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Satellite estimates of cloud-top pressures and cloud amounts for high cloud in the tropics

SIGMUND FRITZ

Mentor Technologies, Inc. 12750 Twinbrook Pkwy., Suite 101, Rockville, MD 20852, USA*

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RESUMEN

Se desarrolla un método para estimar la presión en la cima de las nubes y la cantidad de las mismas cuando la nubosidad ocurre entre los niveles de 100 mb y 200 mb en los trópicos. El método depende de que la radiación en el canal 3 (691 cm^{-1}) de la sonda de alta resolución de radiación infrarroja (High Resolution Infrared Radiation Sonder HIRS 2) es afectada por las nubes en dichos niveles pero no mucho por nubes abajo del nivel de 200 mb.

Las radiancias del canal 3 se utilizan en combinación con las del canal 4 (704 cm^{-1}) para construir un diagrama a partir del cual se pueden estimar la presión en la cima y la cantidad de nubes.

Las observaciones por medio de satélites de las radiancias (temperatura de brillo equivalentes) en los dos canales se usan en los diagramas para obtener los parámetros de las nubes.

Resultados a partir de datos del TIROS N del 11 de junio de 1979 cerca de 1°S, 106°E se comparan con cálculos publicados para dicha fecha.

Los resultados aquí, muestran que los nublados de cielo cubierto alcanzaron el nivel de 100 mb. Los datos publicados muestran nubes con cerca de 50% de cubierta nubosa que no alcanzan el nivel de 200 mb.

ABSTRACT

A method is developed for estimating the cloud top pressure and the cloud amount when clouds occur between the 100 mb and 200 mb level in the tropics. The method depends on the fact that the radiance in the High Resolution Infrared Radiation Sounder channel 3 (691 cm^{-1}) is affected by clouds at those levels but is not affected much by clouds below the 200 mb level. Channel 3 radiances are used together with radiances from channel 4 (704 cm^{-1}) to construct a diagram from which the cloud top pressure and cloud amount can be estimated.

Satellite observations of radiances (equivalent brightness temperatures) in those two channels are entered into the diagram to yield the cloud parameters.

The result from TIROS N data for June 11, 1979 near 1°S, 106 E, are compared to published computations for that date.

The results here show that overcast clouds reached the 100 mb level. The published data show clouds with about 50% cloud cover which do not reach the 200 mb level.

1. Introduction

The importance of cloud parameters for climate and forecasting research and for other uses has led to the International Satellite Cloud Climatology Project (ISCCP) (Schiffer and Rossow, 1983). In addition, cloud height and cloud amount are of obvious interest for both military and civilian aviation.

* This work was done mainly at the University of Maryland, College Park, MD

The influence of high convective clouds in the tropics has taken on additional significance recently. Many meteorologists claim that the increasing atmospheric CO_2 would lead to increasing air temperature in the troposphere through the greenhouse effect (Schneider, 1990). However Lindzen (1990) maintains that high convective clouds in the tropics with attendant sinking air outside the cloud could lead to a negative feedback of CO_2 increases on air temperature; this could reduce the temperature increases calculated in models of the greenhouse effect.

In addition, high convective cloud in the tropics are a source of water vapor in the lower stratosphere (see e.g., World Meteorological Organization, 1985). This water vapor is then transported dynamically to high latitudes where it enters in ozone chemistry equations. Thus Solomon (1990) found that water vapor and ice play roles in the chemistry of the Antarctic "ozone hole".

Because of the importance of clouds, many methods have been employed for estimating cloud parameters from satellite radiance observations. These methods have been reviewed by Isaacs *et al.* (1986), who list a great many references. Some of these methods involve the use of actual or simulated radiance measurements from satellite sounding instruments, such as HIRS (Susskind *et al.*, 1987, Eyre and Menzel, 1989; Wielicki and Coakley, 1981).

Many of these studies attempt to determine properties of all types of clouds. For example, Susskind *et al.* (1987) estimate the cloud amount and cloud-top height for the whole world with a coarse resolution of about 125 km, by averaging many instantaneous fields of view (each about 17 km wide at nadir). They use TIROS-N, HIRS 2 observations, channels 4 through 7 in the 15μm CO_2 band, plus the 11μm water vapor window.

Eyre and Menzel (1989) use simulated "data". Moreover, they consider only middle latitude conditions and limit their cloud height retrieval to levels below 200 mb. They also use HIRS type channels 4 to 12; but the principle pair they favor are channels 7 and 8 (13.4μm and 11.1μm). Wielicki and Coakley (1981) also used simulated "measurements", and report middle latitude error analyses. ***None of these authors used channel 3.***

By contrast to those types of all-inclusive goals, in this paper we shall estimate only cloud top heights and cloud amount for cirrus topped convective clouds in the tropics. In the tropics the tropopause typically reaches 100 mbs and we assume that clouds do not extend above the tropopause. Therefore the clouds which we investigate have tops between 100 and 200 mbs, a type of clouds which many investigators exclude from their studies. Moreover, *they do not use channel 3*, which is uniquely applicable for clouds with tops between 100-200 mb levels. As far as we know this is the first paper to use channel 3 to determine cloud properties.

Figure 1 shows the "weighting functions" for channels 2, 3 and 4; these correspond to wavenumbers 679, 691 and 704 cm^{-1} respectively. Channel 4 and the even more transparent channels on HIRS will be influenced by most clouds in the troposphere. By contrast channels 2 and 3 will be affected mainly by high clouds, and especially by cloud tops which lie between 100 and 200 mbs; i.e., just below the tropical tropopause. Thus all clouds will be observed by all transparent channels; but unless the clouds modify the radiances in channel 2 and 3 they probably do not lie above 200 mbs, although channel 3 does have some small "weight" below 200 mbs.

In this initial study we have selected the observations for June 11, 1979 near 1°S, 106°E. This contains a situation observed by Susskind *et al.* (1987) in a region of extensive cloudiness, with relatively high clouds in their *average* data. We shall examine individual field-of-view (FOV) observations (about 20 km resolution) to see the variation of clouds within the 125×125 km^2 area which they observed. The purpose is to see whether the use of channel 3 will improve the estimate of cloud top pressure and cloud amount in that region.

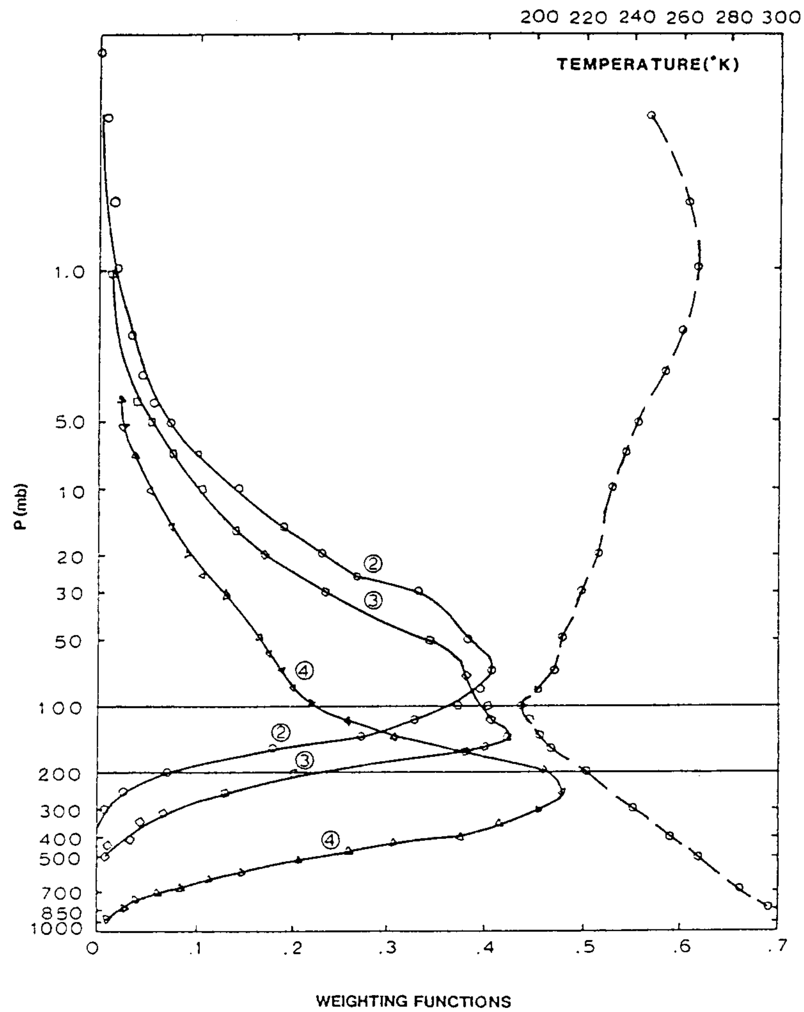

Fig. 1. (Left) Weighting functions for HIRS channels 2, 3 and 4; (right) observed tropical temperatures (°K) vs. pressure (mb). (Temperature scale along top.)

2. Data

a. Brightness equivalent temperature (radiance)

The HIRS 2 data were received from NCAR. Some of the data for channel 4 (ν = 704 cm^{-1}) are shown in Figure 2. Each vertical column represents observations during a single scan, approximately from SW to NE. The area shown is bounded by (6.35, 100.6E) to (0.8°S, 99.4E) along the top, and (3.3S, 119E) to (2.5°N, 118.4E) along the bottom. The zenith angles, (θ), of each viewed spot are evaluated along each horizontal line of data. Near 1°S, 106°E an area of cold equivalent temperature (T_ϵ) appears. The coldest T_ϵ is about 206K. For $\theta = 0$, high values of T_ϵ exceed 230K. For $\theta \approx 52$, high values of $T_\epsilon \approx 227$ K.

Figure 3 contains data for channel 3 (691 cm^{-1}). Low values of $T_\epsilon \approx 212$K appear in the area of the cold cloud found in channel 4.

Since the cold clouds affect channel 3, those clouds lie above the 200 mb level; and we assume that the coldest clouds reach the tropopause; i.e., the 100 mb level.

CHANNEL 4, RADIANCE $[T_\epsilon(^\circ K)]$

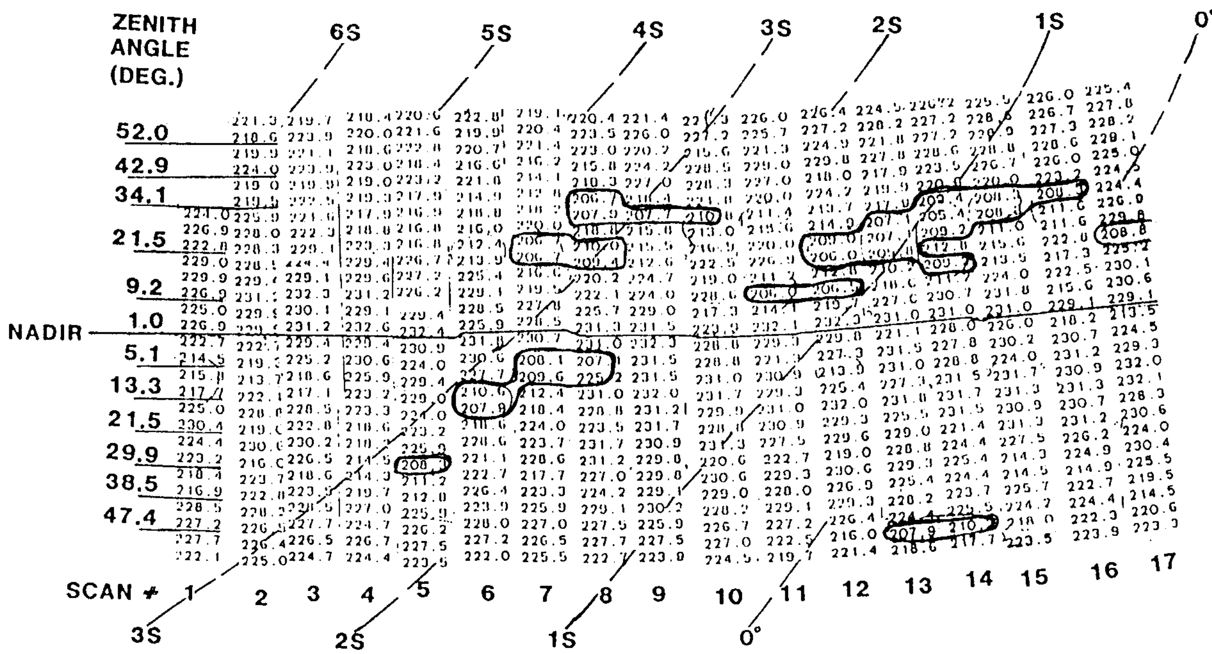

Fig. 2. Observed radiances (equivalent temperature) for HIRS channel 4, for June 11, 1979. Isolines for $T_{\epsilon 4} = 210$K have been drawn. Instrument scan lines have been numbered, from 1 to 17. The zenith angles corresponding to the data points are indicated on the left. Some latitude lines are indicated. See text for longitude coordinates.

CHANNEL 3, RADIANCE $[T_\epsilon(^\circ K)]$

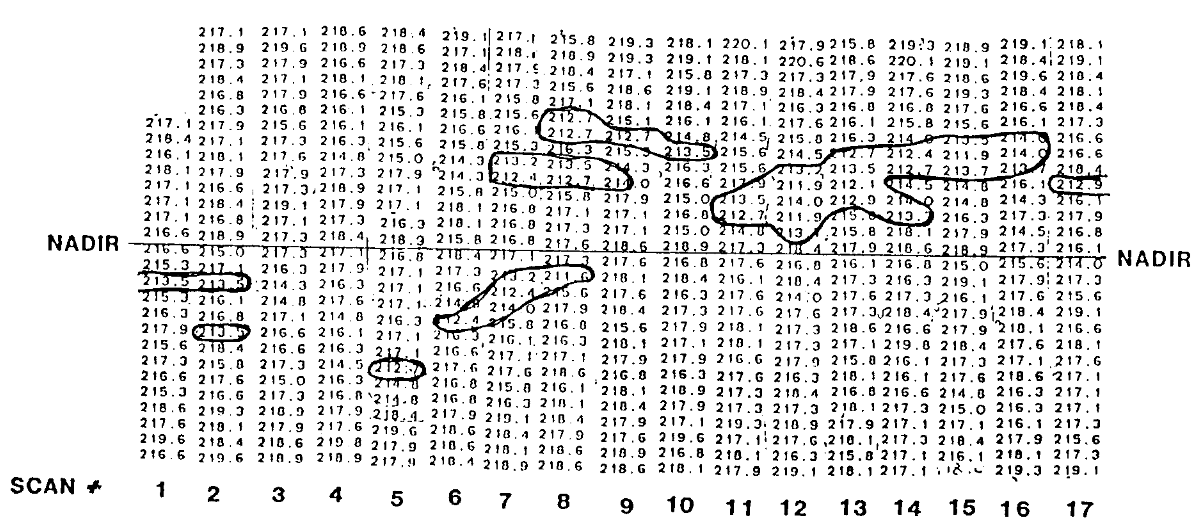

Fig. 3. Observed radiances (equivalent temperatures) for HIRS channel 3. Isolines for $T_\epsilon = 214$K have been drawn. Other details as in Figure 2.

High values of T_ϵ are about 218 K and are more or less independent of zenith angle.

Finally, Figure 4 shows the data for channel 2. These data seem more noisy; although there is a dip in the T_ϵ value near the cold cloud indicated in channel 4, the noise in this channel may obscure any real influence of the cloud on the observed radiance. In this channel there is nevertheless, a definite increase in T_ϵ from about 218K for $\theta = 0^\circ$ to about 222K for $\theta = 50^\circ$, as would be expected, since the temperature increases with height in the stratosphere. Figure 1 shows that channel 2 peaks above 100 mbs.

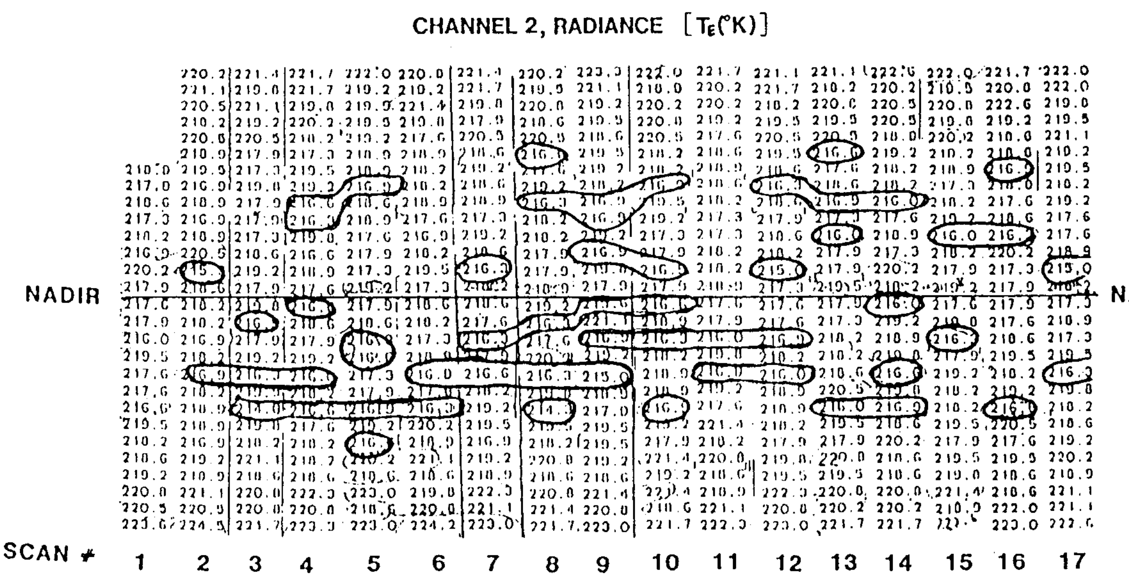

Fig. 4. Observed radiances (equivalent temperatures) for HIRS channel 2. Isolines for T_ϵ = 217 K have been drawn. Other details as in Figure 2.

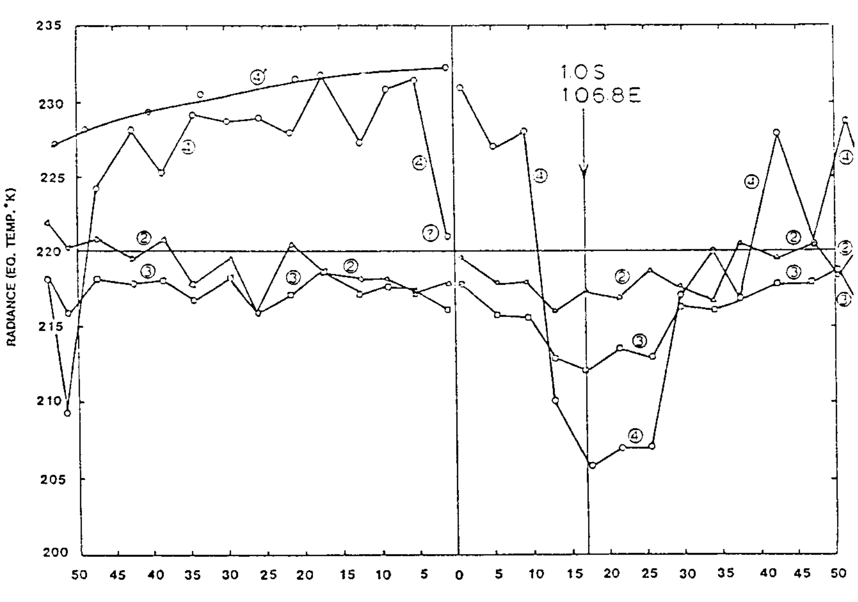

Fig. 5. Observed radiance (equivalent temperature) vs zenith angle for channels 2, 3 and 4, from scan number 13 (see Fig. 2 and 3). Curve 4′ shows the calculated values for channel 4 for cloudless conditions. The data at 1.0S and 106.8E are indicated by the arrow line.

To illustrate the variation of the radiances (T_ϵ) with zenith angle, we have selected the data for the scan labelled 13 in Figs. 2-4. The data in this scan are shown in Figure 5. Here we see minima in the three channels near $\theta = 20^\circ$at a location near 1.0S, 106.8E. Obviously, channel 3 radiance has been reduced by a cloud there, so that the cloud top is at high levels, and probably above 200 mb. We assume that the value $T_\epsilon = 206$, 212.1, 216.6 in channel 4, 3 and 2, respectively, represent radiances for an opaque cloud whose top is located at the 100 mb height; i.e., at the tropopause (Fig. 1).

b. Air temperature

We have selected the radiosonde temperature profile, located at 3°N, 110°E; these were the nearest archived observed values to the cloud area being studied here. The temperature profile is shown in Figure 1.

c. Transmittances

For overcast conditions the radiance (I), observed at the satellite can be estimated from

$$I = \epsilon_c B(\nu,\ T_c)\tau_c(\nu,\ p) + \int_{\tau_c}^{1} B(\nu,\ T)d\tau \tag{1}$$

$$d\tau = \left(\frac{d\tau}{dlnp}\right)dlnp;$$

$\left(\frac{d\tau}{dlnp}\right)$ is the "weighting function" shown in Figure 1 for zero zenith angle.

Here ϵ is the cloud emissivity, τ is the transmittance from any air level to the satellite, the subscript "c" refers to the cloud, B is the Planck function at frequency, ν, and temperature, T; the pressure is "p".

Since the satellite does not "see" the Earth's surface at the opaque wave-lengths (Fig. 1.), for cloudless, clear conditions

$$I_{clr}(\nu) = \int_{0}^{1} B(\nu,\ T)d\tau. \tag{2}$$

Calculations of I are needed in order to estimate cloud parameters from measured radiances.

Obviously "τ" must be known if calculations are to be made. Many investigators used the τ's given in Weinreb *et al.* (1981). Unfortunately when these τ's are applied for overcast and clear conditions as in Eq. 1 and 2, we do not get a match with the observed radiances in channels 2-4. In fact Weinreb (1979) had already noted that it was necessary to use τ^α to make calculation agree with observation. The constant, α, varied from about 0.98 to 1.1 for our channels, but for channel 3 ($\sim$ 691 cm^{-1}) he could not find any "α" which made the calculations agree with the mean of a set of cloudless radiosondes.

We also could not find an "α" to reach agreement between observed and calculated values for channel 3. For channel 2 we used $\alpha = 0.85$, for channel 4 we used 1.1, and in addition small additional corrections were required. But for channel 3 (691 cm $^{-1}$) we could not find a suitable "α". Adjustments to the "τ"s for that channel were made manually until agreement was achieved. The weighting functions, based on τ, and the temperatures used are shown in Figure 1. The agreement between calculated and observed radiances (equivalent temperatures) are shown in Table 1.

Throughout, the values of τ have been corrected for increased path length by raising τ to the power 0.5 (sec $\theta + 1$) (Fleming, 1982).

Table 1. Observed and calculated equivalent temperatures (°K). (Zenith angle = 21°)

Channel No.	Cloudless		Overcast	
	observed	calculated	observed	calculated
4	~ 231	231.5	~ 206	205.0
3	~ 218	217.9	~ 212	212.1
2	~ 218	218.5	~ 217	216.6

3. Calculation of cloud top pressure and cloud amount

When the sky is not overcast, for opaque clouds the observed radiance is given by

$$I = N[B(\nu,\ T_c)\tau_c + \int_{\tau_c}^{1} B(\nu,\ T)d\tau] + (1 - N)\int_{0}^{1} B(\nu,\ T)d\tau \qquad (3)$$

"N" is the cloud fraction.

In Eq. 3 it is assumed that the clouds are opaque. For semi-transparent clouds ϵN would replace N, the cloud fraction. However for the highly absorbing CO_2 channels, extensive convective clouds are probably nearly opaque. Wiscombe *et al.* (1984) mention a program for calculating radiances, fluxes and emissivities of clouds at frequencies in the 15μm CO_2 band.

Wiscombe's program was run to calculate the emissivity of clouds lying between 100 mb and 500 mbs, approximately 10 km thick. According to those calculations, such clouds have emissivities greater than 0.9. Therefore, those clouds are nearly "black". Fritz and Rao (1967) also showed that, in the water vapor absorption band near 6.7 μm, cirrus (~ 5 km thick) are more opaque than they are in the water vapor window. Platt *et al.* (1987) find that tropical cirrus, with thickness of 3.2 km or less, had a beam emittance of 0.115 and flux emittance of 0.3; they mention that anvil cirrus had an emissivity of 0.6. Their observation were in 10-12 μm water vapor window.

The clouds considered in this report are doubtless more opaque than those observed by Platt *et al.* (1987). First, the clouds are observed in highly absorbing CO_2 wavelengths. The scatter inside the cloud increases the path length through the absorbing CO_2 and makes the cloud more opaque. Secondly, our clouds are doubtless thicker than 3 km, and probably consist of convective, multi-layered clouds; this too would make them more opaque.

We have calculated the radiances reaching the satellite in each of the 3 channels, for varying cloud fractions and varying cloud top pressures. For zenith angle = 21°, the results are plotted in Figure 6*. In Figure 6, the two long outside lines apply for N = 10, and p_c = 100 mb

* Changes of several degrees in air temperature near the tropopause (Fig. 1) produce only a few tenths of degrees change in calculated radiance equivalent temperature.

respectively. The topmost line, nearly horizontal, represents $p_c = 200$ mb. Other lines represent $N = 5$ to 9 tenths, and $p_c = 115$, 135 and 150 mb.

Let $T_{\epsilon 3}$ represent the equivalent brightness temperature for channel 3, and let $T_{\epsilon 4}$ represent the same quantity for channel 4.

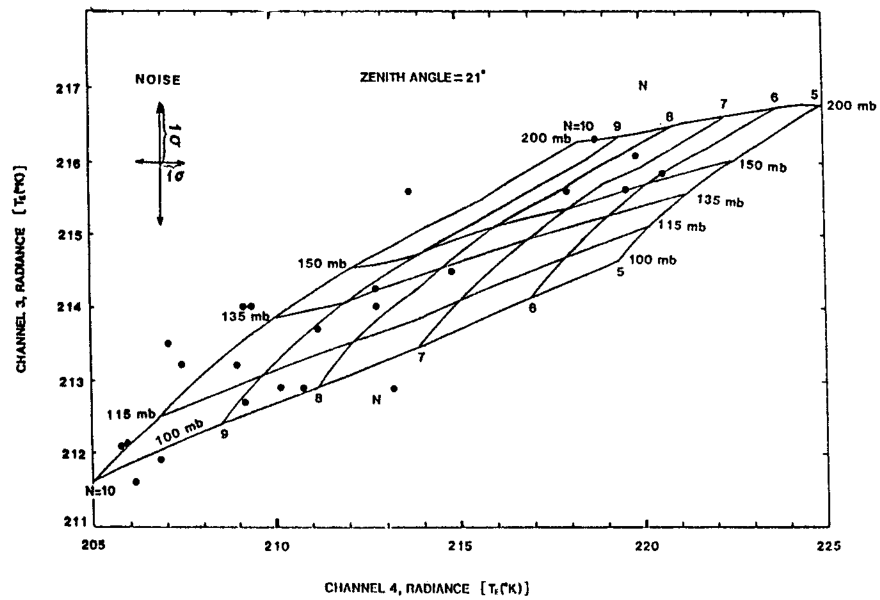

Fig. 6. Calculated diagram giving cloud top pressure (mb) and cloud amount, N, in tenths, for zenith angle = 21°, when observed values of $T_{\epsilon 3}$ and $T_{\epsilon 4}$ are entered on the diagram. Some observed radiance values, black dots, have been entered on the diagram. Noise vectors based on on-board calibration.

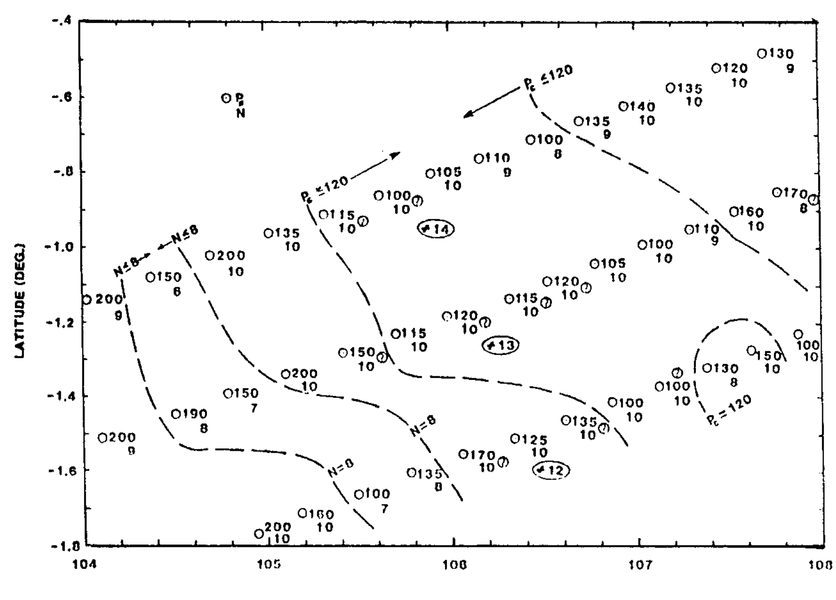

Fig. 7. Values of cloud top pressure (p_c) in mbs, and cloud amount (N), in tenths, from some observed values of radiance for scan numbers 12, 13 and 14, at latitudes and longitudes shown on the axes. The points with question marks (?) are points which required application of "noise" vectors to bring the points inside the limits of Figure 6.

If we enter the diagram, in Figure 6, with observed values of $T_{\epsilon 3}$ and $T_{\epsilon 4}$ we can note the corresponding values of p_c and N. We have entered a number of observed pairs of T_ϵ on Figure 6; these points belong to scans numbered 12, 13 and 14 in Figures 2 and 3, when the zenith angle was smaller than 21°. The diagram in Figure 6 varies very little for those zenith angles. For the most part the points fall within the limits of the diagram. But sometimes, the points fall outside; this occurred mainly at a few points when $T_{\epsilon 4}$ was cold, $T_{\epsilon 4} < 210$ K, but $T_{\epsilon 3}$ was too warm. If we apply the noise vectors shown in the diagram, these points will fall near the line for $N = 10$. The noise vectors are based on satellite on-board calibrations*. Some cloud p_c and N in the vicinity of 1°S, 106E obtained by entering the observed $T_{\epsilon 3}$ and $T_{\epsilon 4}$ into Figure 6 are plotted on Figure 7.

We note $p_c \leq 115$ mb with $N = 9$ or 10, mainly along a swath from 0.8°S, 106E, to 1.4S, 107E. Outside this swath the clouds were still high with $p_c \leq 200$ mb and mainly $N \geq 8$; near 1.3S, 104.6E, the high clouds may have been more broken with $N = 6$ or 7. In the presence of multiple cloud layers, this should only be interpreted to mean that the most opaque clouds were probably not overcast at 100 mbs in this region.

4. Comparison with other computations

The data were chosen for June 11, 1979, because Susskind *et al.* (1987) had published results for that date. If we look at their Plate 2, we find that in the vicinity of 1°S, 106E, the clouds do not reach above the 200 mb level, and probably not even above the 300 mb level. However, it should be noted that their findings are averaged over 125 × 125 km; therefore clouds reaching to the 100 mb level over smaller areas might not be discernable.

They did find that region to be covered with at least 55% cloudiness.

It would be interesting to compare the method of Susskind *et al.*, for high spatial resolution computations, with ours. It would also be valuable to compare the results of all investigations with independent measurements, such as airplane observations. But that would doubtless require a special observational program.

Comparison of our methods with Lidar measurements on the Earth Observing System (EOS, 1990) to be launched in the mid 1990's would be desirable.

5. Further work

We have developed a chart from which the height and amount of high clouds in the tropics can be estimated. For this we have used the observed HIRS radiances in channel 3 (691 cm^{-1}) and channel 4 (704 cm^{-1}). These are fairly opaque CO_2 channels. We have not used channel 2 (679 cm^{-1}) because it is probably too noisy for use in the tropics; for small zenith angles in the tropics the observed radiance (equivalent temperature) varied only from about 216K to 220K, or about ±2 K from a mean value. Occasional values of 215K were observed. Since the "noise" is about ±1 K, it may be difficult to extract the true signal from the data. Nevertheless interesting "streaks" appear in the data (Fig. 4) which need to be explained.

Data from other channels might be useful to support the result in Figure 6. Alternatively, HIRS channel 3 can serve to support calculations of high cloud tops obtained by other methods. For example, Menzel *et al.* (1983) described a method for obtaining cloud top heights, among other things. They use less opaque channels than HIRS channel 3, plus the 11.2μm infrared

* The sensors are calibrated on board the satellite against black bodies whose temperatures are measured. The noise is measured by pointing the sensors toward space.

window. They calculate observed cloud tops up to 100 mbs over the United States in April 1982. If those clouds were opaque enough, they should have been noticeable in HIRS channel 3.

We need also to compute the cloud radiance properties for thinner clouds. If we extend Figure 6 to $N = 1$ to 5, such broken clouds are probably more often thinner than the more overcast cases. Such thin clouds present special problems which are not considered here.

The method developed here, together with radiance measurements from additional opaque channels, should be applied to more recent satellite data. These estimates of those high cloud parameters could be compared with estimates from routine operational estimates, or from independent measurements. Here again, comparison with Lidars measurements on EOS would be useful.

The method could also be applied to any other region where clouds exist above the 200 mb level.

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