MEASURED EFFECTIVE LONG-WAVE EMISSIVITY OF CLOUDS

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ABSTRACT

Measurements of the effective long-wave emissivity of clouds, equivalent to one minus the slab transmissivity, are obtained through thermal energy relations at cloud tops and bases after the manner of Gergen. Radiometric measurements are employed. Aircraft-verified cloud heights and measured effective cloud emissivities provide a basis for determining the presence of middle and high clouds. Such clouds result in large changes in radiation flux and apparent earth temperature measurements from satellites and high level balloons.

Symbol	*Definition*	*Appears in equation*
$F_1\downarrow$	Downward long-wave radiative flux, level 1	1
$F_1\uparrow$	Upward long-wave radiative flux, level 1	1
$F_2\downarrow$	Downward long-wave radiative flux, level 2	2
$F_2\uparrow$	Upward long-wave radiative flux, level 2	2
F_{E1}	Equivalent long-wave radiative flux, level 1	1, 6
F_{E2}	Equivalent long-wave radiative flux, level 2	2, 6
ϵ^*	Effective long-wave cloud emissivity	3, 6
F_{c1}	Long-wave radiative flux from cloud, level 1	1
F_{c2}	Long-wave radiative flux from cloud, level 2	2
F_{B1}	Equivalent long-wave radiative flux, cloud assumed black, level 1	4, 6
F_{B2}	Equivalent long-wave radiative flux, cloud assumed black, level 2	5, 6
$F\uparrow$	Upward long-wave radiative flux	7
u	Optical depth (cm.) of absorbing gas	7
σ	Stefan-Boltzman constant, 0.817×10^{-10} cal./cm.^{2} min. deg.^{4}	7
$\bar{T}$	Mean air temperature (°K.) of atmospheric layer	7
$(u)_w$	Optical depth of atmospheric water vapor (precipitable centimeters)	7
$(u)_c$	Optical depth of atmospheric carbon dioxide (atmospheric centimeters)	7
$(u)_o$	Optical depth of atmospheric ozone (atmospheric centimeters)	7
T_0	Earth's surface temperature (°K.)	7

1. INTRODUCTION

Measurements of the long-wave emissivity or transmissivity of clouds above the earth's surface are difficult and, consequently, scarce. Notable among measurements of long-wave transmissivity of clouds are those of Gergen [4], Gates and Shaw [3], and Brewer and Houghton [1]. However, the importance of the transmission properties of clouds to infrared satellite and balloon measurements of the atmosphere, is well known. The thermal energy exchange between the earth, the atmosphere, and space is strongly influenced by cloud cover. Opaque (to long-wave radiation) cloud layers provide a high cold radiating source near their tops for upward-streaming radiation above the clouds. On the other hand, thermal energy considerations must include the transmissivity or emissivity of clouds that are not opaque. For here radiation above the clouds comes not only from the clouds but also from earth and atmosphere beneath. Gates and Shaw [3] outline the problems in obtaining measurements of cloud emissivity requiring observations of drop size distribution and concentration in the cloud, cloud thickness, and cloud composition. The inaccessibility of the clouds and the compound instrument problem have required aircraft or large balloon probes.

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Following the general principles of a procedure developed by Gergen [4] in his "black ball" experiments for the determination of "blackness" of clouds, but using observed upward and downward flux rather than calculated, it was possible to make several measurements of the long-wave emissivity of clouds. The radiometersonde (Suomi and Kuhn [11]) is well suited for such measurements, since it has been aloft through most cloud types. Aircraft verifications of the actual bases and tops of the clouds under observation were obtained, and all measurements were at night.

The principal purpose of the research described is to measure the effective long-wave emissivity of clouds. This may be subdivided into the location of cloud layers by infrared observations; the measurement of their effective emissivity, one minus the cloud's slab transmissivity; and the application of high and middle cloud emissivity in analyzing satellite infrared observations.

The method of accomplishing the purposes of the research is best summarized in the research technique.

First, the effective long-wave emissivity includes both the actual cloud emissivity and the cloud scatter effects and is defined by ϵ^*, equivalent to one minus the slab transmissivity. To obtain the effective infrared emissivity of clouds we measure the equivalent infrared flux, defined as one-half the sum of the upstreaming and downstreaming radiant flux at a plane in the atmosphere parallel to the earth's surface, in this case a cloud top or base. By considering the thermal energy budget at the base and top of a cloud the observed fluxes algebraically reduce to the above-defined cloud emissivity.

Having observations of cloud emissivities one may calculate the upward flux of infrared radiation at satellite level in the presence of clouds by means of one of the various forms of the transfer equation. A review of observations of TIROS infrared data has illustrated effects of clouds and possible atmospheric particulates. The 7–30-micron broad response channel on TIROS, as well as the 8–12-micron "window" channel have shown large changes in the apparent earth temperature. McGee [8] and Wark, Yamamoto, and Lienesch [12] have noted that in many cases these appear to be related to the presence of clouds. Such clouds can be high cirrus, unseen from the ground. Riehl [9] speaks of strong radiative cooling in the Caribbean, and Gergen [5] notes that an observation of high clouds with a transmissivity of 71 percent produces a 35 percent attenuation of the upward-streaming flux. Radiometersonde measurements have shown similar attenuations. With satellite observations of the upward flux and an atmospheric (radiosonde) sounding from the same area, it is possible to employ measured effective emissivities in adjusting the calculated flux to equal the observed. This is accomplished by interposing a "black" or "gray" cloud at selected heights, the cloud's effect being that of attenuation and re-radiation at lower temperatures. Thus, while qualitatively it is well known that "unseen" high clouds may greatly reduce the magnitude of the upward flux, this procedure apparently provides a quantitative measure of the effects of cloud emissivities on certain satellite measurements.

2. INSTRUMENTAL PROCEDURE

For these emissivity measurements, it was necessary to secure measurements of the height of both the cloud bases and tops as well as a complete vertical radiation profile in the infrared through the cloud. The radiometersonde (Kuhn [6], Bushnell and Suomi [2]) was the infrared radiation probe. Aircraft observations of cloud bases and tops for each of four cloud situations gave the necessary data on the vertical distribution of the clouds. It will be shown, as Gergen [4] did previously, that vertical profiles of the equivalent radiation (defined above) can indicate cloud bases and tops.

3. EMISSIVITY CALCULATIONS

From figure 1, indicating the distribution of radiative fluxes above and below a cloud layer in the atmosphere, we can form the equations for the thermal energy transfers at the top and base of the cloud. Let us suppose that a cloud layer between levels 1 and 2 has a gray body effective emissivity ϵ^*. At the level 1 there are two radiation currents contributing to the equivalent radiation, F_E, namely, $F_1\downarrow$ and $F_1\uparrow$. Similarly at level 2 we have $F_2\downarrow$ and $F_2\uparrow$. We may form the equations

$$2F_{E1}=F_1\downarrow+F_1\uparrow=(1-\epsilon^*)F_2\downarrow+\epsilon^*F_{c1}+F_1\uparrow \qquad (1)$$

$$2F_{E2}=F_2\downarrow+F_2\uparrow=(1-\epsilon^*)F_1\uparrow+\epsilon^*F_{c2}+F_2\downarrow \qquad (2)$$

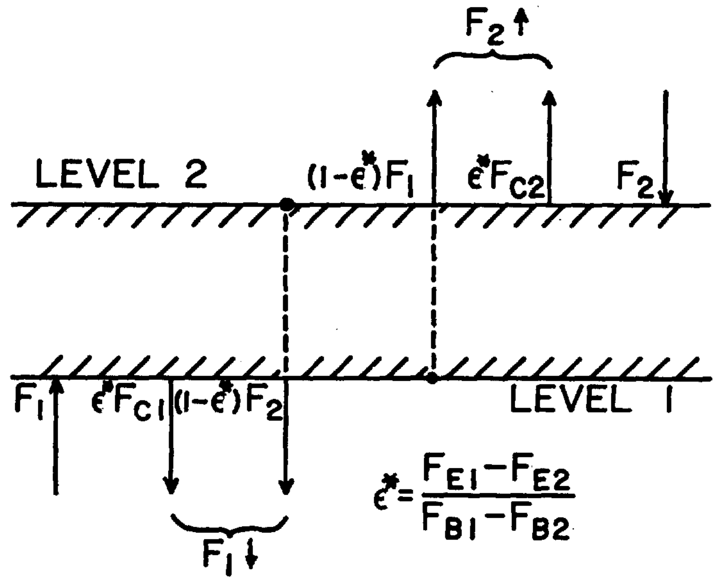

Figure 1.—Cloud layer and associated radiative fluxes.

where

$$F_1\downarrow=(1-\epsilon^*)F_2\downarrow+F_{c1} \quad \text{and} \quad F_2\uparrow=(1-\epsilon^*)F_1\uparrow+F_{c2}$$

Subtracting equation (2) from equation (1) we obtain:

$$2F_{E1}-2F_{E2}=-\epsilon^*F_2\downarrow+\epsilon^*F_1\uparrow+\epsilon^*F_{c1}-\epsilon^*F_{c2} \qquad (3)$$

A simple consideration of the energy transfers at the cloud top and base, assuming the cloud to be black, while considering similar actual observations of a "gray" cloud, leads one to believe that a relatively simple algebraic relationship between equations similar to (1) and (2) would provide the effective cloud emissivity. In effect we compare energy transfers for a gray and a black cloud by means of the ratio of equivalent radiations for the gray and the assumed black cloud.

The equivalent radiation for a black cloud, symbolized by F_B instead of F_E, is defined as one-half of the sum of the black body radiation, F_c, at the base or top of a cloud and $F_1\uparrow$ or $F_2\downarrow$. Then we may write:

$$2F_{B1}=F_{c1}+F_1\uparrow \qquad (4)$$

$$2F_{B2}=F_{c2}+F_2\downarrow \qquad (5)$$

Substituting equation (4) and (5) in equation (3) we obtain:

$$\epsilon^*=(F_{E1}-F_{E2})/(F_{B1}-F_{B2}) \qquad (6)$$

To review, $F_1\uparrow$, $F_1\downarrow$, $F_2\uparrow$, $F_2\downarrow$ are all measured quantities. Actually F_{c1} and F_{c2} are measured in that their temperatures are also measured. It should also be noted that the water vapor *flux emissivity* is accounted for in the equations and does not affect the measured effective cloud emissivity.

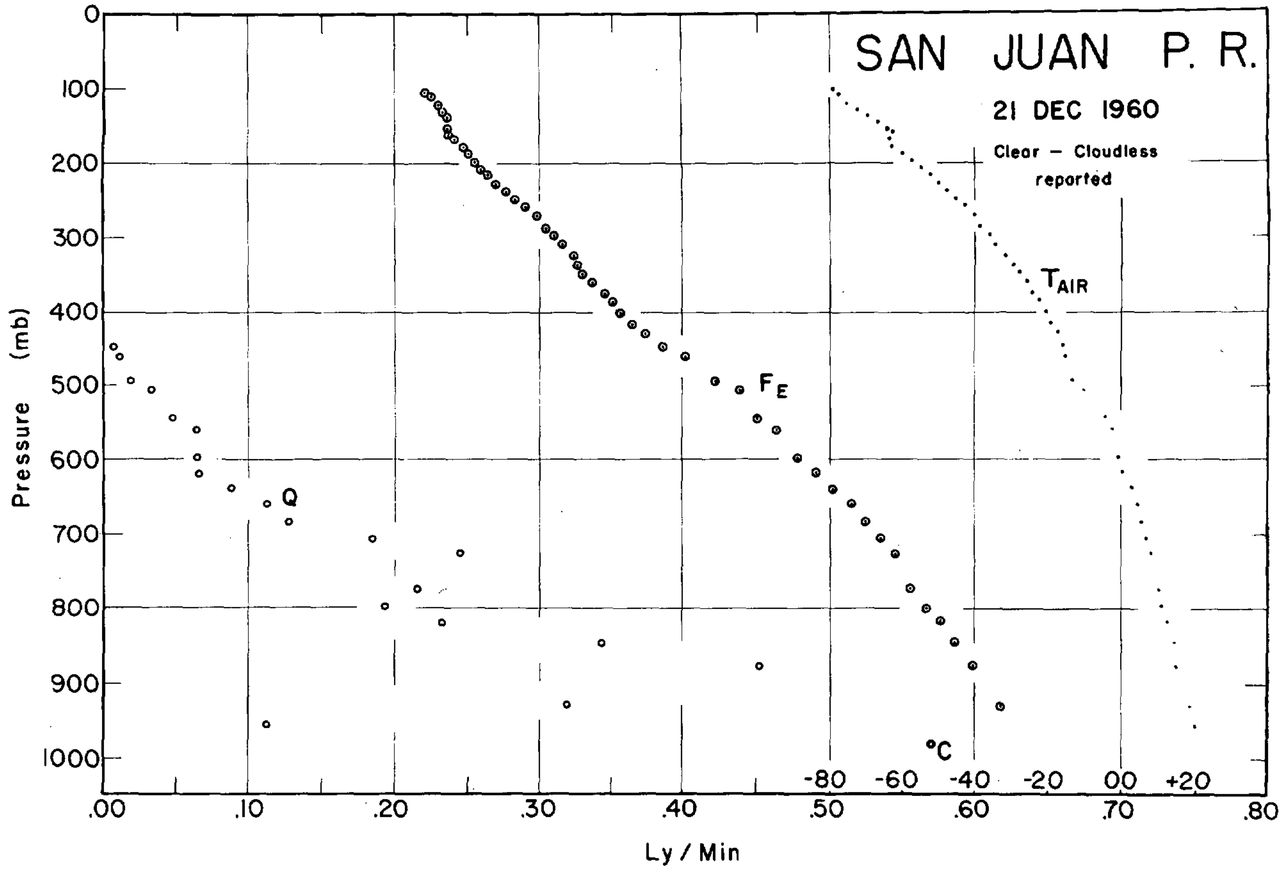

FIGURE 2.—Equivalent radiation, F_E, air temperature T_{AIR}, and mixing ratio Q, San Juan, P.R., December 21, 1960.

4. RESULTS OF EMISSIVITY MEASUREMENTS

Figures 2 through 6 summarize the cloud emissivity observations. Certain conclusions can be drawn. Figure 2 demonstrates an essentially linear plot of the equivalent radiation for a reported cloudless sky at San Juan, P.R., on December 21, 1960. In each of figures 2 through 6 the ordinate is pressure on a linear scale and the abscissa has two scales, one for temperature in degrees Celsius and the other for radiation in langleys per minute.

In figure 3 for Madison, Wis., the observed cloud top and base are indicated. The equivalent radiation profile changes abruptly at 900 mb., the cloud base, and then resumes its previous lapse abruptly at 855 mb., the cloud top. The solution of equation (6) gives an emissivity of 0.98 for this 10/10 stratocumulus cloud. As a result of inaccuracies in the measurement of the exact height of the cloud bases and tops, it is possible for the effective emissivity, ϵ^*, to exceed 1.00 by a small amount. Two standard errors in radiometersonde-measured upward or downward flux are equivalent to 0.006 ly. min.$^{-1}$ (4.2 watts m.$^{-2}$). This random error effect may result in a ± 7 percent error in the effective cloud emissivity.

Figure 4 illustrates an observed 9/10 altocumulus cloud layer at Peoria, Ill., on Jan. 13, 1961. Observations of the equivalent radiation profile give an effective cloud emissivity of 60 percent by equation (6). In all figures the Q, or mixing ratio, curve is given in grams per kilogram and utilizes the numerical values of the radiation scale. It is interesting to see the mixing ratio decrease through the cloud, from 570 through 490 mb. in this example.

The two examples in figures 5 and 6 illustrate the emissivity determinations for observed middle and high clouds. Figure 5 illustrates altocumulus clouds overlain by cirrostratus sheets with tops at 250 mb. The multilayer effect reduces, somewhat, the sharpness of the change in the equivalent radiation profile. Emissivity evaluation by equation (6) gives 75 percent for this relatively deep cloud. In figure 6, the only verified example of a high cirrostratus sheet, 9/10 overcast, the profile of equivalent radiation is almost discontinuous at 235 mb. and at 160 mb., the cirrus top. Emissivity was calculated to be 59 percent.

From the four verified cloud observations we have obtained a range in the effective long-wave cloud emissivities of from 98 percent for low stratiform clouds to 59 percent for a 9/10 cirrostratus sheet. Among the 75 emissivity computations made without aircraft verification of cloud bases and tops, the emissivities for all cloud types range from 10 to 100 percent. The latter calculations, based upon ground cloud observations, and with bases and tops of clouds located by the equivalent radiation profile, provided cirrus emissivities for 55 cases.

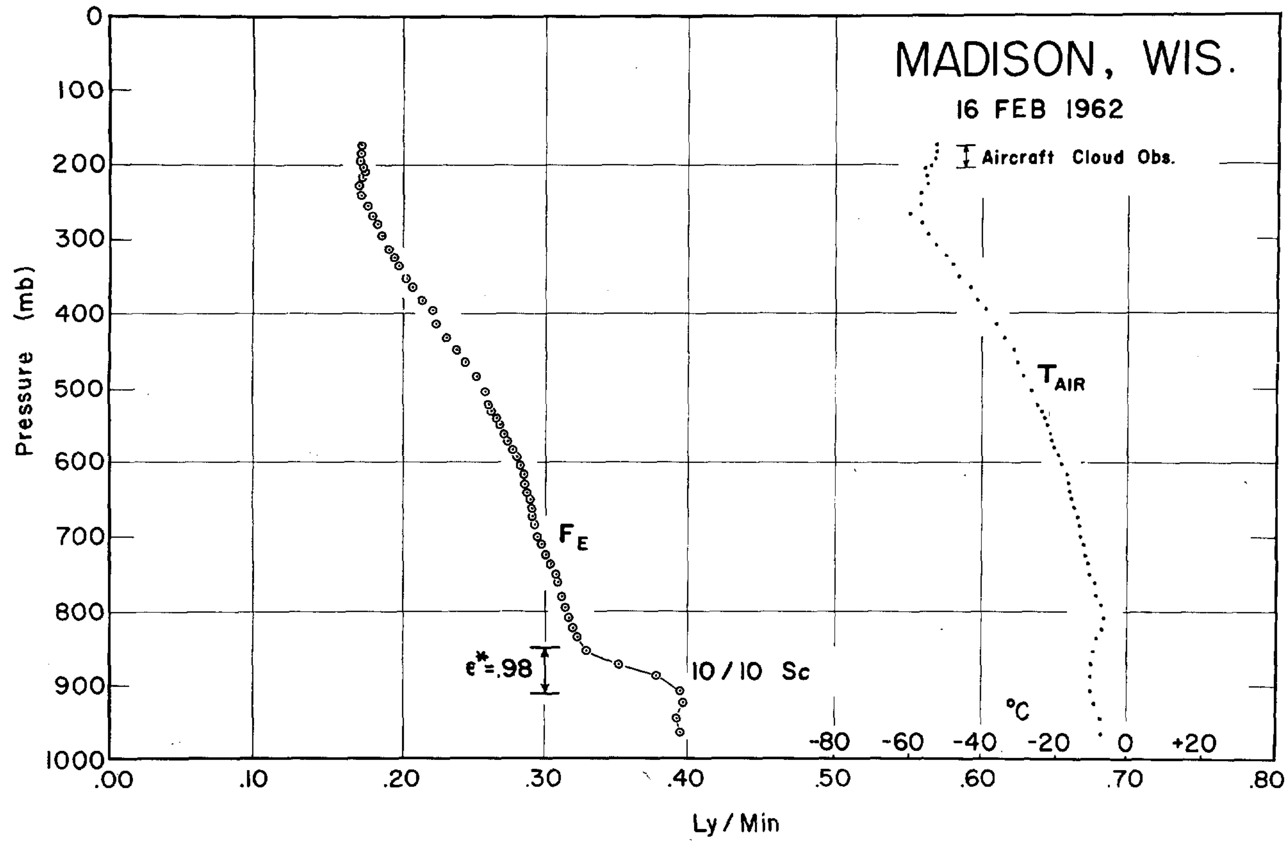

FIGURE 3.—Equivalent radiation, F_E, air temperature, T_{AIR}, and mixing ratio, Q, Madison, Wis., February 16, 1962.

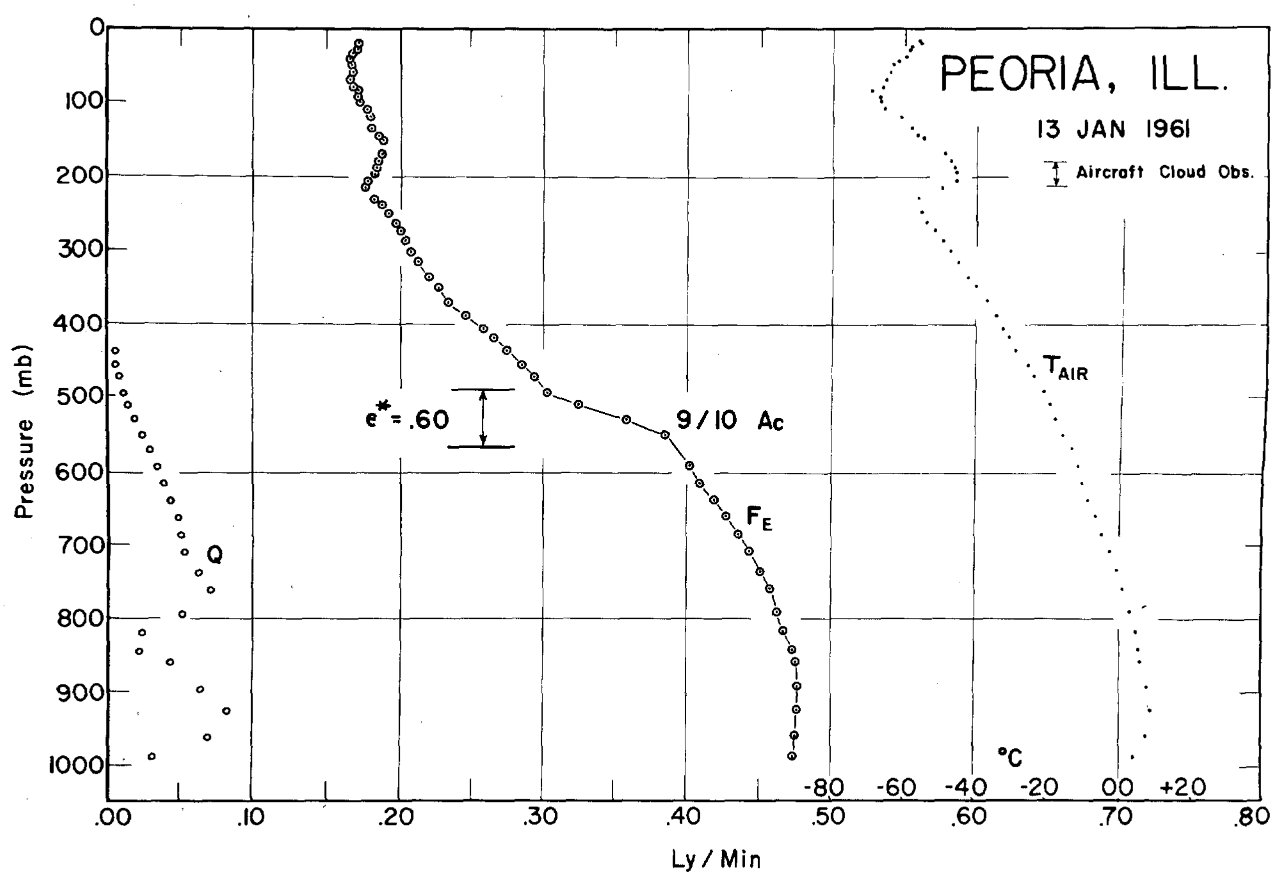

FIGURE 4.—Equivalent radiation, F_E, air temperature, T_{AIR}, and mixing ratio, Q, Peoria, Ill., January 13, 1961.

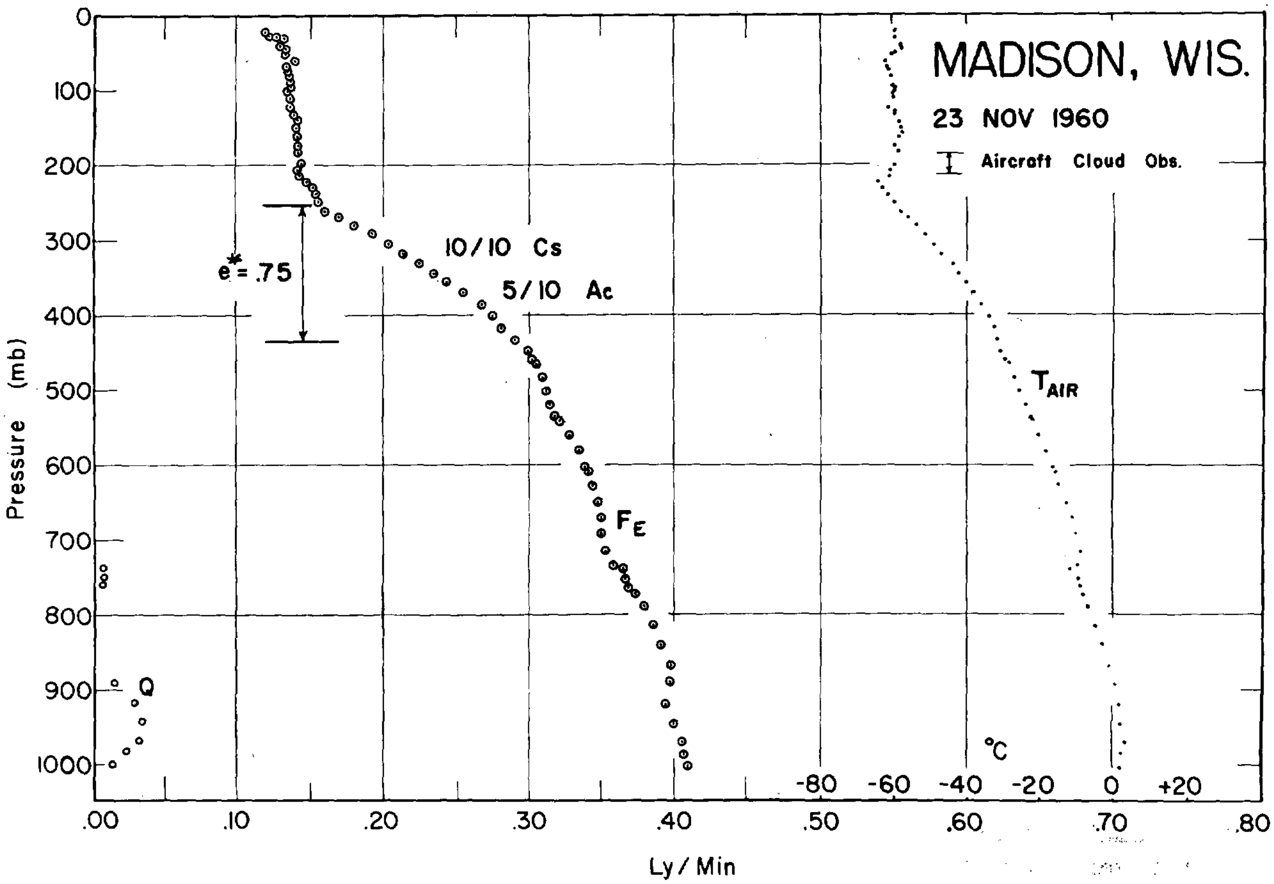

Figure 5.—Equivalent radiation, F_E, air temperature T_{AIR}, and mixing ratio, Q, Madison, Wis., November 23, 1960.

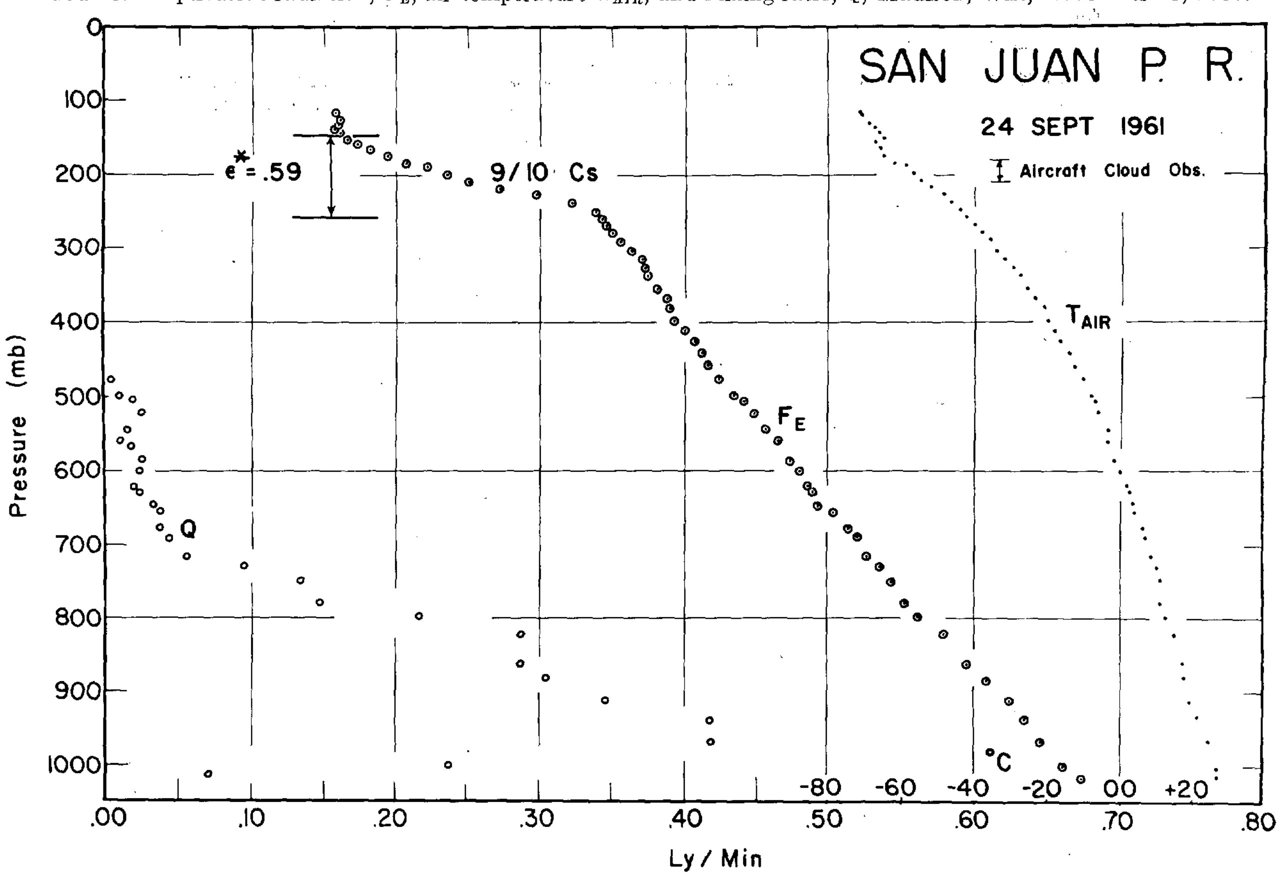

Figure 6.—Equivalent radiation, F_I, air temperature, T_{AIR}, and mixing ratio, Q, San Juan, P.R., September 24, 1961.

The cirrus emissivity range was from 10 to 75 percent,in general agreement with findings of Brewer and Houghton [1] from airborne bolometer measurements at cloud bases and tops. Potentially this method affords an important tool for a climatology of cloud type emissivities.

5. CLOUD EFFECTS ON SATELLITE RESULTS

The transfer equation employing flux emissivities over isothermal atmospheric layers provides a calculation of the upward infrared flux from conventional radiosonde information for comparison with TIROS II outgoing radiation measurements. The transfer equation for upward flux at a reference level in the atmosphere is given by

$$F\uparrow=\int_0^u \sigma\overline{T}^4(u)_w(\partial\epsilon_f(u)_w/\partial u)du+\int_0^u \sigma\overline{T}^4(u)_c(\partial\epsilon_f(u)_c/\partial u)du$$
$$+\int_0^u \sigma\overline{T}^4(u)_o(\partial\epsilon_f(u)_o/\partial u)du$$
$$+\left(1.0-\int_0^u (\partial\epsilon_f(u)_w/\partial u)du-\int_0^u (\partial\epsilon_f(u)_c/\partial u)du\right.$$
$$\left.-\int_0^u (\partial\epsilon_f(u)_o/\partial u)du\right)\sigma T_0^4 \quad (7)$$

The use of equation (7) in computing radiative flux by numerical techniques is described in textbooks dealing with radiant energy transfer. A recent use is described by Kuhn [7]. Effects of overlap in the 15.0-micron carbon dioxide band and the rotational water vapor band were minimized by reducing the carbon dioxide flux emissivities by 12 percent.

Two examples of cloud effects on TIROS outgoing radiation flux observations over International Falls, Minn., are cited. The satellite measurements of upward flux and the synoptic cloud observations were furnished by Soules [10]. On December 23, 1960 at 2100 LST the satellite sensors over International Falls observed an outward flux of 0.243 ly. min.$^{-1}$ At this time the total sky cover was 10/10 with 4/10 opaque sky cover. The calculated outward flux from equation (7), not considering clouds, is 0.272 ly min.$^{-1}$ employing the International Falls 1800 LST radiosonde data for this date. Recalculating the upward flux by equation (7) after interposing a 60 percent "black" cirriform cloud at 6.7 km., at measured air temperature, gives a calculated flux of 0.235 ly. min.$^{-1}$, in close agreement with the measured flux. The determination of the 6.7 km. cloud height was accomplished by successive computer trial computations. Cloud attenuation of the upward-streaming radiation is evident from the fact that transfer equation calculations based upon the atmospheric water vapor and carbon dioxide, alone, gave significantly larger upward flux calculations than the flux observed from the TIROS satellite. Only after a gray cloud interposed did the two fluxes agree.

On January 16, 1961, at 1600 LST, during a pass over International Falls, the TIROS II infrared sensors measured an outward flux of 0.250 ly. min.$^{-1}$ Calculating the upward flux after interposing a 60 percent "black" cloud at 7.3 km. reduced the previously calculated flux without presence of cloud to 0.255 ly. min.$^{-1}$ Again cloud attenuation is evident. From the results of these examples it appears that further study and calculations of cloud height and attenuation along these lines would be worth while. More TIROS data are now available.

6. CONCLUSION

In spite of the indirect method of obtaining the heights of cloud bases and tops, and in spite of the uncertainty in using air temperature in a cloud composed of liquid water droplets to obtain black body cloud flux, it appears that a preliminary climatology of the effective emissivity of clouds following this method is of value.

Moreover, the implications for cloud height determination as an adjunct to working out satellite cloud height techniques are of interest. Large changes in apparent earth temperature, measured by satellite sensors, may be quantitatively explained along lines such as those discussed and it is in these latter two lines of research that further work may be beneficial as a satellite backup study.

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