The Albedo of Water as a Function of Latitude

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(Manuscript received 1 December 1978, in final form 6 March 1979)

ABSTRACT

The latitude dependence of water albedo is usually taken from one of a number of tables available in the literature, but these tables all derive from a single series of calculations, made in 1952, for clear skies at noon in the middle of each month. This article contains new tables, in which the albedos are averaged over all radiation received at all elevation angles of the sun (also tabulated). The tables are by month and year, for latitudes 0° (10°) 90° and latitude belts 0–10° (10°) 80–90°, 0–30° (30°) 60–90° and 30–90°. One set is based on the Fresnel equation, another on the data of Grishchenko. In the latter set, albedos are 2–4 percentage points higher at low latitudes, and up to 20 points lower near the pole, than those now in use.

1. Introduction

The albedo of open water helps to determine the energy balance of the world's surface, seven-tenths of which is aqueous. The low reflectivity of this large expanse of water is responsible for much of the heat absorption in the earth-atmosphere system. Large shifts of climate may occur if some or all of the water is replaced by ice. Therefore it is important, in analyses of the global energy balance and of climatic change, to have reliable data on the variation of albedo.

This albedo is known to vary with water turbidity, wave height and the ratio of diffuse to total radiation. It is largely dependent, however, on the angle of incidence of the direct radiation, or its complement, the solar elevation angle. It is usual in large-scale studies to average this dependence in some way over time, and to set down the albedo as a function of latitude in suitable tables, from which data are drawn as needed. The literature contains a small number of standard sources for these tables (Budyko, 1956, 1974; Posey and Clapp, 1964; Kondratyev, 1969; Miranova, 1973), and many studies take figures directly from these (Hummel and Reck, 1979) or use the data in constructing more general quantities (Sellers, 1973; Lian and Cess, 1977).

This practice is justified by the bulk of the calculations which would otherwise be needed, but it is disconcerting to realize that the basic calculations have been done only once, in 1952 (Sivkov, 1952). Kondratyev (1969) and Miranova (1973) quote the Sivkov data unchanged, while Posey and Clapp (1964) quote Budyko's version (1956, 1974) of the Sivkov data. Budyko *et al.* (1954) weighted the original figures by the ratio of diffuse to total radiation, allowing a constant albedo of 10% to water under diffuse radiation. Sivkov (1952) used the Fresnel equation to calculate albedos, at midday on the middle day of each month, at every 5° of latitude from 0° to 90°. His figures are thus approximations, and they can be improved on with the benefit of modern computing machinery.

In this article, I present improved tables for the albedo of water as a function of latitude, based on an accurate weighting for radiation received at different elevation angles.

2. Radiation

The flux of radiation through a plane at the top of the earth's atmosphere and parallel to its surface is (Budyko, 1974)

$$q_s = S \sin E, \quad (1)$$

where $S = s(\bar{d}/d)^2$, $s = 1367$ W m^{-2} is the solar constant (Willson, 1978) and $(\bar{d}/d)$ is the ratio of the average to the instantaneous earth-sun distance:

$$(\bar{d}/d) = 1/(1 - 0.01673 \cos\tau),$$

with $\tau = 2\pi t/365$ if it is calculated for each day t (Smart, 1976). The elevation angle E $(=\pi/2 - Z$, where Z is zenith angle) is a function of latitude θ, solar declination δ, and hour angle h:

$$\sin E = \sin\theta \sin\delta + \cos\theta \cos\delta \cosh. \quad (2)$$

The declination is given by

$$\delta = 0.4093 \sin[2\pi(t - 79.75)/365].$$

0027-0644/79/060775-07$05.75

TABLE 1. Percentage radiation* for latitudes 0–90°, Northern Hemisphere year.

θ (deg)	Q (MJ m^{-2})	Elevation angle e 90°	85°	80°	75°	70°	65°	60°	55°	50°	45°	40°	35°	30°	25°	20°	15°	10°	5°	0°
90	5368		—	—	—	—	—	—	—	—	—	—	—	—	—	51.0	24.9	14.2	7.5	2.5
80	5548		—	—	—	—	—	—	—	—	—	—	—	14.1	19.9	19.2	18.7	17.7	8.0	2.5
70	6128		—	—	—	—	—	—	—	—	—	10.7	15.3	15.0	14.2	13.1	11.6	9.7	7.2	3.2
60	7375		—	—	—	—	—	—	—	7.9	11.7	11.8	11.7	11.4	10.8	10.0	9.0	7.6	6.2	1.9
50	8896		—	—	—	—	—	5.6	8.7	9.2	9.5	9.7	9.6	9.5	9.3	9.0	9.6	6.0	3.2	1.0
40	10310		—	—	—	3.9	6.4	7.1	7.7	8.2	8.5	8.6	9.0	9.4	11.1	7.8	5.4	3.7	2.2	0.7
30	11500		—	2.4	4.4	5.4	6.2	6.9	7.5	8.0	8.6	9.4	11.7	8.8	6.7	5.2	4.0	2.8	1.7	0.6
20	12390		2.3	4.0	4.9	5.8	6.5	7.3	8.1	9.1	11.8	9.3	7.5	6.3	5.2	4.3	3.3	2.4	1.4	0.5
10	12950		1.1	3.5	7.2	7.5	7.9	9.0	11.8	9.7	8.2	7.1	6.3	5.5	4.6	3.5	3.0	2.1	1.3	0.4
0	13160		1.0	3.0	5.2	8.0	14.0	11.3	9.3	8.3	7.5	6.7	6.0	5.2	4.4	3.7	2.9	2.1	1.2	0.4

* 100 $Q(e)/Q$.

(Both declination and earth-sun distance change slowly with time and are calculated anew only once for each day.)

To find the radiation for a part of the day, of duration $2T$ centered at noon, it is necessary to integrate (2):

$$\int_{-T}^{T} \sin E dt = \frac{1}{\omega}\int_{-H}^{H} (\sin\theta \sin\delta + \cos\theta \cos\delta \cos h)dh$$
$$= \frac{2}{\omega}(H \sin\theta \sin\delta + \sin H \cos\theta \cos\delta),$$

where $\omega = \pi/43200$ rad s^{-1} is the angular velocity of the earth's rotation, and T (in time units) and H (in angular measure) are the endpoints of the interval. It is important to note that these endpoints are not necessarily sunrise and sunset. We obtain

$$Q(H) = \int_{-T}^{T} q_s dt$$
$$= S\frac{2}{\omega}(H \sin\theta \sin\delta + \sin H \cos\theta \cos\delta). \quad (3)$$

Here $Q(H)$ is the total radiation received in the interval from $-H$ to $+H$. We wish to know how much radiation is received within 5° elevation-angle classes, E = 90–85°, 85–80°, etc. To find these quantities we establish a variable e, which is to take on successively the values 85°, 80°, . . . , 0°, and we evaluate (3) between the endpoints

$$\pm H(e) = \cos^{-1}\{[\sin(e\pi/180) - \sin\theta \sin\delta]/\cos\theta \cos\delta\},$$
$$e = 85, 80, \ldots, 0. \quad (4)$$

This yields an overlapping set of totals $Q[H(e)]$. It is useful to define the radiation received within 5° elevation angle classes as

$$Q(e) = Q[H(e)] - Q[H(e + 5°)],$$

where it is understood, for example, that Q (85°) is the total radiation for $85° < E \leqslant 90°$.

In practice the first step is to determine E_{max}, the elevation angle at noon (where $\cos h = 1$), and to integrate only for $e \leqslant E_{max}$. If $E_{max} \leqslant 0$ the day is skipped.

TABLE 2. Percentage radiation* for 10° and 30° latitude belts, Northern Hemisphere year.

θ (deg)	Q (MJ m^{-2})	Elevation angle e 90°	85°	80°	75°	70°	65°	60°	55°	50°	45°	40°	35°	30°	25°	20°	15°	10°	5°	0°
80–90	5457		—	—	—	—	—	—	—	—	—	—	—	4.5	18.9	25.9	24.9	15.6	7.7	2.4
70–80	5828		—	—	—	—	—	—	—	—	—	2.4	11.3	16.8	16.3	15.3	13.9	12.5	8.7	2.8
60–70	6727		—	—	—	—	—	—	—	1.7	8.3	13.1	13.3	12.9	12.3	11.3	10.0	8.3	6.2	2.6
50–60	8166		—	—	—	—	—	1.2	5.9	9.9	10.4	10.5	10.5	10.3	9.8	9.3	8.8	7.6	4.5	1.3
40–50	9636		—	—	—	0.8	4.2	7.4	8.1	8.6	8.9	9.1	9.2	9.3	9.7	9.6	7.3	4.6	2.6	0.8
30–40	10929		—	0.5	2.8	5.3	6.2	6.9	7.5	8.0	8.4	8.9	9.8	10.4	8.7	6.2	4.6	3.2	1.9	0.6
20–30	11969		1.3	3.4	4.6	5.5	6.3	7.0	7.7	8.4	9.6	10.7	9.4	7.2	5.8	4.7	3.6	2.6	1.5	0.5
10–20	12699		1.5	4.5	6.0	6.4	7.1	8.0	9.4	10.7	9.9	7.9	6.8	5.8	4.9	4.0	3.1	2.2	1.3	0.4
0–10	13079		1.0	3.1	5.7	8.6	10.4	11.2	10.4	8.7	7.7	6.8	6.1	5.3	4.5	3.7	2.9	2.1	1.3	0.4
60–90	6281		—	—	—	—	—	—	—	1.0	4.9	8.5	11.4	13.3	14.2	14.0	12.7	10.3	7.1	2.6
30–60	9739		—	0.2	1.2	2.6	4.1	5.8	7.3	8.6	9.0	9.3	9.8	10.0	9.3	8.0	6.5	4.7	2.7	0.8
0–30	12601		1.3	3.7	5.5	6.9	8.0	8.9	9.3	9.3	9.0	8.3	7.3	6.0	5.0	4.1	3.2	2.3	1.4	0.4
30–90	8813		—	0.2	1.0	2.1	3.3	4.7	5.9	7.2	8.2	9.2	10.1	10.6	10.2	9.2	7.7	5.8	3.6	1.2

* 100 $Q(e)/Q$.

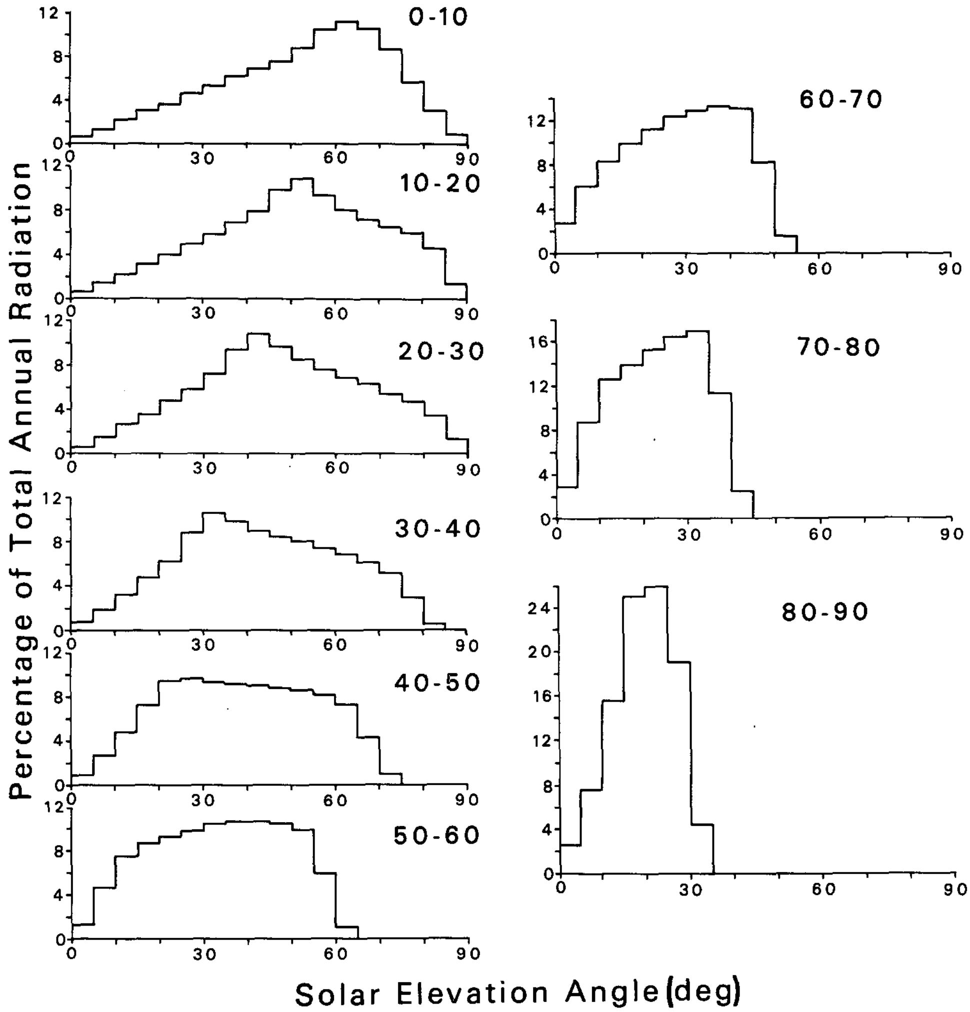

FIG. 1. Radiation as a function of elevation angle for 10° latitude belts.

A difficulty arises poleward of 66° latitude, where $\cos\theta$ approaches zero and the sun is continuously above the horizon in summer. At these latitudes, (3) is replaced by an iterative scheme, which is required to converge with an error in $H(e)$ not exceeding 0.5°, or 2 min.

The function $Q(e)$ for each month and for the year is computed by summing daily values. (These daily values are totals, not fluxes, per unit area.) The annual function is tabulated, as percentages of total annual radiation Q, in Table 1 for latitudes from 0° to 90° in 10° steps.

The equivalent function averaged over latitude can be a convenient variant, and it is displayed in Table 2 for 10° and 30° latitude belts, and for the cap poleward of 30°. Fig. 1 shows histograms for the 10° belts. These data are averages, weighted by area, of $Q(e)$ computed at latitude steps of roughly 1°. For each 1° latitude zone the areal weight is

$$(\sin\theta_1 - \sin\theta_0)/(\sin\Theta_1 - \sin\Theta_0),$$

where Θ stands for the wider latitude belt and θ for the 1° zone; subscripts 1 and 0 stand for poleward and equatorward margins, respectively. For each zone $Q(e)$ is computed at the areal midline $\bar{\theta} = \sin^{-1}[\frac{1}{2}(\sin\theta_1 - \sin\theta_0)]$, neglecting the ellipticity of the earth's surface.

3. Albedo

The dependence of water albedo on variables such as wave height is complex, but a good approximation is available by considering a plane surface of pure water under direct radiation, for which the Fresnel equation (Fig. 2) holds, i.e.,

$$a_F = 50\left[\frac{\sin^2(Z - r)}{\sin^2(Z + r)} + \frac{\tan^2(Z - r)}{\tan^2(Z + r)}\right], \quad (5)$$

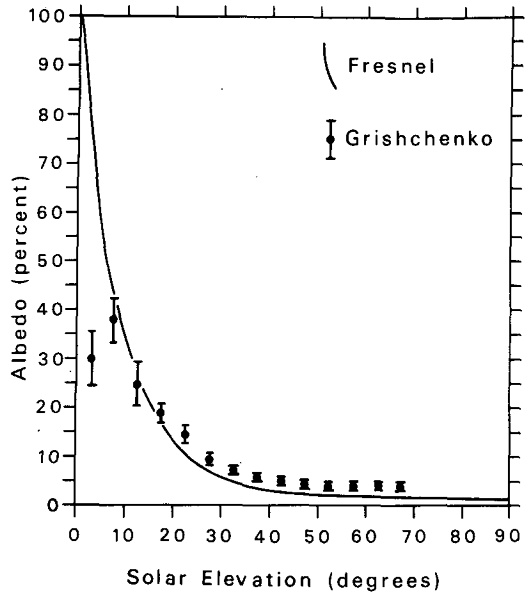

FIG. 2. The albedo of water as a function of elevation angle, from the Fresnel equation and from the data of Grishchenko; symbols for the latter are means, bounded by standard deviations (vertical bars), in 5° classes.

where a_F is the "Fresnel albedo" (percent) and r is the angle of refraction

$$r = \sin^{-1}(\sin Z/n).$$

Here n is the refractive index of water, equal to 1.33 ± 0.01 over wavelengths of quantitative importance in the radiation spectrum at the earth's surface.

The Fresnel albedo is the basis of Sivkov's table, and of its direct descendants such as that of Miranova (1973). It can be thought of as representing the ideal state, from which water surfaces deviate under the influence of wind, water-mass and air-mass turbidity, cloudiness and such lesser variables as temperature and the spectral distribution of incident radiation. Table 3 shows Fresnel albedos computed with the improved data base illustrated in Table 1 [monthly tables (Cogley, 1979) are not shown here]; Table 4 is based similarly on Table 2. Albedos from (5), with $Z = 87.5°\ (-5.0°)\ 2.5°$, were weighted by $Q(e)$ for each month and for the year.

One shortcoming of the Fresnel albedo is that it neglects the atmospheric attenuation of direct radiation which occurs even in the absence of clouds.

TABLE 3. Monthly mean Fresnel albedo (percent) of open water for latitudes 0° to 90°.

θ (deg)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Month												
90	—	—	76.2	34.6	14.2	10.7	12.5	26.1	59.5	—	—	—	18.8
80	—	76.2	45.7	24.9	14.6	11.0	12.8	21.5	37.8	74.4	—	—	17.6
70	76.2	51.4	25.0	13.9	11.0	10.8	10.9	12.5	20.6	42.4	76.2	—	14.3
60	45.7	26.7	14.4	9.1	7.4	7.0	7.2	8.4	12.4	22.7	41.7	54.2	11.5
50	23.2	15.1	9.4	6.8	5.9	5.7	5.8	6.4	8.4	13.3	21.5	26.9	9.0
40	13.4	9.7	6.9	5.6	5.2	5.0	5.1	5.4	6.4	8.8	12.6	15.0	7.1
30	8.8	7.0	5.7	5.0	4.8	4.7	4.7	4.9	5.4	6.6	8.5	9.6	5.9
20	6.6	5.7	5.0	4.6	4.6	4.6	4.6	4.6	4.9	5.5	6.4	7.0	5.3
10	5.5	5.0	4.7	4.5	4.6	4.7	4.7	4.6	4.6	4.9	5.4	5.7	4.9
0	4.9	4.7	4.5	4.6	4.9	5.0	4.9	4.7	4.5	4.6	4.9	5.0	4.8

TABLE 4. Monthly mean Fresnel albedo (percent) of open water for 10° and 30° latitude belts.

θ (deg)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Month												
80–90	—	76.2	52.8	29.0	14.7	10.6	12.7	23.8	45.7	76.2	—	—	18.1
70–80	76.2	59.2	32.1	17.9	13.2	11.0	12.3	16.1	26.7	50.8	76.2	—	15.9
60–70	56.2	34.9	18.4	11.0	8.7	8.5	8.6	10.0	15.6	29.5	51.9	66.6	12.6
50–60	31.0	19.4	11.4	7.8	6.5	6.2	6.4	7.3	10.0	16.8	28.5	36.8	10.1
40–50	17.2	11.8	8.0	6.1	5.5	5.3	5.4	5.9	7.3	10.6	16.0	19.7	7.9
30–40	10.7	8.1	6.2	5.2	4.9	4.8	4.9	5.1	5.8	7.5	10.1	11.9	6.4
20–30	7.6	6.3	5.3	4.8	4.7	4.7	4.6	4.7	5.1	6.0	7.3	8.1	5.5
10–20	6.0	5.3	4.8	4.6	4.6	4.7	4.6	4.6	4.7	5.2	5.8	6.3	5.0
0–10	5.2	4.8	4.6	4.6	4.7	4.9	4.8	4.6	4.5	4.7	5.1	5.3	4.8
60–90	56.2	37.6	23.1	14.9	10.9	9.6	10.3	13.4	20.2	33.1	52.2	66.6	14.2
30–60	15.5	11.3	7.9	6.2	5.5	5.4	5.5	5.9	7.3	10.3	14.6	17.2	7.8
0–30	6.1	5.4	4.9	4.6	4.7	4.7	4.7	4.6	4.8	5.2	5.9	6.4	5.1
30–90	16.4	13.1	10.0	8.0	6.9	6.5	6.7	7.6	9.3	12.2	15.8	17.8	9.0

TABLE 5. Monthly mean Grishchenko albedo (percent) of open water for latitudes 0° to 90°.

θ (deg)	Month Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
90	—	—	30.1	29.3	17.1	14.8	16.0	24.6	34.2	—	—	—	19.3
80	—	30.1	31.9	22.5	16.0	13.1	14.5	20.6	29.4	30.5	—	—	17.5
70	30.1	33.8	22.9	14.8	11.6	11.2	11.4	13.4	20.2	31.3	30.1	—	14.1
60	33.9	24.0	15.5	10.5	8.8	8.4	8.6	9.8	13.6	21.6	32.1	35.5	12.0
50	22.0	16.1	10.8	8.4	7.5	7.3	7.4	8.0	9.9	14.4	21.0	24.1	10.2
40	14.5	11.1	8.5	7.3	6.8	6.7	6.8	7.1	8.0	10.3	13.8	16.1	8.6
30	10.3	8.6	7.3	6.7	6.5	6.4	6.4	6.6	7.1	8.2	10.0	11.1	7.6
20	8.3	7.4	6.7	6.4	6.3	6.3	6.3	6.4	6.6	7.2	8.1	8.7	6.9
10	7.2	6.7	6.4	6.3	6.4	6.4	6.4	6.3	6.3	6.6	7.1	7.4	6.6
0	6.6	6.4	6.3	6.4	6.6	6.8	6.7	6.4	6.3	6.4	6.6	6.8	6.5

In other words, there is always a diffuse component of total radiation. It is well known that water albedo is virtually constant under diffuse radiation, at a value between 6 and 10%. Diffuse radiation should therefore reduce the marked dependence of the Fresnel albedo on elevation angle, raising low values and reducing high ones. In particular, the high values should be reduced considerably, because when the sun is low in the sky the diffuse component becomes large. A data set which demonstrates these effects especially well is that of Grishchenko (1959), who presents over 200 careful measurements of albedo at elevation angles from 0° to 70°. His data for wave heights of 0.1 to 0.7 m, and cloud cover of 0 to 25%, are shown in Fig. 2 as averages in 5° classes. The "Grishchenko albedo" can be seen to decrease at very low elevation angles.

Nuñez *et al.* (1971, 1972) give data of comparable quality with those of Grishchenko, although without his thorough analysis of errors. When their data for cloudless sky and $^1/_{10}$–$^5/_{10}$ cloud are combined and grouped in 5° elevation angle classes (Cogley, 1979), they too reveal a decrease at low E. The Nuñez *et al.* means are slightly lower than the Grishchenko means at low E, presumably because of the cloudier skies. Unfortunately, their cloudless-sky graph has only two albedos at elevation angles <5°, so that it is hard to say by how much scattered clouds reduce the albedo.

Tables 5 and 6 show Grishchenko albedos computed by weighting the averages of Fig. 2 (extrapolated to 90°) with the functions $Q(e)$ from Tables 1 and 2. They are recommended as "normals" for fair-weather albedo, assuming scattered light cloud and a moderately agitated sea surface as part of the norm. The empiricism of these normals deserves to be noted. It is a compromise between the simplicity of (5) and the complexity of allowing exactly for variables which alter the albedo slightly; the cost of including these variables would be a multiplication of the number of tables.

4. Comparisons

Table 7 is a digest of Sivkov's table, with Grishchenko albedos (from Table 5) following the Sivkov

TABLE 6. Monthly mean Grishchenko albedo (percent) of open water for 10° and 30° latitude belts.

θ (deg)	Month Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
80–90	—	30.1	33.3	25.3	16.7	13.3	15.0	22.6	31.7	30.1	—	—	18.1
70–80	30.1	33.7	26.6	17.8	13.8	12.3	13.2	16.3	23.8	32.9	30.1	—	15.7
60–70	34.0	28.1	18.5	12.2	9.9	9.5	9.7	11.3	16.3	25.4	33.6	32.5	12.8
50–60	26.3	19.3	12.7	9.3	8.0	7.7	7.9	8.8	11.4	17.4	24.9	29.4	11.1
40–50	17.8	13.1	9.5	7.7	7.1	7.0	7.0	7.5	8.8	12.0	16.9	19.8	9.4
30–40	12.1	9.7	7.8	6.9	6.6	6.5	6.6	6.8	7.5	9.1	11.6	13.2	8.0
20–30	9.1	7.9	7.0	6.5	6.4	6.4	6.4	6.4	6.8	7.6	8.9	9.7	7.2
10–20	7.6	7.0	6.5	6.3	6.3	6.4	6.3	6.3	6.4	6.9	7.5	7.9	6.7
0–10	6.9	6.5	6.3	6.3	6.5	6.6	6.5	6.3	6.3	6.5	6.8	7.0	6.5
60–90	34.0	28.8	21.1	15.2	12.0	10.9	11.5	14.0	19.2	26.6	33.6	32.5	14.2
30–60	15.8	12.5	9.4	7.8	7.2	7.0	7.1	7.5	8.8	11.6	15.2	17.1	9.2
0–30	7.7	7.1	6.6	6.4	6.4	6.4	6.4	6.4	6.5	6.9	7.6	8.0	6.8
30–90	16.2	13.6	11.0	9.3	8.4	8.1	8.2	9.0	10.5	12.9	15.7	17.3	10.2

TABLE 7. Sivkov albedos compared with recalculated Grishchenko albedos (in parentheses).

θ	Month												
(deg)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year*
90	—	—	— (30)	42 (29)	23 (17)	18 (15)	21 (16)	32 (25)	— (32)	—	—	—	25 (19)
80	—	— (30)	50 (32)	22 (22)	12 (16)	10 (13)	11 (14)	17 (21)	34 (29)	— (30)	—	—	15 (18)
70	— (30)	54 (34)	25 (23)	12 (15)	8 (12)	7 (11)	7 (11)	10 (13)	18 (20)	38 (31)	— (30)	—	11 (14)
60	47 (34)	26 (24)	13 (16)	7 (10)	6 (9)	5 (8)	5 (9)	6 (10)	10 (14)	20 (22)	38 (32)	55 (36)	10 (12)
50	23 (22)	14 (16)	8 (11)	5 (8)	5 (8)	4 (7)	4 (7)	5 (8)	7 (10)	11 (14)	20 (21)	27 (24)	8 (10)
40	12 (15)	8 (11)	6 (8)	5 (7)	4 (7)	4 (7)	4 (7)	4 (7)	5 (8)	7 (10)	11 (14)	14 (16)	6 (9)
30	8 (10)	6 (9)	5 (7)	4 (7)	4 (6)	4 (6)	4 (6)	4 (7)	4 (7)	5 (8)	7 (10)	8 (11)	5 (8)
20	6 (8)	5 (7)	4 (7)	4 (6)	4 (6)	4 (6)	4 (6)	4 (6)	4 (7)	4 (7)	5 (8)	5 (9)	4 (7)
10	5 (7)	4 (7)	4 (6)	4 (6)	4 (6)	4 (6)	4 (6)	4 (6)	4 (6)	4 (7)	4 (7)	5 (7)	4 (7)
0	4 (7)	4 (6)	4 (6)	4 (6)	4 (7)	4 (7)	4 (7)	4 (6)	4 (6)	4 (6)	4 (6)	4 (7)	4 (6)

* Sivkov albedo is sum of monthly averages weighted by monthly radiation totals, and divided by Q from Table 1.

albedos in parentheses. The new values are 2–4 percentage points higher than the old, save that in winter months poleward of 50°, and all year at the pole, the new albedos are lower by up to 20 points. These reductions, mainly from allowing for diffuse radiation, have little impact on annual averages since they apply to only small quantities of radiation. The year-round reduction at 90°, however, helps to dampen considerably the dependence of albedo on latitude. The annual average albedo now varies by only 13 points instead of 21 points from equator to pole; for June, the spread is 8 rather than 15 points.

The newly computed Fresnel albedos (Table 3) relate to direct radiation as do the Sivkov albedos, but they account for all of the incident radiation. Because of this, and because they increase much more sharply at low elevation angles, they are about 1 point higher in low latitudes, up to 4 points higher in high latitudes, and 1–7 points lower at the pole itself.

Budyko's table (1956, 1974), used by Posey and Clapp (1964) among others, is more strongly damped than Table 5, since it incorporates the contribution of clouds to diffuse radiation.

5. Conclusion

The data of Sivkov remain valuable where a clear-sky, high-noon albedo is desirable. However, in large-scale studies it is usually preferable to budget for all of the incident radiation; in such studies the Grishchenko albedos will be more accurate. At the equator, they imply a 50% increase in reflected radiation, or a 2% loss of absorbed radiation; at the pole, there is a 24% reduction in reflected radiation, or an 8% gain in absorption. These changes are not insignificant.

The Grishchenko albedos may be undesirable for some purposes. If so, the Fresnel albedos may be applied to the problem at hand, together with accurate data on whatever other variable is of concern. For some uses one might wish to start again from the beginning; the algorithm of Section 2 takes up very little computer time.

I have refrained from computing semi-empirical cloudy-sky albedos, comparable to those of Budyko. The cloud cover observed today may not correspond to that expectable in analytically interesting situations, such as those where the state of the earth surface determines global climate. Different cloud covers may be found over surfaces of ice and of open water; the ice cover of polar waters fluctuates in the Ewing-Donn glacial theory (Ewing and Donn, 1956) and in other oscillatory models of the Quaternary such as Saltzman's (1978). Palaeoclimates of the Cenozoic and Mesozoic involve poles which were more or less continuously ice-free, and intermittently both terrestrial and oceanic as a consequence of sea-level change and continental drift.

Acknowledgments. I thank Trent University and the National Research Council of Canada for financial support, Scott Munro for a critical review, and Roy Underhill for his valuable services as an assistant.

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