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SNOW ALBEDO AND ENERGY EXCHANGE STUDIES ON ANTARCTIC ICE SHELF (DAKSHIN GANGOTRI)

Punit Vashisth

Snow and Avalanche Study Establishment

Abstract

The study of snow albedo has been initiated over Antarctic ice shelf. Attempts have been made to identify the effect of various snow-met parameters on albedo. Presence of ice layers and melt water in snowpack are observed to reduce the albedo values. At very low solar elevation angles, a reduction in albedo values has been observed. Presence of clouds has been observed to increase albedo values linearly. A decrease in albedo with increase in melt water amount has been observed for both natural melt and artificial water spraying processes. The energy exchange components of short wave flux, long wave flux, sensible heat flux and latent heat flux have been evaluated to get the total energy exchange over ice shelf. Further studies have been planned to investigate albedo values ot various types of snow surfaces over Antarctic ice shelf, polar ice and continental ice.

Introduction

The net energy loss in the polar regions is a key factor controlling the global energy balance and pattern of atmospheric temperatures. The questions like, how does the atmosphere at low latitudes respond to the changes in the polar sink, what are the positive and negative heat exchange processes etc. need to be answered. The answer to above questions lies in the knowledge of energy balance over polar regions. It is the albedo and reflectance of snow surface which is crucial parameter in determination of energy balance.

Albedo over snow surface is a coupled function of many atmospheric and snow parameters. These parameters like snow grain size and type, age of snowpack, melt water concentration on snow surface, cloud amount and type, solar elevation angle, etc. are coupled with each other and it is difficult to determine the influence of individual parameter on albedo. However, this is a subject of great interest to make significant headway for development of a quantitative understanding. Although many efforts have been initiated for albedo studies in Antarctica, and encouraging results have been obtained, yet individual factor quantification has not been achieved. The current studies aim at bridging this gap as well as developing a nomograph accounting for various controlling parameters.

In Antarctica, albedo studies has been initiated by SASE during Fifteenth Indian Expedition. The study comprises three parts namely— (a) the determination of the qualitative and quantitative influence of various snow and meteorological parameters on reflectance and albedo of snowpack, (b) the quantification of the albedo decay process with age of snowpack and (c) the development of a nomograph accounting for various controlling parameters. However during the XV Antarctic expedition, emphasis was given to the study of effect of various parameters on albedo over Antarctic ice shelf.

Significance of Albedo Studies in Antarctica

Being the ratio of reflected to the incident short wave solar radiation, the albedo of any surface controls the amount of radiative energy being reflected backwards, thereby controlling the thermal regime of the surface. Snow has extremely high albedo values ranging between 95% for fresh branched grain snow to 50% for old melting coarse grained snow. The spectrally integrated albedo $A(\lambda)$ of any surface can be estimated as:

$$A(\lambda) = \frac{\int_{\lambda_1}^{\lambda_2} r(\lambda) I(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} I(\lambda) d\lambda} \quad \dots (1)$$

where, $r(\lambda)$ = the reflectance value at wavelength

$I(\lambda)$ = the intensity of incident radiation at wavelength.

The radiation falling on snow surface is spectrally reflected and absorbed depending on the reflection and absorption coefficient of snowpack. The difference in albedo values of snow and ice covered polar regions and sea water results in differential heating and leads to local (Katabatic winds) and global (Upper Westerlies) atmospheric circulations. The atmospheric circulation models thus requires albedo of snowpack and its variation with different parameters as an essential component. Estimates of the radiative energy components like short and long wave energy fluxes also require detailed understanding of albedo of snow. The short wave radiative energy absorbed by snowpack "Q_s^{abs}" is related to incident short wave energy "Q_s^{inp}" and snowpack albedo "A" as:

$$Q_s^{abs} = Q_s^{inP}(1-A) \quad \dots (2)$$

This makes the study of snow albedo imperative in Antarctica for development of any atmospheric circulation model. Apart from the atmospheric

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circulation, the ablation rates of snow are also governed by snow albedo. The estimates of the mass balance over Antarctica, and the remote sensing studies requires a detailed understanding of ground truth albedo measurements, and its variation.

General Atmospheric Circulation and Albedo of Snow in Antarctica

The amount of energy received from sun varies with latitude. About three times more energy is received at equator compared to the poles. Inspite of smaller surface area, being covered by snow, poles radiate large amount of 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 heat at equator and a deficit at higher latitudes. As poles are not getting colder and the tropics are not getting warmer, 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 which maintains the balance is called the general circulation of atmosphere. It operates by absorbing heat in equatorial belt and losing it to colder regions towards the poles.

The upper westerlies in the atmosphere are at work over two quarters of globe, north and south of 30 degree latitude. The poles, due to very high reflectance and albedo values, reflect most of the incident radiation, thereby reducing the +ve energy import and cooli ng 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 (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 of in Northern hemisphere. This has important effect on world climate including the convergence and preponderance of tropical storms. Being the only parameter controlling the energy exchange and hence the thermal regime of the area, snow albedo study in Antarctica is very important for understanding atmospheric circulation over entire globe.

Local Circulations (Katabatic Winds) and Antarctic Ice Shelf Albedo

Very large difference in albedo values of snow (70 to 90%) and water bodies (2 to 20 %) leads to differential heating. When the two type of surfaces' are in close vicinity as in case of Antarctic ice shelf, a strong temperature difference prevails between the two. The negative energy budget over polar region cools the snow surface, as a result a cold surface air layer develops. This being heavier, flows down the slope of Antarctic continent. Under favourable conditions, these winds can attain hurricane force, and act like shear, causing snow to move. These strong katabatic winds are mainly responsible for mass transport over Antarctic ice shelf. The albedo of snow plays an important role in generation of these winds, making the albedo study in Antarctica imperative.

Aim of Snow Albedo Studies in Antarctica

The studies are aimed at the following :

(a) To determine dependence of snow albedo on following:
   (i) Solar elevation angle
   (ii) Cloud amount and type
   (iii) Snow surface wetness (Melt Concentration)
   (iv) Snow grain shape and size

(b) To determine the decay of snow albedo with age of snowpack.

(c) To determine the magnitude of energy exchange across snowpack.

(d) To prepare a nomograph for the determination of snow albedo under different snow met conditions.

Experimentation and Observations

Making best use of the clear sky during Jan and Feb 1996, an observation station for albedo measurements and experimentation, was set up at Dakshin Gangotri (70°-05' S ; 12° 00' E) on ice shelf. Following experimentation and data collection were carried out on regular basis :

(a) Integrated snow albedo (0.3 - 3.0 µm) (Albedometer)

(b) Global insolation (0.3 - 3.0 µm) (Pyranograph)

(c) Net Radiation Balance (0.3 - 80 µm) (Net Radiometer)

(d) Ambient, Maximum, Minimum and Snow Temperatures (Thermometers and Thermal probe)

(e) Relative Humidity (Dry and Wet bulb Thermometers)

(f) Atmospheric Pressure (Barometer)

(g) Wind Speed and Direction (Anemometer and Wind Vane)

(h) Snow grain size and type (Crystal Gauge and Micromike)

(i) Melt water concentration on snow surface (Dielectric Capacitance Meter)

(j) Cloud amount and type (Manual Observation)

(k) Snow surface characteristics (Manual Observation)

(1) Snow density (Density meter).

The integrated albedometer and net radiometer were installed on a stand, 1.2 meters above the snow surface for continuous measurement **(Photo-1a).** The output of integrated albedometer and net radiometer was taken on the dual channel Electro Poly Recorders over electrosensitive silver coated paper charts **(Photo-1b).** The Pyranograph, was mounted on the top of a 2.5 meter high tower. Stevenson screen for housing dry bulb, wet bulb, maximum and minimum temperatures was also mounted on the same tower **(Photo-2a).** Hand held anemometer was used for wind speed measurements. Apart from regular collection and analysis of data, artificial water spraying experiments were also performed to understand effect of melt water concentration on snow surface **(Photo-2b).**

Results and Discussion

The vast stretches of polar snow/ice provides excellent natural study site for snow albedo study. The data of albedo and snow-met conditions was collected throughout the summer period (8^{th} Jan to 14^{th} Feb 1996). Various experiments to study the effect of different parameters on albedo of snow were performed during the course of study. The process of energy exchange over Antarctic ice shelf was also monitored. The analysis of experiments and collected data yields following results :

(a) Variation in different snow- met parameters at dakshin gangotri

The average daily albedo on Antarctic ice shelf has been found to be lower (60 to 75%) as compared to albedo in Himalayas and Alpine regions (85 to 95%). The ice layers present within Antarctic snowpack do not contribute to reflected radiation, and major part of the radiation incident over the ice sheet is transmitted in a forward direction, resulting in low albedo values. The presence of melt water over snow surface also reduces the surface reflectance resulting in low albedo values. **Fig.1(a)** shows variation in average albedo values. The mean albedo values for January 1996, February 1996 and entire period of measurement are'observed to be 71.375%, 68.75% and 70.365% respectively.

Figs l(b),(c),(d) show variation in daily insolation, ambient temperature and snow surface temperature, respectively. The average insolation during Jan 96, Feb 96 and entire measurement period were 434.41, 254.44 and 365.183 $cal/cm^2/day$, respectively. The average snow surface temperatures during these periods were -3.551°C, -3.338^{D}C and -3.477°C, respectively. The average

Photo 1(a): Pyranometer based Albedometer, used for integrated albedo measurement on Antarctic ice shelf (Dakshin Gangotri: 70° 05' S; 12° 00'E)

Photo 1(b): Electropoly recorders (EPR) with silver coated electrosensitive charts used for continuous recording of intergrated albedo and net radiation

Photo 2(a) : 2.5 meter tower containing Pyranograph. Anemometer and Stevenson Screen at D.G.

Photo 2(b): Artificial water spraying experiment being conducted on Antarctic ice shelf for monitoring effect of free water on reflectance characteristics of snow

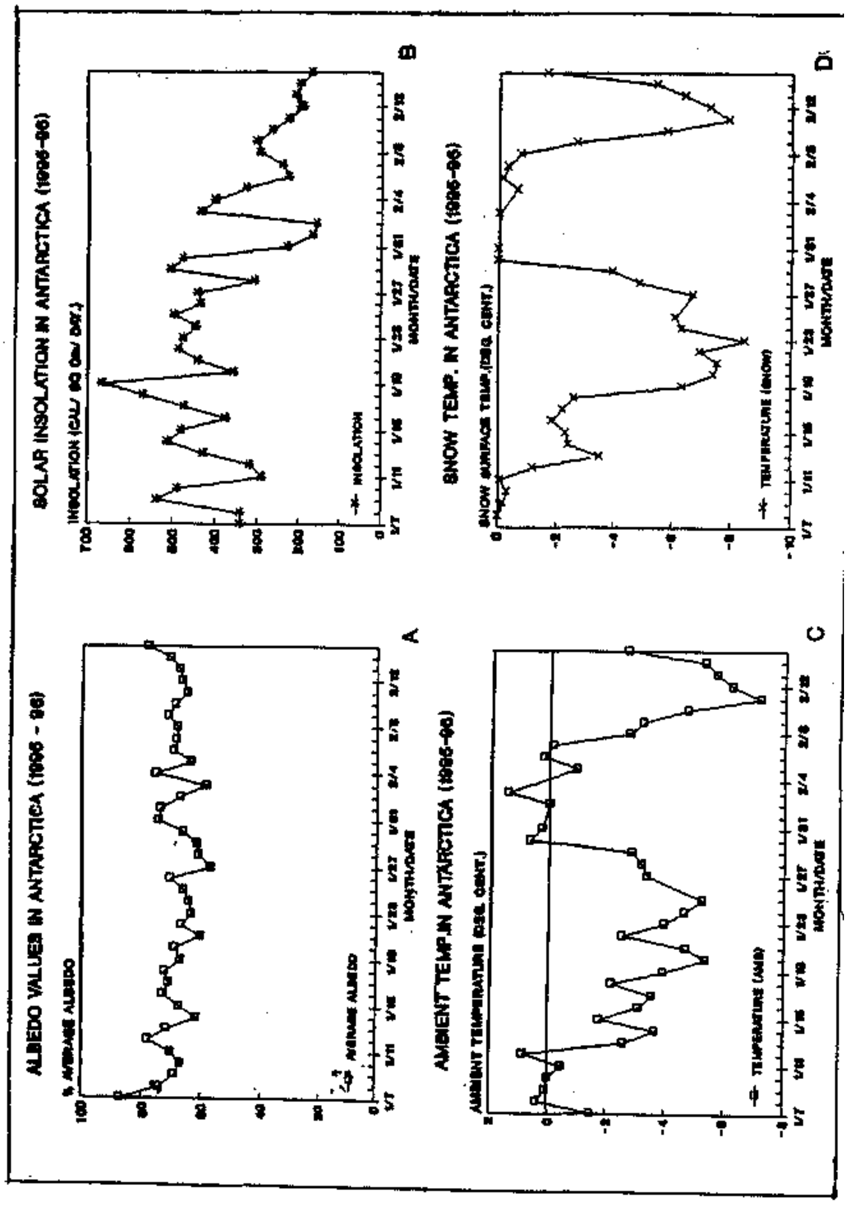

Fig. 1: Variation of snow-met parameters in Antarctica

ambient temperatures remained generally below zero degree centigrade, the average temperatures during Jan 1996, Feb 1996 and entire period of measurement being -2.417°C, -2.832°C and -2.561°C, respectively. The lowest minimum and maximum temperatures recorded at Dakshin Gangotri were -21.5°C on 20th Jan 96 and +5.3°C on 12th Jan 96, respectively. Particularly high temperatures, which prevailed during 31st Jan 96 to 4th Feb 96, resulted in rain during a blizzard on 3rd Feb 96, which is a rare phenomenon over Antarctic ice shelf.

(b) Albedo variation with cloud amount:

The albedo values are found to follow an increasing trend with increase in cloud amount. This increase can be attributed to the fact that clouds whenever present, absorb most of the infrared radiation and allows only the visible spectrum to reach snow surface, for which snow has very high reflection coefficients. The absence of infrared radiation under cloudy condition thus results in increase of integrated albedo values. The average albedo values are found to show an excellent correlation with average cloud amount. The results in Fig.2(a) show an increase in albedo values with increase in cloud octa. Fig 2(b) shows an increase in average albedo from a value of 61 to 70% as the cloud amount increases from 0 to 8 octa.

The variation of integrated albedo values with cloud amount over Antarctic shelf has been found to follow a straight line as :

$$A = Bx + C \qquad ...(3)$$

where,

A. = Average integrated albedo value
x = Average cloud octa
B = 1.6446015 and C = 57.9703 are empirical constants.

The maximum error between predicted and observed albedo values has been obtained below 3.54%. The correlation coefficient and standard deviations between estimated and observed values have been obtained as 77.75% and 0.42433, respectively.

(c) Albedo decay with age of snowpack :

A sharp decay in albedo values has been observed with age of snowpack, 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 snow surface.

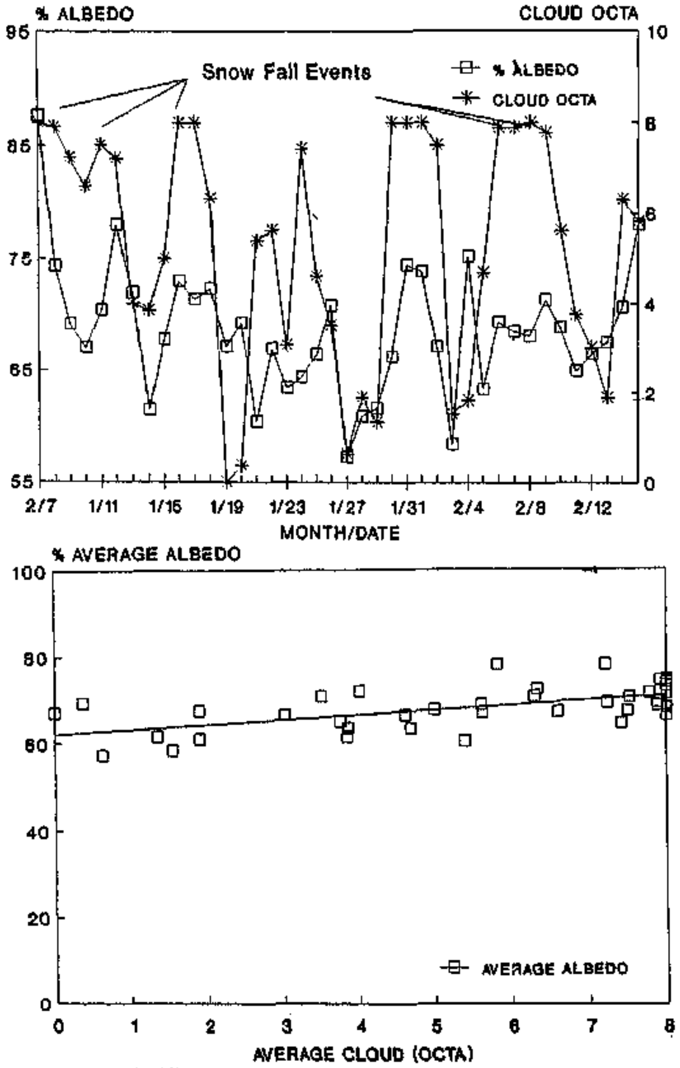

Fig. 2: Albedo variation with cloud amount in Antarctica

Immediately after the snow fall event, the rate of decay process is quite sharp followed by a comparative slower decay rate. The initial sharp decay rate is due to the rapid loss of branches of fresh snow grains due to difference in vapour pressure prevailing over 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. This results in slower decay rates due to slower rates of metamorphism and grain growth. The albedo decay rates have been observed to be quite high in the month of Jan 1996 compared to Feb

1996 due to high temperatures prevailing over ice shelf in January. Figs 3(a) to 3(d) show the albedo decay with age of snowpack observed at Dakshin Gangotri after fresh snow fall event.

(d) Albedo variation with melt water concentration

The estimation of albedo variation with melt water concentration on snow surface has been made by not only monitoring the natural melt process but also by performing the artificial water spraying experiments. Fig.4(a) shows the decrease in albedo values with increase in melt water concentration over snow surface under natural melt conditions. The melt water on one hand has higher absorption coefficient values as compared to snow in near infrared spectral range and on the other hand it also increases the effective snow grain radius by forming a thin quasi-liquid layer around ice grains. Both these factors reduces the albedo values.

The artificial water spraying experiments show a sharp reduction in integrated albedo values with increase in water concentration on snow surface as shown in Fig.4(b). The reduction in albedo continues till snow is completely saturated with water. After that, water percolates down and a sudden increase in albedo has been observed. On further increasing water amount, the albedo reduces again, but the reduction is slower in comparison to the initial reduction.

The rate of albedo reduction under artificial water spraying has been observed to be much faster compared to natural melt process. The reason being, the natural melting process is slower and water gets sufficient time to percolate down after satisfying the capillary retentivity of snow. This results in slow reduction in albedo values.

(e) Albedo variation with solar elevation angle

An increase in albedo has been observed with increase in solar elevation angle for clear sky days, Fig.5(a). The albedo has been observed to follow a diurnal hysteresis pattern with low albedo values in early morning hours and high values in mid noon hours. However, in Himalayan region, a reverse phenomenon of reduction in albedo with increase in solar elevation has been observed.

Major amount of incident solar radiation at low solar elevation angle lies in the near infrared spectral range, for which, snow has high absorption coefficients. Moreover, the radiation incident at low solar elevation angle is reflected at grazing angle, and the albedometer placed at a height of 1.2 meter above snow surface could not detect it. These two factors result in low albedo values for clear days at low solar elevation angles. As the day progresses, the

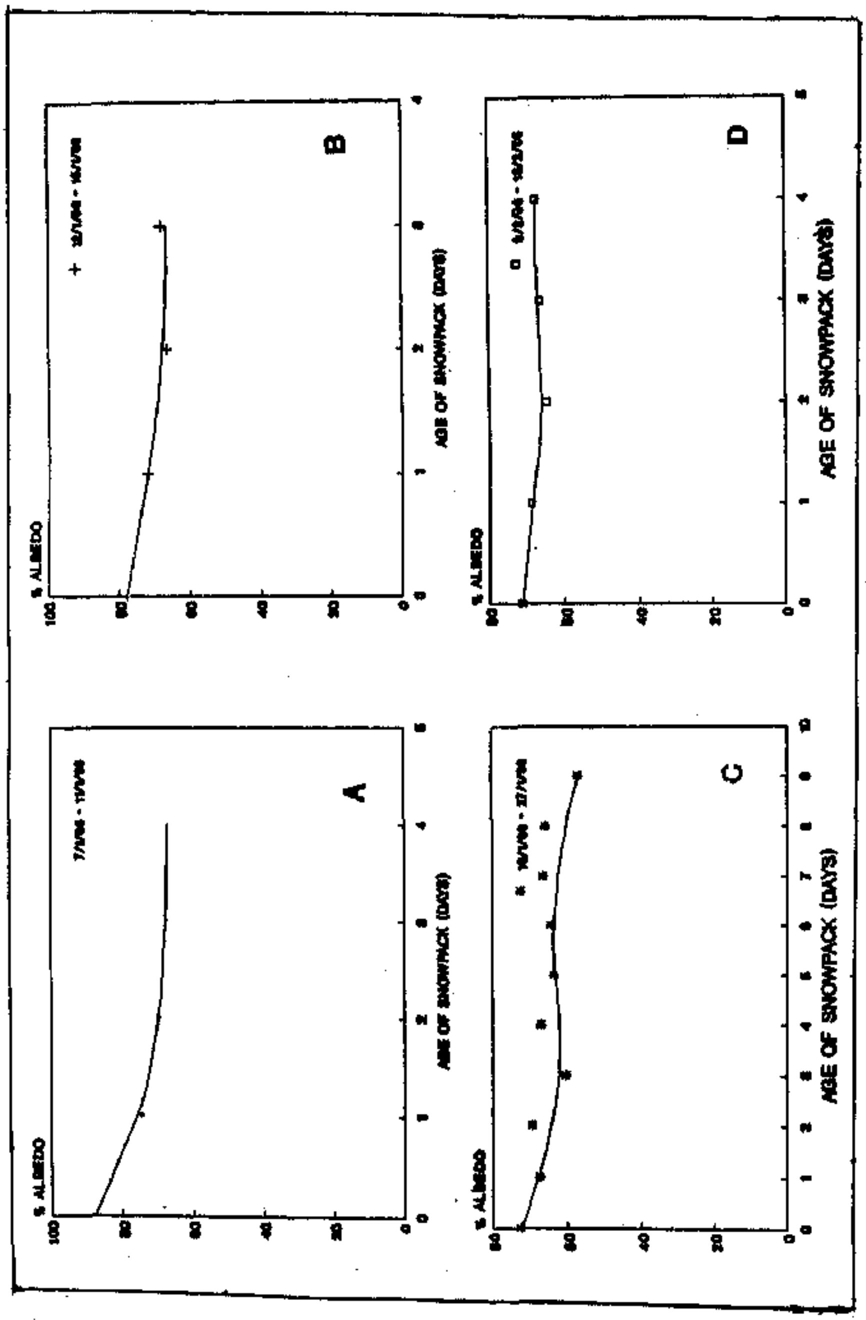

Fig. 3 : Albedo decay with age of snowpack in Antarctica

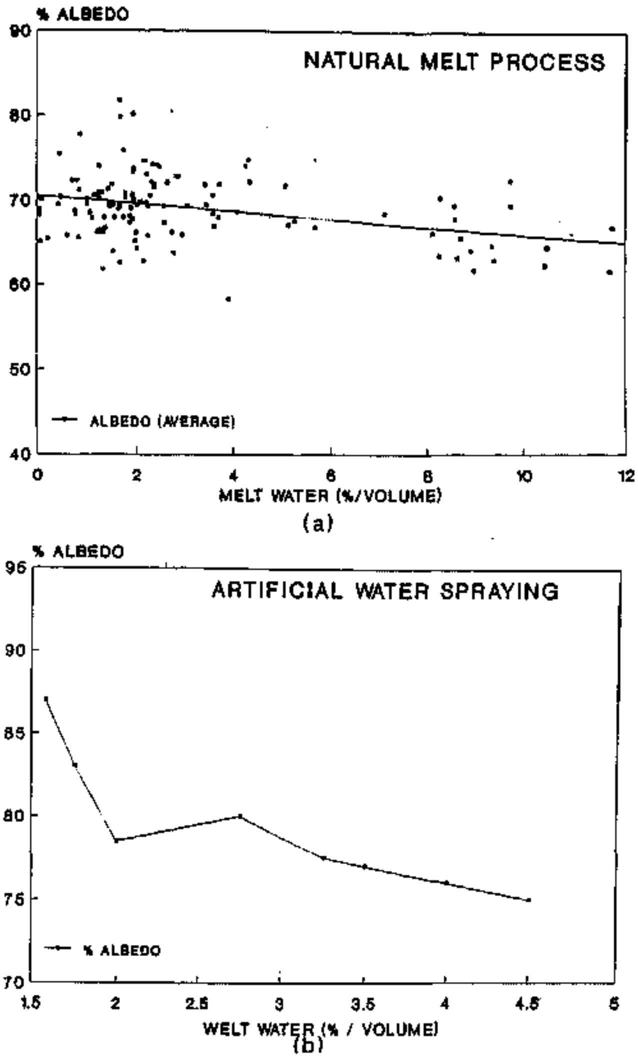

Fig. 4 : Albedo variation with melt water in Antarctica

incident solar spectra shifts towards visible spectral range for which snow is a good reflector. The radiation at high incidence is reflected at higher angle. Thereby high albedo values during mid-noon hrs. are obtained. In comparison to this, in Himalayan region, the terrain features restricts the radiation at low elevation angles, and radiation is incident over snow surface only at high elevation angles. This results in decrease of albedo values with increase in solar elevation angle.

The presence of clouds however reverses the phenomenon of albedo variation with solar elevation angle, Fig.5(b). A decrease in albedo has been observed with increase in solar elevation angle. In presence of clouds most of the infrared radiation is absorbed due to water vapours present in clouds and only the visible spectrum reaches snow surface. High albedo values are there fore obtained even at low elevation angles. Presence of clouds diffuses the incident solar radiation, thereby resulting in increase of effective incident angle.

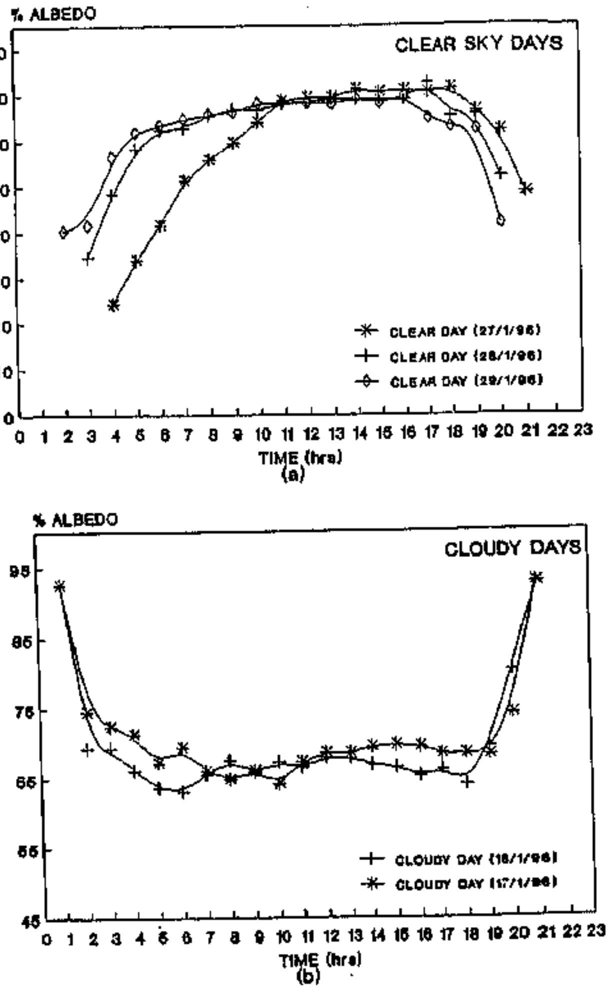

Fig. 5 : Albedo variation with solar elevation in Antarctica

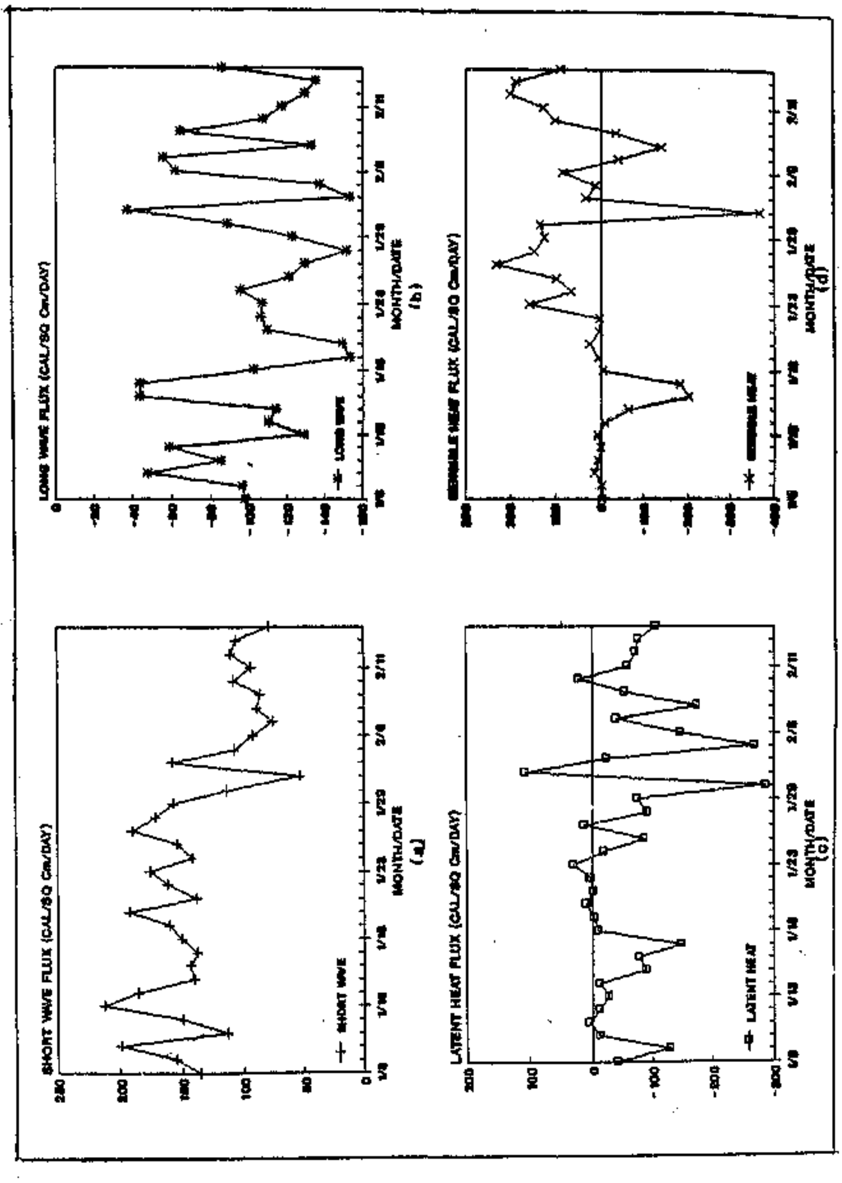

Fig. 6 : Various energy fluxes over Antarctic ice shelf

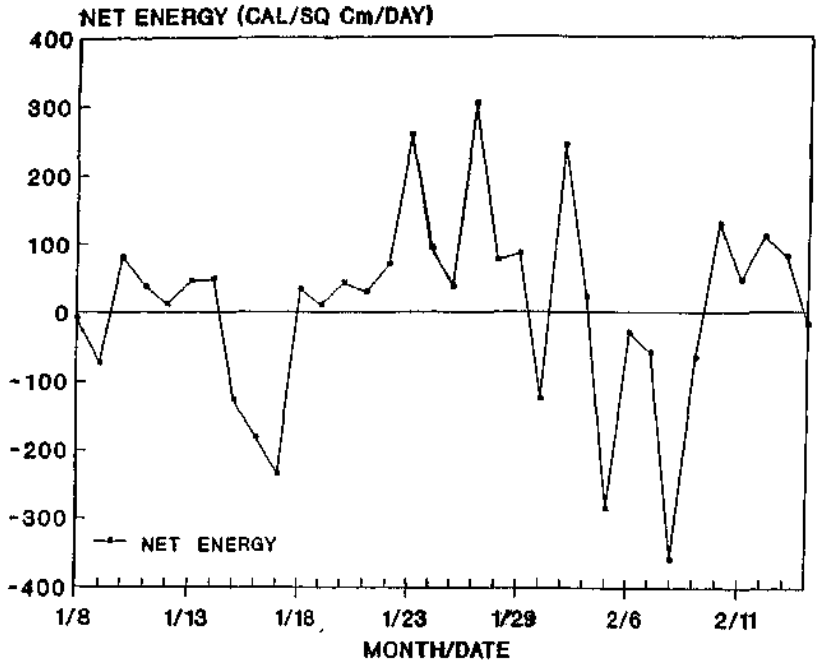

Fig. 7 : Total energy balance over Antarctic ice shelf

The scattered radiation will thus be reflected at a higher angle and will be detected by albedometer, to yield high integrated albedo.

(f) Energy balance studies over ice shelf

The calculations for energy balance estimates over Antarctic ice shelf have been performed. Various incoming and outgoing fluxes like Short Wave Radiation Flux, Long Wave Radiation Flux, Latent Heat Flux and Sensible Heat Flux have been calculated for Dakshin Gangotri location. The short and long wave energy fluxes have been calculated using the albedo and global incident radiation as input parameters. The latent heat flux is the result of melting and freezing of snow. The sensible heat flux has been calculated taking into account the temperature difference between snow surface and atmosphere and wind activity over the snow surface. The Results of the calculations are as shown in Figs 6(a) to 6(d). The net energy balance over ice shelf is shown in **Fig.7.** The net shortwave radiation flux has been observed to be positive throughout the period of measurement, the average value being 136.24 cal/cm^2/day. The average Long wave radiation flux, Latent heat flux and Sensible heat flux values have been obtained as -96.44 cal/cm^2/day, -54.293 cal/cm^2/day and 24.230

cal/cm^2 /day, respectively. The average net energy exchange across snowpack was found to be 9.7366 cal/cm^2/day.

Future Work

In the 15th expedition, snow albedo values were measured at Antarctic ice shelf, in the vicinity of Dakshin Gangotri only. This cannot give the true picture of albedo values of the entire Antarctic continent. Future studies are aimed at extending the area of the work above and below the equilibrium line and to carry out the measurement of albedo over various types of surfaces in Antarctica including Ice Shelf, Blue ice, Continental ice, Ice covered with fresh snow and Water Bodies etc.

In future expeditions, the study will also incorporate the efforts to prepare a nomograph for determination of snow albedo under different snow-met conditions. This will cater for clouding, age of snowpack, surface characteristics, snow cover thickness over ice layers and diurnal variation. Studies are also planned to include the spectral albedo measurements in 0.30 to 2.50 m range for determination of absorption and reflection characteristics of snow and ice.