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REMOTE SENSING OF CLOUD DISTRIBUTION

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ABSTRACT

Day and night mapping of the global distributions of the horizontal cloud-cover and the corresponding cloud-top pressure levels can be derived from the same infrared data used to derive clear column temperature profiles. Application to the 15 μm VTPR data are given. Extension of this approach for the determination of the radiative transfer properties of clouds are presented and the possibility of using such information to infer cloud types is discussed.

1. INTRODUCTION

The most important atmospheric parameters of interest in studying radiative transfer in cloudy atmospheres are the clear-column vertical temperature profiles, the amounts, heights, and radiative transfer properties of clouds. Clouds play a major role in the radiative processes in the earth atmospheres both in the absorption and reflection of solar radiation and in the emission of thermal energy. A knowledge of the vertical location, the horizontal distribution and the optical properties of clouds provides information on the heat sources and sinks, storage rates and transport phenomena in the atmosphere. Such information play a critical role in determining the drives for motions in the atmosphere and oceans.

Visible and infrared pictures of clouds indicate the existence of clouds, but do not give information about their altitudes or their radiative transfer parameters which are essential for the estimate of their types. By contrast, infrared temperature sounding data permit the determination of the horizontal and vertical distribution of clouds provided that all the sounding channels observe the same field of view at the same time. The requirement of simultaneous observations is necessary because clouds are usually a very inhomogeneous medium both vertically and horizontally.

2. APPROACH

The upwelling radiance from a planetary atmosphere is a function of the thermal state of the atmosphere, the concentration of radiatively active gases, and the extents, heights, and radiative transfer properties of clouds and aerosols. Thus, in principle, it should be possible to recover useful information about the physical and chemical structure of an atmosphere from analysis of the upwelling radiance. However, the problem in analyzing such data lies in finding ways to uncouple the effects of these variables and retrieve the true values of each unknown separately. *By treating the cloud effects as short term oscillations over the clear-column upwelling radiance,* an analytical method was developed by Chahine (1974) to retrieve clear-column vertical temperature profiles from radiance measurements made in the presence of clouds. The method requires radiance data measured in two spectral regions and over two adjacent fields of view having different amounts of clouds. The uncoupling of the effects of clouds is carried out without any a priori information about the amounts, heights and optical properties of the clouds in the fields of view. Once the clear-column temperature profiles are determined the same radiance data could then be used to determine the heights, amounts, and radiative transfer properties of clouds.

Formulation of this approach is straightforward. It will be carried out here in two steps:

First, we consider the radiance $\tilde{I}(\nu)$ measured at frequency ν in the presence of clouds, and define the corresponding clear-column radiance $I(\nu)$ as

$$I(\nu) = B(\nu,T_s)\ \tau(\nu,p_s) + \int_{\ln p_s}^{-\infty} B[\nu,T(p)\ \frac{\partial\tau(\nu,p)}{\partial \ln p}\, d \ln p \qquad (1)$$

where $\tau(\nu,p)$ is the transmittance of a clear-column of gaseous absorbers between pressure level p and the sounder. B is the blackbody Planck function and T(p) is the clear-column vertical temperature profiles. Next we express the difference between $I(\nu)$ and $\tilde{I}(\nu)$ in terms of an expansion function $G(\nu,p)$ and an expansion coefficient N as

$$I(\nu) - \tilde{I}(\nu) = NG(\nu,p_c, \ldots) + N'G'(\nu,p_c \ldots) \qquad (2)$$

In this first step we don't need to define the form of $G(\nu,p)$ because we aim to eliminate it. Detailed discussion of this approach is given by Chahine (1977). For simplicity we take here one expansion team only and consider observations made over two adjacent fields of view (subscripts 1 and 2) having different amounts of clouds, such that $\tilde{I}_1 \neq \tilde{I}_2$ and write Eq. (2) as

$$\begin{aligned} I_1(\nu) - \tilde{I}_1(\nu) &= N_1\ G(\nu,p, \ldots) \\ I_2(\nu) - \tilde{I}_2(\nu) &= N_2\ G(\nu,p, \ldots) \end{aligned} \qquad (3)$$

Now, if the two fields of view are continguous we can assume that $I_1(\nu) \simeq I_2(\nu)$ and drop their subscripts. Equation (3) becomes then

$$I(\nu) = \tilde{I}_1(\nu) + \eta[\tilde{I}_1(\nu) - I_2(\nu)] \quad \text{where} \quad \eta = \frac{N_1}{N_2 - N_1} = \text{constant} \tag{4}$$

Determination of T(p) and $I(\nu)$ could be carried out according to the methods described by Chahine (1974, 1975, 1977).

In the second step we substitute the value of $I(\nu)$ into Eq. (3) and write

$$N_1 \, G(\nu, p_c, \ldots) = I(\nu) - \tilde{I}_1(\nu) \tag{5}$$

for each sounding frequency ν_i. The left-hand side of Eq. (5) contains all the radiative transfer properties of the clouds and the terms on the right-hand side are all known. We need now to formulate or model the expansion function $G(\nu, p \ldots)$.

3. CLOUD MODELING

To deduce the properties of clouds one is faced with the problem of solving the complete equation of transfer in a Mie scattering medium. This sort of approach is not practical here because of the small number of available measurements. Thus we are confined to use simple black or nonblack cloud models consisting of one, two or three layers.

For the types of data currently available from infrared sounders observations made in the range between 3.7 μm and 15 μm, we need consider only one layer cloud models. We could express $G(\nu, p, \ldots)$ in terms of only a small set of cloud parameters such as the fractional cloud cover N_c, the mean cloud top pressure level p_c, the cloud emissivity ε_c, transmissivity t_c, and reflectivity ρ_c.

a. Single Layer of Black Clouds

In most radiation models it is assumed for simplicity purposes that all clouds, except cirrus, are sufficiently thick and dense to be treated as black clouds with emissivity $\varepsilon_c = 1$. Low stratus and cumulus water clouds have emissivities which are close to unity. Yamamoto et al. (1970) have shown that for long-wave radiations dense water cloud absorbs more than 90% of infrared radiation within a depth of 50 m. Thus if we set the source function at the cloud level p_c to be the Planck function value $B[\nu, T_c(p_c)]$ we can express $G(\nu, p)$ for $\varepsilon_c = 1$ as

$$G(\nu, p_c) = B(\nu, T_s)\, \tau(\nu, p_s) + \int_{\ln p_s}^{\ln p_c} B[\nu, T(p)] \frac{\partial \tau(\nu, p)}{\partial \ln p} \, d \ln p \tag{6}$$

$$- B[\nu, T(p_c)]\, \tau(\nu, p_c) \quad ,$$

where the only unknown on the right-hand side is the cloud top pressure level p_c.

Determination of p_c can be accomplished by considering two sounding frequencies, say ν_1 and ν_2 for which $\tau(\nu,p_s)$ is preferably small in order to minimize the effect of changes in earth surface emissivity. From Eq. (5) and Eq. (6) we write, for, say, the first field of view

$$\frac{G(\nu_1,p_c)}{G(\nu_2,p_c)} = \frac{I(\nu_1) - \tilde{I}_1(\nu_1)}{I(\nu_2) - \tilde{I}_1(\nu_2)} \tag{7}$$

and solve for p_c by trial and error in a manner similar to the approach described in Section 4.b by Chahine (1975).

The values of the expansion coefficient N in this case are the effective fractional cloud cover which is the product of the actual fractional cloud cover N_c and the actual cloud emissivity, $N \simeq N_c\ \varepsilon_c$. N can be readily derived from Eq. (5) using ν_1 or ν_2 as

$$N_1 = \frac{I(\nu_1) - \tilde{I}_1(\nu_1)}{G(\nu_1,p_c)} \tag{8}$$

Application of this model to the analysis of the VTPR sounder data has been carried out and the results will be discussed in Section 4.

b. Single Layer of Transmitting Clouds

The assumption of black clouds is attractively simple but its validity is questionable to say the least. Many common types of stratocumulus clouds do not become black until their thickness exceeds half a kilometer. The emissivity of middle-level and cirrus clouds remains less than one even when their thickness exceeds several kilometers. A useful procedure to treat non-black clouds is to assume the cloud to be transmitting but not reflecting with

$$\varepsilon_c(\nu) + t_c(\nu) = 1$$

By considering observations in two spectral regions, say $[\nu] = 4.3$ μm and $[\nu'] = 15$ μm CO_2 bands, we can derive an expression for the ratios of emissivities in the two bands as

$$\frac{\varepsilon_c(\nu)}{\varepsilon_c(\nu')} = \frac{I(\nu) - \tilde{I}_1(\nu)}{I(\nu') - \tilde{I}_1(\nu')}\ \frac{G(\nu',p_c)}{G(\nu,p_c)} \tag{9}$$

Since the cloud emissivity is frequently dependent and a strong function of the water content of clouds and their thickness, the ratios of the emissivity can be used for deducing the cloud optical thickness and identify their types. The determination of N, $\varepsilon(\nu)/\varepsilon(\nu')$ and p_c is carried out simultaneously by the method of trial and error starting with $p_c \le p_s$ in a manner slightly more elaborate than the one followed for black clouds. Numerical simulations of this approach are currently under way and the results will be applied to the HIRS II data.

4. APPLICATION OF BLACK CLOUD MODEL TO VTPR DATA

Satellite verification of this approach has been carried out and the results are shown in Figs. 1, 2, and 3. The computations were carried out, in collaboration with M. Halem, J. Susskind, and J. Forkash, using 15 μm VTPR data from the NOAA 4 satellite. The determination of the clear column radiance for the VTPR (i.e. the clear column temperature profile) requires the use of a priori assumptions about the surface temperature. The surface temperature here was obtained from the NOAA Analysis. The effects of errors in T_s on the retrieved values of p_c is small particularly for p_c < 700 m according to McCleese (1976).

The resulting sample of cloud distribution shown here corresponds to one week of VTPR data from January 1 - 7, 1975 averaged on the GSFC-GLAS model grid size of 4° latitude by 5° longitude.

The effective fractional cloud cover distribution varied between 0% and 89%. The graphical illustrations in Fig. 1 show

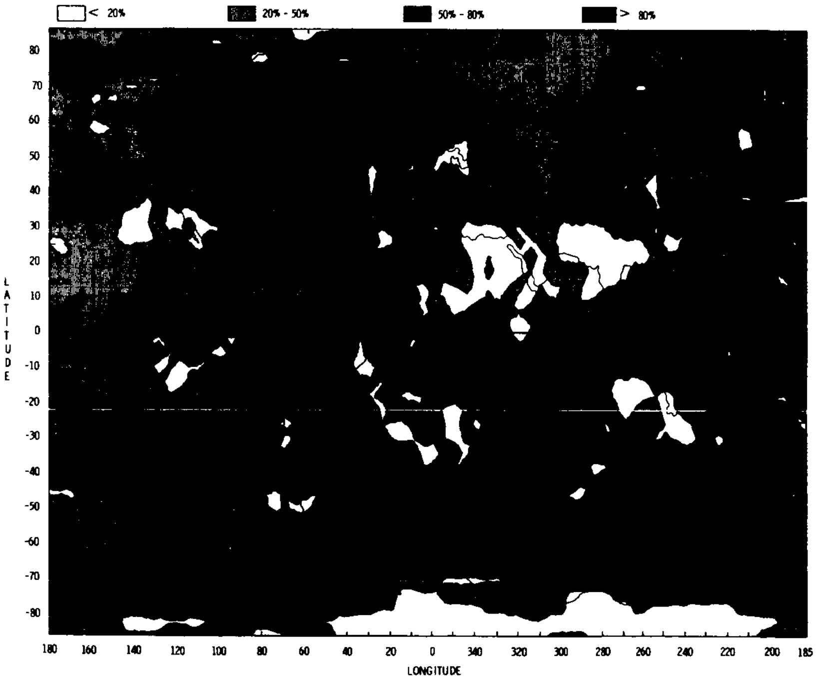

Fig. 1 — Map of effective infrared fractional cloud cover derived from the VTPR Sounder data for the period of January 1 - 7, 1975.

this distribution in four shades corresponding to the ranges less than 20%, 20% - 50%, 50% - 80%, and greater than 80%. The results obtained by this technique agree very well with the results obtained by J. C. Sadler of the University of Hawaii for the same period of time.

The cloud top pressure levels varied between surface and 145 mb and the results illustrated in Fig. 2 show the cloud top level distribution in three shades corresponding to surface-500 mb, 500 mb - 250 mb and above 250 mb. These results possess the basic features of the global circulation and compare well with the small amount of available information. Additional verifications are still required.

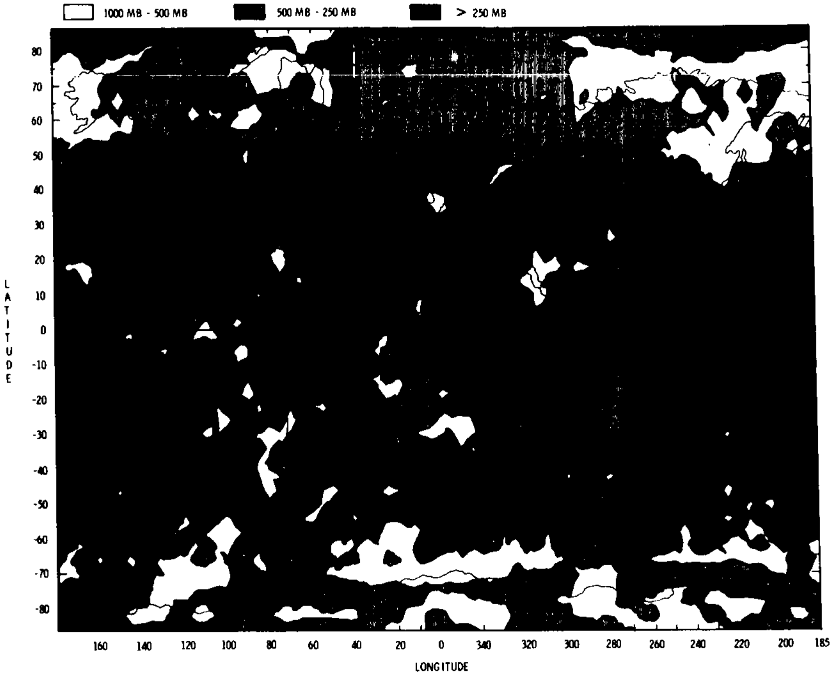

Fig. 2 — Map of effective cloud top pressure level distribution derived from VTPR Sounder Data for the period of January 1 - 7, 1975.

Statistical averages are presented in Fig. 3 which give the meridional profiles of zonally averaged cloud distribution, in fractions, and the cloud top pressure levels in mb: The Global average of the effective cloud cover as seen in the 15 μm band is shown to be 0.41, corresponding to 0.40 for the northern hemisphere and 0.42 for the southern hemisphere.

The standard deviation of the fractional cloud cover for the 4° wide zone is given also in Fig. 3. The average zonal standard deviation is 0.24 which is close to the value corresponding

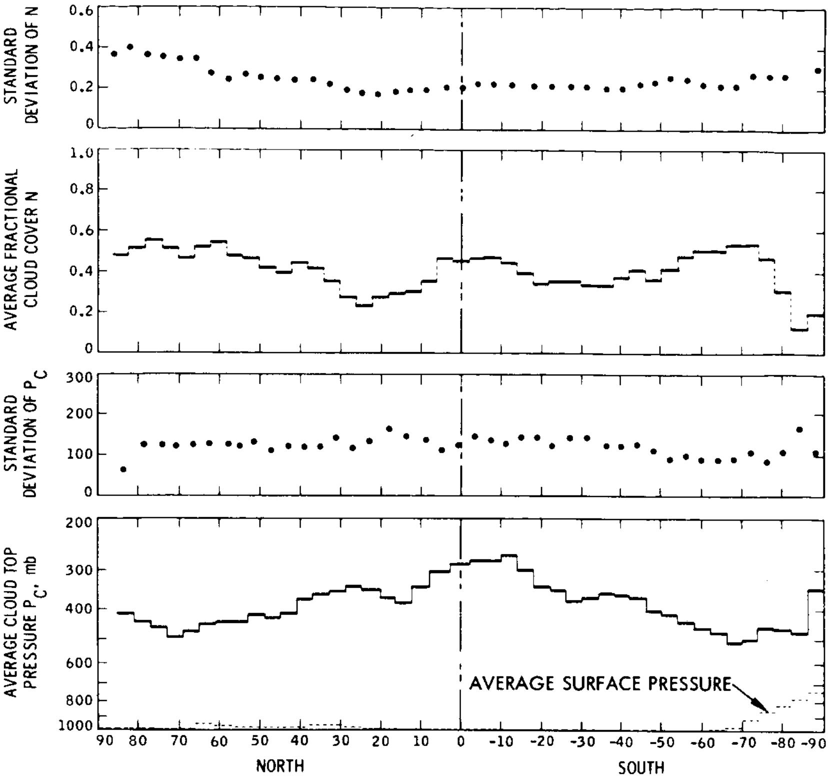

Fig. 3 — Meridional profiles of zonally averaged infrared cloudiness for January 1 - 7, 1975.

to a constant probability distribution p(X) = 1 on [0,1]. By contrast, the standard deviation of the meridionally averaged fractional cloud distribution is 0.1. Thus, the dispersion (variance) of the meridional distribution of clouds is six times larger than the zonal dispersion.

5. CONCLUSION

The results shown in Figs. 1, 2, and 3 demonstrate the capability of temperature sounding radiance data to yield meaningful information about the cloud distribution even under black cloud model assumptions. More extensive verifications still need to be carried out.

Extension of this technique to transmitting clouds will provide information about the true cloud distribution and emissivity. The emissivity could be used in conjunction with the cloud height and amount of yield information about the types of clouds.

Further extension of this technique to the cases of reflecting clouds and to multiple cloud layers is, in principle, possible, but application of these cloud models to current sounder data is not meaningful because of the poor vertical resolution provided by current operational sounders.

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