NOTES AND CORRESPONDENCE

Changes in the Amount of Cloudiness and the Average Surface Temperature of the Earth

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1. Introduction

The average surface temperature of the planet earth depends upon the amount of incoming solar radiation and the magnitude of the greenhouse effect produced by the earth's atmosphere. The incoming solar radiation is a function of the earth's distance from the sun and the planetary albedo of the earth. The earth's planetary albedo consists of three components—the cloud albedo, the atmospheric albedo, and the earth's surface albedo. Of these three components, the cloud albedo makes the largest contribution to the planetary albedo. The magnitude of the greenhouse effect depends upon the infrared opacity or transmissivity of the atmosphere, which is a function of the amount and distribution of infrared absorbing gases, and the amount and height of the clouds. Thus, cloudiness influences the earth's temperature in two conflicting ways. For example, an increase in the amount of cloudiness will, on the one hand, increase the earth's planetary albedo, thus causing a decrease in the amount of solar radiation available to heat the earth, which would lead to a decrease in average surface temperature, and on the other hand, increase the magnitude of the greenhouse effect, which would lead to an increase of the average surface temperature.

It is of interest to estimate the changes in average surface temperature that would occur if the average amount of cloudiness was changed substantially from its present value of about 50 per cent. We have developed a simple greenhouse model that allows such an estimate to be made. This greenhouse model permits the average surface temperature to be computed if one knows the planetary albedo, the amount and height of the clouds, and the infrared opacity of the atmospheric gases.

2. Greenhouse model

In our model, it is assumed that the earth's atmosphere consists of two layers: 1) a lower layer, the troposphere, in which the temperature decreases linearly with height at a given rate, and 2) an upper layer, the stratosphere, in which the temperature is constant with height. The following radiative equilibrium conditions are assumed to prevail: 1) there is a balance between incoming solar radiation and outgoing infrared radiation at the top of the atmosphere, and 2) the stratosphere is in gross infrared radiative equilibrium—that is, the net flux of infrared radiation at the tropopause is equal to the net flux of infrared radiation at the top of the atmosphere.

Additional assumptions include the following: 1) the atmosphere acts as a grey absorber for infrared radiation; 2) the clouds behave as black bodies for infrared radiation.

With this atmospheric model, one can compute the net infrared flux at the tropopause and at the top of the atmosphere. With the use of the two radiative equilibrium conditions, it is possible to determine the average surface temperature, and, in addition, the pressure at the tropopause.

In a grey troposphere with constant temperature lapse rate, the black body flux varies with infrared opacity—which is directly proportional to pressure—as follows:

$$(B/B_g)=(\tau/\tau_g)^{4k} \tag{1}$$

where k is a constant that depends upon the lapse rate, and the subscript g refers to the surface.

For the stratosphere, in which the temperature is constant with altitude, we have

$$B=B(\tau_t), \tag{2}$$

where τ_t is the infrared opacity of the stratosphere, and $B(\tau_t)$ is the black body flux at the level τ_t.

The cloud-tops are assumed to be located at one level in the atmosphere; the infrared opacity of the atmosphere above the cloud-top is represented by τ_c. A fraction n of the sky is covered by clouds. The variation of B as a function of τ and the position and amount of clouds are shown schematically in Fig. 1.

From the two radiative equilibrium conditions, one can derive the following two equations (see Ohring *et al.*, 1964, for details of the derivation).

$$(1-n)\left[2E_3(\tau_g-\tau_t)+\frac{2}{\tau_g{}^{4k}}\int_{\tau_t}^{\tau_g}\tau^{4k}E_2(\tau-\tau_t)d\tau\right]$$

$$+n\left[p^{4k}2E_3(p\tau_g-\tau_t)+\frac{2}{\tau_g{}^{4k}}\int_{\tau_t}^{p\tau_g}\tau^{4k}E_2(\tau-\tau_t)d\tau\right]-2\left(\frac{\tau_t}{\tau_g}\right)^{4k}[1-2E_3(\tau_t)]$$

$$=(1-n)\left[2E_3(\tau_g)+\frac{2}{\tau_g{}^{4k}}\int_{\tau_t}^{\tau_g}\tau^{4k}E_2(\tau)d\tau\right]+n\left[p^{4k}2E_3(p\tau_g)+\frac{2}{\tau_g{}^{4k}}\int_{\tau_t}^{p\tau_g}\tau^{4k}E_2(\tau)d\tau\right]. \quad (3)$$

$$\left(\frac{T_e}{T_g}\right)^4=(1-n)\left[2E_3(\tau_g)+\frac{2}{\tau_g{}^{4k}}\int_{\tau_t}^{\tau_g}\tau^{4k}E_2(\tau)d\tau\right]+n\left[p^{4k}2E_3(p\tau_g)\right.$$

$$\left.+\frac{2}{\tau_g{}^{4k}}\int_{\tau_t}^{p\tau_g}\tau^{4k}E_2(\tau)d\tau\right]+\left(\frac{\tau_t}{\tau_g}\right)^{4k}[1-2E_3(\tau_t)]. \quad (4)$$

In these equations, the E's are exponential integrals, p represents the ratio (τ_c/τ_g), and T_e is the effective temperature of the incoming solar radiation after correcting for albedo losses.

If the various parameters are specified, equation (3) can be solved for τ_t by using numerical techniques for the integrations and an iterative procedure. Once τ_t is determined, it can be substituted into equation (4), which is then solved to obtain the magnitude of the greenhouse effect, represented by (T_g/T_e). The numerical techniques are described in detail in Ohring *et al.* (1964).

3. Computations and results

Given the incoming solar radiation, the amount of clouds, the infrared opacity of the clear atmosphere, the tropospheric lapse rate, and the ratio of cloud-top pressure to surface pressure, we can compute, with the greenhouse model described above, the average surface temperature of the earth. In particular, we would like to perform this computaton for three different amounts of total cloudiness: the present average—50 per cent (London, 1957); no cloudiness at all—0 per cent; and a large amount of cloudiness—90 per cent. The various parameters necessary for the computations are specified as follows. The infrared opacity of the clear atmosphere, τ_g, is taken to be 1.6, which corresponds to an infrared flux transmissivity of 10 per cent. The cloud-tops are assumed to be located at one level in the atmosphere, which is taken to be 500 mb; hence, $p=0.5$. This is an average value based upon our analysis of climatological cloud statistics presented by London (1957); a value of about 5 km for the average cloud-top height was obtained in this analysis. The tropospheric lapse rate is taken to be 6 K km^{-1}, which corresponds to a k value of 0.176.

For the present average amount of cloudiness, 50 per cent, the planetary albedo is 35 per cent, and for totally clear skies, the planetary albedo is 15 per cent; both of these values are based upon computations by London (1957). The planetary albedo for the case of 90 per cent cloudiness is assumed to be 50 per cent, based upon an extrapolation of the albedo for no clouds and the albedo for 50 per cent cloudiness. The amounts of cloudiness and the corresponding albedos are shown in Table 1.

Table 1. Amount of cloudiness and corresponding planetary albedo.

Amount of cloudiness	(%)	0	50	90
Planetary albedo	(%)	15	35	50

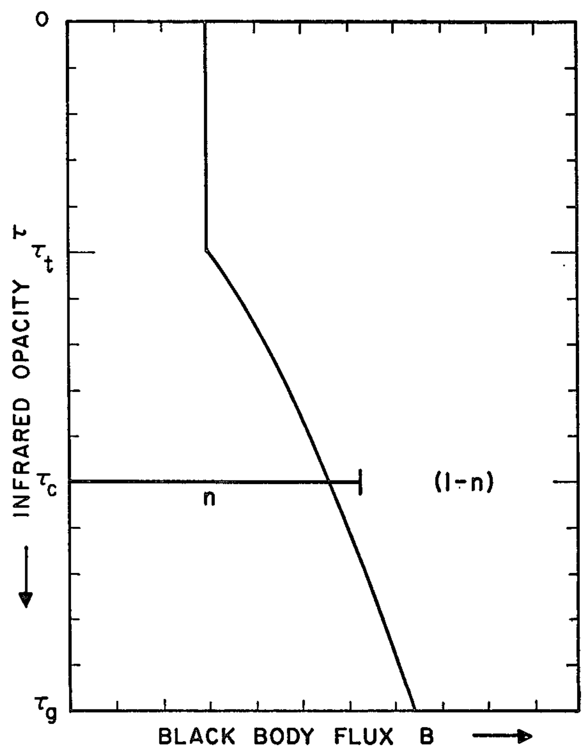

Fig. 1. Schematic diagram of variation of black body flux with infrared opacity, and amount and position of clouds.

The effective temperature of the incoming solar radiation remaining after albedo losses, T_e, is obtained from

$$\sigma T_e^4 = (1-A)I_0,$$

where σ is the Stefan-Boltzmann constant, A is the planetary albedo, and I_0 is the average insolation at the top of the atmosphere, which is equal to 0.5 cal cm^{-2} min^{-1}.

For the computations, it is assumed that there are no changes in atmospheric infrared opacity, in tropospheric or stratospheric temperature lapse rate, and in the height of the cloud-tops as the amount of cloudiness is changed to 0 per cent and to 90 per cent. The results of the computations for the three different cloud amounts are shown in Table 2.

TABLE 2. Changes in the amount of cloudiness and the average surface temperature of the earth.

Amount of cloudiness (%)	T_g/T_e	T_e(°K)	T_g(°K)	τ_t/τ_g
0	1.13	270	305	0.263
50	1.186	252	299	0.181
90	1.23	236	290	0.131

In Table 2, the magnitude of the greenhouse effect is represented by T_g/T_e, where T_g is the computed average surface temperature, and T_e is the effective temperature of the incoming solar radiation. The ratio τ_t/τ_g represents the computed ratio of tropopause pressure to surface pressure.

For 50 per cent cloudiness—the present amount—the computed average surface temperature is 299K, which is within 4 per cent of the observed average surface temperature of about 288K. As the amount of cloudiness increases, the magnitude of the greenhouse effect increases but the effective temperature of the incoming solar radiation decreases. The net result is a decrease in surface temperature with increasing cloudiness amount. If the cloudiness amount is increased to 90 per cent, the surface temperature would be 290K; this represents a decrease of 9K from the computed value of the present average surface temperature. If all clouds are eliminated from the atmosphere, the surface temperature would be 305K; this represents an increase of 6K above the computed value of the present average surface temperature. Thus, it appears that even with quite dramatic changes in the amount of cloudiness, the earth's average surface temperature would change by less than 10K. This small range is due to the dual role that cloudiness plays in the earth's energy budget.

The last column of Table 2 shows the computed ratio of tropopause pressure to surface pressure. For the present amount of cloudiness, this turns out to be 0.181, which corresponds to an average tropopause pressure of 181 mb. The observed average tropopause pressure is probably close to 200 mb. From Table 2 it can be seen that as the amount of cloudiness increases, the tropopause pressure decreases, going from 263 mb with no clouds to 131 mb with 90 per cent cloudiness.

4. Conclusions

Calculations with a simple greenhouse model for the earth's atmosphere indicate that: 1) the average surface temperature would decrease by 9K if the average amount of cloudiness is increased from its present value of 50 per cent to a value of 90 per cent, and 2) the average surface temperature would increase by 6K if all clouds were eliminated from the atmosphere. More detailed computations of changes in the earth's surface temperature as a result of changes in average cloud amount should consider the changes in atmospheric infrared opacity (due to changes in water vapor content), in vertical temperature structure, and in average height of the clouds that would probably accompany large scale changes in the average total amount of cloudiness. However, the present computations do yield some insight on the effect of changes in cloudiness on the earth's surface temperature, and should be useful in studies of climatic change.

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