Cirrus Clouds and the Climate

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19 February 1971

ABSTRACT

Cirrus clouds may act to cool or warm the earth's surface, depending upon their infrared emissivity. Direct observation of cirrus cloud emissivities in mid-latitude and tropical environments indicates that cirrus may produce different effects at different latitudes. In the tropics, cirrus emissivities were large enough to cause a significant warming tendency while mid-latitude data showed a cooling effect.

Does the presence of cirrus clouds tend to warm or cool the earth's surface? Manabe and Strickler (1964) show that the effect of cirrus clouds, in a thermal equilibrium model of the atmosphere with convective adjustment, depends primarily upon two parameters: the cloud height, and its infrared emissivity or blackness to radiation in the 3300–100 cm^{-1} region.

At a given height, an emissivity greater than the "critical blackness" (see solid curve in Fig. 2) would result in warming at the earth's surface, while a cloud emissivity less than the "critical blackness" would cause cooling at the earth's surface. Because of the crucial role played by the cirrus emissivity, it's careful measurement is necessary in order to assess possible climatic effects of high clouds. Also, as pointed out by Manabe and Strickler (1964), Möller (1943), Riehl (1962) and Cox (1969), the cirrus layer itself is warmed by radiative convergence.

It is the purpose of this note to report measurements of the infrared emissivity of cirrus clouds and assess from the data at hand the possible role of cirrus clouds in modifying the climate.

The balloonborne radiationsonde records air temperature, relative humidity and radiometer temperatures, from which one may deduce the upward and downward infrared irradiance, all as a function of pressure. From the above data one must deduce cloud top and cloud base, discard broken cloud cases, and then calculate the infrared emissivity of the cloud deck.

Kuhn (1963) and Gergen (1958) show how the divergence of the upward and downward irradiance as a function of height may be used to detect clouds. The ability of the radiometer to detect clouds was utilized as follows. A numerical radiative transfer calculation (Kuhn and Cox, 1967) was performed using the measured profiles of temperature and relative humidity. However, the computation was repeated N times for an ascent with N data levels, each time assuming that a different layer of the atmosphere was saturated with water vapor. Such a series of computations was made for both the upward and downward irradiances. The calculated changes in the two irradiance values were then compared with the measured data. If the observed divergence through a layer exceeded the divergence calculated when that layer was assumed saturated, the layer was defined as containing a cloud. The technique described above performed satisfactorily when applied to data reported by Kuhn and Suomi (1965) for which independent aircraft observations of cloud top and base were available.

The problem of broken or horizontal inhomogeneous clouds is a nemesis to calculations of cloud emissivity. Smith (1968) shows that one cannot really distinguish between cloud amount (coverage) and cloud emissivity and that the product of the two parameters is the significant factor. In order to overcome this problem, the upward and downward irradiances were examined independently. One can perhaps best understand this technique by referring to Fig. 1.

In Fig. 1 at time t_1 the downward irradiance measured by the radiometer is affected by both clouds and clear sky. As the radiometer proceeds to height H_2 at time t_2, the downward irradiance is largely determined by the clear sky downward irradiance. The change in the downward irradiance between t_1 and t_2 could be misinterpreted as a cloud and an emissivity of the apparent "cloud" could be calculated. But since significant divergence of the upward irradiance would not occur during the time interval t_1 to t_2, the case would be disallowed. Only when significant divergence of both irradiances occurs in the same layer was the layer classified as cloud and an emissivity calculated. The above argument may be repeated for the time interval t_2 to t_3 but in this case only the upward irradiance would be affected.

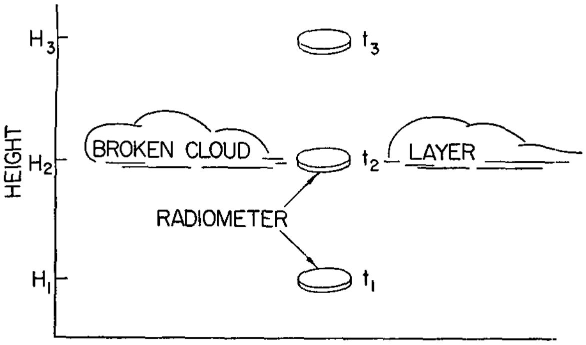

FIG. 1. Position of radiometer as a function of time and height relative to a broken cloud deck (time $t_1<t_2<t_3$; height $H_1<H_2<H_3$).

The emissivity calculation for layers designated as cloudy was carried out in a manner similar to that described by Gergen (1958). The emissivity is defined as the ratio of the observed change in irradiance through a cloud layer to the change which would have occurred had the cloud been black ($\epsilon=1.0$). The emissivity defined in this fashion is often called the "effective emissivity" since it includes the effects of all constituents in the cloud layer, gas and particulates alike, and implicitly contains effects of scattering since it is derived from observed irradiance data. We write this this emissivity as

$$\epsilon=(H_{EQ_B}-H_{EQ_T})/(\sigma T_B^4-\sigma T_T^4). \qquad (1)$$

In Eq. (1) $H_{EQ}=(H\uparrow+H\downarrow)/2$, where $H\uparrow$ and $H\downarrow$ are the upward and downward observed irradiances, the subscripts B and T refer to cloud base and cloud top, T is the absolute temperature, and σ the Stefan-Boltzman constant.

Eq. (1) represents a combination of the effects a cloud has on the upward and downward irradiance. It is necessary to use a parameter composed of the combined effects because the upward and downward irradiances incident upon the cloud have quite different spectral distributions of energy. The main difference occurs in the 1250–835 cm^{-1} region commonly called the "atmospheric window." For the upward irradiance beneath a cloud, the 1250–835 cm^{-1} region contains a relatively large amount of energy originating from the earth's surface. Interposing a grey cloud results in a decrease in this energy dictated by Planck's law by the factor $(e^{C\nu/T}-1)^{-1}$, where e is base of natural logarithms, C a constant, ν wavenumber, and T the absolute temperature. In essence we would be changing T in the above factor from a warm surface temperature to a cold cloud temperature, moderately decreasing the irradiance. However, for the downward irradiance above the cloud this spectral region is practically void of energy, except for an ozone contribution near 1042 cm^{-1}. Interposing a cloud emitting as a grey body quickly fills this gap in the energy spectrum. Therefore, a cloud is generally more efficient in modifying the downward irradiance and would have a higher grey body emissivity for this direction than for the upward irradiance.

Balloonborne radiationsonde data from 345 ascents taken during IQSY were analyzed in the aforementioned manner. The data represented two latitudinal regimes, mid-latitudes and tropics. The mid-latitude data were primarily from Greenbay, Wis., and Sterling, Va. Tropical soundings were from Guam and Palmyra Islands in the Pacific. Data were collected for all seasons except at Palmyra.

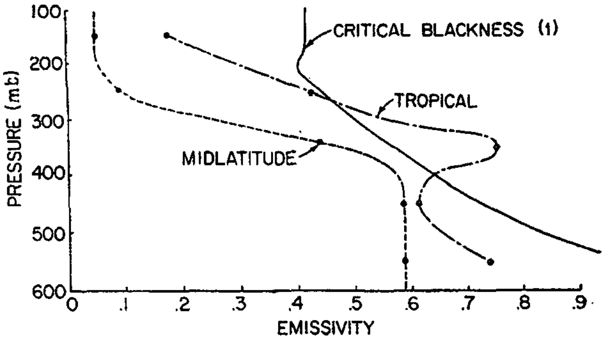

Fig. 2. Measured cirrus cloud infrared emissivities and the "critical blackness" curve from Manabe and Strickler (1964).

As clouds were detected they were placed in the even 100-mb layer in which they occurred. Then an arithmetic mean cloud emissivity for each 100-mb layer was computed. These are the plotted data points in Fig. 2.

The solid black curve is the "critical blackness" computed by Manabe and Strickler (1964). Emissivity values to the right of this curve would result in a net warming effect at the surface of the earth, values to the left would have a net cooling effect at the surface.

Looking at all the curves in Fig. 2, we see a strong tendency for surface warming by cirrus in the 300–400 mb layer for the tropical case. When we recall that the points connected by the curves in Fig. 2 are mean values, there is a chance for warming to occur in the 400–500 mb layer as well as the 200–300 mb layer. For the mid-latitude case, since the entire observed emissivity curve is to the left of the "critical blackness" curve, it appears here that cirrus, in general, has a net cooling effect on surface temperature.

A few general statements of the effects of cirrus are possible based on our present knowledge of the energy budget of the atmosphere. Cirrus clouds exert a surface heating tendency in the tropics, an area which already has a large energy surplus at the surface. While at the same time, cirrus has a net cooling effect on the surface in mid-latitudes. This combined effect enhances an existing latitudinal radiative energy imbalance. The surface in the tropics becomes more of a heat source while at higher latitudes the surface becomes more of a heat sink. It also appears that if cirrus with natural radiative characteristics were produced artifiically, as in the case of jet contrails, this imbalance situation would be further enhanced. The final significance of the net effect of cirrus clouds can best be established through the use of numerical models since we now have good estimates of cirrus emissivity from the data in Fig. 2.

This research was supported by the Environmental Research Laboratories, NOAA, under Grant E-22-55-70 (G) and by Grant GA-018783 from the Atmospheric Science Section, National Science Foundation.

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