On the Relationship between Clear-Sky Planetary and Surface Albedos

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ABSTRACT

Based on simulations, a simple linear relationship is derived between planetary albedo and the surface albedo for the case of clear skies. This relationship enables one to estimate the planetary albedo, given only the surface albedo, and vice versa. The standard error of estimate is 0.028. The estimation of planetary albedo from surface albedo is checked by comparing zonally averaged clear-sky planetary albedos, estimated from zonally averaged surface albedos, to satellite determinations of zonally averaged minimum albedos for monthly mean conditions. The minimum albedos are assumed to be representative of the clear-sky planetary albedos. The results show root-mean square differences of 0.05 between the estimated clear-sky planetary albedos and the minimum albedos.

More accurate relationships can be obtained if one uses an additional parameter—the solar zenith angle. In this case, the standard errors of estimate are reduced to 0.017 for a zenith angle of 0°, 0.018 for a zenith angle of 60° and 0.021 for a zenith angle of 85°.

1. Introduction

The purpose of this note is to show that a simple linear relationship can be derived for estimating clear-sky planetary albedo given only surface albedo, and vice versa. Such a relationship has a number of important applications including climate modeling, cloudiness determinations from satellite observations, and surface energy budget estimates from satellite observations.

2. Derivation of relationship

The relationship between planetary albedo and surface albedo for clear-sky conditions is developed from simulations with the solar radiation absorption model described by Lacis and Hansen (1974). In their approach, absorption of solar radiation is parameterized as a function of the water vapor distribution, the zenith angle of the sun, the albedo of the earth's surface and the ozone distribution. It can be shown that using these parameterizations, the clear-sky planetary albedo can be represented as the sum of two functions

$$\alpha = f_1(\mu_0, O_3) + f_2(\mu_0, H_2O, O_3, R_g), \quad (1)$$

where μ_0 is the cosine of the solar zenith angle, O_3 and H_2O represent the ozone and water vapor distributions, respectively, and R_g is the surface albedo. Here f_1 can be written as (symbols correspond closely to those of Lacis and Hansen 1974)

$$f_1 = \bar{R}_r(\mu_0) - \bar{R}_a(\mu_0)[A_{O_3}(x_t + x_t^*) - A_{O_3}(x_t)], \quad (2)$$

where $\bar{R}_r(\mu_0)$ is the albedo for a pure Rayleigh atmosphere, which, in parameterized form, is given by

$$\bar{R}_r(\mu_0) = 0.28/(1 + 6.43\mu_0), \quad (3)$$

where $\bar{R}_a(\mu_0)$ is the Rayleigh albedo of the underlying atmosphere for ozone absorption,

$$\bar{R}_a(\mu_0) = 0.219/(1 + 0.816\mu_0). \quad (4)$$

In Eq. (2) A_{O_3} is the O_3 absorptivity, x_t the total atmospheric O_3 path length for the incoming solar radiation, and x_t^* is the total O_3 path length for the solar radiation reflected by a Rayleigh atmosphere. The term in brackets represents the O_3 absorptivity for the solar radiation scattered upwards by a Rayleigh atmosphere for which the underlying surface has an albedo of zero. Thus, f_1 represents the planetary albedo of a clear (i.e., cloudless) atmosphere above a non-reflecting surface. The f_2 can be written as

$$\begin{aligned} f_2 = \{1 - \bar{R}_r(\mu_0)(1 - 0.0685R_g)^{-1} - A_{O_3}(x_t) - A_{H_2O} \\ \times (y_t + y_t^*) - [1 - 0.856\bar{R}_a(\mu_0)](1 - 0.144R_g)^{-1} \\ \times [A_{O_3}(x_t + x_t^*) - A_{O_3}(x_t)]\}R_g, \quad (5) \end{aligned}$$

where A_{H_2O} is the water vapor absorptivity, y_t is the total atmospheric H_2O path length for the incoming solar radiation, and y_t^* is the total H_2O path length for solar radiation reflected by the surface. The sum of the terms within the braces can be thought of as an effective "two way" transmittance of the atmosphere for solar radiation that traverses the atmosphere and is scattered or reflected back to space. The denominators account for multiple reflections between the atmosphere and the surface.

With this treatment of solar radiation, the planetary albedo was simulated for a variety of surface albedos, solar zenith angles and water vapor distributions. Application of multiple regression analysis to the resulting data set revealed that the planetary albedo is mainly a linear function of the surface albedo. For example, based upon 1080 data points, surface albedo alone was able to explain 98% of the variance of planetary albedo, with a standard error of planetary albedo of 0.028. Thus, for many problems a one-predictor regression scheme using surface albedo alone appears to be justified.

The derived relationship is of the form

$$\alpha = a + bR_g \tag{6}$$

with $a = 0.0587$ and $b = 0.730$.

Recalling the above discussion of the solar absorption model, one can identify a with the mean planetary albedo of a clear atmosphere above a nonreflecting surface and b with the mean effective "two-way" transmittance of the clear atmosphere. For low surface albedos the planetary albedo is greater than the surface albedo; this is a result of the importance of the contribution of Rayleigh scattering to the planetary albedo when the surface albedo is small. At large surface albedos, the planetary albedo is less than the surface albedo; this is due to the depletion of the solar radiation by atmospheric absorption, which reduces the reflected solar radiation reaching the top of the atmosphere. There is a crossover point at which the planetary and surface albedos are equal. For Eq. (6), this occurs at an albedo value of 0.22.

3. Test of relationship

To assess the reliability of the calculated relationship, the derived regression equation was tested using observed data. These consist of zonally averaged minimum planetary albedo derived from NOAA scanning radiometer (SR) observations (assumed to be equal to the clear sky albedo), zonally averaged surface albedo by Robock (1980), and the so-called clear sky, local-noon surface albedo by Hummel and Reck (1979). Surface albedos from both Robock, and Hummel and Reck were read off from their figures for the months of January, April, July and October. In the case of Hummel and Reck's data, their seasonal values were assumed to represent the mid-seasonal months. Further, in order to avoid certain uncertainties in the data at higher latitudes, all data used are restricted to 60°N to 60°S. The method of assessing the derived equation was to compute the root-mean-square error (RMSE) of the planetary albedo defined by

$$\mathrm{RMSE} = \left[\frac{\Sigma(\alpha' - \alpha)^2}{n}\right]^{1/2}, \tag{7}$$

where α' is the zonal average planetary albedo computed from (6), using one of the above two sources for surface albedo, and α is the observed zonally averaged minimum albedo. When Robock's (1980) surface albedo values are used, an RSME of 0.05 is obtained; when Hummel and Reck's values are used, the RSME is 0.06. These RMSE's should not be considered as errors but as differences between the estimated albedos and the "observed" albedos. The differences arise partially, perhaps mainly, as a result of errors of the estimation equation but also as a result of uncertainties in the observed zonally averaged surface albedos and clear-sky planetary albedos. The difference in RSME between the two sets of surface albedos may be attributable in part to the fact that Hummel and Reck's seasonal data were interpreted as representing the mid-seasonal months. Considering the uncertainties involved in such a comparison, the agreement of estimated and "observed" clear-sky albedos must be considered quite reasonable.

One may derive relationships similar to (6) empirically using the above observational data sets of minimum albedo and surface albedo. Comparison of the empirical coefficients with the coefficients obtained from simulations would represent an additional check of (6). Table 1 lists the coefficients derived theoretically and empirically as well as their standard errors of estimate. It can be seen that both coefficients, a and b, from the simulations, agree reasonably well with those derived empirically, especially with those based on Robock's surface albedos.

A somewhat similar study was made by Preuss and Geleyn (1980). For given model atmospheres and using the two stream approximation, they calculated the reflected solar radiation for two different surface albedo values. For each model atmosphere they then derived a linear relation between the planetary albedo and surface albedo. The average values of the intercept and slope of their equation are, respectively, 0.101 and 0.59 for June and 0.108 and 0.57 for January–February. These numbers differ quite significantly from our observational and theoretical results discussed above.

The agreement of the NOAA SR clear-sky albedo observations with the theoretical regressions suggests that although the SR albedos are based upon measurements in the visible region of the spectrum they yield, at least for zonal averages, reasonable values for the broadband clear-sky albedo. Calculations by Briegleb and Ramanathan (1982) also imply that observations in the visible region (0.5–0.7 μm) would yield a good estimate of the zonally averaged broadband clear-sky albedo.

TABLE 1. Coefficients of the equation $\alpha = a + bR_g$ and RMSEs

Method	a	b	RMSE
Simulations Eq. (6)	0.0587	0.730	0.03
Empirical, Robock R_g	0.0597	0.756	0.05
Empirical, Hummel & Reck R_g	0.0784	0.676	0.05

Recently, in connection with climate modeling studies, some interest has been generated in the magnitude of the surface albedo of the Sahara desert region. Based on observations of 16 target areas (~500 km × 500 km each) over the Sahara desert area for a period of 12 days in November 1978, the ERB (Nimbus 7) gave an average minimum albedo of 36.7%. If one inserts this value into Eq. (6), one obtains a surface albedo of around 0.42. Similarly, if one uses the regression of R_g on α, i.e., $R_g = -0.0724 + 1.3464\alpha$, one also obtains a surface albedo of 0.42, since the correlation between R_g and α is close to unity. Since the Nimbus 7 observations are close to local noon and since there is a tendency for the surface albedo to increase with increasing solar zenith angle, the actual mean daily surface albedo is probably a few hundreths higher than 0.42. Interestingly, an even higher value (0.46) is predicted by the Preuss and Geleyn (1980) equation. These albedos are much higher than those usually attributed to desert regions (e.g., Budyko, 1974, p. 55, gives a value of 0.28, and Hummel and Reck, 1979, give values of 0.25 to 0.31 for the Sahara region), although Otterman and Fraser (1976) have derived a value of 0.44 from Landsat observations, and Rockwood and Cox (1978) have obtained values of up to 0.50 from aircraft observations.

4. Improved relationships

From the discussion in Section 2, it is obvious that the clear-sky planetary albedo is not only dependent on surface albedo but also on the solar zenith angle, and the water vapor and ozone distributions. Of these three variables, the one most likely to be available in a data set is the solar zenith angle. To determine the effect of including information on the solar zenith angle, the simulations discussed in Section 2 were classified according to solar zenith angle and regression equations similar to (6) were derived for a number of individual zenith angles. The resulting coefficients and associated standard errors of estimate are shown in Table 2. As would be expected, an increase of solar zenith angle leads to an increase in *a*—as a result of the increased atmospheric albedo due to increased Rayleigh scattering—and a decrease in *b*—as a result of the decreased effective "two way" atmospheric transmittance due to increased absorption. The RSME's are reduced from the value of 0.028 obtained without consideration of solar zenith angle to values of 0.02 or somewhat less. Thus, depending on the purpose of the estimate and the availability of information on the solar zenith angle, either the general relationship based on all solar angles or a specific relationship for a particular zenith angle can be used to estimate surface albedo from clear-sky planetary albedo, and vice versa.

TABLE 2. Coefficients of the equation $\alpha = a + bR_g$ and RSMEs for different solar zenith angles.

Solar zenith angle (deg)	*a*	*b*	RSME
0	0.031	0.776	0.017
20	0.033	0.773	0.018
40	0.041	0.761	0.018
50	0.048	0.748	0.018
60	0.060	0.729	0.018
65	0.069	0.713	0.019
70	0.081	0.692	0.019
75	0.099	0.661	0.020
80	0.126	0.610	0.020
85	0.174	0.509	0.021

5. Concluding remarks

There are certain limitations to the relationships presented here, based, in part, on the limitations of the solar radiation model used in the simulations. The model does not include the relatively small effects of O_2 and CO_2 absorption, nor of aerosol absorption and scattering. Aerosol effects could be significant for certain regions and times of the year. The model also assumes that the surface albedo is not a function of wavelength. However, these limitations should not affect the use of these simple relationships to obtain quick approximate estimates of surface albedo, given clear-sky planetary albedo, and vice versa, particularly for those situations when no information is available on the atmospheric water vapor content. They should also be suitable for use in simple climate models for parameterizing the clear-sky planetary albedo in terms of the surface albedo, in a manner similar to the way the longwave flux is parameterized in terms of surface temperature.

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