RESULTS OF THE COMPUTATION OF CLOUD HEIGHTS, EMISSIVITY, AND COVER FROM LONG- AND SHORT-WAVE RADIATION DATA

by

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Abstract

Both emissivity and partial coverage of clouds within a radiometer's field of view present problems in determining cloud-top temperatures from radiation data. By reducing the field of view to a few miles in diameter on the Earth, the chances of measuring radiation from either cloud or clear areas by a radiometer such as the HRIR on board Nimbus I and II are greatly increased. The horizontal dimensions of clouds, ranging from small cumulus to large cumulonimbus, vary so much, however, that it is not practical to design a radiometer that might be called a super-HRIR. Examination of Gemini pictures reveals a cloud-size distribution that would discourage any effort to reduce a radiometer's field of view beyond a certain angle. The emissivity of clouds presents another difficulty in determining cloud-top temperature, since a cloud of low emissivity permits the background radiation to pass through the cloud. In order to overcome these basic problems, a method of determining various radiative characteristics of clouds by combining short- and long-wave radiation data was devised for the computation of a quantity called the "whiteness" of clouds and defined as the ratio of the cloud albedo and the emissivity. The whiteness was then converted into "relative whiteness" to reduce the influence of non-isotropic radiation as much as possible. Finally, a set of equations was developed in an attempt to compute the emissivity, albedo, and temperature of clouds separately. Results indicate that the emissivity of cirrus clouds is rather small, but their albedo is much smaller than their emissivity, thus occasionally creating situations where invisible cirrus clouds are detected by a long-wave sensor. Such invisible or extremely faint cirrus would contribute to the radiation balance of the Earth in such a manner that the greenhouse effect is increased.

1. Basic Problems in Radiation Measurements Involving Clouds

Radiation measured over a region of horizontally uniform, cloud-free atmosphere does not vary appreciably as a function of the radiometer's field of view as long as the background radiation is uniform. Once clouds are brought into the field of view, their parameters—such as temperature, amount, reflectance, emissivity, etc.—significantly affect the measured value and necessitate complete examination of each parameter in order to determine its influence.

To deal with the realistic problems, the cloud photographs in Fig. 1 were prepared. The left photograph shows a detailed view of cumulus and cirrus clouds taken from a Gemini spacecraft. Out-of-focus images in the center and right pictures were obtained by simulating the patterns which would appear if the half-power field of view were 5 and 20 mi., respectively. An area of low clouds in the left picture, designated by a circle of 10-mi. diameter, includes over 60 small cumuli. When the cloud patterns are obtained by radiometers with a large field of view, it is not feasible to identify cloud types contributing to the radiometric data. Another area in the left picture, indicated by double concentric circles, is of thin cirrus clouds. The same area appearing in the center and right pictures gives almost identical radiation to that of the cumulus areas, making it impossible to distinguish these two extreme cloud types. In other words, a region of scattered, white cumuli and one of overcast, gray cirrus clouds may reflect the same amount of sunlight.

We encounter similar difficulties in cloud identification by using long-wave radiation data. In this case, an area of scattered, high clouds and that of overcast, low, or middle clouds exhibit very similar radiation characteristics. Due to the fact that a cloud, especially a thin one, cannot be regarded as a blackbody even in a crude approximation, determination of cloud types from radiation data requires complete analysis of the basic parameters of the clouds.

Presented in the left diagram of Fig. 2 is the effective emissivity, $\bar{\varepsilon}$, for 8–12 micron sensors computed as a function of the liquid water content, W, under the thin water-film assumption presented by McDONALD.[1] The influence of cloud temperatures within the 200 and 300°K range is negligibly small. The absorption coefficient for water should be changed into that for ice when cirriform clouds are involved. Furthermore, the limitation in applying the thin water-film assumption to actual clouds presents various problems which have not been solved. Nevertheless, the vertical distribution of the effective emissivity gives at least a crude idea as to the problem of how thick a cloud should be in order to be assumed to be black.

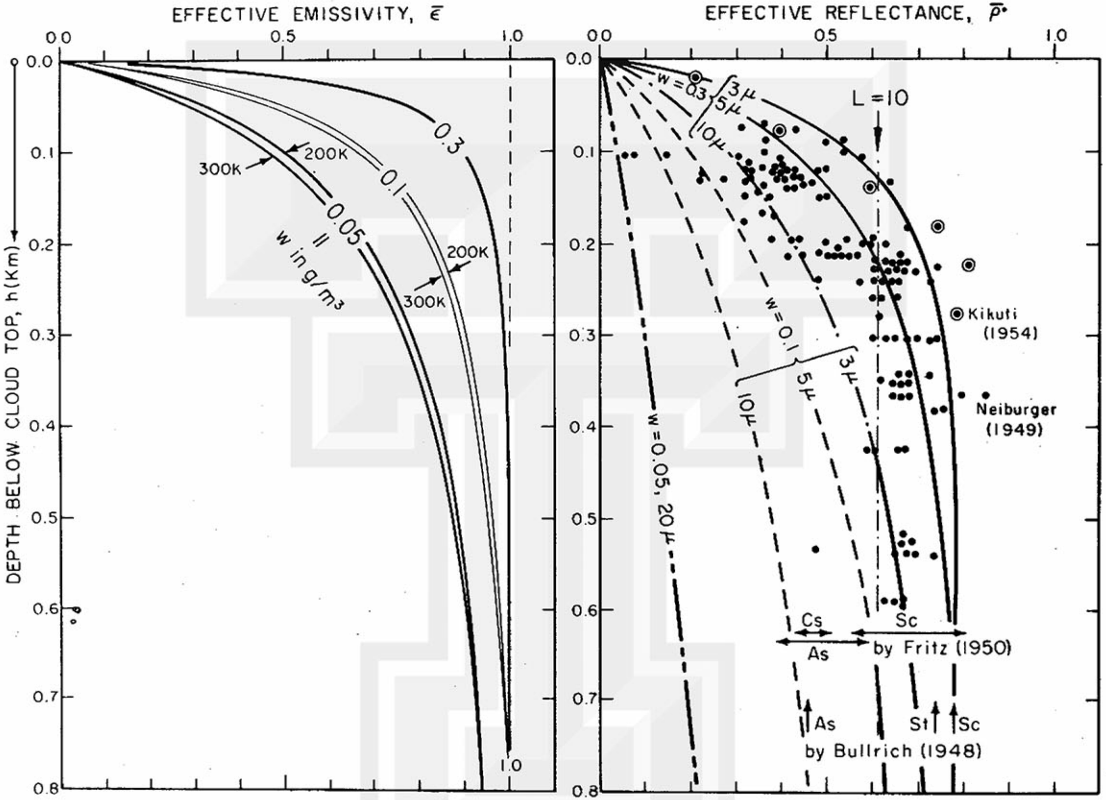
EFFECTIVE EMISSIVITY, $\bar{\epsilon}$
EFFECTIVE REFLECTANCE, $\bar{\rho}$
DEPTH BELOW CLOUD TOP, h(Km)
0.3
0.1
0.05
w in g/m³
200K
300K
1.0
L = 10
w = 0.3
3 μ
5 μ
10 μ
w = 0.1
w = 0.05, 20 μ
Kikuti (1954)
Neiburger (1949)
Cs
As
Sc
by Fritz (1950)
St
by Bullrich (1948)

Fig. 2

As in the case of stratus and cumuliform clouds with a liquid water content of several tenths gm^{-3}, the emissivity increases to about 0.9 at a depth of 100 m. Most of the convective clouds in a growing stage may thus be regarded as blackbodies. A cirriform cloud with $W = 0.05$ gm^{-3} must be over 1 km or 3000 ft thick in order to be regarded as a blackbody. We are not able to relate the size distribution and liquid (solid) water content with either the thickness or appearance of cirriform clouds ranging from thick cirrostratus to barely visible or invisible cirrus. Our guess, at the present time, is that the contribution of emissivity and of temperature to the radiant emittance of relatively thin cirrus is more or less similar, suggesting that radiation patterns may represent emissivity and/or temperature of high clouds. It is therefore necessary to know or to estimate the one in order to compute the other.

Effective reflectance, $\bar{\rho}$, as shown in the right diagram of Fig. 2, presents more complicated problems, because the reflectance depends, among other things, upon both the liquid water content and the drop-size distribution of the clouds. The reflectance for clouds with less than 10 times L, the mean free path of light, was computed from Fritz's[2] formulae, while that above $L = 10$ was estimated from measurements by BULLRICH,[3] NEIBURGER,[4] FRITZ,[5] and KIKUCHI *et al.*[6] For convective clouds with $W = 0.3$ gm^{-3}, the reflectance increases to about 0.7 or 0.8 as the thickness increases to about 1 km. This increase is much slower than that of the emissivity, indicating that a convective cloud is closer to a blackbody than to a whitebody as far as its radiative characteristics are concerned. The tremendous reduction of reflectance due to increasing drop size often results in a gray cloud, especially when the size exceeds 10 or 20 microns. The top of most growing cumuliform clouds is characterized by small drop sizes, permitting us to assume that the reflectance levels off at a depth of less than 500 m.

The reflectance of cirriform clouds with $W = 0.05$, for instance, is extremely small in comparison with their emissivity. Since the reflectance decrease appreciably with increasing particle sizes, some cirrus with 100-micron or larger crystals may not be detectable with a short-wave sensor, though it affects outgoing long-wave radiation.

2. Spectral and Spatial Responses of a Radiometer

In order to gather sufficient energy for detection, a radiometer must have a definite field of view. The total power received by the radiometer is expressed by

$$P = A \iint N_{(\lambda,\omega)} \phi_\lambda \phi_\omega \, d\omega \, d\lambda, \tag{1}$$

where $N_{(\lambda,\omega)}$ denotes the spectral radiance given as a function of λ and ω; ϕ_λ, the spectral response; ϕ_ω, the spatial response; A, the area of the lens that collects radiant energy; and ω, the solid angle within the field of view. Without determining the absolute value of P, a radiometer is usually calibrated by using a target with N_λ, which does not vary with ω. Thus we write

$$\overline{N}\int \phi_\omega d\omega = \int\int N_{(\lambda,\omega)}\phi_\lambda\phi_\omega d\omega d\lambda, \tag{2}$$

where $\overline{N}=\int N_\lambda\phi_\lambda d\lambda$ is called the effective radiance. This equation can never be solved unless $N_{(\lambda,\omega)}$ is known. If we know this, however, no radiation measurements are necessary to begin with.

Under the assumption that N_c, the cloud radiance, and N_b, the background radiance, are constants within the field of view, we write Eq. (2) as

$$\begin{aligned}\overline{N} &= \frac{\int \phi_\omega d\omega_c}{\int \phi_\omega d\omega}\int N_{c\lambda}\phi_\lambda d\lambda + \frac{\int \phi_\omega d\omega_b}{\int \phi_\omega d\omega}\int N_{b\lambda}\phi_\lambda d\lambda \\ &= n\overline{N}_c+(1-n)\overline{N}_b,\end{aligned} \tag{3}$$

where suffixes c and b designate the clouds and their background; and n, the radiometric cloud cover which varies naturally with ϕ_λ, the spectral response of the radiometer. It is evident, from this equation, that the measured value of $\overline{N}$ includes the parameters, N_c, N_b, and n, thus necessitating their individual determination.

3. Concept of Combining Long- and Short-Wave Radiation Data

A solution toward the determination of individual quantity out of measured values can be obtained by combining radiation data from multi-wave sensors with identical fields of view. In this paper, however, a long- and a short-wave sensor are utilized.

The effective radiant emittance obtained by a long-wave sensor can be written as

$$\overline{W} = n\bar{\varepsilon}\overline{B}_c+(1-n\bar{\varepsilon})\overline{B}_b, \tag{4}$$

where $\bar{\varepsilon}$ denotes the effective emissivity within the range of the sensor's spectral response, and $\overline{B}_c$ and $\overline{B}_b$ are the effective radiant emittance of blackbodies placed respectively at the cloud and the background levels. After introducing the equivalent blackbody cloud cover, $n_B=\bar{\varepsilon}n$, we write

$$\overline{W} = n_B\overline{B}_c+(1-n_B)\overline{B}_b. \tag{5}$$

To obtain a similar equation applicable to short-wave radiation, we define albedo as $\overline{A}=\pi\overline{N}/\overline{W}^*\cos\zeta^*$, where $\overline{W}^*$ denotes the effective solar constant and ζ^*, the solar zenith angle. The measured albedo can now be written

$$\bar{A} = n\bar{\rho}\bar{A}_w + (1-n\bar{\rho})\bar{A}_b, \tag{6}$$

where $\bar{\rho}$ is the effective reflectance of the clouds; $\bar{A}_w$, the albedo of a whitebody placed at the cloud height; and $\bar{A}_b$, the albedo of the background. By introducing the equivalent whitebody cloud cover, $n_w = \bar{\rho}n$, we write

$$\bar{A}_w = n_w\bar{A}_w + (1-n_w)\bar{A}_b. \tag{7}$$

Due to atmospheric scattering, $\bar{A}_w$ is always smaller than 1.0; and it can be written approximately as

$$\bar{A}_w = 1 - ka_0\bar{B}_c/\bar{B}_b, \tag{8}$$

where k is the correction factor of about 0.6 and a_0, the extinction coefficient between the sea level and the top of the atmosphere. The extinction coefficient of the standard atmosphere can be computed as a function of the satellite and solar zenith angles.

4. Generalized Solution of Cloud Parameters

To obtain a generalized solution of cloud parameters, we must first define the whiteness of the cloud,

$$\beta = \bar{\rho}/\bar{\varepsilon}. \tag{9}$$

Due to the fact that the reflectance of even a very bright cloud does not usually exceed 0.8 or 0.9, β for a blackbody cloud remains below these values. Defining standard white clouds, or in shortened form, standard clouds, as those that are highly reflective, we call $\beta_s = \bar{\rho}_s : \bar{\varepsilon}_s$ the whiteness of standard clouds.

The whiteness of a cloud relative to β_s is termed the relative whiteness, which is expressed as

$$\beta_r = \frac{\beta}{\beta_s} = \frac{\bar{\varepsilon}_s\bar{\rho}}{\bar{\varepsilon}\bar{\rho}_s}. \tag{10}$$

Since we can consider cumuliform clouds with reasonable thickness as reflecting almost like a standard cloud, we may assume $\beta_r = 1.0$ for these clouds.

The solutions of Eqs. (4), (6), and (8) thus obtained are

$$\bar{B}_c = \bar{B}_b \frac{\bar{B}_b - \beta_s\beta_r\bar{\pi}(1-\bar{A}_b)}{\bar{B}_b - \beta_s\beta_r ka_0\bar{\pi}}, \tag{11}$$

where $\bar{\pi} = (\bar{B}_b - \bar{W})/(\bar{A} - \bar{A}_b)$ is called the effective pseudo-radiant emittance. When $\beta_r = 1.0$, as in the case of convective or dense clouds, Eq. (11) is reduced to

$$\bar{B}_c = \bar{B}_b \frac{\bar{B}_b - \beta_s\pi(1-\bar{A}_b)}{\bar{B}_b - \beta_s ka_0\bar{\pi}}, \tag{12}$$

which can be computed by determining the areal distribution of $\bar{B}_b$, $\bar{A}_b$, $\bar{\pi}$, β_s, and a_0.

For clouds with small emissivity, Eq. (11) should be solved with respect to $\beta = \beta_s \beta_r$, thus

$$\beta = \frac{\bar{B}_b}{\bar{\pi}} \frac{\bar{B}_b - \bar{B}_c}{\bar{B}_b(1-\bar{A}_b) - ka_0 \bar{B}_c}, \tag{13}$$

which can be estimated only when reasonable values of $\bar{B}_c$ are known. In practice, however, $\bar{B}_c$ is computed from (11). If $\bar{B}_c$ gives values greater than that of the coldest cirriform clouds, $\bar{B}_{ci}$, we may assume that the clouds in the field of view are located on the curve connecting A with B in Fig. 3. These high clouds located along the line, BC, will result in $\bar{B}_c$ smaller than $\bar{B}_{ci}$, or often negative values. If so, the computation of β should be made by using Eq. (13).

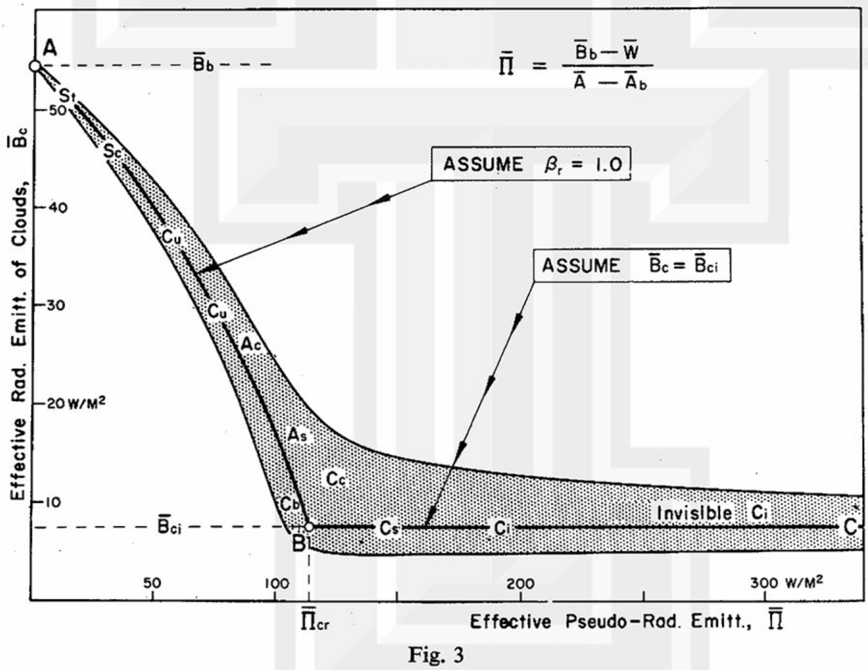

Fig. 3

A large number of test computations made by using known cases of cloud environments revealed that the majority of the clouds in the atmosphere seen from the satellite are located inside the stippled area in Fig. 3. If we try to distinguish these varieties of clouds according to $\bar{B}_c$, the effective radiant emittance of clouds regarded as blackbodies, all high cirriform clouds would appear to be identical. The use of $\bar{\pi}$, the effective pseudo-radiant emittance, would permit us to distinguish thin clouds from thick ones even though their temperatures are identical.

5. Conclusions

A solution of a radiometer's power equation, including both spectral and spatial responses, was obtained in such a form that the influence of clouds and their background inside a scan spot can be separated by combining short- and long-wave radiation data obtained by scanning radiometers. It has become feasible to compute cloud temperature under the assumption that the relative whiteness is 1.0, even though the cloud distribution inside the field of view is unknown. For high clouds with a relative whiteness considerably less than 1.0, whiteness can be estimated by assuming that their effective radiant emittance is very close to that of high cirriform clouds.

At the present time the relationship between $\overline{\rho}$ and $\bar{\varepsilon}$ for the given whiteness of cirriform clouds is not very well known. Computed values of β as a function of the liquid water content and the drop-size distribution very strongly suggest that β also depends upon the cloud thickness, thus making it very difficult to estimate the emissivity and the reflectance separately. The use of the equivalent blackbody cloud cover, n_B, and the equivalent whitebody cloud cover, n_W, is therefore suggested, since each of these represents a product of actual cloud cover and emissivity or reflectance.

References

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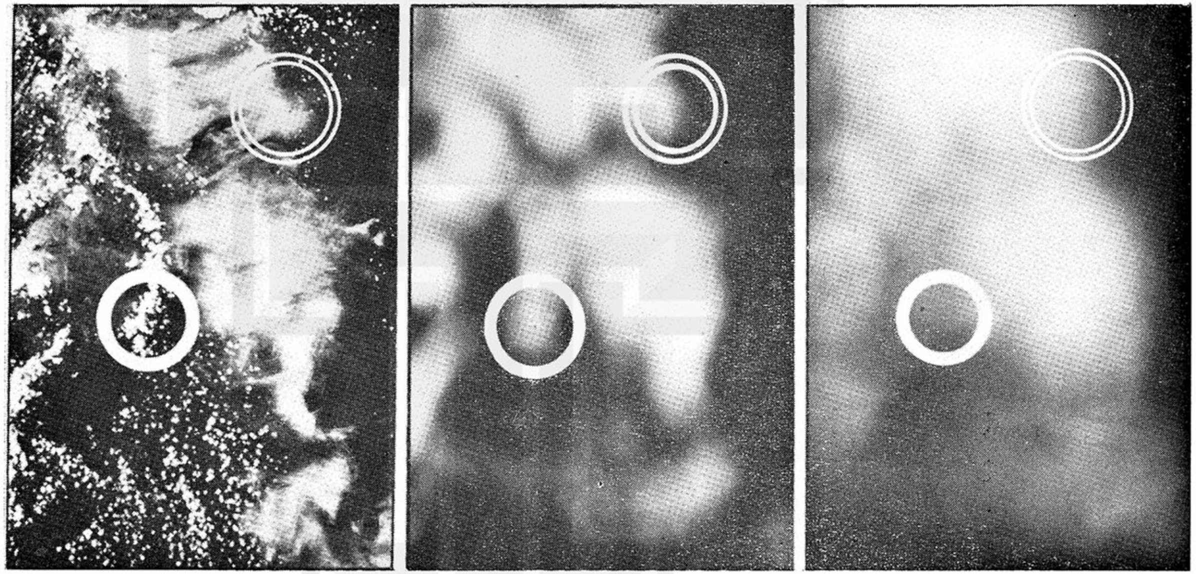

Fig. 1