Annual Cycle of Surface Albedo

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(Manuscript received 6 March 1979, in final form 23 October 1979)

ABSTRACT

Monthly mean surface albedo for the full spectral range of incoming solar radiation and average atmospheric properties is estimated for the period 1 April 1974–31 March 1975. It can be considered approximately representative of average conditions in the last decade. The monthly global surface albedo, averaged without weighting for radiation income, ranges from 15.7% in August to 17.9% in December, with an annual average of 17.0%. This is higher than most previously published figures. The difference is partly due to the averaging method, and partly to our more accurate satellite based information on snow and ice covers. Parameterized albedo values of characteristic surface types were compiled from published references. Estimates are zonally averaged separately for land and ocean in 2° latitudinal belts.

1. Introduction

This work is meant to provide improved estimates of zonal mean monthly surface albedos for use in climate models. Because observations of seasonal changes in surface reflectance are few and available only on local or, at most, regional scales, our results are necessarily approximate. They refer to the period from 1 April 1974 through 31 March 1975. During this time fluctuations of snow and pack ice covers, the key seasonal variables influencing surface albedo, were analyzed in two-week intervals. Comparison with snow and ice cover variations from 1967–77 shows that the selected interval is close to the average decadal conditions (Kukla and Gavin, 1979).

2. Data sources

Our results are based on the following:

1) Fleet Weather Facility Ice Charts for the Arctic and Antarctic Oceans (FLEWEAFAC, 1974/75) analyzed in two week intervals for the area occupied by sea ice in five different concentrations. The area was measured with grid overlays [2° × 2° equatorward of 60°N and 70°S, 2° × 4° poleward of 70°S and 60–80°N, and 2° × 8° between 80 and 90°N (cf. Kukla, 1976)].

2) The National Oceanic and Atmospheric Administration (NOAA) Snow and Ice Boundary Charts for the Northern Hemisphere continents (National Environmental Satellite Service, 1974–75) analyzed in two-week intervals for the area occupied by snow in different reflectivity grades. The area was measured with grid overlays.

3) Albedo values for sea ice concentrations obtained from a compilation of published measurements mostly in the Arctic Basin.

4) Estimated albedo of NOAA's snow cover reflectivity classes 1–3, obtained by Batten *et al.* (1977) from computer analysis of selected Very High Resolution Radiometer tapes from Arctic and Sub-Arctic North America.

5) Albedo values of snow-free land surfaces and glaciers, based on a compilation of published data.

6) Albedo values of water bodies, based on the data of Payne (1972) for 60°N to 60°S and on the compilation of published measurements for higher latitudes.

3. Parameterization of surface albedo values

The range of published albedo values for characteristic surface types was compiled from literature and is presented in Table 1. It is large in most categories. This is due to the fact that surface reflectivity varies not only with respect to material composition, but also with roughness, moisture content, solar angle, angular and spectral distribution of ground level irradiation, etc. (Nkemdirim, 1972; Monteith and Szeicz, 1961; Graham and King, 1961; Coulson *et al.*, 1965; Barkstrom, 1972; Arnfield, 1975; Marshunova, 1961; Howard, 1973). Most surfaces when moist have an albedo several percent lower than when dry. Outside the snow and ice boundaries the variation in surface moisture accounts for a large part of the intra-annual albedo variability. The angular and spectral distribution of incoming radiation significantly influences surface albedo in the high and middle latitudes during the

0027-0644/80/010056-13$07.25

TABLE 1. Range of published measurement of surface albedo and the median values used in this study.

Surface type	Range	Sources*	Value(s) selected for this study
Snow-free and ice-free surfaces			
1) Water bodies between 90°–60°	6–44%	Budyko, 1956; Payne, 1972	10%
2) Water bodies between 0°–60°	5–20%	Kung *et al.*, 1964; Payne, 1972; Budyko, 1956; Robinson, 1959; Kondratyev, 1969	6–10%
3) Tropical rainforest	7–15%	Posey and Clapp, 1964; Rockwood and Cox, 1978; Oguntoyinbo, 1970	10%
4) Naturally vegetated terrain, farmland, common soils, stony deserts, etc.	7–25%	Posey and Clapp, 1964; Robinson, 1959; Mukhenberg, 1963; Kung *et al.*, 1964; Kondratyev, 1969; Oguntoyinbo, 1970; Jarvis *et al.*, 1976; Lewis and Callaghan, 1976; Rauner, 1976; Ripley and Redmann, 1976; Rockwood and Cox, 1978	17%
5) Semi-deserts and deserts with light colored soils	20–33%	Posey and Clapp, 1964; Rockwood and Cox, 1978; Kung *et al.*, 1964; Oguntoyinbo, 1970; Otterman, 1976, 1977a	22%
6) Deserts with light colored sands, salt playas, etc.	28–44%	Mukhenberg, 1963; Otterman, 1977a; Kung *et al.*, 1964; Raschke *et al.*, 1973; Rockwood and Cox, 1978	35%
Snow-covered land			
1) Mountains with scattered snow			25%
2) NOAA reflectivity Class 1	25–35%	Batten *et al.*, 1977	30%
3) NOAA reflectivity Class 2	35–55%	Batten *et al.*, 1977	45%
4) NOAA reflectivity Class 3	60–70%	Batten *et al.*, 1977	65%
5) Snow-covered ice sheets and ice caps in the Arctic and Antarctica	75–89%	Marshunova and Chernigovskii, 1966; Kondratyev, 1969; Hoinkes, 1961; Marshunova, 1961; Ambach, 1974	80%

Sea ice

FLEWEAFAC ice areal coverage class (octas)	Albedo value used in this study
2.5	25%
4.5	45%
6.0	60%
6.5	70%
8.0	80%
8.0, bare ice with melting snow and puddles	60%

* The first source reported the lowest albedo and the second the highest.

cold season when the atmospheric humidity is low. It plays a minor role, if any, in temperate latitudes where the atmospheric humidity is high, diffuse component strong and the near-infrared part of ground irradiation weak (Dave and Braslau, 1975).

Instrumentation and the arrangement of experiments also may influence the measurements and contribute to large scatter in reported values.

Only a few studies provide a complete report of measurement conditions. Data on surface moisture, atmospheric humidity, ratio of direct to diffuse radiation and spectral range of the sensors are frequently omitted, making comparisons of reported values difficult.

Obviously, a large uncertainty exists as to how representative the measurements are in time and space. We decided to select the median value of published data falling within individual categories (Table 1). Few exceptions were made. We suspect that most measurements, especially the airborne ones, were done under relatively favorable weather conditions which may have skewed the data in favor

TABLE 2. Average zonal monthly surface albedo estimates (%): land and ocean (for full spectral range of incoming solar radiation and average atmospheric conditions).

Latitude	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
90–88°N	80.0	80.0	80.0	80.0	80.0	80.0	60.0	60.0	80.0	80.0	80.0	80.0
–86°N	80.0	80.0	80.0	80.0	80.0	80.0	60.0	60.0	80.0	80.0	80.0	80.0
–84°N	80.0	80.0	80.0	80.0	80.0	80.0	60.0	60.0	80.0	80.0	80.0	80.0
–82°N	78.7	78.7	78.7	78.7	78.7	78.6	58.6	58.4	78.0	78.7	78.7	78.7
–80°N	77.7	77.7	77.7	77.7	77.7	77.6	57.1	54.8	72.1	75.0	76.0	76.0
–78°N	75.2	75.8	75.4	75.6	75.8	75.5	55.5	51.9	63.4	71.5	73.8	75.4
–76°N	72.2	73.2	73.4	74.8	74.7	70.2	50.8	45.0	53.5	61.9	66.3	70.2
–74°N	67.1	67.2	67.0	66.3	67.8	62.5	44.3	38.0	42.0	56.5	64.1	65.3
–72°N	64.7	65.2	64.0	64.3	63.0	58.9	40.3	31.8	28.3	47.7	60.3	62.3
–70°N	61.7	61.8	61.8	60.6	61.0	53.9	33.6	24.8	26.5	43.7	58.1	60.3
–68°N	60.5	61.2	59.8	57.7	55.5	40.1	25.1	18.2	19.7	37.2	55.6	59.5
–66°N	60.4	59.9	57.2	51.4	49.5	30.5	20.6	18.0	19.1	37.2	49.0	59.4
–64°N	56.5	55.7	54.0	49.0	43.9	24.1	18.3	17.2	18.3	33.8	42.4	58.1
–62°N	52.5	48.7	49.4	44.0	37.6	22.9	18.1	15.8	16.4	28.2	37.1	54.2
–60°N	45.9	45.7	48.8	41.8	34.5	21.9	17.2	15.2	16.0	23.1	33.2	48.5
–58°N	39.1	38.4	40.7	33.2	26.8	18.4	14.3	12.9	12.8	17.9	25.8	42.4
–56°N	34.2	37.6	37.5	29.0	22.9	17.2	13.8	12.7	12.7	17.6	22.6	37.5
–54°N	32.2	35.7	34.5	24.6	20.7	15.9	13.1	12.7	12.6	17.2	21.3	29.9
–52°N	31.0	35.3	33.0	21.5	18.7	14.1	13.1	13.3	13.3	17.1	20.3	28.4
–50°N	29.0	34.9	32.7	21.1	18.3	14.0	13.0	13.5	13.7	16.2	19.7	26.3
–48°N	26.4	32.1	27.4	19.6	15.8	13.5	13.0	13.7	13.7	15.2	18.3	22.3
–46°N	23.9	31.2	25.9	16.8	15.0	13.4	13.0	13.5	13.7	14.7	17.2	21.6
–44°N	21.9	26.6	20.9	14.6	13.6	13.1	12.9	12.9	13.4	14.3	15.0	18.1
–42°N	20.5	22.9	18.0	14.4	13.2	12.6	12.5	12.5	13.1	13.8	14.5	17.7
–40°N	18.2	18.8	15.8	14.2	13.0	12.5	12.5	12.5	13.0	13.8	13.7	16.9
–38°N	16.6	16.8	14.5	13.6	12.7	11.8	11.7	11.5	12.1	13.0	12.7	15.0
–36°N	16.2	15.3	14.4	13.0	12.2	11.6	11.4	11.2	11.7	12.8	12.5	14.2
–34°N	16.2	15.2	13.9	13.5	13.1	12.5	12.0	11.8	11.7	12.6	12.9	15.1
–32°N	16.0	13.9	13.7	13.1	12.8	12.5	12.5	12.4	12.3	13.0	13.3	14.7
–30°N	16.0	14.8	14.7	13.8	13.7	13.7	13.6	13.6	13.6	14.1	14.2	15.6
–28°N	16.1	15.0	14.7	14.7	14.2	14.1	14.0	14.0	13.9	14.5	14.7	15.2
–26°N	15.2	14.2	14.1	13.3	13.3	13.3	13.3	13.3	13.3	14.0	14.1	14.5
–24°N	13.3	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	12.7	13.3	13.3
–22°N	13.7	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.7	13.7
–20°N	13.5	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	13.5	13.5
–18°N	12.9	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.9	12.9
–16°N	12.1	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	12.1	12.1
–14°N	10.1	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	10.1
–12°N	9.5	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	9.5
–10°N	8.9	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.9
– 8°N	9.3	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	9.3
– 6°N	8.6	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	8.6
– 4°N	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
– 2°N	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4
– 0	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4
0– 2°S	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3
– 4°S	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
– 6°S	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
– 8°S	7.8	7.8	7.8	7.8	8.6	8.6	7.8	7.8	7.8	7.8	7.8	7.8
–10°S	7.9	7.9	7.9	7.9	8.7	8.7	7.9	7.9	7.9	7.9	7.9	7.9
–12°S	7.7	7.7	7.7	7.7	8.5	8.5	7.7	7.7	7.7	7.7	7.7	7.7
–14°S	7.4	7.4	7.4	7.4	8.2	8.2	7.4	7.4	7.4	7.4	7.4	7.4
–16°S	8.4	8.4	8.4	8.4	9.2	9.2	8.4	8.4	8.4	8.4	8.4	8.4
–18°S	8.7	8.7	8.7	8.7	9.4	9.4	9.4	9.4	8.7	8.7	8.7	8.7
–20°S	8.6	8.6	8.6	8.6	9.3	9.3	9.3	9.3	8.6	8.6	8.6	8.6
–22°S	8.3	8.3	8.3	8.3	9.1	9.1	9.1	9.1	8.3	8.3	8.3	8.3
–24°S	8.9	8.9	8.9	8.9	9.7	10.4	9.7	9.7	8.9	8.9	8.9	8.9
–26°S	9.0	9.0	9.0	9.0	9.7	10.5	9.7	9.7	9.0	9.0	9.0	9.0
–28°S	8.8	8.8	8.8	9.6	10.4	11.2	10.4	9.6	9.6	8.8	8.8	8.8
–30°S	8.7	8.7	8.7	9.5	10.3	11.1	10.3	9.5	9.5	8.7	8.7	8.7
–32°S	8.4	8.4	8.4	9.3	10.1	10.9	10.1	9.3	9.3	8.4	8.4	8.4

TABLE 2. (*Continued*)

Latitude	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
−34°S	8.2	8.2	8.2	9.0	9.8	10.7	9.9	9.1	9.1	8.2	8.2	8.2
−36°S	7.0	7.0	7.0	7.9	8.8	9.8	9.0	8.0	8.0	7.0	7.0	7.0
−38°S	6.9	6.9	7.8	8.7	9.6	10.6	10.7	8.8	7.8	7.8	6.9	6.9
−40°S	6.5	6.5	7.4	8.4	9.3	10.4	10.4	8.5	7.5	7.5	6.5	6.5
−42°S	6.5	6.5	7.4	8.4	9.4	10.4	10.4	8.5	7.6	7.5	6.5	6.5
−44°S	6.4	6.4	7.4	8.4	9.4	10.4	10.4	8.5	7.5	7.5	6.6	6.6
−46°S	6.4	6.4	7.4	8.3	9.4	10.4	10.4	8.5	7.5	7.4	6.5	6.5
−48°S	6.3	7.2	7.2	8.3	10.3	10.5	10.5	8.5	8.4	7.4	6.3	6.3
−50°S	6.3	7.3	7.3	8.3	10.3	10.5	10.5	8.5	8.5	7.4	6.4	6.4
−52°S	6.2	7.2	7.2	8.2	10.3	10.4	10.6	8.6	8.5	7.3	6.3	6.3
−54°S	7.2	7.2	7.2	8.2	10.3	10.4	10.4	9.4	9.4	8.3	7.2	7.2
−56°S	7.1	7.1	8.1	9.1	10.3	10.4	10.4	10.4	10.5	10.2	9.2	8.1
−58°S	8.0	8.0	9.0	10.0	10.0	10.3	11.1	14.2	20.6	19.7	13.7	10.3
−60°S	8.0	8.0	9.0	10.0	10.0	13.6	21.2	26.1	35.2	33.5	23.4	14.1
−62°S	10.8	10.0	10.0	10.0	14.0	27.1	43.0	51.2	51.2	48.9	34.0	17.6
−64°S	12.3	10.9	11.2	13.9	35.1	51.9	66.8	68.0	67.6	64.5	49.2	24.4
−66°S	23.2	19.7	21.5	36.4	54.2	64.0	72.4	75.1	77.4	74.4	65.6	41.7
−68°S	38.3	32.5	34.9	44.1	63.6	75.0	78.8	79.8	79.5	79.5	70.8	57.8
−70°S	49.9	42.3	45.1	61.1	76.7	80.0	80.0	80.0	79.8	79.8	76.2	68.3
−72°S	65.5	61.0	65.2	79.3	80.0	80.0	80.0	80.0	80.0	80.0	78.1	73.5
−74°S	66.9	64.3	70.6	80.0	80.0	80.0	80.0	80.0	80.0	79.5	77.4	72.3
−76°S	70.2	70.9	74.2	80.0	80.0	80.0	80.0	80.0	80.0	80.0	78.6	74.5
−78°S	69.3	69.3	75.5	80.0	80.0	80.0	80.0	80.0	80.0	79.9	77.1	73.1
−80°S	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
−82°S	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
−84°S	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
−86°S	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
−88°S	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
−90°S	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0

of a relatively dry surface. Thus, for example, in the case of tropical rainforests, which are almost constantly wet, we departed from a median value of 12% obtained under clear skies and adopted an average reflectivity of 10%.

4. Comments

Our choice of ice-free ocean albedo in high latitudes is lower than most other estimates. A calm ocean has high specular reflectance at low solar elevations under clear skies (Payne, 1972). Albedos of up to 44% were reported. A rough sea, however, has a lower albedo. Under cloudy skies, when diffuse radiation dominates, water albedo is low. Chopped white caps do not increase the albedo considerably (Payne, 1972). In accordance with published measurements, the ocean albedo in high latitudes under cloudy skies was taken as close to 6%. Under clear skies with average winds the albedo in summer is considered to be around 11–12% and in fall and spring, with low solar angle, around 17%. Given the relatively high cloudiness during summer we took 10% as the average value for high latitudes.

Data of Batten *et al.* (1977) for snow reflectivity of NOAA charts were parameterized from a wide range of measured brightness fields. They should be taken as first-order approximations; Batten's precision limits are shown in Table 1. The value for scattered mountain snow was obtained by assuming that one-third of the area is snow-covered with an albedo of 45% and two-thirds snow-free with an albedo of 17%.

Batten's values apply to snow-covered land. Their broad range is due to varying type and density of vegetation, surface roughness and variable depth of snow cover. Tundra, deeply plowed farmland, rocky escarpments, tall grass prairies, etc., have lower albedo when snow covered than flat lands with little or no vegetation, or ice. Snow-covered forests have a low albedo. Differences result from the presence of protruding dark objects such as stems of vegetation, soil lumps, boulders, etc. The deeper the snow, the more complete the coverage. Once the snow is approximately a foot deep, a further increase in depth results in negligible changes in regional albedo. Dense coniferous forests with even a foot or more of snow on the ground preserve a low reflectance, only a few percent higher than the summer value (Kung *et al.*, 1964; Berglund and

TABLE 3. Average zonal monthly surface albedo estimates (%): ocean and pack ice only (for full spectral range of *incoming* solar radiation and average atmospheric conditions).

	Month											
Latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
90–88°N	80.0	80.0	80.0	80.0	80.0	80.0	60.0	60.0	80.0	80.0	80.0	80.0
–86°N	80.0	80.0	80.0	80.0	80.0	80.0	60.0	60.0	80.0	80.0	80.0	80.0
–84°N	80.0	80.0	80.0	80.0	80.0	80.0	60.0	60.0	80.0	80.0	80.0	80.0
–82°N	80.0	80.0	80.0	80.0	80.0	80.0	60.0	60.0	80.0	80.0	80.0	80.0
–80°N	80.0	80.0	80.0	80.0	80.0	80.0	57.5	55.7	74.1	76.6	77.8	77.8
–78°N	75.9	77.3	77.3	77.6	78.1	78.3	56.8	51.6	65.6	72.5	75.2	77.3
–76°N	72.8	74.0	74.2	76.0	75.9	70.6	48.7	43.6	52.7	60.2	65.3	70.1
–74°N	66.5	66.6	66.3	66.1	68.0	61.0	43.0	37.3	41.4	54.2	62.5	64.1
–72°N	63.2	64.1	62.3	62.9	63.5	59.5	41.4	31.1	23.3	41.5	56.3	59.4
–70°N	59.0	57.7	58.1	56.4	57.1	55.1	37.4	24.6	24.3	33.4	50.6	54.9
–68°N	51.7	54.0	54.0	54.5	46.1	39.8	25.8	11.5	10.3	17.3	39.8	48.8
–66°N	41.9	43.0	43.9	41.7	38.5	30.6	18.4	10.9	10.0	12.9	26.9	37.4
–64°N	45.2	42.4	40.8	42.8	32.6	22.8	14.3	10.7	10.4	10.0	19.3	31.6
–62°N	38.6	42.2	40.9	38.6	30.1	25.2	15.0	10.0	10.0	12.1	19.0	32.5
–60°N	37.1	39.1	47.0	38.5	29.7	22.7	13.9	10.0	10.0	10.0	15.0	31.4
–58°N	28.7	29.1	31.8	26.7	22.3	15.6	9.9	7.0	7.0	10.0	10.9	37.9
–56°N	22.3	25.9	26.4	22.6	16.6	12.7	8.8	7.0	7.0	9.2	11.2	30.1
–54°N	18.0	21.0	21.5	15.6	13.7	11.5	7.3	7.0	7.0	9.0	10.4	15.6
–52°N	13.9	15.8	15.7	10.6	8.7	7.9	6.1	7.0	7.0	9.0	10.3	12.2
–50°N	13.7	16.8	15.3	12.1	9.5	7.2	6.1	7.0	7.0	8.0	10.0	12.0
–48°N	10.0	10.0	8.0	7.0	6.0	6.0	6.0	7.0	7.0	8.0	10.0	10.0
–46°N	10.0	10.0	8.0	7.0	6.0	6.0	6.0	7.0	7.0	8.0	10.0	10.0
–44°N	10.0	9.0	7.0	7.0	6.0	6.0	6.0	6.0	7.0	8.0	10.0	10.0
–42°N	10.0	9.0	7.0	7.0	6.0	6.0	6.0	6.0	7.0	8.0	10.0	10.0
–40°N	10.0	9.0	7.0	7.0	6.0	6.0	6.0	6.0	7.0	8.0	10.0	10.0
–38°N	10.0	9.0	7.0	7.0	6.0	6.0	6.0	6.0	7.0	8.0	10.0	10.0
–36°N	10.0	9.0	7.0	7.0	6.0	6.0	6.0	6.0	7.0	8.0	10.0	10.0
–34°N	9.0	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0	8.0	9.0
–32°N	9.0	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0	8.0	9.0
–30°N	9.0	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0	8.0	9.0
–28°N	9.0	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0	8.0	9.0
–26°N	9.0	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0	8.0	9.0
–24°N	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0	7.0
–22°N	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0	7.0
–20°N	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0	7.0
–18°N	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0	7.0
–16°N	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0	7.0
–14°N	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0
–12°N	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0
–10°N	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0
– 8°N	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0
– 6°N	7.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0
– 4°N	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
– 2°N	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
– 0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
0– 2°S	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
– 4°S	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
– 6°S	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
– 8°S	6.0	6.0	6.0	6.0	7.0	7.0	6.0	6.0	6.0	6.0	6.0	6.0
–10°S	6.0	6.0	6.0	6.0	7.0	7.0	6.0	6.0	6.0	6.0	6.0	6.0
–12°S	6.0	6.0	6.0	6.0	7.0	7.0	6.0	6.0	6.0	6.0	6.0	6.0
–14°S	6.0	6.0	6.0	6.0	7.0	7.0	6.0	6.0	6.0	6.0	6.0	6.0
–16°S	6.0	6.0	6.0	6.0	7.0	7.0	6.0	6.0	6.0	6.0	6.0	6.0
–18°S	6.0	6.0	6.0	6.0	7.0	7.0	7.0	7.0	6.0	6.0	6.0	6.0
–20°S	6.0	6.0	6.0	6.0	7.0	7.0	7.0	7.0	6.0	6.0	6.0	6.0
–22°S	6.0	6.0	6.0	6.0	7.0	7.0	7.0	7.0	6.0	6.0	6.0	6.0
–24°S	6.0	6.0	6.0	6.0	7.0	7.0	7.0	7.0	6.0	6.0	6.0	6.0
–26°S	6.0	6.0	6.0	6.0	7.0	7.0	7.0	7.0	6.0	6.0	6.0	6.0
–28°S	6.0	6.0	6.0	7.0	8.0	9.0	8.0	7.0	7.0	6.0	6.0	6.0
–30°S	6.0	6.0	6.0	7.0	8.0	9.0	8.0	7.0	7.0	6.0	6.0	6.0
–32°S	6.0	6.0	6.0	7.0	8.0	9.0	8.0	7.0	7.0	6.0	6.0	6.0
–34°S	6.0	6.0	6.0	7.0	8.0	9.0	8.0	7.0	7.0	6.0	6.0	6.0

TABLE 3. (*Continued*)

Latitude	Month Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
-36°S	6.0	6.0	6.0	7.0	8.0	9.0	8.0	7.0	7.0	6.0	6.0	6.0
-38°S	6.0	6.0	7.0	8.0	9.0	10.0	10.0	8.0	7.0	7.0	6.0	6.0
-40°S	6.0	6.0	7.0	8.0	9.0	10.0	10.0	8.0	7.0	7.0	6.0	6.0
-42°S	6.0	6.0	7.0	8.0	9.0	10.0	10.0	8.0	7.0	7.0	6.0	6.0
-44°S	6.0	6.0	7.0	8.0	9.0	10.0	10.0	8.0	7.0	7.0	6.0	6.0
-46°S	6.0	6.0	7.0	8.0	9.0	10.0	10.0	8.0	7.0	7.0	6.0	6.0
-48°S	6.0	7.0	7.0	8.0	10.0	10.0	10.0	8.0	8.0	7.0	6.0	6.0
-50°S	6.0	7.0	7.0	8.0	10.0	10.0	10.0	8.0	8.0	7.0	6.0	6.0
-52°S	6.0	7.0	7.0	8.0	10.0	10.0	10.0	8.0	8.0	7.0	6.0	6.0
-54°S	7.0	7.0	7.0	8.0	10.0	10.0	10.0	9.0	9.0	8.0	7.0	7.0

(See Table 2 for latitudes 54°S–90°S).

Mace, 1972). Only on rare occasions in the fall and early spring when wet snow freezes on branches or when hoar frost grows on the needles do dense coniferous forests have albedos considerably higher than summer values.

Ice sheets in Greenland and Antarctica and snow-covered sea ice were assigned an albedo of 80%. Spectral radiative models (Bergen, 1975) and measurements (Grenfell and Maykut, 1977; Bryazgin and Koptev, 1970; O'Brien and Munis, 1975; Mellor, 1977) show the albedo of snow surfaces to be significantly higher in visible wavelengths than in the near-IR. Due to low atmospheric moisture in these regions the difference between snow albedo under cloudy and under clear skies is considerable. The albedo of fresh snow should be close to 75% in clear weather, while under heavy overcast with moist air close to 90% (Choudhury and Chang, 1978). Only freshly deposited or reblown snow has such high reflectance. Several days after deposition the albedo drops due to metamorphism of the upper layer (Bergen, 1975; Petzold, 1977). Our estimate of 80% is averaged for overcast and relatively moist atmospheric conditions lasting half of the time.

Estimates of regionally representative albedo values of sea ice differ widely. Our summer values for the Arctic Basin are largely based on data collected by U.S. and U.S.S.R. drifting stations between 1950–64 and summarized by Chernigovskii (1970). He reports large year-to-year variations of the Arctic pack albedo. We also used measurements of the Arctic Ice Dynamics Joint Experiment showing a relatively large day-to-day variability (Pautzke and Hornoff, 1978). This variation in time is also apparent in the measurements of Langleben (1968; 1969; 1971), Grenfell and Maykut (1977), Holmgren and Weller (1974) and Chernigovskii (1963).

The albedo of broken ice with exposed water was obtained from compiled measurements taken principally in the Arctic Basin (Chernigovskii, 1970; Hanson, 1961; Kuznetsov and Timerev, 1973; Holmgren and Weller, 1974; Langleben, 1968; 1969; 1971). The data show reasonable agreement with a model in which water, bare sea ice and snow-covered sea ice are assigned fixed reflectivity values and where the proportion of the three components is allowed to change. Values used were 10% for water, 60% for bare sea ice and 80% for snow-covered ice. When open water exceeds 50% all the ice floes are assumed bare, otherwise they are snow covered. One exception occurs during full summer when the average regional albedo of melted and puddled pack ice surfaces in the central Arctic was taken as 60%, in agreement with the estimates of Grenfell and Maykut (1977), Chernigovskii (1963) and Marshunova (1961). There is close agreement between our albedo values for different ice concentrations and those measured by Kuznetsov and Timerev (1973). Departures do not exceed 4%.

5. Zonal averages

Monthly zonal averages are in Table 2. Monthly averages for ocean from 90°N to 55°S are presented in Table 3. The open water data from Payne (1972) and others and the ice cover data (FLEWEAFAC, 1974/75) with corresponding albedos (Table 1) were summed and averaged for each 2° latitudinal belt.

Average monthly surface albedo of snow-free land was chosen separately for 2° by 2° blocks. The snow-free land class (Table 1) considered dominant was chosen to represent the block. Selection was made with the use of Defense Meteorological Satellite Program images (Dickinson *et al.*, 1974) and the surface types shown in atlases (Fullard *et al.*, 1970; Gerasimov, (1964). Results are in Table 4.

The DMSP images were calibrated over the oceans (Payne, 1972), over parts of the United States (Kung *et al.*, 1964) and in Northwest Africa (Rock-

TABLE 4. Average zonal monthly surface albedo estimates (%): land only (for full spectral range of incoming solar radiation and average atmospheric conditions).

Latitude	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
84–82°N	65.0	65.0	65.0	65.0	65.0	64.5	43.9	42.1	57.1	65.0	65.0	65.0
–80°N	69.5	69.5	69.5	69.5	69.5	69.1	55.7	50.8	64.3	69.5	69.5	69.5
–78°N	70.0	70.0	70.0	70.0	69.7	67.5	59.5	53.0	57.4	68.8	70.0	70.0
–76°N	70.5	70.5	70.5	70.5	70.1	68.6	58.6	50.5	57.3	68.1	70.5	70.5
–74°N	68.8	68.8	68.8	67.2	68.0	66.3	47.8	39.8	44.1	62.9	68.8	68.8
–72°N	67.3	67.3	67.3	66.7	65.9	56.6	38.3	32.7	37.3	58.1	67.3	67.3
–70°N	66.4	66.4	66.3	65.1	65.0	53.8	29.5	25.1	28.9	55.0	66.4	66.4
–68°N	66.1	65.5	63.0	59.6	58.8	40.5	24.8	22.3	25.4	49.3	65.3	66.1
–66°N	65.6	64.7	60.8	54.3	52.4	30.6	21.2	19.9	21.7	44.2	64.9	65.6
–64°N	65.4	58.8	57.2	50.4	46.7	24.4	19.0	18.9	19.5	39.8	48.1	64.8
–62°N	58.2	51.3	53.0	46.2	40.6	21.9	19.0	18.3	19.1	34.8	44.5	63.2
–60°N	50.2	49.0	49.9	42.4	36.9	21.5	18.8	17.7	18.9	29.7	42.2	57.8
–58°N	47.2	45.7	47.7	37.9	30.0	20.5	17.8	17.5	17.4	24.1	37.5	45.9
–56°N	44.4	47.6	46.6	34.5	28.5	20.5	17.8	17.4	17.5	24.8	32.4	43.8
–54°N	44.0	47.7	45.2	31.9	26.4	19.5	17.8	17.2	17.1	23.9	30.3	41.5
–52°N	42.0	47.8	43.9	28.5	25.1	18.1	18.1	17.4	17.3	22.2	26.6	38.6
–50°N	39.5	47.2	44.8	28.9	24.3	18.0	17.7	17.4	17.7	21.2	25.8	35.4
–48°N	38.1	47.9	41.2	26.4	22.7	18.8	18.5	17.2	18.5	20.3	24.3	31.1
–46°N	33.7	46.3	38.7	23.7	21.9	18.5	18.8	17.0	19.1	19.9	22.8	29.7
–44°N	33.3	43.1	34.4	21.7	20.7	19.7	19.4	17.0	19.4	20.2	20.5	25.6
–42°N	30.5	37.3	29.4	23.4	21.0	19.4	19.6	17.3	19.7	20.1	20.0	25.5
–40°N	27.5	30.1	26.0	22.6	20.9	20.4	19.8	20.0	19.8	20.3	20.2	24.9
–38°N	24.8	27.5	24.7	22.6	21.8	19.7	19.5	19.1	19.1	19.9	19.1	21.9
–36°N	22.8	24.8	25.6	21.9	21.6	20.0	20.0	18.9	18.8	19.9	19.4	20.6
–34°N	26.3	26.7	25.1	27.3	23.1	21.5	20.4	19.9	19.7	20.5	21.2	23.6
–32°N	23.6	23.9	24.6	25.2	22.5	22.4	21.7	21.5	21.4	21.7	22.4	22.9
–30°N	24.8	24.5	24.8	24.3	23.3	23.5	23.0	23.4	23.1	23.0	23.1	23.6
–28°N	26.0	26.2	26.9	27.6	25.7	25.4	25.2	25.4	24.9	25.0	24.1	23.9
–26°N	24.3	24.7	26.0	24.0	24.0	24.2	24.0	24.0	24.0	24.2	23.0	22.5
–24°N	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9
–22°N	25.6	25.6	25.6	25.6	25.6	25.6	25.6	25.6	25.6	25.6	25.6	25.6
–20°N	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1
–18°N	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1
–16°N	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0	24.0
–14°N	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5
–12°N	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8	17.8
–10°N	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9
– 8°N	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1
– 6°N	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
– 4°N	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
– 2°N	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9
– 0	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7	11.7
0– 2°S	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
– 4°S	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
– 6°S	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
– 8°S	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3	13.3
–10°S	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4
–12°S	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2
–14°S	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9
–16°S	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7	16.7
–18°S	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8
–20°S	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
–22°S	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6
–24°S	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
–26°S	18.6	18.6	18.6	18.6	18.6	18.6	18.6	18.6	18.6	18.6	18.6	18.6
–28°S	18.8	18.8	18.8	18.8	18.8	18.8	18.8	18.8	18.8	18.8	18.8	18.8
–30°S	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0
–32°S	18.6	18.6	18.6	18.6	18.6	18.6	18.9	18.6	18.6	18.6	18.6	18.6
–34°S	18.3	18.3	18.3	18.3	18.3	18.6	18.6	18.6	18.6	18.6	18.3	18.3
–36°S	18.2	18.2	18.2	18.2	18.2	19.0	19.8	19.8	19.0	19.0	19.0	18.2
–38°S	17.4	17.4	17.4	17.4	17.4	18.2	19.1	19.1	18.2	18.2	18.2	17.4
–40°S	17.0	17.0	17.0	17.0	17.0	20.7	20.7	20.7	18.9	18.9	18.9	17.0

TABLE 4. (Continued)

Latitude	Month Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
−42°S	17.0	17.0	17.0	17.0	18.9	20.7	20.7	20.7	20.7	18.9	18.9	17.0
−44°S	17.0	17.0	17.0	17.0	19.0	21.0	21.0	21.0	21.0	19.0	19.0	19.0
−46°S	17.0	17.0	17.0	17.0	19.2	21.3	21.3	21.3	21.3	19.2	19.2	19.2
−48°S	20.5	17.0	17.0	20.5	24.0	31.0	31.0	31.0	24.0	24.0	20.5	20.5
−50°S	20.1	20.1	20.1	20.1	23.2	29.4	29.4	29.4	29.4	23.2	20.1	20.1
−52°S	21.7	21.7	21.7	21.7	26.3	35.7	45.0	45.0	35.7	26.3	21.7	21.7
−54°S	17.0	17.0	17.0	21.7	26.3	35.7	35.7	35.7	35.7	26.3	21.7	21.7
−56°S	17.0	17.0	17.0	17.0	28.2	39.4	39.4	39.4	39.4	28.2	22.6	17.0

(See Table 2 for latitudes 56°S–90°S).

wood and Cox, 1978). The average monthly surface albedo of snow-free land in this study was kept constant throughout the year as was that of snow-covered ice sheets in central Greenland and Antarctica. Snow in South America was reconstructed from a satellite-derived cloud-cover atlas (Miller and Feddes, 1971), assuming that the extent in 1974–75 did not considerably differ from 1967–70. Snow fields in South America were considered to have an albedo of 45%.

6. Conclusions

Results are presented in Tables 2–5 and Figs. 1–4. It can be noted that according to our highly parameterized reconstruction:

1) Between 40°N and 55°S and 80–90°S, the annual range of mean monthly surface albedo does not exceed 10% (Fig. 1).

2) The largest seasonal range of surface albedo occurs between latitudes 60° and 70° in both hemispheres (Fig. 1).

3) The zone with a large seasonal change of surface albedo is considerably more extensive in the Northern than in the Southern Hemisphere (Fig. 1).

4) Average annual surface albedo exhibits a slow steady rise from the equator to about 60°N latitude and a sharp rise between 60–80°N and 58–70°S (Fig. 2).

5) Surface albedo varies little between 30°N and 55°S and from 80–90°S (Fig. 2).

TABLE 5. Summary of average surface albedo estimates (%).

	Month Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
Northern Hemisphere													
60–90°N	61.6	61.2	61.0	58.1	55.5	45.1	32.2	28.1	32.0	44.4	53.7	61.5	49.5
30–60°N	22.7	24.6	22.5	17.8	15.6	13.7	12.8	12.7	12.9	14.6	16.4	21.2	17.3
0–30°N	10.9	10.3	10.3	10.3	10.2	10.2	10.2	10.2	10.2	10.3	10.5	10.8	10.4
0–90°N	22.1	22.4	21.6	19.5	18.3	16.2	14.1	13.5	14.1	16.5	18.5	21.5	18.2
0–90° (land)	33.8	35.4	34.0	29.4	27.4	23.2	20.9	20.4	20.8	25.1	27.6	32.6	27.6
0–90° (ocean)	14.4	13.9	13.5	13.0	12.4	11.6	9.7	9.0	9.7	10.8	12.5	14.2	12.1
Southern Hemisphere													
60–90°S	46.5	44.0	46.1	53.1	61.6	67.7	72.8	74.4	74.5	73.5	67.1	56.1	61.5
30–60°S	7.2	7.2	7.7	8.7	9.8	10.6	10.9	9.9	10.3	9.7	8.2	7.5	9.0
0–30°S	8.2	8.2	8.2	8.3	8.9	9.1	8.6	8.5	8.3	8.2	8.2	8.2	8.4
0–90°S	13.0	12.6	13.1	14.5	16.3	17.6	18.1	18.0	18.0	17.5	16.1	14.4	15.8
0–90°S (land without Antarctica)	16.3	16.2	16.2	16.2	16.3	17.0	17.0	17.0	16.7	16.5	16.4	16.4	16.5
0–90°S (ocean with Antarctica)	12.5	12.1	12.6	14.2	16.3	17.6	18.3	18.2	18.2	17.7	16.1	14.1	15.7
Globe													
90°S–90°N	17.5	17.5	17.4	17.0	17.3	16.9	16.1	15.7	16.0	17.0	17.3	17.9	17.0
90°S–90°N (land without Antarctica)	29.4	30.6	29.5	26.1	24.6	21.6	19.9	19.5	19.8	22.9	24.8	28.5	24.8
90°S–90°N (ocean with Antarctica)	13.3	12.8	13.0	13.7	14.7	15.1	14.8	14.4	14.7	14.9	14.6	14.1	14.2

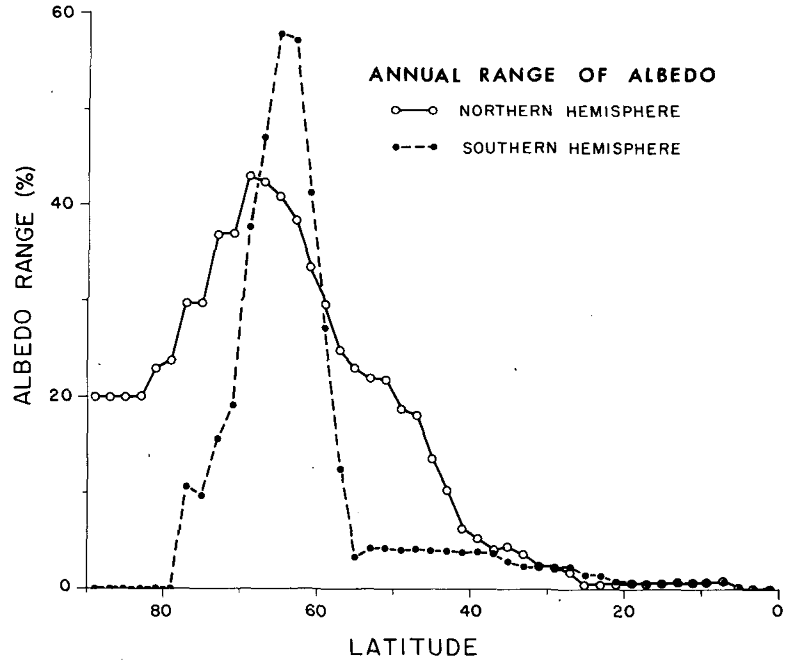

FIG. 1. Annual range of zonal monthly surface albedo estimates by 2° latitudinal belts.

Our annual average values between 15°N and 45°S come close to the estimates of both Hummel and Reck (1979) and Sellers (1965) (Fig. 2). Between 15 and 75°N our values are in agreement with Hummel and Reck, whereas those of Sellers are consistently lower. Between 75 and 90°N our data are higher than those of both papers.

The seasonal values of Hummel and Reck differ little from ours between 45°N and 35°S (Fig. 3), while those for 45 to 90°N and south of 35°S show significant differences.

Schutz and Gates (1972, 1973, 1974), using the parameterizations of Posey and Clapp (1964), tabulated surface albedo for three selected seasons (Fig. 4). Reasonable agreement with our values is seen between 60°N and 50°S but not in the high latitudes.

In general, our surface albedo reconstruction for 1974–75 with realistic snow and ice input departs significantly from formerly published estimates in high latitudes. Our annual global average of 17.0% is considerably higher than the 13.39% reported by Flohn (1975), and 15.4% given by Otterman (1977b). One reason is that we did not weight the albedo values by radiation income; we took albedo as a surface property independent of actual irradiation amounts. Such weighting, while perhaps useful for some climatic applications, would introduce an additional element of uncertainty into the result.

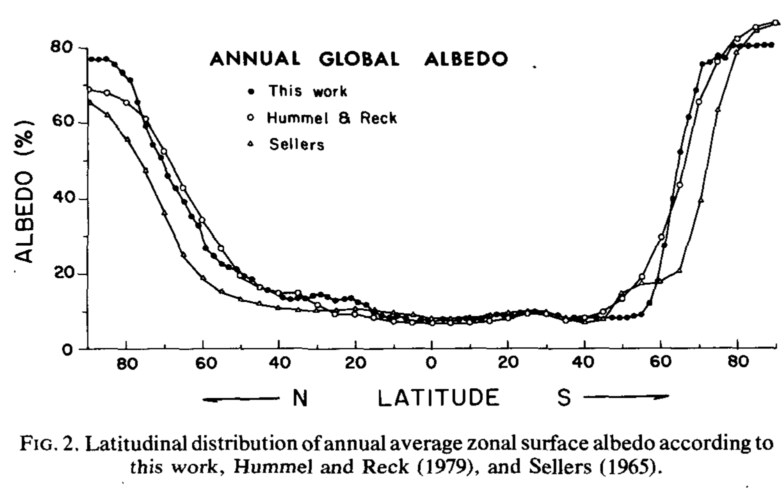

FIG. 2. Latitudinal distribution of annual average zonal surface albedo according to this work, Hummel and Reck (1979), and Sellers (1965).

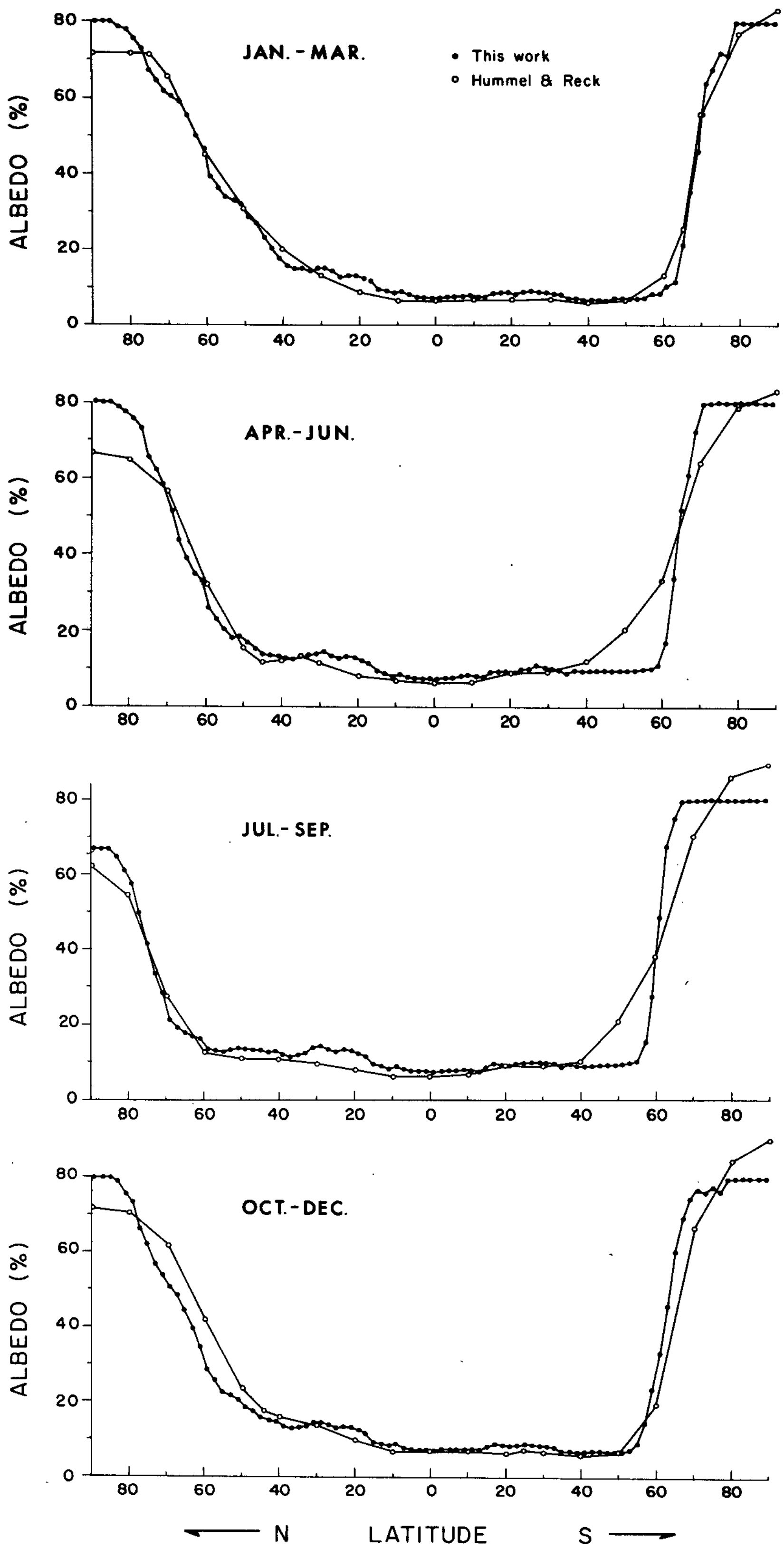

FIG. 3. Latitudinal distribution of seasonal zonal surface albedo. From this work and Hummel and Reck (1979).

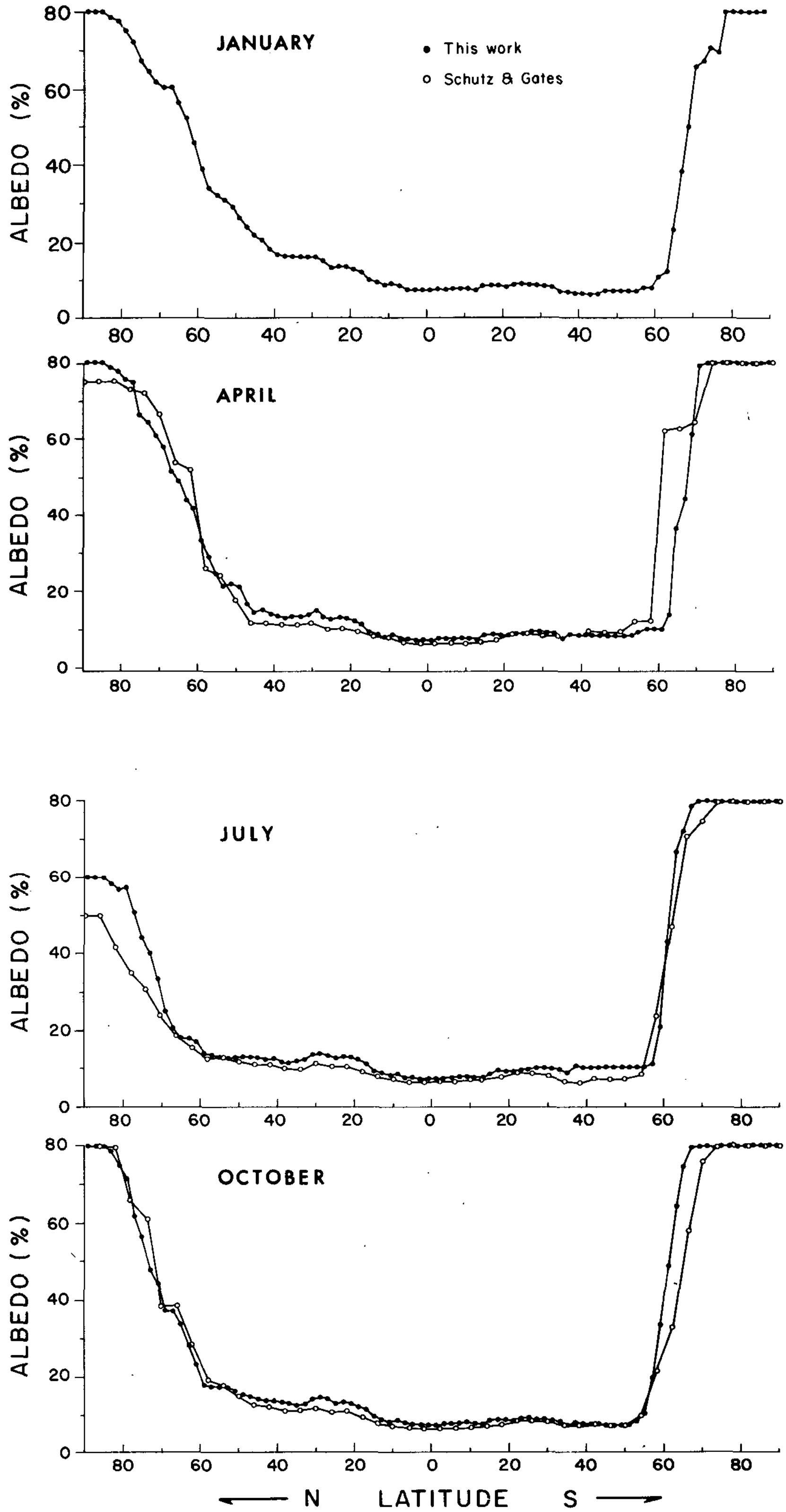

FIG. 4. Latitudinal distribution of zonal surface albedo for selected months after this work and Schutz and Gates (1972, 1973, 1974).

Acknowledgments. We thank N. Untersteiner for his guidance and suggestions, E. S. Batten, J. Otterman, A. Berger, M. Matson, W. Donn and K. Hunkins for comments, and R. Lotti and B. Taylor for technical assistance. The research was supported by the National Science Foundation Grant ATM77-28522. This is Lamont-Doherty Geological Observatory of Columbia University Contribution No. 2942.

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