Some Characteristics of the Albedo of Snow

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ABSTRACT

Spring snowcovers exhibit a substantial contribution of a specular component to their reflection of solar radiation. This anisotropy can be measured with radiometers with small aperture, here with a TIROS radiometer. Indicatrices thus determined are dependent on solar angle. They are of importance for interpreting albedo values and for reducing air- or spaceborne reflectance data taken under distinct nadir angles.

1. Introduction

With the increasing use of airborne radiometers to determine the albedo of the earth's surface, caution has to be extended as to the nature of the reflective process. Spectral characteristics, and particularly the contribution of specular to an all-present diffuse component of reflectance, may lead to under- or overestimations in albedoes of larger areas.

The albedo of natural surfaces is composed of a diffuse and a specular component. Some surfaces, like many plant formations and soils, reflect the shortwave solar and scattered radiation almost entirely diffuse, while others, like water, snow and ice or certain crops contribute a varying percentage of the albedo by specular reflection processes.

The most apparent specular reflection of undisturbed water surfaces can be calculated using Fresnel's formulas, while those of natural waters, disturbed by waves or ripples, were measured by different authors (see, for example, Cox and Munk, 1954).

Over snow fields and glaciers, due to the rough surface, the contribution of the specular component of the reflection is much smaller, but still apparent, as can be concluded by the inspection of the daily course of the albedo.

In Fig. 1, a few examples of daily variations of the albedo are presented. They are for different regions of the world and over a spectrum of different snow conditions (Hubley, 1955; Tooming, 1960; Sauberer and Dirmhirn, 1952). Some measurements of albedo over dry snow have also been made more recently by Korff *et al.* (1974) and Dirmhirn (1967).

Occasional airborne measurements of the areal distribution of reflected radiation from snow surfaces have been carried out during the past eight years. These measurements are extremely difficult due to the fact that the underlying surfaces are not horizontal and uniform over a large area, and results from those attempts were somewhat controversial (Raschke *et al.*, 1973; Bartman, 1967; Salomonson and Marlatt, 1968; Korff and Vonder Haar, 1974). If measurements are made on the ground, uniform and horizontal surfaces can be selected and the above-mentioned errors eliminated. This was the reason an instrument close to the ground was used in this study.

The daily variation of the albedo measurement over snow and ice is the result of two processes and a measurement error: (i) the varying contribution of specular reflection from the snow surface with solar angle, (ii) the metamorphism (recrystallization on the surface and within the snow pack) of the snow during one day's time, and (iii) an instrumental error, due to a deviation of pyranometers or photocells from the cosine law.

Two of the effects, those due to the specular reflection (i) and the instrumental error (iii), are dependent on the angle of incidence of the direct solar radiation, and are thus symmetric around local noon.

The second contribution, the metamorphism of the snowcover, results, in general, in a decrease of the albedo. The heat applied to the snowcover during daytime by radiative processes is used for recrystallization processes and subsequently for a decrease in the many facets of the minute crystals of fresh fallen snow. Thus, the scattering processes in the uppermost layer of the snow are diminished, and radiation can penetrate deeper into the snow where increased absorption can take place. This results in a general decrease of the reflected portion of the shortwave solar and scattered radiation. Since metamorphism is an irreversible process, a snowcover which is once undergoing a change by metamorphism cannot recover during the night. The decrease in albedo due to metamorphism thus results in an overall decrease in

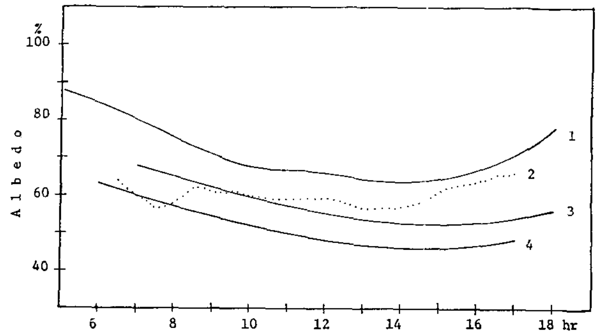


FIG. 1. Daily variation of albedo on a clear day.

1. Lemon Creek Glacier, near Juneau, Alaska, Summer 1954 (Hubley, 1955).
2. Granular snow, Tartu, USSR, March 1956 (Tooming, 1960).
3. Snow and firn, Sonnblick, Austria, September 1950 (Sauberer and Dirmhirn, 1952).
4. As in 3, except for July 1950.

the albedo of a snowcover from day to day, as can be seen in Fig. 2 (Eckel and Thams, 1939; U. S. Army Corps of Engineers, 1956).

While refreezing of the melted surface layer during the night results in an increase in the albedo in the morning hours, this effect contributes only to the surface (angular) reflection (i), which occurs mornings *and* evenings and appears as a symmetric component of albedo.

The contribution of metamorphism to the daily variation of albedo can sometimes be seen as an asymmetry in the course of the albedo (see Fig. 1) shifting the minimum toward the afternoon. This shift has to be considered when measurements are taken at a certain hour (or solar angle) to determine an "average" albedo for the day. Morning and afternoon values at the same solar angle differ under these conditions, and data at both times have to be averaged to find a representative value of the albedo of the day.

The two other effects, the actual physical process of the specular reflection, and the instrumental error, both resulting in a symmetric variation of the daily variation of the measured albedo, cannot be separated. Calculations of the error can be made, however, if the deviation of the pyranometer in question from the cosine law is known. All commercial pyranometers exhibit this deviation starting from solar zenith angles of about 70°.

Since the direct beam component contributes the main part of the incoming shortwave radiation on clear days, the global radiation may be underestimated at low sun angles when a deviation of the cosine law exists in a pyranometer. In measuring the reflected radiation from the snowcover, however, most of the rays come from the favorable angles within an incidence angle of 70°. The highly specular component from over 70° contributes only a minor part of the reflected radiation. Thus the reflected radiation is measured almost correctly, while the measured incoming radiation values are too low when an instrumental error exists. Since the latter is the denominator in calculating the albedo, values will be too high.

While the actual effect of the sun angle on the albedo cannot be separated from the instrument error by using pyranometers, it can well be determined with instruments with small opening angles. Thus the indicatrix of the reflected radiation from the snowcover can be determined and the albedo derived by spatial integration. Measurements of this type were carried out during the winter 1972–73 and shall be discussed here.

2. Instruments and methods

Measurements of the angular distribution of the reflected shortwave radiation were made over wide horizontal snowfields using the third channel of a TIROS radiometer (TIROS III Users Manual, 1962). This channel is designed with a filter in front of the bolometer receiver to permit transmission of a waveband from 0.2 to 4.5 μm, thus covering the whole shortwave solar and scattered radiation band.

The opening angle of the instrument is 5° for the half-power point, an angle small enough to determine the indicatrix of the reflected radiation.

Measurements were taken in intervals of 15° nadir angle and 45° azimuth angle.

To determine the overall albedo, a pyranometer [Star pyranometer (Dirmhirn, 1958)] was used, and incoming and reflected radiative flux measured alternately.

3. Results

While the reflectivity from fresh fallen snow is almost isotropic (negligible specular component), the

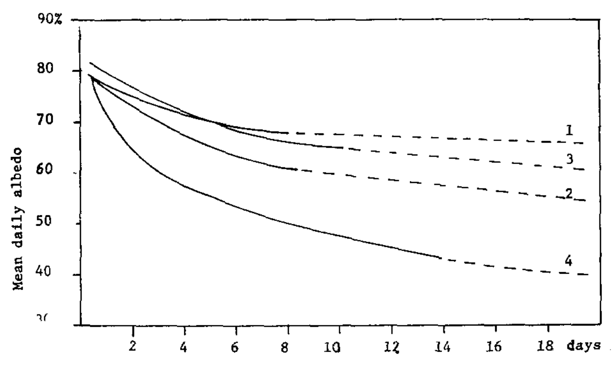


FIG. 2. Variation of albedo with time.

1. Air temperature $t<0°C$, Davos, Schwitzerland (Eckel and Thams, 1939).
2. As in 1, except for $t>0°C$.
3. Accumulation season, Central Sierra Snow Laboratory (U. S. Army Corps of Engineers, 1956).
4. As in 3, except for melt season.

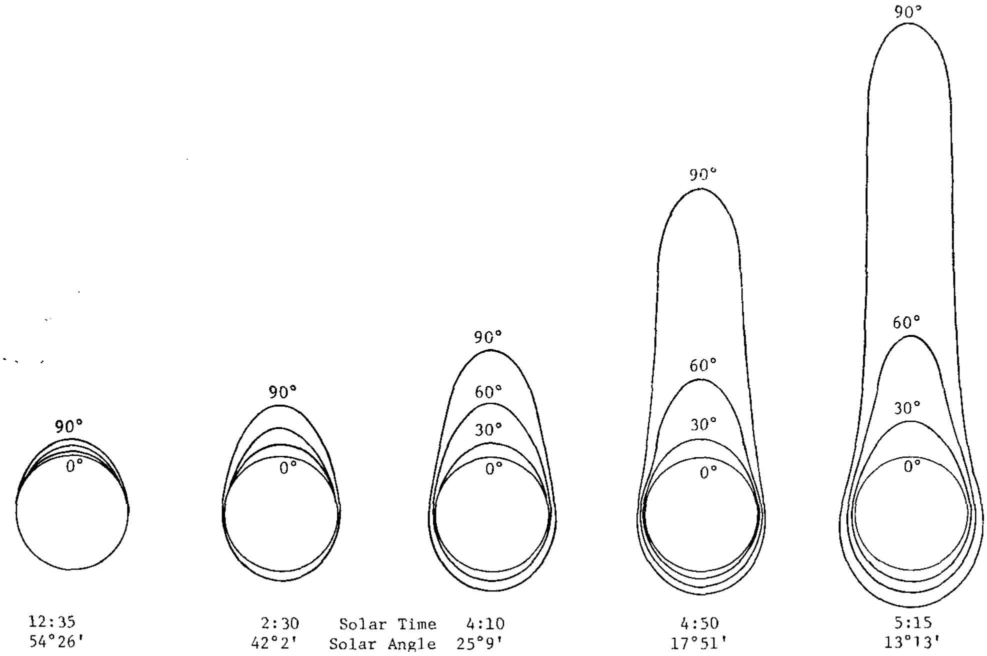


FIG. 3. Indicatrices of snow reflectance at different solar angles (daytime) on 4 April 1973.

specular component increases with the age of the snowcover, and, in particular, with the number of melting and refreezing processes toward the end of the season. In order to observe the maximum possible effect, the measurements were taken over spring snow when glazing during sunrise and sunset was obvious.

Fig. 3 shows the angular distribution of the reflected solar and scattered radiation from a horizontal snowfield in Cache Valley, Utah. Times chosen were 1235, 1430, 1610, 1650 and 1715 solar time on 4 April, corresponding with solar angles of 54°, 42°, 25°, 18° and 13°.

In Fig. 3, the top of each drawing represents 0° solar azimuth angle relative to the solar plane. The inner circle shows the vertical reflectance value while the expanding curves of each drawing represent the 30°, 60° and 90° nadir angle measurements—each relative to the vertical measurement.

It is apparent that the forward scattering component is predominately changing with daytime. A small amount of backscatter could be observed and no appreciable effect could be seen at 90° azimuth angle.

The five drawings in Fig. 3 show the strong increase in forward scatter with decreasing solar angle. It is also apparent that the light column is restricted in angle, since azimuth angles of 45° are only slightly affected by the high forward scatter. This compares well with natural water surfaces as described by Cox and Munk (1954).

The question now is how this relatively narrow, highly reflecting forward scatter affects the albedo as measured by pyranometers.

A pyranometer, designed with a plane receiver surface, weights the reflected radiation from different angles according to the cosine of the angle of incidence. Thus, a cosine weighting function has to be applied to the distribution of the radiation shown in Fig. 3. The measured albedo is then determined from the two relations:

$$R_S+R_D=\int_0^{\pi/2}\int_0^{2\pi}(r_s+r_d)_{\theta\phi}\cos\theta\,\sin\theta d\theta d\phi,$$

where R_S+R_D is the sum of the incoming solar and scattered radiation, r_s+r_d the incoming radiation beam widths, and θ and ϕ the zenith and solar azimuth angles; and

$$a(R_S+R_D)=\int_0^{\pi/2}\int_0^{2\pi} i_{\theta,\phi}\cos\theta\,\sin\theta d\phi d\theta,$$

where a is the albedo, i the intensity of the reflected radiation, θ the nadir angle, and ϕ the solar azimuth angle as before.

In this integral a is the albedo measured with pyranometers, $i_{\theta,\phi}$ are the individual values measured with the TIROS radiometer and displayed in Fig. 3, and $\cos\theta$ the weighting function of the pyranometer. Since both instruments are sensitive and of reasonably flat response [$f(\lambda)=\text{constant}$] over the entire wave range of the solar spectrum (0.2–4 μm), we may omit the integration over wavelength and write

$$a=\int_{\lambda=0.2\ \mu\text{m}}^{4\ \mu\text{m}} a_\lambda d\lambda,$$

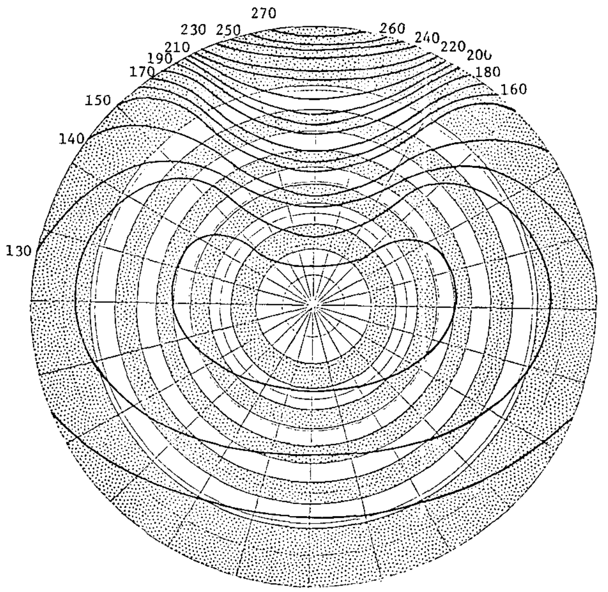


FIG. 4. Isopleths of snow reflectance measured with a narrow angle radiometer, corrected for the cosine of the nadir angle. Each clear and stippled concentric zone is equivalent to 10% of the effective area with regard to an instrument of plane receiver (cosine corrected). For 18° solar angle (1610 solar time).

or for individual values with regard to azimuth and nadir angles

$$a_{\theta,\phi}=\int_{\lambda=0.2\ \mu m}^{4\ \mu m} a_{\lambda,\theta,\phi}d\lambda.$$

The integrals for the data in this study were determined by graphical integration, using the data of Fig. 3 and applying the relationship of $\cos\theta\ \sin\theta d\phi d\theta$ to the nadir angle of measurement θ (as pictured in Fig. 4 for the 1610 measurement).

In Fig. 5 the measured values for the reflected radiation with the pyranometer and with the directly downward pointing TIROS radiometer are plotted against solar time. The calculated values for reflected

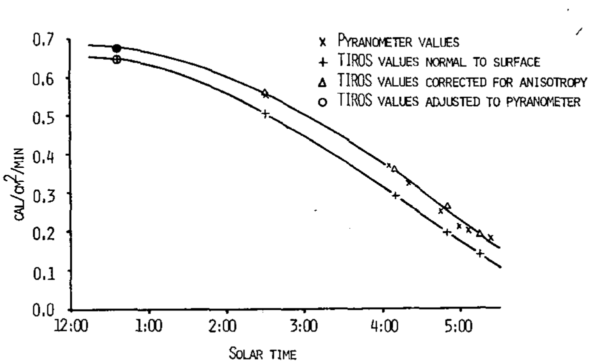
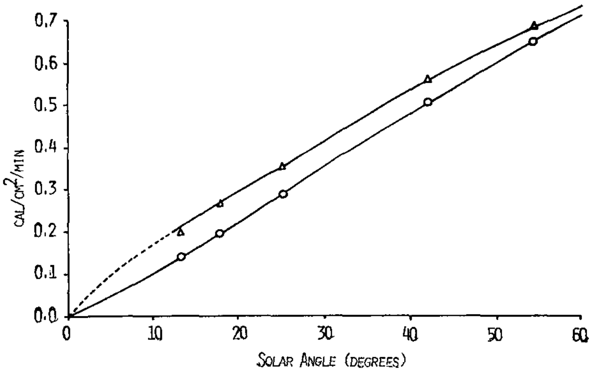


FIG. 5. Values of the measured reflectance with a radiometer of limited opening angle (+), and reflected radiation measured with a pyranometer (×). Calculated values (△) are derived by integration of indicatrix (as shown in Fig. 4).



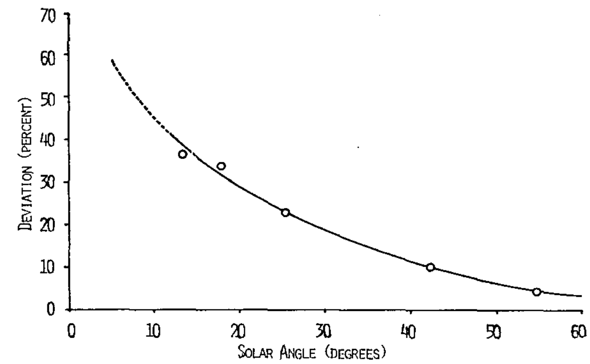


FIG. 6a. Reflectance (nadir angle 0°) measured with TIROS radiometer (circles) and albedos (triangles) measured with pyranometer, for different solar angles.

FIG. 6b. Deviation of albedos (pyranometer values) from reflectance (TIROS radiometer values) as a function of solar angle (derived from Fig. 6a).

radiation from graphical integration of the indicatrix from individual measured values with the TIROS radiometer are also plotted in this figure.

In plotting the reflectance measurements against solar angle ($90°-\theta$), as in Fig. 6a, an almost linear curve can be drawn through the points, i.e., directly downward looking instruments of restricted aperture measure reflected radiation fluxes which are dependent only on the angle of incidence (provided a limited time is taken into consideration while metamorphism is negligible). The angular integrated reflected radiation, however, is not linearly dependent on solar angle (Fig. 6a). The percent of deviation of albedo from the vertical reflectance value increases with the angle of incidence (decreasing solar angle) as shown in Fig. 6b. The deviation amounts to more than 20% at 25° solar angle and almost 50% at 10°.

4. Conclusion and outlook

The specular component of snowcover can well be determined by field measurements of an indicatrix with instruments of small aperture and by comparing the integrated values with albedo measurements [for other approaches see, e.g., Coulson *et al.* (1964);

Middleton *et al.* (1952); Hapke and Van Horn (1963)]. Measurements over snowpack of different maturity will be done in the future. The method lends itself easily to the development of nomograms with the snow condition as a parameter.

Once the nomogram is developed, it should be possible to determine the albedo from measurements of reflectances at any nadir angle using both the nomogram and polar coordinate distributions. This would simplify the determination of albedo considerably, reducing measurements of daily variations to only one or two a day.

Knowledge of the indicatrix of different natural surfaces will also help to intelligently interpret reflectance measurements from satellites. Since the readings taken by satellite radiometers are depicting small areas on the ground seen under different nadir angles, it depends on the spot seen in the indicatrices in Fig. 3 which conversion has to be applied to arrive at "true" albedo values. For surfaces with a considerable specular component of the albedo, like snow, these corrections can be considerable.

Also, knowledge of the indicatrices of snowcover vs metamorphism will ultimately provide the snow hydrologist with a tool to intelligently determine the condition (maturity) of the snow surface from remote platforms.

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REFERENCES

Bartman, F. L., 1967: The reflectance and scattering of solar radiation by the earth. Tech. Rept., University of Michigan, Ann Arbor, NASA CR 83954, 13 pp.

Coulson, K. L., G. M. B. Bouricius and E. L. Gray, 1964: Effect of surface properties on planet-reflected sunlight. Paper presented at Third International Radiation Conference, Leningrad, August.

Cox, C., and W. Munk, 1954: Statistics of the sea surface derived from sun glitter. *J. Marine Res.*, **13**, 198–227.

Dirmhirn, Inge, 1958: Untersuchungen an Sternpyranometern. *Arch. Meteor. Geophys. Bioklim.*, **B9**, 124–128.

——, 1967. On the applicability of silicon cells in atmospheric radiation studies. Atmos. Sci. Paper No. 113, Colorado State University.

Eckel, O., and Ch. Thams, 1939: Untersuchungen über Dichte-, Temperatur und Strahlungsverhältnisse der Schneedecke in Davos. *Geologie der Schweiz*, No. 3, Hydrologie, hiefering, 273–340.

Hapke, Bruce, and Hugh Van Horn, 1963: Photometric studies of complex surfaces, with applications to the moon. *J. Geophys. Res.*, **68**, 4545–4570.

Hubley, R. D., 1955: Measurements of diurnal variations in snow albedo on Lemon Creek Glacier, Alaska. *J. Glaciol.*, **2**, 560–563.

Korff, Hans C., Jeffrey J. Gailiun and Thomas H. Vonder Haar, 1974: Radiation measurements over a snowfield at an elevated site. Atmos. Sci. Paper No. 221, Colorado State University.

——, and Thomas H. Vonder Haar, 1974: Use of surface albedo and satellite measurements to determine the shortwave energy balance over a cloud-free, high altitude snowfield. Tech. Rept. NASA Grant NGR 06-002-102, Colorado State University.

Middleton, W. E. Knowles and A. G. Mungall, 1952: The luminous directional reflectance of snow. *J. Opt. Soc. Amer.*, **43**, 572–579.

Raschke, Ehrhard, Thomas H. Vonder Haar, Musa Pasternak and William R. Bandeen, 1973: The radiation balance of the earth-atmosphere system from Nimbus 3 radiation measurements. NASA TN D-7249.

Salomonson, V. U., and W. E. Marlatt, 1968: Anisotropic solar reflectance over white sand, snow and stratus clouds. *J. Appl. Meteor.*, **7**, 475–483.

Sauberer, F., and I. Dirmhirn, 1952: Der Strahlungshaushalt horizontaler Gletscherflaechen auf dem Hohen Sonnblick. *Geogra. Ann.*, **34**, 261–290.

TIROS III Users Manual, 1962: Aeronomy and Meteorology Division, Goddard Space Flight Center, NASA, Greenbelt, Md.

Tooming, H., 1960: Daily and seasonal variations of albedo over some natural surfaces in the Estonian SSR. *Tr. Inst. Fiz.-Astron. Akad. Nauk Est. SSR*, No. 2, 115–163.

U. S. Army Corps of Engineers, 1956: Snow hydrology. Summary report of the snow investigations. North Pacific Division Corps of Engineers, Portland, Ore.