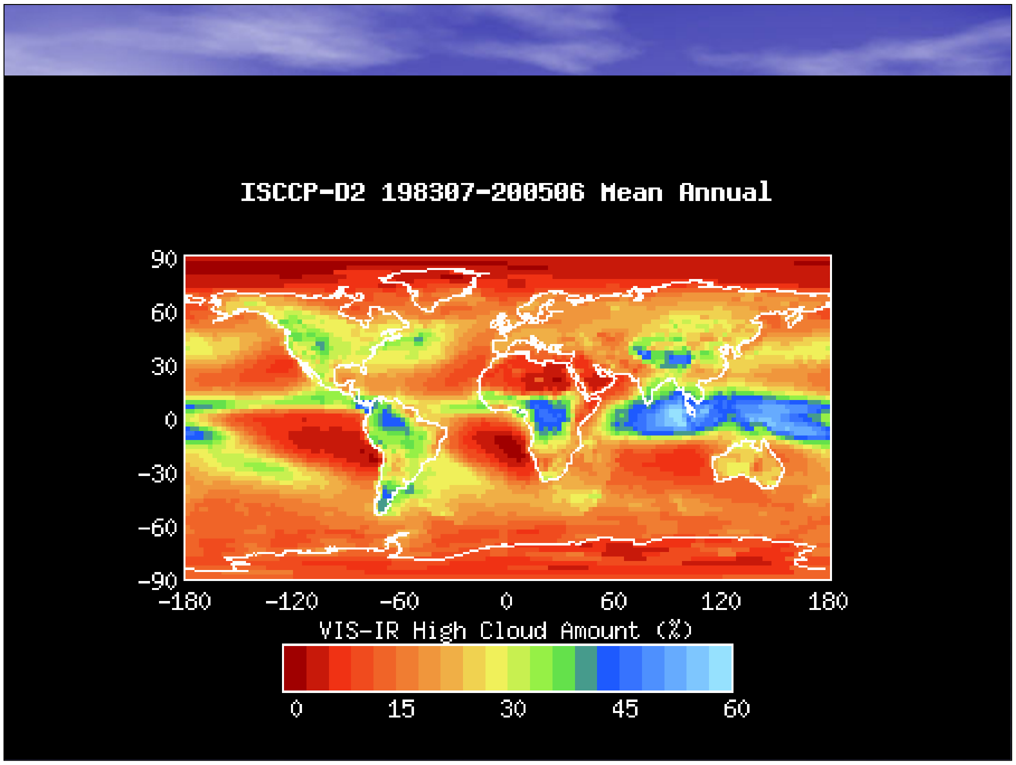
Surface property issue – snow and low cloud can have the same albedo, making the visible threshold useless regardless of its value

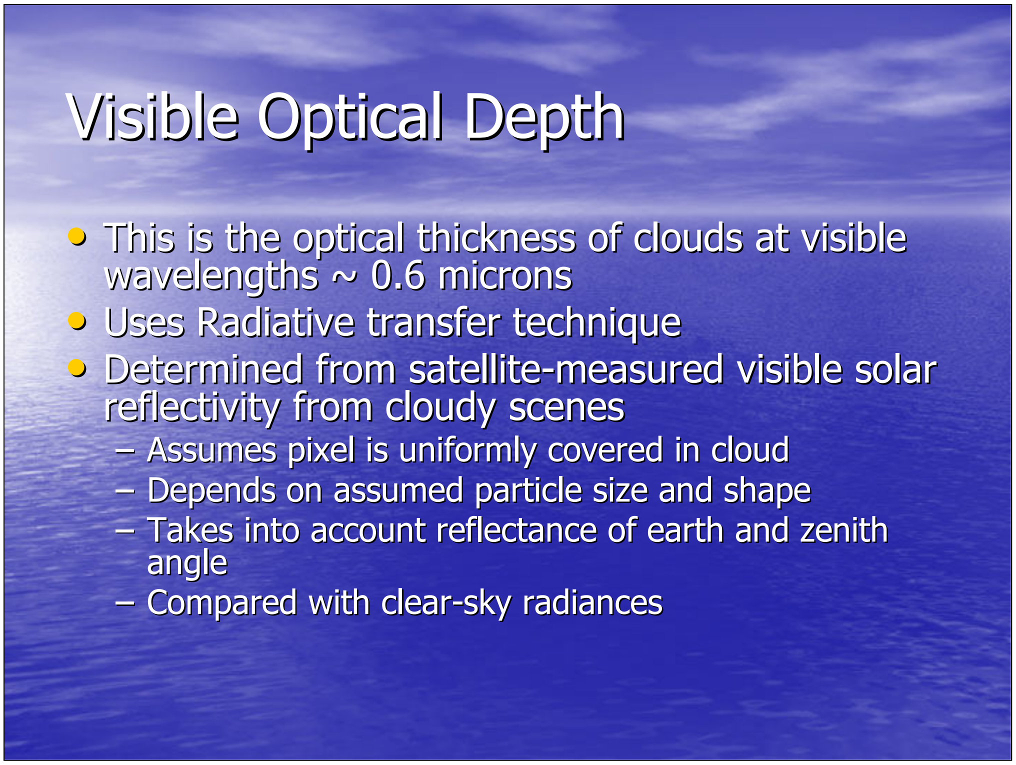
Finally, multiple levels of clouds present problems for all retrieval techniques. Threshold techniques are generally limited to determining cloud amount (and cloud-top pressure) unless combined with other radiative transfer techniques.



Cloud cover fraction This parameter represents the fractional area covered by clouds as observed from above by satellites. It is estimated by counting the number of satellite fields-of-view (called pixels, about 5 km across for ISCCP) that are determined to be cloudy and dividing by the total number of pixels in a region about 280 km across. Cloud amount for lower-level clouds is only that fraction of the area actually observed to be covered by clouds at that level. This way of determining cloud amount assumes that each cloudy pixel is covered completely by clouds.


ISCCP-D2 198307-200506 Mean Annual
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
VIS-IR Low Cloud Amount (%)
No data
0
15
30
45
60


ISCCP-D2 198307-200506 Mean Annual
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
VIS-IR High Cloud Amount (%)
0
15
30
45
60

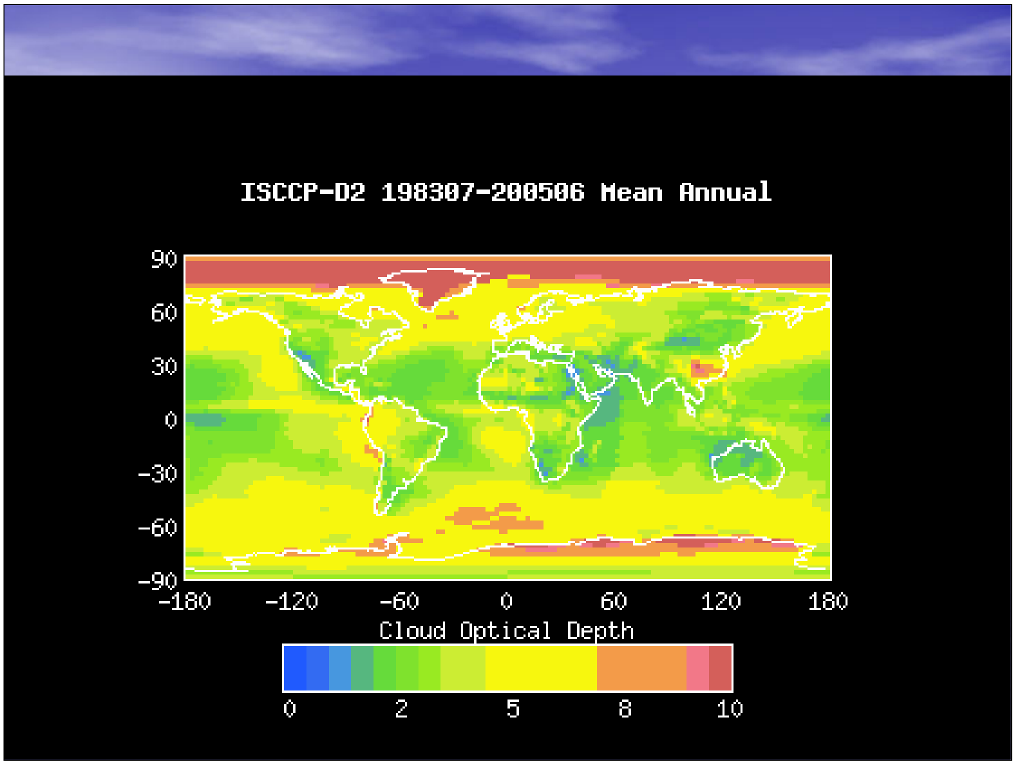


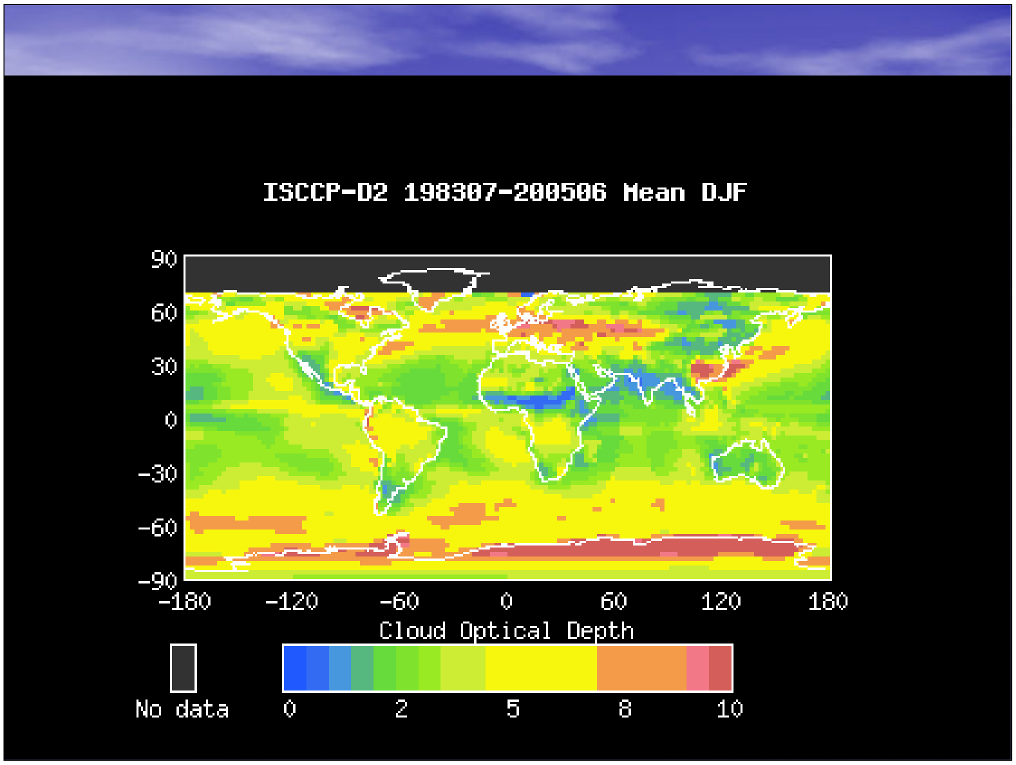
Cloud optical thickness and its mesoscale variability This parameter represents the optical thickness of clouds at visible wavelengths (approximately 0.6 microns). It is determined from the satellite-measured visible solar reflectivity of cloudy scenes, assuming that the pixel is uniformly covered by clouds. The retrieval depends on an assumed particle size and shape. The standard ISCCP products assume that clouds warmer than 260 K are liquid clouds composed of spherical droplets with an effective radius of 10 microns and that colder clouds are ice clouds composed of crystals with a fractal shape (aspect ratio unity) that have an effective radius of 30 microns. If the mesoscale variability is needed to correct for this variability, then we provide a parameter, epsilon, that can be used for this purpose. It also takes into account the reflectance of the Earth.

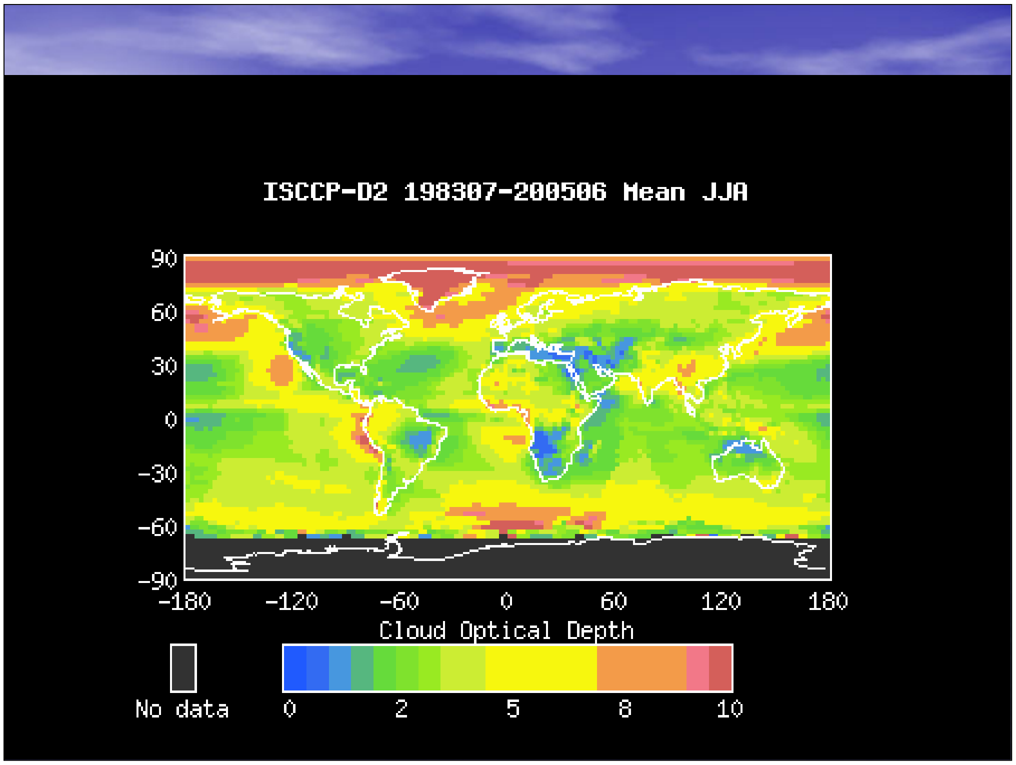
<u>Radiative Transfer Techniques</u>

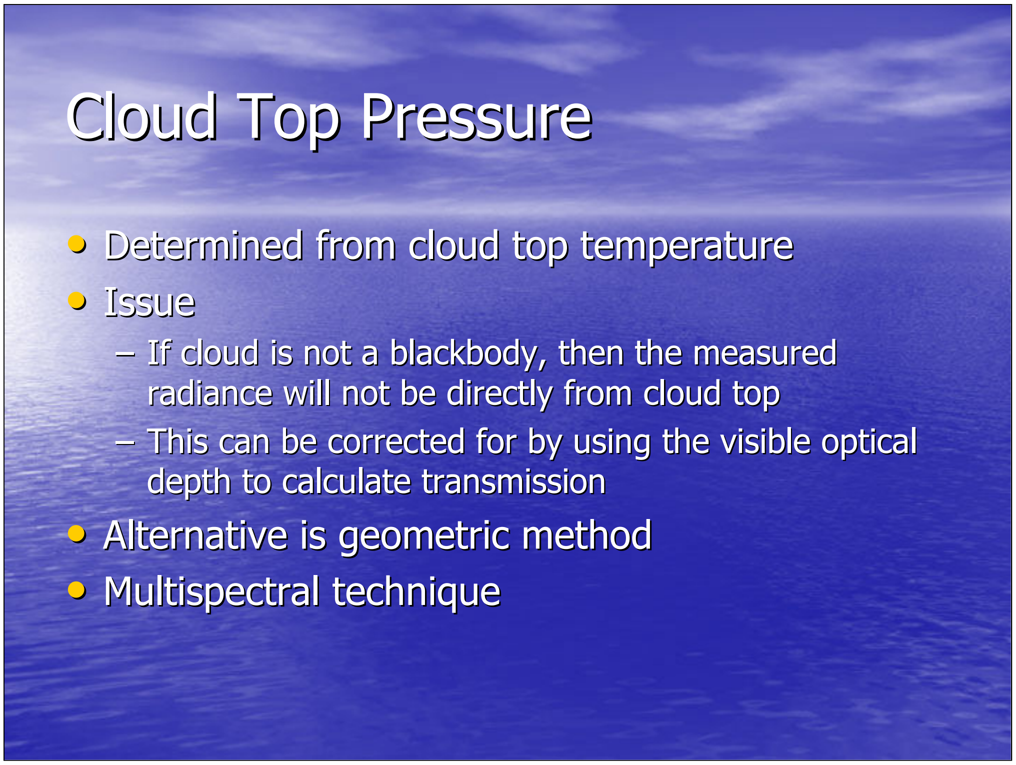
All cloud retrieval techniques can be broken into two steps: (1) cloud detection and (2) parameter retrieval. Radiative transfer techniques come into play after the cloud has been detected. Radiative transfer techniques are used to determine cloud properties. The advantage is that they allow the retrieval of parameters, like cloud optical depth and microphysical properties, that are not retrievable with other methods.

This technique has been used with AVHRR data to retrieve visible optical depth, cloud-top temperature, cloud amount, and an indication of cloud phase and cloud drop size. The idea is that certain wavelengths are sensitive to certain cloud properties. For example, that visible radiance are affected primarily by the cloud optical depth. Then several versions of cloud models with run with variations in the cloud microphysical properties. RT calculations were then performed to determine the reflectance, transmittance and absorptance of plane-parallel cloud layers as functions of optical depth, zenith angle and azimuth angle and several wavelengths. Comparison between the observed clear radiances, measured visible reflectance with the models yields information about the cloud optical depth, cloud-top temperature and cloud amount.


ISCCP-D2 198307-200506 Mean Annual
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
Cloud Optical Depth
0
2
5
8
10

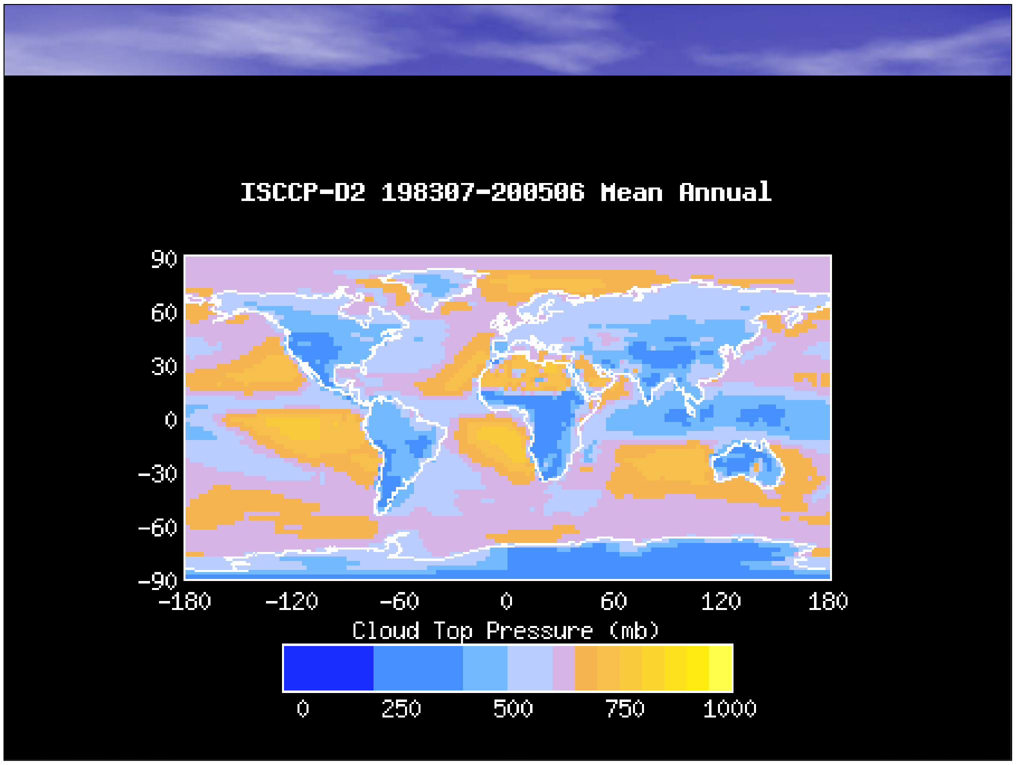

ISCCP-D2 198307-200506 Mean DJF
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
Cloud Optical Depth
No data
0
2
5
8
10

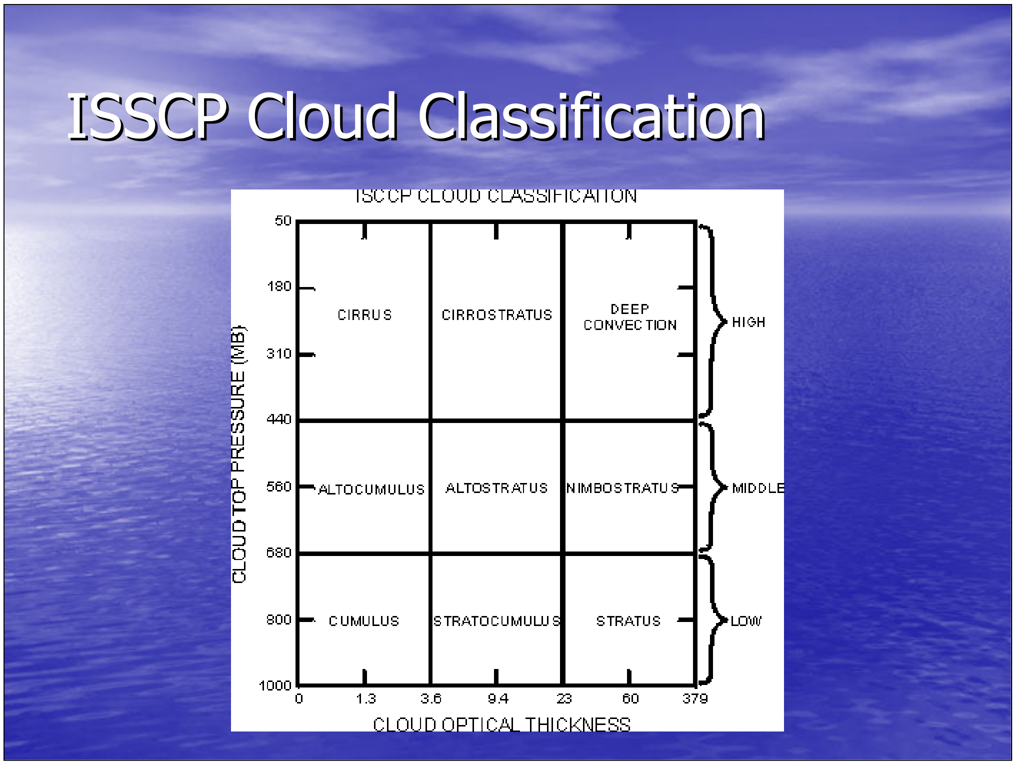

ISCCP-D2 198307-200506 Mean JJA
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
Cloud Optical Depth
No data
0
2
5
8
10



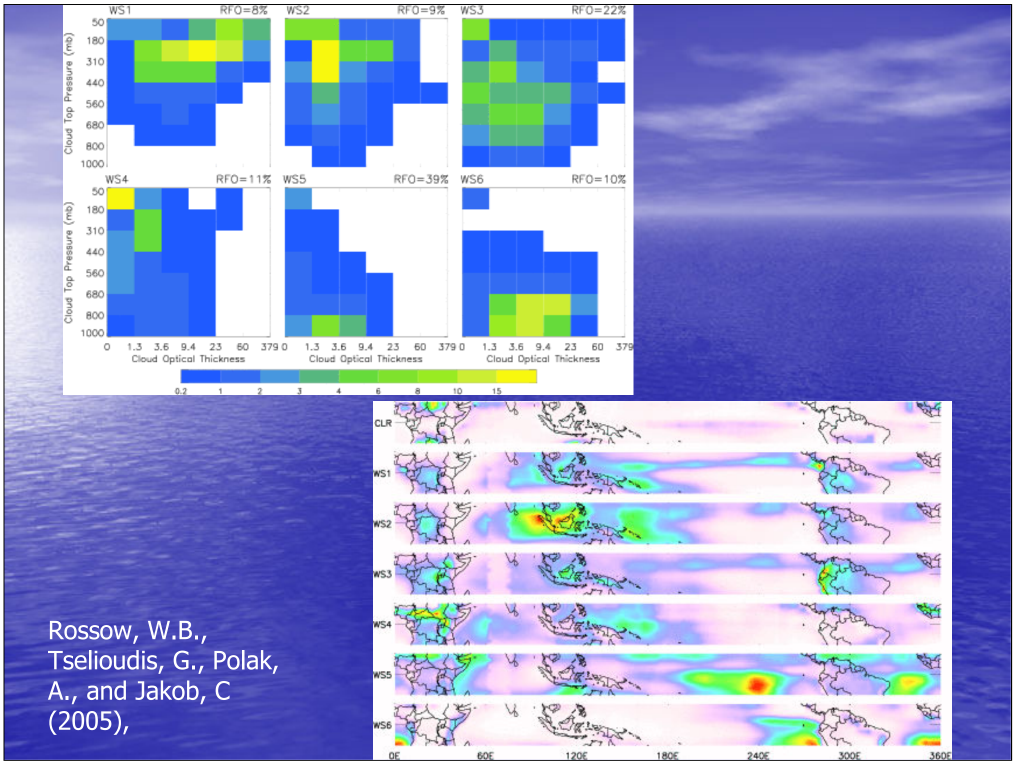
Cloud top pressure This parameter represents the location of the "radiating" top of the clouds; if there is a very tenuous upper portion, this value may be below where the first cloud particles are found. Cloud top pressure is determined from cloud top temperature, which the satellite measures more directly, using a profile of atmospheric temperature with pressure. It can be considered as equivalent to cloud top height above mean sea level. Cloud top pressure calculated by ISCCP really uses the IR channels, but the visible optical depth may be used to calculate transmission and account for errors due to emission from clouds that are not black bodies.

A very different approach to cloud height retrieval involves making geometric measurements with satellite images. One technique uses low sun angles to analyze observations of cloud shadows on the earth’s surface. A more useful technique is stereoscopy, which involves simultaneous viewing of the same cloud by different satellites (or different imagers on the same satellite at different steps of the pass). A great advantage to stereo viewing is that it only depends on geometry, and does not require accurate knowledge of the temperature profile or the cloud-top temperature.


ISCCP-D2 198307-200506 Mean Annual
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
Cloud Top Pressure (mb)
0
250
500
750
1000



Cloud Types A value of cloud top pressure and optical thickness is obtained for each cloudy pixel during the daytime. This information can be used to classify different cloud types as shown in the figure. The cloud type names here represent only an approximate climatological relationship between the satellite-measured optical parameters and the classical morphological cloud types. However, a detailed comparison of the satellite and surface-based cloud observations supports this assignment of names.



Example of how ISCCP data can be used:

We can determine where and with what frequency different cloud regimes exist

Multispectral technique

A $$L_{cld} = \frac{L_{IR} - (1 - N\varepsilon)L_{clr}}{N\varepsilon}$$

B $$L_{vis} = N\gamma_{cld}E_{sun} + (1-N)\gamma_{clr}E_{sun}$$

C $$L_{IR} = (1-N)L_{clr} + N\varepsilon L_{cld} + N(1-\varepsilon)L_{clr}$$

D $$N = \frac{L_{vis} - \gamma_{clr}E_{sun}}{(\gamma_{cld} - \gamma_{clr})E_{sun}}$$

(Not covered in class)

Multispectral techniques are cloud retrieval techniques that rely on radiance measurements in two or more wavelengths and use simple models to make retrievals. There is a bispectral technique by Reynolds and Vonder Haar that uses visible and infrared channels to retrieve cloud amount and cloud-top temperature. It assumes that each pixel has one cloudy layer. The solar radiation is modeled as solar radiation reflected from cloud tops and from the surface. This is similar to what was described with the sounding retrievals. (See equation A) Where *N* is the cloud amount, *gcld* and *gclr* are the bi-directional reflectances of the clouds and the surface and *Esun* is the solar irradiance. The last three are assumed to be known. *Esun* is assumed to be the same at the surface and at cloud top.

The radiance in the infrared channel is modeled similarly as being emitted by the surface (through holes in the cloud), emitted by the cloud and transmitted through the cloud after being emitted by the surface. (See equation B) Where *e* is the cloud emittance and *Lcld* is the radiance the cloud would have if it were black, and *Lclr* is the radiance of the clear area. *Lclr* and *e* are assumed known. These two equations can be combined to be solved for *N* and *Lcld*. (See equations C and D).

After *Lcld* has been retrieve then the cloud-top temperature can be calculated using the Planck function. Remember that if *e* < 1, then the temperature will represent the temperature of the interior of the cloud rather than the cloud-top temperature. Cloud-top height may be retrieved by comparing the cloud-top temperature with a sounding to determine at what height that temperature occurred.