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# Effect of clouds and free water on snow albedo

**Punit VASHISTH**
Instruments Research and Development Estt, Raipur, Dehradun-248008, India

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## Abstract

Study of spectral reflectance and integrated albedo of snow has been carried out with special emphasis on the effects of cloud amount and free water concentration on snow surface. Experiments have been performed in laboratory, by illuminating snow samples using an artificial light source to estimate effect of free water concentration on reflectance characteristics of snow and the results have been compared with field measurements at two different stations in Great Himalayan ranges and one station over Antarctic ice shelf. Empirical relationship has been developed to estimate variation in snow albedo with cloud amount.

## 1. Introduction

The reflection, absorption and transmission of solar radiation by any geological surface govern the radiation budget and local climate. For a highly reflecting surface like snow, this dependence is strong due to negative radiation budget. The variation of snow albedo with meteorological and snow parameters is extremely important in investigating the overall energy budget across the snowpack, in predicting the rate and type of snow metamorphism thereby improving avalanche prediction techniques, study of the ablation rates of snowpack and climatic modelling of snow bound regions. Considerable progress has been made to understand optical properties of snow, but the effects of cloud cover and free water concentration on snow albedo are yet to be understood. The present study on snow albedo and reflectance has been initiated to understand the effect of solar radiation on seasonal snowpack in Himalayan ranges. The study, which includes investigations on the effect of cloud amount and free water concentration on snow albedo, has been used to evaluate the snow metamorphism rates and avalanche prediction.

Ice has a complex refractive index that is of fundamental importance in determining the amount of incident radiation absorbed or scattered by ice crystals. Irvine and Pollock (1968) have tabulated the real and imaginary refractive indices for normal incidence of radiation. In case of a strongly absorbing media, the radiation absorbed will depend on both real and imaginary components of the complex refractive index. In near infrared spectral range (0.70 to 3.00 $\mu$m), the value of the real refractive index of ice differs significantly from the refractive index of water. The high absorption coefficient values of water in this wavelength make water much more absorptive compared to ice. Whereas in visible spectrum (0.40 to 0.70 $\mu$m), the absorption coefficient of ice is similar to that of distilled water (Hobbs, 1974).

A part of clear sky incident solar radiation gets reflected from the surface of a particulate material like snow and the rest penetrates below the surface depending on the absorption coefficients. The total reflectance of snow surface is divided into surface reflectance and volumetric multiple scattering (Choudhury and Chang, 1979; 1981; Warren, 1982; Vashisth, 1994). Due to low absorption coefficient values, most of the visible radiation gets reflected from snow surface (>95% reflectance). High absorption coefficients reduce the multiple volumetric scattering, in near infrared radiation leading to low reflectance values.

## 2. Laboratory and field experimentation

### *2.1. Field measurements*

In the course of the present study, measurements have been made at two different field locations situated at 3000 m altitude in Pir Panjal range (Station-I) and 3800 m altitude in Western Himalayan range (Station-II). Albedo studies have also been conducted over Antarctic ice shelf. At both the stations, the seasonal snow cover build up starts during December-January and stays till May. The snowpack depth varies between 20 cm to 4.5 m. The average annual snowfall at field station-I and II varies between 10-12 m and 6-8 m respectively. The standing snow cover built up at both the stations varied between 1-3 m during the period of measurement. During the observation period, the average air temperatures at station-I in the year 1993-94 and 1994-95 were −8.2℃ and −5.0℃ respectively. At station-II, the average air temperature was −12.3℃ during the observation period of December to March (1993-95). The Antarctic observation site was situated near Indian Antarctic Station (70°05′S, 12°00′E) over ice shelf and observations were made during January-March 1995. The average air temperature at Antarctica was −2.5℃.

The integrated snow albedo, spectral reflectance, global and diffused incident radiation, cloud amount and type, snow grain shape and size have been monitored at hourly intervals. Integrated albedo was measured using a thermocouple based albedo meter and the output was continuously recorded over an electro poly chart recorder. Spectral measurements of reflected and incident radiation were recorded using a GER spectral radiometer in 0.3-2.5 $\mu$m spectral range. The amount of free water in snow pack was measured using a dielectric moisture meter. Snow grain size and type were measured using a moving stage micrometer and a stereo-zoom microscope.

### 2.2. *Laboratory experiments*

For estimation of albedo and reflectance variation with free water concentration in snowpack, artificial water spraying experiments were performed in laboratory with snow samples maintained at a temperature of −2℃ whereas the temperature of sprayed water was maintained at 0℃. Snow samples of 20×20 ×20 cm with known grain sizes were prepared and illuminated artificially using a 500-watt photographic lamp at fixed elevation angle of 40°. This avoids any variation in reflectance values due to change in incident angle of radiation. The snow sample was weighted before spraying water and then a fixed amount of distilled water was sprayed uniformly all over the surface of snow sample. The variation in reflectance values of snow was measured using a spectral radiometer. The initial densities of snow samples were between 320 kg m$^{-3}$ to 440 kg m$^{-3}$ and after spraying the water, the final density of samples reached as high as 660 kg m$^{-3}$. To avoid any variation in reflectance values due to change in snow grain size due to freezing of water, all the readings are taken within a time period of three to five minutes.

## 3. Results and discussion

### 3.1. *Albedo variation with clouds*

Clouds have significant effect on the solar spectrum reaching earth's surface. A thick cloud layer contains large amount of perceptible water in gaseous, liquid or solid state, which makes it behave like a black body for IR radiation (Rusin, 1961). It has been observed that clouds, whenever present affects the snow albedo in two different manners. For an optically thick snowpack, an increase in the integrated albedo values with increase in cloud amount has been observed. This can directly be inferred from the fact that under cloudy conditions, the radiation reaching snow surface is restricted to visible spectrum. Due to high reflectance values of snow in this spectrum, high albedo values are obtained. Secondly, under cloudy conditions a major part of the incident radiation is diffused. This diffused radiation has significant amount of near horizontal angles of incident radiation. The surface reflectance from snow, which is governed strongly by elevation angle of incident radiation increases sharply at low elevation angles to yield high-integrated albedo values as indicated by Choudhury and Chang (1981). Figure 2(a) and 2(b) show the experimental results obtained under simulated laboratory conditions for direct and diffused reflectance by snow for snow samples having grains diameter as 0.5 mm and 1.0 mm respectively. It is evident that the diffused reflectance values are higher compared to direct reflectance values.

Kortum (1969) tabulated the reflectance for different single scattering ($\omega_o$) values for direct and diffused irradiance. Using the tabulated phase function and $\omega_o$ values, diffused and direct reflectance values from snow surface have been evaluated. Results indicate that the reflectance from snow surface for diffused illumination is much higher compared to direct illumination. The presence of clouds increases the diffused radiation and hence the reflectance values leading to higher integrated albedo. Sagan and Pollack (1967) while investigating the anisotropic scattering from clouds of Venus obtained similar results.

Figure 1(a)-1(d) indicates increase in integrated albedo values with cloud amount. Each data point in the figure is the average of eight, hourly measurements. The figure indicates that irrespective of type of cloud, albedo increases by 8-10% as the cloud amount increases from 0 to 8 octa. The average albedo value of station-I is higher during the year 1993-94 (~75%) as compared to the year 1994-95 (~65%). This can be attributed to the fact that the average temperatures during 1994-95 were higher compared to 1993-94, which resulted in higher melting and metamorphism rates leading to bigger snow grain diameters and more free water on snow surface. Based on experimental data, an empirical relationship (eq. 1) has been formulated to estimate increase in albedo for cloudy conditions.

$$Ac = 1.03N + Ao, \qquad (1)$$

where $Ac$: Integrated albedo for cloudy sky condition (in percent)
$N$: Amount of cloud (octa)
$Ao$: Integrated albedo for clear sky condition (in per-

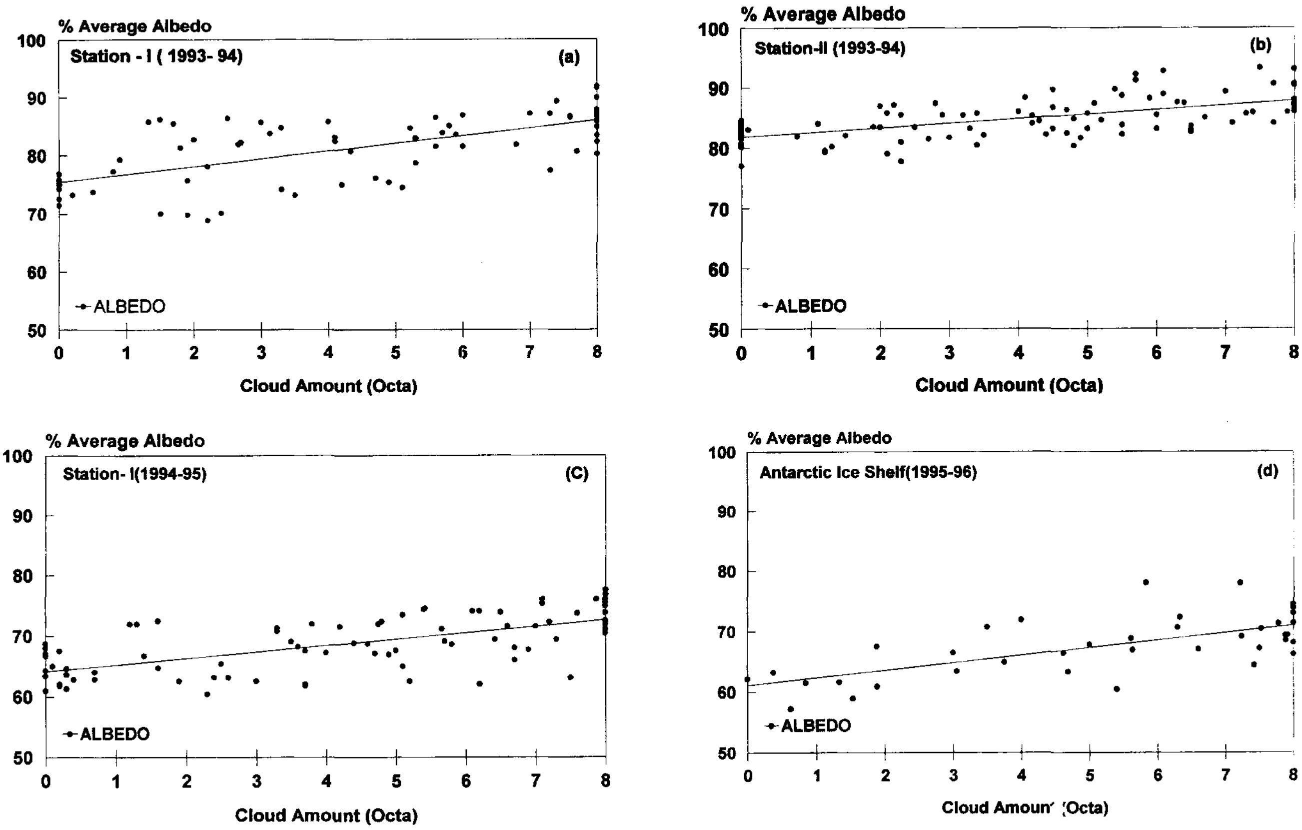


Fig. 1. Variation of integrated snow albedo with cloud amount at station-I situated at 3000 m altitude in Pir Panjal ranges, Station-II situated at 3800 m altitude in West Himalayan ranges and Antarctic ice shelf (70°05′S, 12°00′E).

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The effect of cloud amount on integrated snow albedo is highlighted in Fig 2(c) and 2(d) also. The daily variation of average albedo values is plotted against the average cloud amount (in octa) for station-I and station-II respectively. Each data point in the figure is average of eight, hourly data sets collected during the day. It is observed that there is an increase in albedo values with increase in cloud amount. The sharp rise in the figure indicate snowfall events.

### 3.2. *Effect of free water on snow albedo*

Study indicates that presence of free water even in small quantities reduces the snow albedo significantly. The melting snow crystals releases the condensation nuclei (pollen /dust) from the ice grain, which gets deposited on snow surface. The cumulative addition of impurities makes the snow surface dirty and reduces the reflectance values in visible spectrum. Thus even after refreezing of the water, the albedo does not return to its original value. Another important factor that contributes towards reduction in albedo values is increase in the effective snow grain size due to refreezing of water. The increase in snow grain size reduces reflectance values in near IR spectral range (Wiscombe and Warren, 1980).

Experimental investigations in laboratory and field indicate that as the amount of water over snow surface increases, the albedo and reflectance values decrease. However, for large amount of free water concentrations an interesting phenomenon has been observed. After the saturation limit of the capillary retentivity is reached, the water trapped between snow grains percolates down suddenly, thereby reducing the water amount and decreasing the effective grain radii. This results in sudden increase in albedo values. On further addition of water, the pore space between snow grains starts accumulating water again and reflectance values reduce.

Figure 3(a)-3(b) shows the variation in reflectance values with amount of free water over snow surface. A reduction in reflectance values with increase in free water content is clearly observed. During the studies on dielectric properties of wet snow, Sweeny and Colbeck (1974) showed that the water starts draining down the snow when saturation increases to about 7% of pore volume. Water saturation levels upto 14% can be obtained when drainage is impeded by an obstacle. These values of water drainage matches the results obtained in reflectance measurements, as when the quantity of water over snow surface increases by 4 to 7% of the sample by weight, (0.04 kg to 0.06 kg water) free water percolates down thereby increasing the reflectance values. This phenomenon repeats again when the amount of water reaches between 12–13% (0.08 kg to 0.1 kg water) of sample by weight. It is

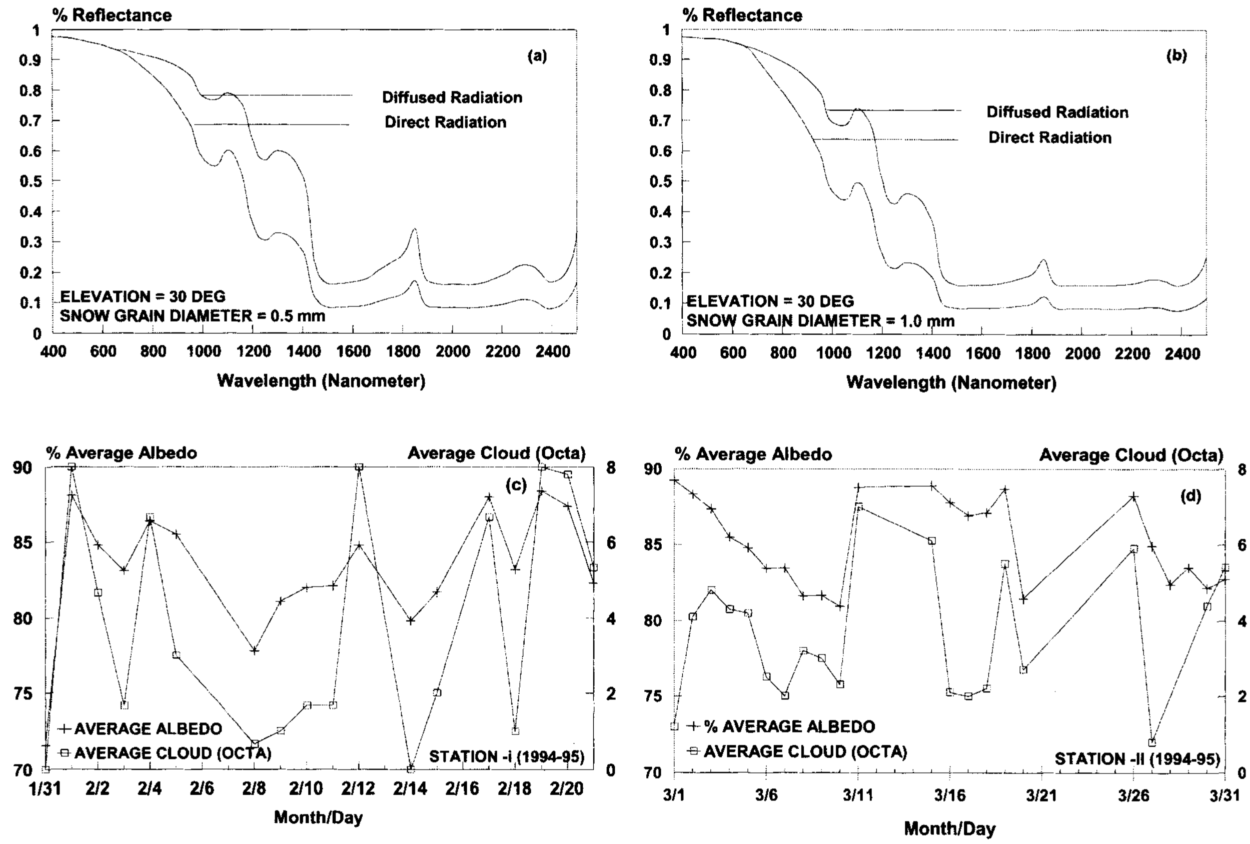


Fig. 2. (a) and (b): Diffused and direct reflectance of snow for grain diameters 0.5 and 1.0 mm with radiation incident on snow samples at 30°, (c) and (d): variation of average integrated albedo with cloud amount for station-I and station-II.

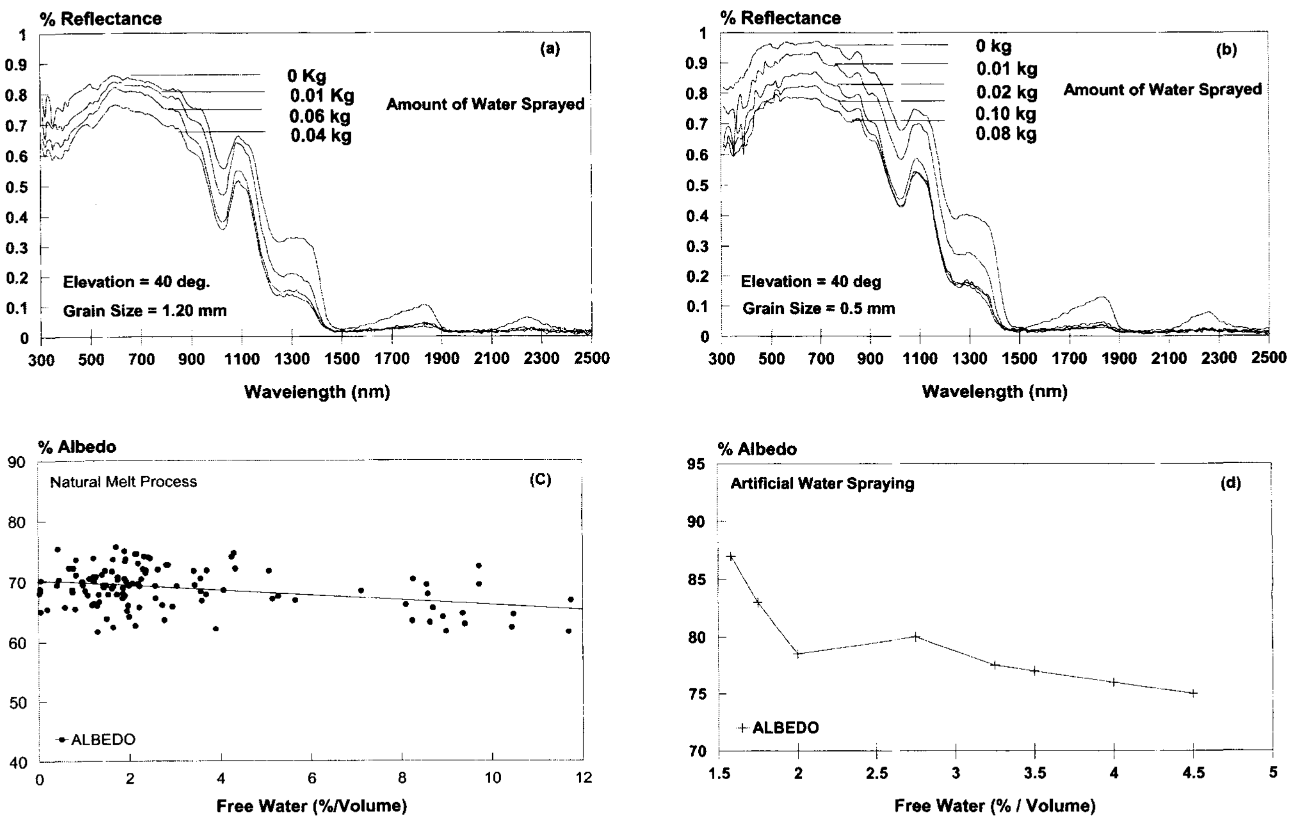


Fig. 3. (a) and (b): Variation in reflectance of snow with free water content; (c) reduction in integrated albedo with increase in free water amount for natural melt process over Antarctic ice shelf; (d) variation in integrated albedo with free water content for artificial water spraying experiment over Antarctic ice shelf.

evident from the figure that that smaller snow grains sample (0.5 mm) has higher reflectance values as compared to larger snow grain samples (1.20 mm). However, the reduction in reflectance values in both the cases remains same.

Figure 3(c) highlights the decrease in integrated albedo with increase in free water amount over Antarctic ice shelf. Each point in figure is an average of four to five data sets taken during a day. The figure indicates a decrease in integrated albedo values by 5-8% with increase in water amount by 2-12%. The scatter in data is due to variation in various other parameters influencing albedo like snow drift on ice shelf, variation in cloud amount etc. Figure 3(d) also shows the variation in integrated albedo values with water for artificial water spraying experiment. A sudden increase in albedo with increase in water content from 2% to 3% by volume is due to percolation of water down the snow surface.

## 4. Conclusion

Theoretical and experimental investigations have been carried out to understand the effects of cloud amount and free water concentration on integrated and spectral albedo values. Cloud cover increases the integrated albedo by reducing the infrared radiation reaching snow surface and also by diffusing the incident radiation. Laboratory and field experiments show distinctive effects of presence of water on albedo values. A decrease in albedo is observed with increase in free water amount. However due to water percolation, a sudden increase in albedo has been observed. The study provides a good understanding of albedo variations with different snow and meteorological parameters.

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