ON THE RELATIONS BETWEEN OUTGOING LONG-WAVE RADIATION, ALBEDO, AND CLOUDINESS

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ABSTRACT

Satellite observations of outgoing long-wave radiation and albedo presented by Winston are used to test a highly simplified radiation model. Computations with the model are consistent with the satellite observations and show that the outgoing long-wave radiation is inversely correlated to the albedo and cloudiness on a broad scale. However, the satellite values of albedo are much smaller than the computed values.

In order to lower the computed values of albedo so as to agree with the satellite ones, we would have to assume that the absorption of short-wave radiation by the water vapor, dust, ozone, and clouds in the atmosphere is equal roughly to twice the values estimated by London.

Assuming that the satellite values are correct, the discrepancies in outgoing long-wave radiation are probably due to the crudeness in the values of the effective atmospheric radiation temperature used in the model which are not well known and which can, therefore, be determined from the satellite values of outgoing long-wave radiation and cloudiness.

1. INTRODUCTION

In the preceding paper, Winston [10], using satellite data, has shown that the long-wave radiation leaving the earth is inversely correlated to the albedo on a broad scale, particularly over oceans and non-desert regions.

The purpose of this note is to use the same satellite observations to test a highly simplified radiation model that contains as parameters both the albedo and the outgoing long-wave radiation. This model can therefore be used to explore the relation between these two parameters as well as their dependence on cloudiness and temperature.

2. OUTGOING LONG-WAVE RADIATION

We shall assume that the surfaces of the earth and of the clouds radiate as black bodies. Furthermore, in this first approximation model the cloudless atmosphere will also be considered as a black body except in the region from 8 to 13μ, where a transparent window will be postulated.

Using this radiation model in the way previously described by the author [1], we obtain the following formula:

$$\gamma = a_1 + \epsilon a_5 + (1-\epsilon) a_3 T'_s + a_4 T' \qquad (1)$$

where γ is the outgoing long-wave radiation, and ϵ is the fractional cloud cover; $T'_s = T_s - T_{s_0}$ where T_s is the surface temperature and T_{s_0} is a constant; $T' = T - T_0$ where T is the effective radiation temperature of the atmosphere that will be determined below and T_0 is a constant. Furthermore, since the temperature is in Kelvin degrees, we have chosen T_0 and T_{s_0} such that $T_0 >> T'$ and $T_{s_0} >> T'_s$. The constants a_1, a_5, a_3, and a_4 are given by

$$a_1 = F(T_{s_0}) + \sigma T_0^4 - F(T_0),$$
$$a_5 = F(T_{c_0}) - F(T_{s_0}),$$
$$a_3 = (\partial F/\partial T)_{T=T_{s_0}},$$
$$a_4 = 4\sigma T_0^3 - (\partial F/\partial T)_{T=T_0}.$$

The function $F(T_i)$ represents the area below the black-body curve corresponding to the window of the radiation model, which is taken between 8μ and 13μ, $\sigma = 8215 \times 10^{-14}$ cal. cm.$^{-2}$°K.$^{-4}$ min.$^{-1}$, and T_{c_0} is the temperature of the upper boundary of the cloud cover.

Taking $T_0 = 229.5°$ K., $T_{s_0} = 288°$ K., and $T_{c_0} = 261°$ K., we obtain the following values for the coefficients in formula (1):

$$a_1 = 2.4768 \times 10^5 \text{ gm. sec.}^{-3},$$
$$a_5 = -4.946 \times 10^4 \text{ gm. sec.}^{-3},$$
$$a_3 = 2.119 \times 10^3 \text{ gm. sec.}^{-3}\ °\text{K.}^{-3},$$
$$a_4 = 1.809 \times 10^3 \text{ gm. sec.}^{-3}\ °\text{K.}^{-1}.$$

In his pioneering work, Simpson [9], who was the first to introduce the concept of a transparent radiation window in meteorology, used the tropopause as the level of effective atmospheric radiation temperature.

More recent work by Elsasser [6] has shown that the amount of water vapor above approximately the 300-mb. level is negligibly small. Therefore it is more realistic to assume that the effective radiation temperature of the atmosphere is near this level. For this reason we have chosen $T_0 = 229.5°$ K., which is the mean temperature at about 300 mb. for April at 35° N. latitude. The departure T' from the mean value T_0 is not well known, and can be determined from formula (1), with satellite values of outgoing long-wave radiation and cloudiness, as will be shown below.

From (1) we see that γ, which is always positive, is equal to a positive constant a_1, plus a negative function, $\epsilon a_5+(1-\epsilon)a_3T'_s+a_4T'$. Therefore, γ is inversely correlated to ϵ, on a broad scale. However, one expects departure from this correlation, especially in middle and higher latitudes, because of the contribution of the terms $(1-\epsilon)a_3T'_s+a_4T'$.

Over desert areas, the correlation fails because, in this case, ϵ is negligibly small, and in formula (1) γ becomes independent of ϵ.

We shall carry out computations using the zonally averaged values of cloudiness for spring 1962, from TIROS IV, given by Clapp [5], and which are shown by the continuous line in figure 1c. For the surface temperature we shall use normal values for April.

The computed values of outgoing long-wave radiation, using formula (1) with these values of cloudiness and surface temperatures and with $T'=0$, are represented by curve II of figure 1a. Its comparison with the zonally averaged satellite values for April 1962 (curve I) shows good agreement in the general pattern. However, except in the middle latitudes, the computed values are lower than the satellite values. Both the satellite and computed values show an inverse correlation with the cloudiness, especially in lower latitudes. The departures from the inverse correlation in middle latitudes are due to the contributions of the terms that depend on the temperature, whose gradient becomes important at middle latitudes.

In formula (1) there exists considerable uncertainty in the choice of the effective atmospheric radiation temperature which was taken equal to T_0. If we assume that the satellite values are correct, we can determine the increase T' in the values of T_0, which would yield the same values as the satellite ones. The computed atmospheric radiation temperature, $T=T_0+T'$, and the corresponding isobaric level are given in table 1 for different latitudes. The corresponding isobaric levels were obtained from London's ([7], p. 91) values, by linear interpolation between temperature and pressure values given at intervals of 1 km.

TABLE 1.—*Effective atmospheric radiation temperature* (T) *for April 1962, computed using satellite values of outgoing long-wave radiation and cloudiness*

Latitude (deg.)	Isobaric Surface (mb.)	T (° C.)	T' (° C.)
5	212.0	−49.3	−5.8
15	195.5	−53.9	−10.4
25	206.5	−53.1	−9.6
35	265.6	−48.1	−4.6
45	324.0	−43.1	−0.4
55	363.0	−41.6	−1.9

3. THE ALBEDO

The albedo can be estimated from the formula

$$(1-\alpha_T)I=[1-(1-k)\epsilon](1-\alpha)(Q+q)_0+(a_2+a'_2+\epsilon b_3)I \tag{2}$$

where α_T is the albedo, I the insolation on a horizontal surface, at the top of the atmosphere, $(Q+q)_0$ is the total radiation received by the surface with clear sky, k is a function of latitude, ϵ is the cloud cover, a_2, a'_2, and b_3 are functions of latitude and season, and α is the albedo of the surface of the earth.

The left side of (2) is the total short-wave radiation absorbed by the earth-atmosphere system. The first term in the right side is the short-wave radiation absorbed by the surface of the earth, where the Savino-Ångström formula (see [4], p. 30) is used to estimate the radiation received at the surface.

Values of $(Q+q)_0$ as function of latitude and month and those of k, as function of latitude, are given by Budyko ([4], p. 32).

The second term in the right-hand side of formula (2) is the short-wave radiation absorbed in the atmosphere, where a_2I is the absorption by water vapor and dust, a'_2I the absorption by ozone in the stratosphere, and ϵb_3I the absorption by the clouds. Except for a'_2, a summary of all the parameters that appear in formula (2) is given elsewhere for all latitudes and seasons ([2, 3]). The values of a'_2I will be taken equal to those of London [7]. Furthermore, for the surface albedo α, we will use Posey and Clapp's [8] values.

From (2) it follows that

$$\alpha_T=1-[1-(1-k)\epsilon](1-\alpha)\frac{(Q+q)_0}{I}-a_2-a'_2-\epsilon b_3. \tag{3}$$

Since k and α are smaller than one, and $(Q+q)_0/I$ and ϵb_3 are never negative, it follows that α_T is linearly correlated to the cloudiness ϵ, except when ϵ is equal to zero.

The computations of the zonally averaged albedo made with formula (3) for April are shown in figure 1b. Curve II represents the values computed when Clapp's [5] satellite values of cloudiness for spring 1962 are used. Its comparison with Winston's [10] satellite values (curve I of fig. 1b) shows fair agreement in the general pattern. However the computed values are much higher than the satellite values. If the units of the albedo are in percent, the average difference is equal to 14.

In formula (2) the term representing absorption of short-wave radiation in the atmosphere by water vapor, dust, ozone, and clouds, $(a_2+a'_2+\epsilon b_3)I$, is probably the one that contains most of the uncertainties. The values used in the computations were essentially those of London [7] which (in ly. min.$^{-1}$) are equal to 0.110, 0.102, 0.102, 0.091, 0.084, and 0.076 at latitudes 5°, 15°, 25°, 35°, 45°, and 55°, respectively. To obtain the satellite albedo values we would require an increase of absorption of short-wave radiation of 0.118, 0.098, 0.060, 0.077, 0.086, and 0.090 respectively, at the same latitudes. Therefore we would have to assume that the absorption by the atmosphere is equal roughly to two times the values assumed in the computations. This increase seems to be too large,

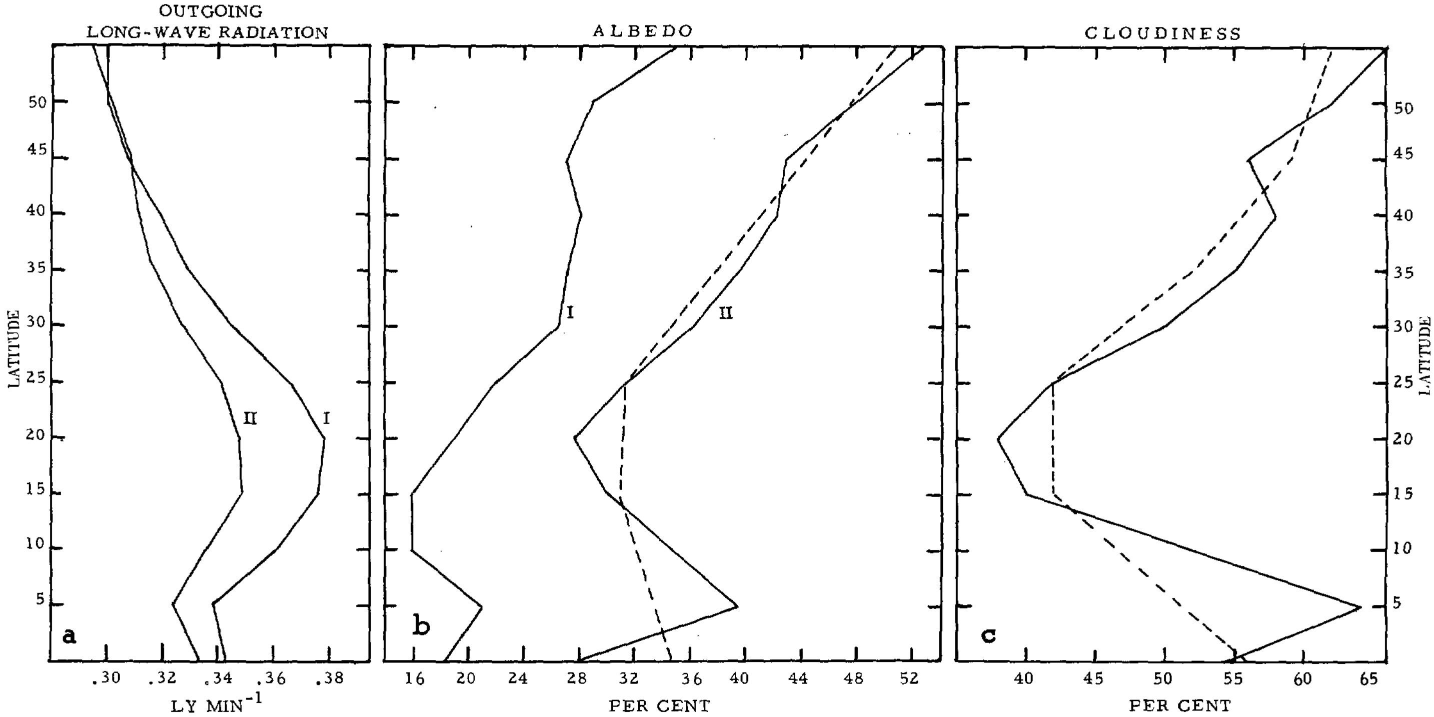

FIGURE 1.—Zonally averaged values of (a) outgoing long-wave radiation, (b) albedo, and (c) cloudiness as functions of latitude in the Northern Hemisphere: In (a), curve II is the outgoing long-wave radiation computed from Clapp's [5] satellite cloudiness for spring 1962 and an effective atmospheric radiation temperature equal to 229.5°K.; and curve I is Winston's [10] satellite outgoing long-wave radiation for April 1962. In (b), curve II is the albedo computed from Clapp's satellite cloudiness for spring 1962; the dashed curve is the albedo computed from London's [7] normal values of cloudiness for April; and curve I is Winston's satellite albedo for April 1962. In (c), the continuous curve is Clapp's satellite cloudiness for spring 1962 and the dashed line is London's normal cloudiness for April.

and suggests that it is very likely that the satellite albedo values are too low, and that more attention has to be given to their calibration.

The dashed line in figure 1b is the computed albedo, using London's [7] normal April values for cloudiness which are shown by the dashed line in figure 1c.

From the comparison of the dashed curve and curve II with curve I in figure 1b it is clear that the computed albedo agrees better with Winston's satellite albedo, when we use in the computations the corresponding satellite cloudiness for the same year, 1962, instead of the normal values.

The satellite cloudiness shows, in fact, strong anomalies which are reflected in both the albedo and the outgoing long-wave radiation. For example at 5° latitude, Clapp's satellite cloudiness (continuous line in fig. 1c) is 13 percent larger than the normal cloudiness. This anomaly in cloudiness introduces an anomaly of 6.3 percent in the albedo and of about -0.013 ly. min.$^{-1}$ in the outgoing long-wave radiation.

Table 2 shows the increase of albedo and outgoing long-wave radiation which results from an increase of 10 percent in cloudiness.

TABLE 2.—*Increase of albedo ($\Delta\alpha_T$) and outgoing long-wave radiation ($\Delta\gamma$) due to an increase of one-tenth in cloudiness*

	Latitude (deg.)					
	5	15	25	35	45	55
$\Delta\alpha_T$ (percent)	4.5	4.6	4.7	4.6	4.1	3.1
$\Delta\gamma$ (ly. min.$^{-1}$)	−0.011	−0.011	−0.010	−0.007	−0.005	−0.003

4. RELATIONS BETWEEN OUTGOING LONG-WAVE RADIATION AND ALBEDO

From the above results it follows that the outgoing long-wave radiation is inversely correlated to the albedo on a broad scale, except when ϵ is negligibly small, or when the terms that depend on the temperature and surface albedo in formula (1) destroy the correlation.

Eliminating ϵ from (1) and (2) we obtain the explicit relation between albedo and outgoing long-wave radiation:

$$\alpha_T = -A\gamma + B \tag{4}$$

where

$$A = \frac{b_3 - (1-k)(1-\alpha)(Q+q)_0/I}{a_5 - a_3 T'_s}$$

$$B = A(a_1 + a_3 T'_s + a_4 T') + 1 - a_2 - a'_2 - (1-\alpha)(Q+q)_0/I.$$

To test formula (4) we shall carry out computations at the equator, where both the satellite data and the arguments given above indicate in a striking way the existence of a relation of type (4) with A and B almost constants.

We shall carry out computations using normal zonally averaged values of surface temperature for April, therefore we will take $T'_s=11°$ C. For the atmospheric effective radiation temperature we shall use the zonally averaged value adjusted to yield the observed satellite outgoing long-wave radiation at the equator. Therefore, we shall take $T'=-3.8°$ C., and shall use the following values: $\alpha=0.06$, $(Q+q)_0/I=0.775$, $a_2=0.134$, $a'_2=0.022$, $b_3=0.034$, and $k=0.31$. The resulting equation is

$$\alpha_T=-4.18\gamma+1.710 \tag{5}$$

where γ is in ly. min.$^{-1}$ and α_T is fractional.

In figure 2, curve I represents the satellite values of the outgoing long-wave radiation at the equator, as a function of longitude for April 1962; curve II represents the satellite values of albedo for the same period; and curve III, the values of albedo computed from formula (5), using the satellite values of outgoing long-wave radiation (curve I). Comparison of curve II with curve I shows that, as pointed out by Winston, there exists a striking inverse correlation between albedo and outgoing long-wave radiation at the equator.

Comparison of curve III with curve II shows that the computed values from formula (5) agree remarkably well with the satellite-observed values of albedo, except that the satellite values are smaller than the computed values by about 8 percent over oceans and about 11 percent over continents.

In conclusion it can be stated that formulas (1), (2), and (4) can be used as an aid to understand and, possibly, adjust the satellite data; and at the same time the satellite observations can be used to improve the formulas.

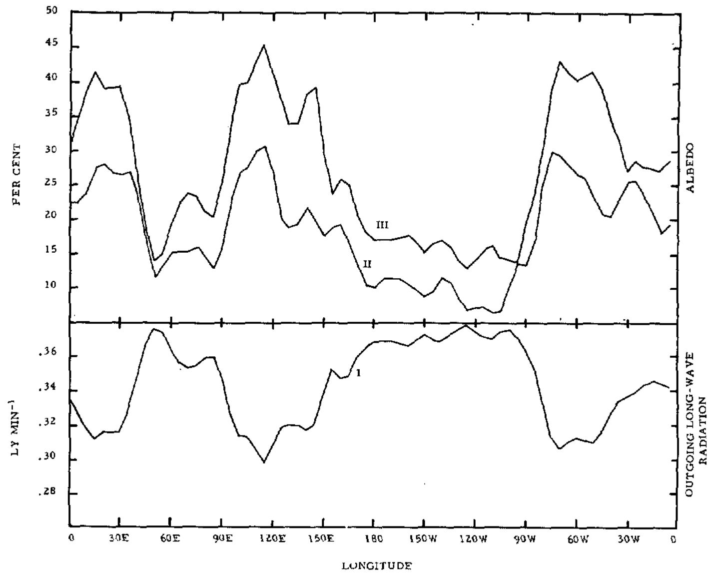

FIGURE 2.—Outgoing long-wave radiation, in ly. min.$^{-1}$, and albedo in percent, at the equator for April 1962: Curve I represents Winston's [10] satellite outgoing long-wave radiation values; curve II, Winston's satellite albedo values; and curve III, computed albedo values.

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