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STUDY ON THE ALBEDO IN DIFFERENT SNOW /ICE MEDIA IN ANTARCTICA AND ESTIMATION OF ENERGY BALANCE

Arun Chaudhary and Amreek Singh
Snow and Avalanche Study Establishment, Manali (H.P.)

Abstract

Measurements of the dependence of albedo in different snow and ice media on solar elevation angle, cloud cover, liquid water content, grain size etc. can be interpreted in terms of single scattering and multiple scattering radiative transfer theory. Detailed albedo measurements were carried out during austral summer and winter periods in different snow and ice media in 1997-98 at different elevated sites in Antarctica. Average albedo values were found to be high in snow medium (Av. 85%), moderate in shelf ice (Av. 75%) and very low (Av. 50%) in the continental ice medium. The albedo was found to be a function of cloud amount, increasing with the amount and thickness. In white out conditions during blizzards high albedo (Av. 83%) was found as compared to clear sky day (Av. 76%) and after blizzard (Av. 78%). It showed dependency on the type of snow also. New snow falling over old snow displayed higher values (90%) than older snow (70%) and it was noticed that albedo decreases with the age of snow . It is a function of melt water in snow pack and decreases with increasing melt water percentage by volume and showed some dependency on the solar elevation. The dependency was slight for solar elevation during day time when 0>~ 10-15 degree but became larger with low angles when 0>~ 3 to 10 degree. Very high albedo values were found (99%) when sun is near horizon. Solar insolation in different months at three different elevated sites was also calculated and it varied from (10-500) In/day (Aug.-Oct.), (350-900) In/day (Nov. - Dec.) to (190-725) In/day (Jan. - Feb.). Net energy balance was found to be negative most of the time in different media at Antarctica.

Introduction

The radiation balance of any snow surface, and with it the surface climate, is influenced by its albedo. The positive and negative energy balance indicates that either surface is gaining or losing energy because of energy transfer between atmosphere and snow surface. The net loss of energy in different media is a key factor in global energy balance and pattern of atmospheric temperature. The energy exchange processes can be explained using knowledge of energy balance. It is the albedo that is main parameter for determining energy balance.

If the reflectivity is high, as it is in Antarctica, the dependency is strong as most of the energy received from the sun is reflected back into space. Hence, in Antarctica the radiation balance is negative for most of the year. To compensate for this, the air warms the surface, thereby loosing energy itself. Hence a cold layer of air normally lies over the Antarctic ice sheet. This inversion layer being heavier than the air aloft at the same height further down the slope, flows downwards (Katabatic wind) towards the coast of the Antarctic continent . Therefore, the albedo plays an important role in the energy balance of the whole continent, especially as the snow in Antarctica is mostly dry and reflects solar radiation very well.

Energy Balance At the Sbow/Ice Air Interface

A snow/ice pack exchanges energy with atmosphere as well as ground. The net energy balance at the snow/ice - air interface is composed of. the turbulent fluxes of sensible and latent heat, heat flux of short and long wave radiation and the heat flux due to snow and rain. Thus the energy exchange between the snowcover and the environment and underlying ground is given by

$$\Delta Q = Q_{rs} + Q_{rl} + Q_l + Q_s \qquad (1)$$

where Q_{rs} is short wave radiation flux, Q_{rl} is long wave radiation flux, Q_l is latent heat and Q_s is sensible heat flux.

The energy received at the snow/ice surface is considered to be utilized in (a) absorption in the top layer (b) conduction and diffusion through the underlying layer (c) satisfying the cold contents of the top layer (d) producing melt at the surface.

However, in the first instance all the energy received at the surface is considered to be used to raise the snow surface temperature and affect melting. In the subsequent stages, heat is conducted through the underlying layers.

A. *Short Wave Radiation*

Short wave radiation reaching snow surface is reflected, transmitted and absorbed by snow. The amount of energy absorbed and reflected depends on the physical properties of snow both at and beneath the surface. The albedo is the most important physical property of snow that controls the amount of radiation absorbed.

The expression for the short wave radiation flux can be given by

$Q_{r\,s} = Q_i . (1\text{-}a)$ langley / day (2)

where

Q_i = Energy received on the snow-ice surface
a = Snow albedo

B. Long Wave Radiation

The radiative properties of snow in the range 5-40 (m imply radiative exchanges strictly confined to the snow/ice surface. The net long wave radiation can be expressed as :

$Qr_l = Q_{rl}^{in} - Q_{rl}^{out} = \sigma\ [\xi T_a^4 - T_s^4]\ [1\text{-}KN]$ (3)

where Ta = Air temperature above snow-ice surface (K)
Ts = Snow surface temperature (K)
K = a coefficient which depends upon type and height of clouds

= . 0.76 for low and thick clouds
= 0.52 Medium clouds
= 0.26 for high clouds
σ = Stefan - Boltzmann constant
ξ = Emissivity of the atmosphere

C. Latent And Sensible Heat Flux

Both are governed by the turbulent exchange processes occurring in the surface boundary layer (layer of constant flux) of the atmosphere above the snow surface.

Latent heat flux is given by

$$Q_l = 0.622\ K_w\ .P_a\ L\ [e_a - e_s]\ V_a\ /\ P \quad (4)$$

Where $K_w = K_N\ [1- (R_I)_B/(RI)_{c\ r}]^2$
$K_N = k^2\ /\ [\ln\ (Z_a\ /Z_o\ )]^2$
$(R_I)_B = (2gZ_a/V_a^2\ )\ [T_a\ - T_s]\ /\ [T_a + T_s]$
p_a = Density of air $1.1\text{x}\ 10^{-3}\ \text{gm/cm}^3$
L = Latent heat of sublimation of ice and snow
= 677cal/gm
e_a = Saturated vapour pressure of the air at temperature T_a
e_s = Saturated vapour pressure over snow/ice surface
P = Atmospheric pressure (mb)
k = 0.4 (Von Karman's constant)
V_a = Velocity of wind at the height of observation
Z_a = Height of obseravation
Z_o = Roughness height of the surface (0.005 m. for smooth surface)
g = Acceleration due to gravity
$(R_I)_B$ = Bulk Richardson number
$(R_I)_{cr}$ = Critical Richardson number

Sensible heat flux is expressed as

$$Q_s = P_a\ C_p\ K_w\ [T_a - \quad T_s] \quad V_a \quad (5)$$

C_p= 0.24 cgs units (specific heat of ice at constant pressure which is a linear function of surface temperature)

Significance of Albedo Studies In Antarctica

Albedo of any surface which is a ratio of intensity of reflected short wave radiation to intensity of incident short wave radiation, controls the amount of radiative energy being reflected backwards thereby controlling the thermal regime of the surface. Snow is the only naturally occurring material which has extremely high albedo values ranging between higher than 90% for fresh snow to 40% for old melting snow.

In polar regions where vast stretches of snow and ice are available, difference in albedo values of different surfaces and sea water results in differential heating and leads to local (Katabatic wind) and Global (upper westerlies) atmospheric circulations. The atmospheric circulation model thus requires albedo of snow/ice medium and its variation with different physical parameters as an essential component. Estimation of different radiative energy flux e.g. short and long wave, latent and sensible heat energy fluxes also require detailed understanding of albedo of snow. This makes the study of albedo in different mediums imperative in Antarctica for development of any atmospheric circulation model. Apart from the atmospheric circulation modelling approach, albedo also plays a significant role in estimation of snow ablation rates. The estimation of mass balance of Antarctic ice sheet through remote sensing also require a detailed understanding of ground truth albedo measurements and its seasonal variation with different snow and meteorological parameters. The importance of albedo studies in Antarctica can be understood from the following discussion:

The amount of energy received from sun varies with latitude. About three times more energy is received at equator compared to the poles. Being covered by snow, poles radiate back larger portion of incident energy due to high albedo values. This makes the outgoing energy more evenly distributed across the latitudes throughout the globe. However, there is a surplus of heat at equator and a deficit at higher latitudes, the poles are not getting colder and the tropics not getting warmer. This is because an equilibrium is maintained by transport of heat from lower to higher latitudes. The largest amount of energy transfer takes place at mid latitudes, which accounts for unsteady weather conditions in those areas. The general transport of energy that maintains the balance is called the general circulation of atmosphere. It operates by absorbing heat in equatorial belt and loosing it to colder regions towards the poles.

The upper westerlies in the atmosphere are at work over two equators of globe, north and south of 30-degree latitudes. The poles due to very high reflectance and albedo values, reflect most of the incident radiation thereby reducing the energy import and cooling down the atmosphere. The Southern Hemisphere has about 80% of oceanic surface and thus more uniform conditions. Cooling over Antarctic continent due to negative radiative energy balance (due to high albedo) ensures a large difference in temperature from frigid to torrid zones. This leads to more circular, tighter whorl of westerlies in the southern hemisphere whose momentum is about 1.5 times that in northern hemisphere. This has important effect on the world climate including the convergence and preponderance of tropical storms. Since the only parameters controlling the energy exchange and hence the thermal regime of the area is albedo, this makes the snow albedo study in Antarctica very important for understanding atmospheric circulation over the entire globe.

Aim Of Albedo Studies in Antarctica

The studies were aimed at the following objectives

(a) To determine dependence of snow albedo on the following parameters

   (1) Cloud amount and type
   (2) Snow surface wetness.
   (3) Solar elevation angle
   (4) Age of snow

(b) Determination of albedo distribution over various parts of Ice shelf, Continental ice and Snow mediums.

(c) To determine the magnitude of energy exchange in different snow-ice media.

Experimentation and Observatory Set Up

During Jan 98 - Feb 99 in Antarctic continent, two observatory station for albedo measurements and experimentation were set up one at Dakshin Gangotri on the Ice Shelf and other over Continental ice south west of Maitri.. Following snow and meteorological parameters were collected in different snow/ice media as shown in table 1.

Table 1 : Instruments used for different physical parameter

S.NO.	Parameter Measured	Instrument used
1	Integrated snow albedo (0.3-3.0μm)	Double pyranometer based albedometer
2	Ambient temperature	Thermometer
3	Snow surface temperature	Dial type sensor thermometer
4	Net radiation	Net radiometer
5	Wind speed and direction	Anemometer and wind vane
6	Snow grain size and type	Crystal gage and micromike
7	Melt water on snow surface	Dielectric moisturemeter
8	Cloud amount and type	Visual observations
9	Snow density	Densitymeter
10	Ice density	Mass and volume of core sample
11	Solar elevation angle	Sun dial method

Results and Discussions

The vast stretch of polar ice/snow with almost similar characteristics, provides excellent natural laboratory for albedo study. The analysis of the experiments and collected data yield following results.

A. Average Albedo Variation In Different Media

The daily average albedo on shelf ice is shown in Fig. 1. The higher average albedo value has been found in snow medium (Av. 90%)as compared to shelf ice (Av. 83%) and continental ice (Av. 50%). The ice layers present within Antarctic shelf ice and also of the continental ice act as constraints in the amount of reflected radiation. Considerable part of the incident radiation falling over the ice sheet is transmitted down, resulting in low albedo values.

The density for the three mediums were found to be in the range of (0.25-0.38) gm/cc for snow, (0.35-0.48) gm/cc for shelf ice and (0.85-0.89) gm/cc for continental ice. There have been many reports of albedo decreasing as density increases. The observed dependence of albedo on density might actually be a dependence on grain size, since large density normally attributed to larger grain size. Due to larger grains on the surface, there is a chance that rays are scattered or bent while crossing air-ice interface. It has a chance of being absorbed only while it is passing through the ice. An increase in grain size also causes an increase in the path length that must be travelled through the ice between scattering opportunities.

B. Albedo Variation With the Cloud Amount

The daily average albedo and average cloud amount was calculated by simple arithmetic mean in order to know their mutual variation. The albedo values are found to show an increase with increase in the cloud amount as shown in Fig.2. In order to know the dependence of albedo on the thickness of clouds, observations have been taken during clear sky day, at the time of blizzard and after blizzard as shown in Fig.3. The average albedo was found to be higher (Av. 83%) during white-out condition in blizzard when cloud thickness is very high as compared to clear sky day (Av. 76%) and after blizzard (Av. 78%). It can be inferred that albedo is a function of both and it increases with increasing cloud amount and thickness. The increase in albedo can be attributed to the fact that clouds absorb the same near infrared radiation that snow would absorb, leaving the shorter wavelengths (for which snow albedo is higher) to penetrate the snow surface. As snow has very high reflectance coefficient in visible spectrum and absorb strongly in the infrared spectrum, the absence of infrared radiation under cloudy conditions results in an increase in the integrated albedo values. The average albedo values are found to show an excellent correlation with cloud amount. The average albedo value increases from 74% to 85% as cloud amount increases from 0 to 8 octa.

The increase in integrated albedo values with cloud amount has been found to follow a straight line increase in the form :

$$A = Bx + C$$

where A = Average albedo value under clear sky condition

x = Average cloud in octa

From Fig.2 B = 1.5368 and C = 73.642 are empirical constants.

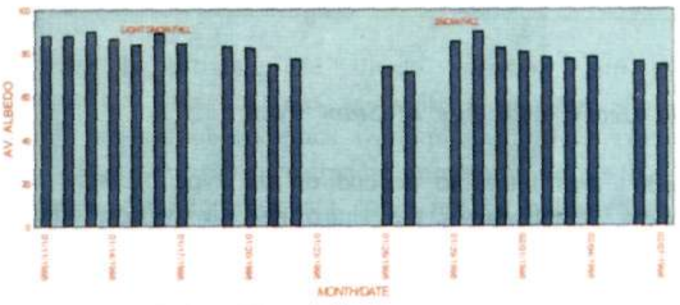

Fig. 1 Albedo variation on the Shelf ice surface

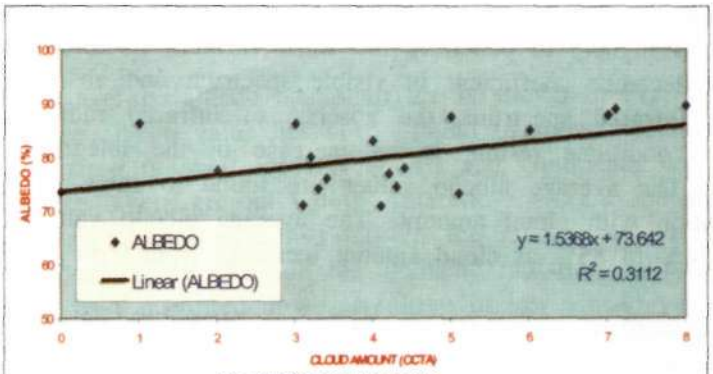

Fig. 2 Albedo variation with cloud amount

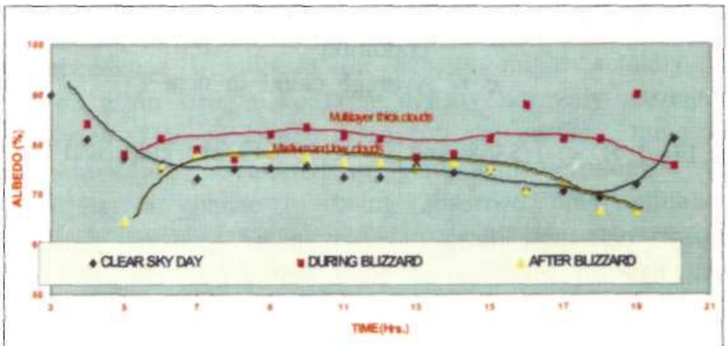

Fig. 3 Albedo variation under different cloud conditions

C. Albedo Decay With Age of Snow Pack

Albedo was found to depend on the type of snow as well as age of snow. Fig.1 shows the sharp rise in average albedo values from 70% to 90 % when new snow falls over the old snow.

A sharp decline in albedo values from 90% to 80% and 89% to 79% has been observed with the age of snow in mid January to first week of February as shown in Fig.4. After the fresh snowfall event, three processes have been observed to govern the decay process namely the metamorphism of fresh branched snow grains, increase in snow grain size and increase in melt water concentration over the snow surface due to radiative heating after the snow fall event. Immediately after the snow fall event, the rate of decay process is quite sharp followed by slower decay rates. The initial fast decay rates are due to rapid loss of branches of fresh snow grains due to different pressures at concave and convex boundaries of snow grains, subsequently the production of melt water and increase in snow grain size takes over and control the albedo decay process which results in slower decay rates due to slow rates of grain growth.

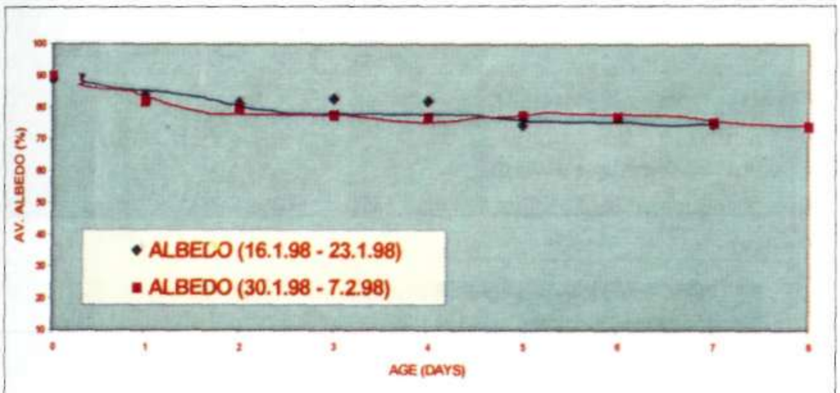

Fig.4 Albedo variation with age of snow pack

D. Albedo Variation With the Melt Water

In order to estimate the albedo variation with melt water concentration on snow surface as well as on the shelf ice, the natural melt process observations were planned to be carried out in the field. Due to some technical problem with the dielectric moisture-meter, the required data could not be collected to come up to any significant result. However, with limited data analysis the albedo was found to decrease with increasing melt water on shelf ice. This result is again conforms to the findings of WWI which cited both experimental and theoretical evidence that the liquid water simply increases the effective grain size thereby affecting albedo, whereas the refractive index contrast between water and ice is very small. The water has not only high absorption coefficient values as compared to snow in near infrared spectral range but it also increases the effective snow grain radius by forming a layer of water around ice grains. All these factors reduce the albedo values in presence of natural melt water on snow surface. Fig 5 shows variation of snow albedo with melt water for shelf ice.

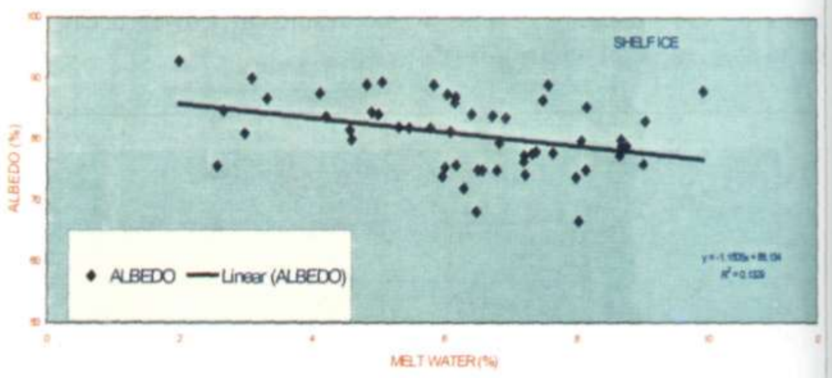

Fig. 5 Albedo variation with natural melt water in Shelf ice

E. Albedo Variation With Solar Elevation

A decrease has been observed in albedo values on clear days with increase in solar elevation from 3 degree to 12 degree approx. It can be seen that, for solar elevation above 12 degree, there is only a slight dependency of the albedo. This is in accordance with the theoretical estimates made during modelling approach in which a decrease in reflectance values has been obtained with increase in solar elevation angle. In Himalayan region also, a reduction in albedo values has been observed with increase in solar elevation. The albedo value has been observed to follow a diurnal hysteresis pattern, the albedo in the morning is higher than in the afternoon for identical solar elevation. The present results obtained are also identical as shown in Fig.6. A thin hoar-frost coating could be formed during periods of low temperature in early morning during clear sky days and remain wet or melting state throughout the rest of the day. In other words we can say that hoar-frost coating is removed as temperature increases during day time resulting in low albedo values during day time period. Apart from that solar radiation incident on snow surface at grazing angle in early morning is reflected back with the grazing angle. The snow absorption is very low at low solar elevation and most of the reflected radiations are absorbed by the pyranometer showing high albedo values in early hours. As the elevation angle increases, the absorption on the snow surface increases due to high penetration which results in low albedo during day time. During cloudy day, the albedo values were found to be low in morning and evening as compared to clear sky day. Day time albedo values during cloudy days are higher. In the morning and evening , the solar elevation angle is very low. The incoming solar radiations are diffused by clouds and and effective solar elevation is changed. The incoming radiations in morning and evening do not incident at grazing angle and radiation energy density on the snow surface also reduces resulting in low albedo values during cloudy days in early morning and late evening.

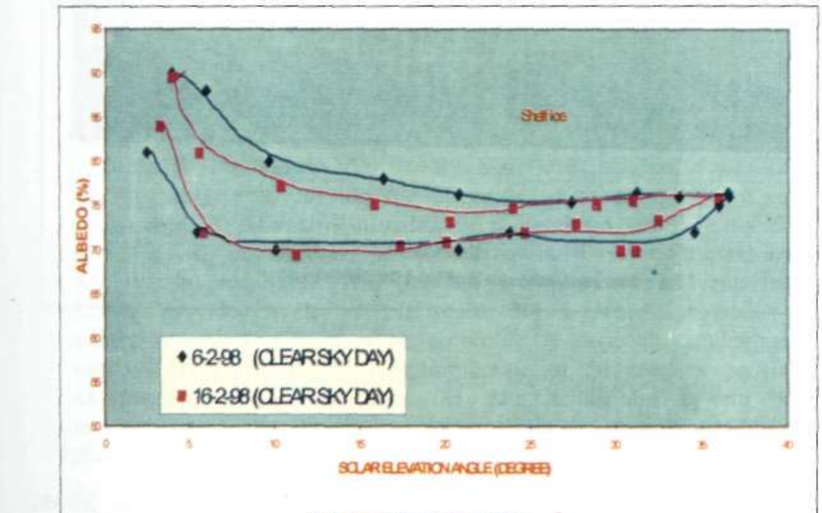

Fig. 6 Diurnal hysteresis of snow albedo

F. Energy Balance In Antarctica

The solar insolation in different months at three different elevated sites were calculated. Fig.7 shows the total amount of solar energy in In/day for the shelf ice, The calculations for energy balance estimates over snow, continental ice medium and shelf ice in Antarctica have also been performed. Various incoming and outgoing energy fluxes like Short wave radiation flux, Long wave radiation flux, Latent heat and Sensible heat flux have been calculated for different snow/ice media. The short and long wave energy fluxes have been calculated using the albedo of snow pack and global incident radiation as input parameters. The latent heat flux is the result of melting and freezing of snow and the sensible heat flux arises as a result of temperature difference and wind activity over the snow/ice surface. The energy balance found to be negative most of the time.

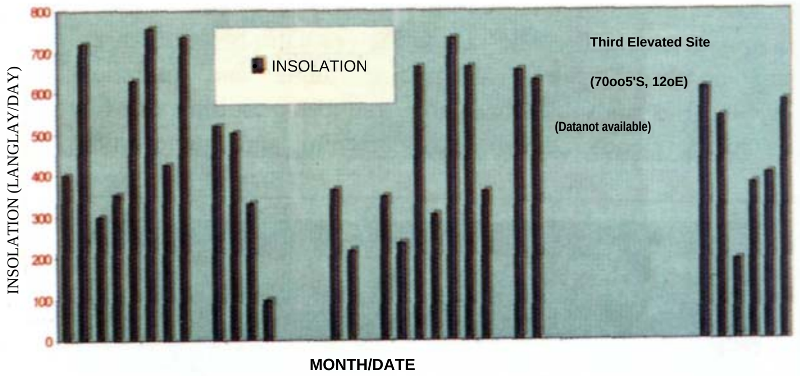

Fig. 7 Solar insolation on the Shelf ice at Dakshin Gangotri

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