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Energy budget model based on albedo and glacio-meteorological parameters of diffrent snow-ice media in Antarctica through ground based observations, 1997-98

V.D. MISHRA and AMREEK SINGH
(Snow and Avalenche 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 summer and winter period in different snow and ice media in 1997-98 at different chosen sites in Antarctica. Average albedo values were found to be high in snow medium (max. 99%) moderate in shelf ice (max.90%) and very low values (max.58%) 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 snowfall over old snow displayed higher values (90%) than older snow (70%) and 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' s during day time when q >» 12-15 degree but became larger with low angles when q > = 3 - 12 degree. Very high albedo values were found (99%) when sun is near horizon. Solar insolation in different months at different three elevated sites also calculated and vary from (10-550) In/day (Aug. - Oct.) , (350-920) In/day (Nov. - Dec.) and (190-750) In/day (Jan. - Feb.). Net energy balance was found to be negative most of the time in different media at Antarctica.

1. Introduction

The interaction of electromagnetic radiation with a natural snow cover is of considerable practical interest and scientific importance. The remote sensing community requires an improved understanding of the optical properties of snow in order to correctly interpret the imagery of snow covered regions and to distinguish between snow pack and cloud covers. Radiant energy transfer is important in the thermodynamics and metamorphosis of the snow pack and is therefore of interest to those who study the mechanical and hydrological properties of the snowpack. Therefore, the establishment of relationships between the optical properties of snow and frequently measured snowpack quantities, such as liquid water content, density, surface temperature etc. would be of considerable utility.

To understand how ablation on a glacier may change if climate changes, one needs to know the albedo and components of the surface energy balance. It is generally accepted that, atleast on mid latitude valley glaciers, the most important processes delivering melt energy in summer are absorption of solar radiation and turbulent exchange of sensible heat. On most glaciers, solar radiation typically provides 75% of the melt energy, although on the lower parts of maritime glaciers this may be closer to 50%.

In recent years, glacier mass balance models have been developed that are based on calculation of all energy transfers between atmosphere and glacier surface(1,2,3) Radiative and turbulent energy fluxes are calculated from climatological data. The surface balance can be prescribed, calculated with an energy balance model(4,5) The energy balance model is an attractive tool for simulating the surface balance, since the physical processes on the surface can be described fairly explicitly in the model. Such studies were usually performed over a short period in one medium and at a single location. In spite of the energy-balance work done so far and the significant increase in our knowledge this has brought about, there is still a need for Glacio - meteorological, radiation data for a long period and at larger area.

It is, however, not easy to obtain such data continuously around the year due to ablation zones and other problems of tremendous weather change in Antarctica. The attempt was made to record the radiation and snow-met data most of the time as and when possible. Furthermore, for budgetary and logistic reasons, it is not feasible to have a permanently manned station at different sites on a glacier tongue.

In this paper, the field scientific work was carried out at three different study sites. One was located on the snow. surface (snow pack in Antarctica is formed due to natural snowfall, snow drift and Blizzards) infront of permanent Indian base station "Maitri" ($70^0$46' S, 11^0 45' E). Maitri is located on Schirmacher oasis to the west of Dakshin Gangotri with the Wohlthat mountain chain lying towards the south(6). Second site was chosen on the Polar ice cap (Blue ice or Continental ice) about 7 km from "Maitri" and the third site for scientific observatory was on the Shelf ice at Dakshin Gangotri (70° 05' S, 12^0 E).We present an analysis of the solar radiation measurements for the period August 97 - Feburary 98 in different snow-ice media. Quantification of dependence of albedo on different physical parameters, and net energy budget has been estimated hourly, daily by incorporating a simple energy balance model.

2. Experimental details

Due to importance of albedo , radiative fluxes in the energy balance model priority was given to accurate radiation measurements. At all the sites in Antarctica, the global radiation and the reflected global radiation were measured with two precision pyranometers one facing upward and other facing downward. These instruments have a nominal sensitivity of 7-8 /iv/w/m^2. They have a flint glass double dome with excellent transmission characteristics for solar radiation in the wavelength range of 0.3 - 3 μm. The instrument was kept at a height of 1.5 mts. on the flat snow - ice surface in order to minimize the cosine error in the measurements due to slope. Glacio-met data were obtained by using meteorological instruments. Snow surface temperature, which is a very important parameter was measured using dial type sensor thermometer having measuring range of -50° C to + 50^0 C with an accuracy of ± 0.5° C. Free liquid water content in the snow pack was measured by using Dielectric Moisturemeter having capacitive sensor plate. The sensor was first calibrated in air and then dielectric constant was measured after inserting the plate in the snow pack. The liquid water content in the snow pack was measured by using the following relationship :

$$e' = 1 + (1.92 \times p) + 0.44 p^2 + 0.187 W + 0.0046 W^2$$

where, ε' = Dielectric constant of snow
p = Snow density
W = Melt water (% by volume)

3. Energy balance at the snow/ice - air interface

A snow/ice pack exchanges energy with (1) environment (2) 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 radiations and the heat flux due to snow and rain. A schematic diagram of energy flux is shown in Fig.1. Thus the energy exchange between the snowcover and the environment and underlying ground is given by [7-9].

$$A Q = Q_{rs} + Q_{rl} + Q_l + Q_s + Q_m + Q_g$$

where Q_{rs} is short wave radiation energy flux, Q_{rl} is long wave radiation flux, Q_l is latent heat and Q_s is sensible heat flux. Q_g is heat exchange at snow-ground interface is very little and Q_m advected heat also does not contribute to energy balance model in Antarctica.

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

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.

3.1 Short wave radiation

Short wave radiations reaching snow surface are 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, which controls the amount of radiation absorbed.

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

$$Q_{rs} = Qi\ (1\text{-}a)\ \text{langlay/day}$$

where Qi = R[l-(0.82-0.000073Z)N] langlay/day
= Energy received on the snow surface

R = 0.8 R_0 (during winter
= 0.85 R_0(during summer)
$R_{,0}$ = Energy received at the top of the atmosphere (langlay)
Qi = Energy received at the surface (langlay/day)
Z = Height of clouds (mts.)
N = Cloud amount in fraction of sky covered (octa)
R = Energy received at the surface on a clear day (langlay)
a = Snow/ice albedo

3,2 Long wave radiation

The radiative property of snow in the range 3-40 mm imply radiative exchanges strictly confined to the snow/ice surface. The net long wave radiation can be expressed as :

$$Q_n = Q_{rl}^{in} - Q_{rl}^{out} = s[\xi T_n^4 \quad T_s^4][1\text{-}KN] \quad (\text{langlay/day})$$

where T_n = Air temperature 2mt. above snow-ice surface (K)
T_s = Snow /ice surface temperature in (K)
K= Cloud type (It is a coefficient which depends upon type and height of cloudiness)
= 0.76 for low and thick clouds
= 0.52 Medium clouds and 0.26 for high clouds
a = Stefan - Boltzmann constant
(1.36 x 10^{12} langlay $K^{''4}$ $S^{''1}$)
§ = Emissivity of surface. For snow depends on wavelength and the angle of incidence.
= 0.9 for snow and ice

3.3 Latent and sensible heat flux

Both are governed by the turbulent exchange processes occurring within 2-3 mts. above the snow surface.

Latent heat flux is given by

Q,	=	0.622K p L [e - e] V /P
where K_w	=	K_N[1- $(R,)_B/(R,)_{cr}]^2$
K_N	=	$kV[\ln(Z_a/Z_{()})]^2$
$(R,)_B$	=	(2gZ/V/) [T - T] / [T + T]
p.	=	Density of air 1.1x 10° (gm/cm^3)
L	=	Latent heat of sublimation of ice and snow
	=	677cal/gm
e.	=	RH [saturated vapour pressure at temp. T] (Pa)
	=	RH [6.1078 exp[17.2693882(T_a-273.16)/ (T-35.80)]]
e	=	Saturated vapour pressure at snow surface temperature (Pa)
RH	=	Relative humidity
P	=	Atmospheric pressure (101300 Pa)
k	=	0.4 (Von Karmans constant)
V.	=	Velocity of wind at the height of observation (mts/sec.)
Z.	=	Height of observation (mts.)
Z	=	Roughness height of the surface
	=	0.005 mts. smooth surface
	=	0.0007 mts. snow on grass
g	=	Gravitational Acceleration (9.81 mt/sec^2)
(R)	=	Bulk Richardson number
$(R_{v\,I})_{cr}$	=	Critical Richardson number (0.2-0.5)

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Sensible heat flux is expressed as

Q =p C K [T-T.JV,

C = 0.24 cal/gm/K (specific heat of ice at constant pressure which is a linear function of surface temperature)

4 Results and discussion

4.1 Average albedo variation in different mediums

The daily average albedo on snow , continental ice and shelf ice is shown in Fig. 2, Fig.3 and Fig.4 respectively. The higher average albedo value has been found in snow medium (max.99%)as compared to shelf ice (max. 90%) and continental ice (max.58%). The ice layers present within Antarctic shelf ice and also of the continental ice partially contribute to reflected radiation. Major part of the incident radiation falling over the ice sheet is transmitted down, resulting in low albedo values.

The density for all 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[101]. 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 has a chance that ray may be scattered or bent when crosses an 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.

4.2 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.5. In order to know the dependency of albedo on the thickness of clouds observation has been taken during clear sky day, at the time of blizzard and after blizzard as shown in Fig.6. The average albedo was found to be higher (83%) during white out condition in blizzard when cloud thickness is very high as compared to Clear sky day (76%) and after blizzard (78%). It can be infered that albedo is a function of both and increases with increasing cloud amount and thickness. The increase in albedo can be attributed lo 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 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 thus results in increase in 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
x = Average cloud octa

From Fig.5 B= 1.5368 and C = 73.642 are empirical constants.

4.3 Albedo decay with age of snow pack

Albedo was found to depends on the type of snow as well as age of snow. Fig-4 shows the sharp rise in average albedo values from 70% to 90 *%* when new snow falls over the old snow. A sharp deacy in albedo values from 88% to 75% and 90% to 74% has been observed with the age of snow in mid January and first week of Feburary as shown in the Fig.7.. 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.

4. 4 Albedo variation with the melt water

In order to estimate the albedo vartiation with melt water concentration on snow surface as well as on the shelf ice, the natural melt process experiments were performed in the field as shown the the Fig.8 and Fig.9 respectively. The albedo was found to decrease with increasing melt water in both the mediums. WWI[11] cited both experimental and theoretical evidence that the effect of liquid water on albedo is simply to increase the effective grain size, because 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 water around ice grains. All these factors reduces the albedo values in presence of" natural melt water on snow surface.

4.3 Albedo variation with solar elevation (diurnal hysteresis)

An decrease has been observed in albedo values on clear days with increase in solar elevation from 3 degree to 12 degree approx. as shown in Fig. 10. 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, Also in Himalayan region, a reduction in albedo values has been observed with increase in solar elevation. The albedo values have been observed to follow a diurnal hysteresis pattern, the albedo in the morning is higher than in the afternoon for identical solar elevation. The diurnal hysteresis has relatively importance of two separate effects: surface morphosis and surface irregularities (sastrugi)[(12)]This shows individual values of albedo derived from hourly incident and reflected radiation measured over would result in a periodicity of 10 hrs. This variation should be attributed to the diurnal deposition and evaporation of a hoar froast coating on the snow surface. The authors"-[1]' have established that a thin hoar froast 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 froast coating could be removed as temperature increased during day time period. For example, on 16 Feburary, 1998 at 0700 local time, the ambient temperature was 265.5K and the surface albedo 0.74 and on the same day at 1600 local time, ambient temperature was 269.5K and albedo 0.70, although solar elevation was of the order of 20 degree. The hysteresis is due solely to the value of the reflected radiation being less in the afternoon than in the morning for identical solar elevation angle. This indicates that the effect is due to some change in the snow surface properties. The other reason is that snow absorption is very low at low solar elevation and most of the reflected radiations are absorbed by the pyranometer results in high albedo values in early morning. As the elevation angle increases the absorption on the snow surface increases due to high penetration results in low albedo during day time.

4.6 Energy balance in Antarctica

The solar insolation in different months at three different elevated sites is shown in Fig.11, Fig.l2and Fig.13. which showed the total amount of solar energy in In/day. The bar shows the total incoming radiative energy in the wavelength range of 0.3-3 mm The part of this energy is reflected and absorbed by the snow-ice surface. The calculations for energy balance estimates over snow, continental ice medium and shelf ice in Antarctica have also been performed as shown in Fig.14, Fig. 15 and Fig.16 respectively. 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 wave energy flux has been calculated using the albedo of snow pack and global incident radiation as input parameters. The short wave radiation flux is positive and reflected and absorbed by the snow-ice surface. Long wave radiation flux is negative and emitted by the snow-ice surface according to Stefan's Boltzman law. 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. They can have both positive and negative values. When latent heat flux is positive e.g. (e_a - e_s) is positive and snow surface temperature is T_s = 0 degree., water vapor condenses as liquid water on the melt-

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ing glacier surface. When (e_a - e_s) is negative, there is a sublimation. Also, when (e_a - e_s) is positive and snow surface temperature is $T_s < 0$ degree., there is condensation from vapor to solid ice. The energy balance is negative most of the time that indicates surface is loosing more energy as compared to gaining from the surrounding.

5. Conclusions

Results are presented from measurements carried out in the period August, 1997 - Feburary, 1998 in different snow-ice media, in Queen Maud land, at Antarctica. Glacio-Meteorological and albedo measurements were carried out in the immediate vicinity of a blue ice area, on shelf ice as well as on natural snow. The surface energy balance is evaluated using a simple model and measured meteorological parameters. The differences in the surface energy balance between snow and ice can be attributed to mainly the differences in albedo, surface roughness, thermal conductivity and short wave radiation extinction coefficient. The long wave radiation flux, latent heat flux and sensible heat flux are mainly responsible for energy exchange between snow-ice air interface. A good qualitative analysis of albedo dependence on melt water and cloud amount is obtained. The correlation of albedo with cloud amount, melt water are very important parameters for use in energy balance model.The dependence of albedo on the age of snow pack gives idea about the metamorphic activity in the snow pack. Diurnal hysteresis of snow albedo indicates that effect of hoar-frost will be dependent on the strength of solar radiation, snow-ice surface and ambient temperature.

6. Acknowledgements

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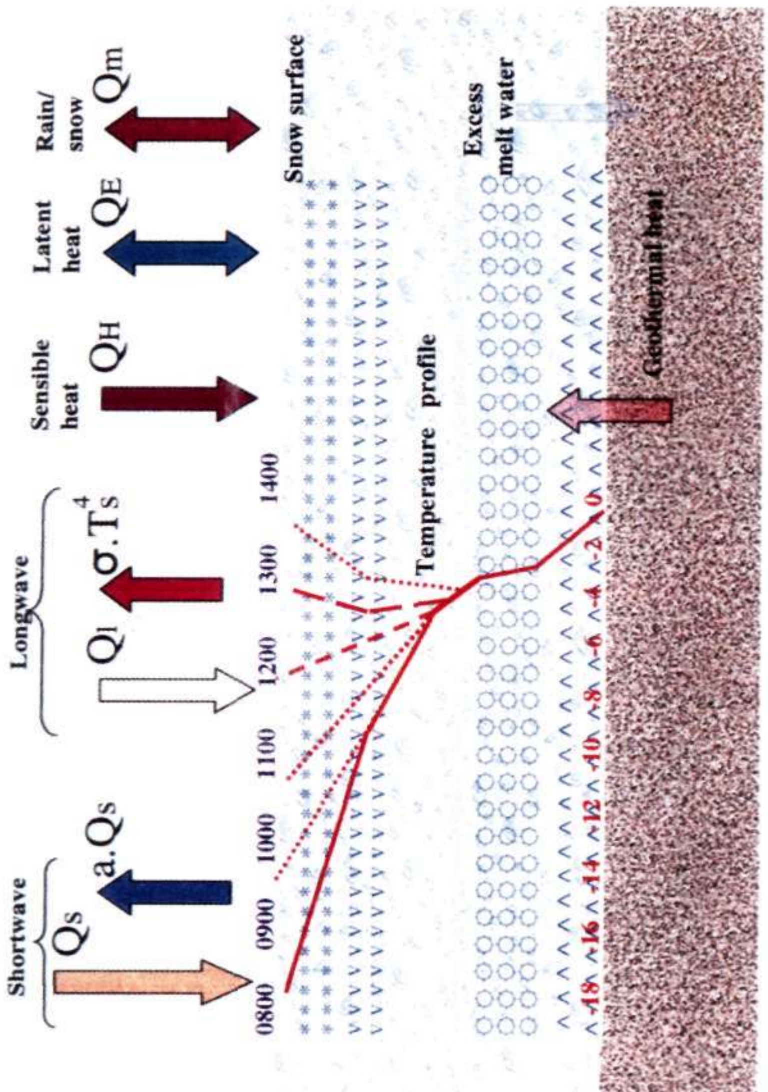


Fig. 1: Schematic diagram of energy exchange process in snowcover-atmosphere-ground system

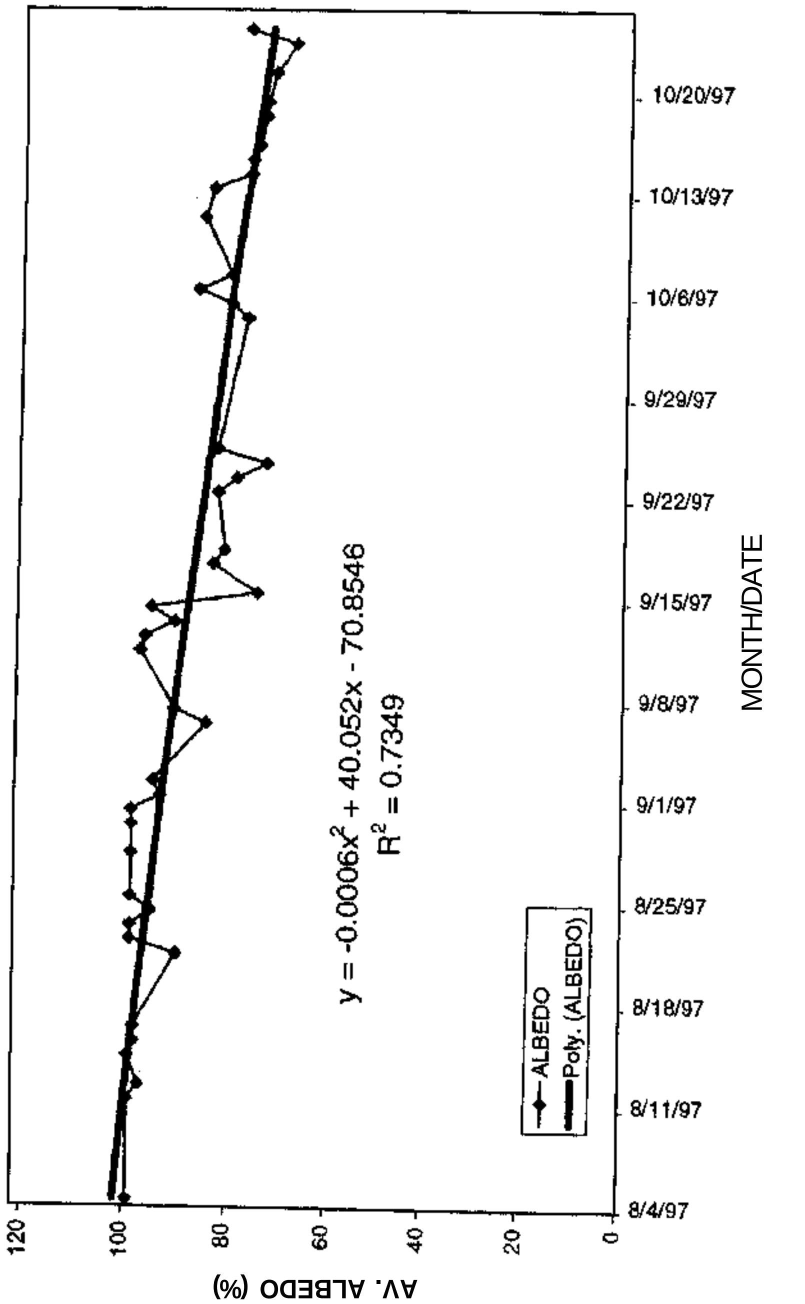


Fig.2 Daily albedo variation on the snow surface

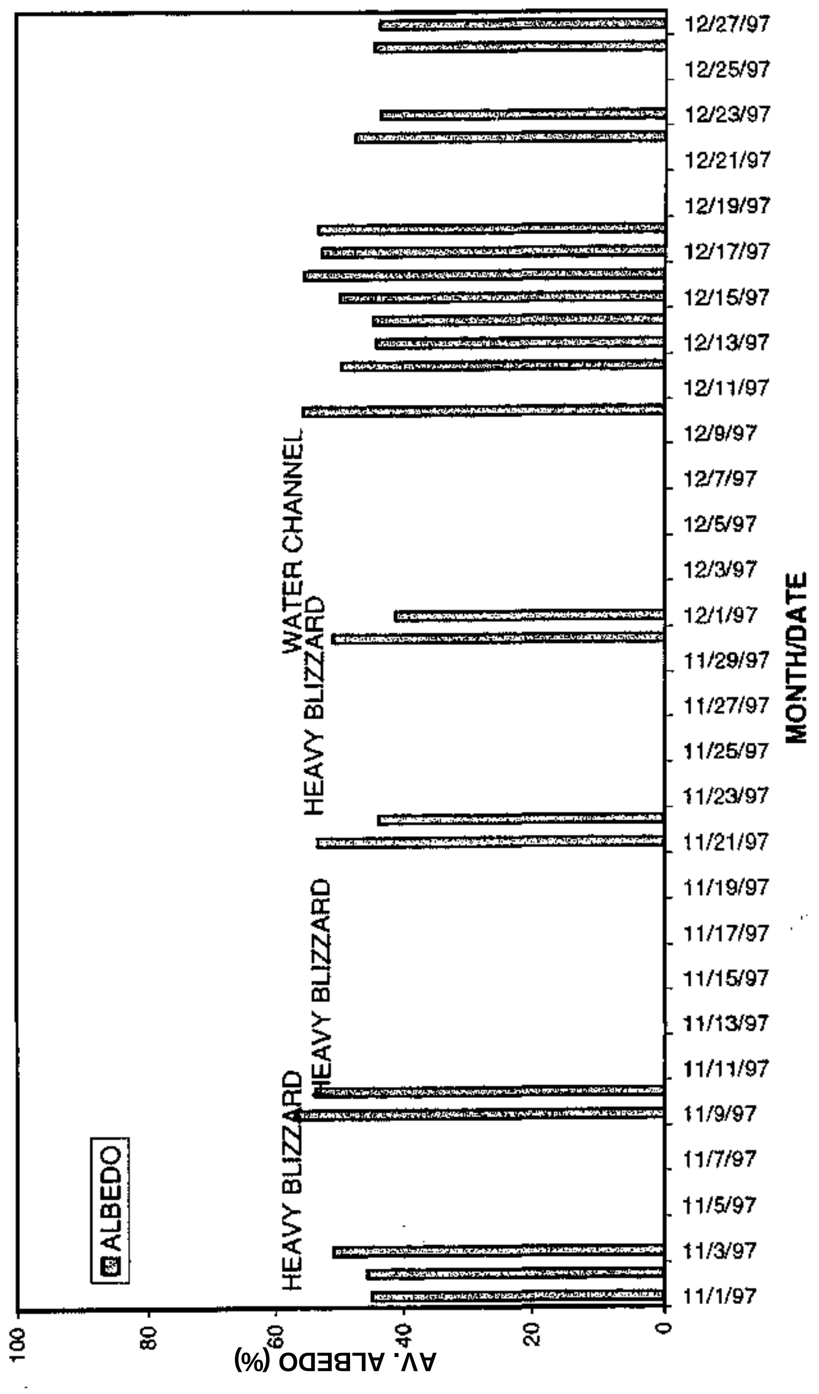


Fig.3 Albedo values on the Continental ice surface

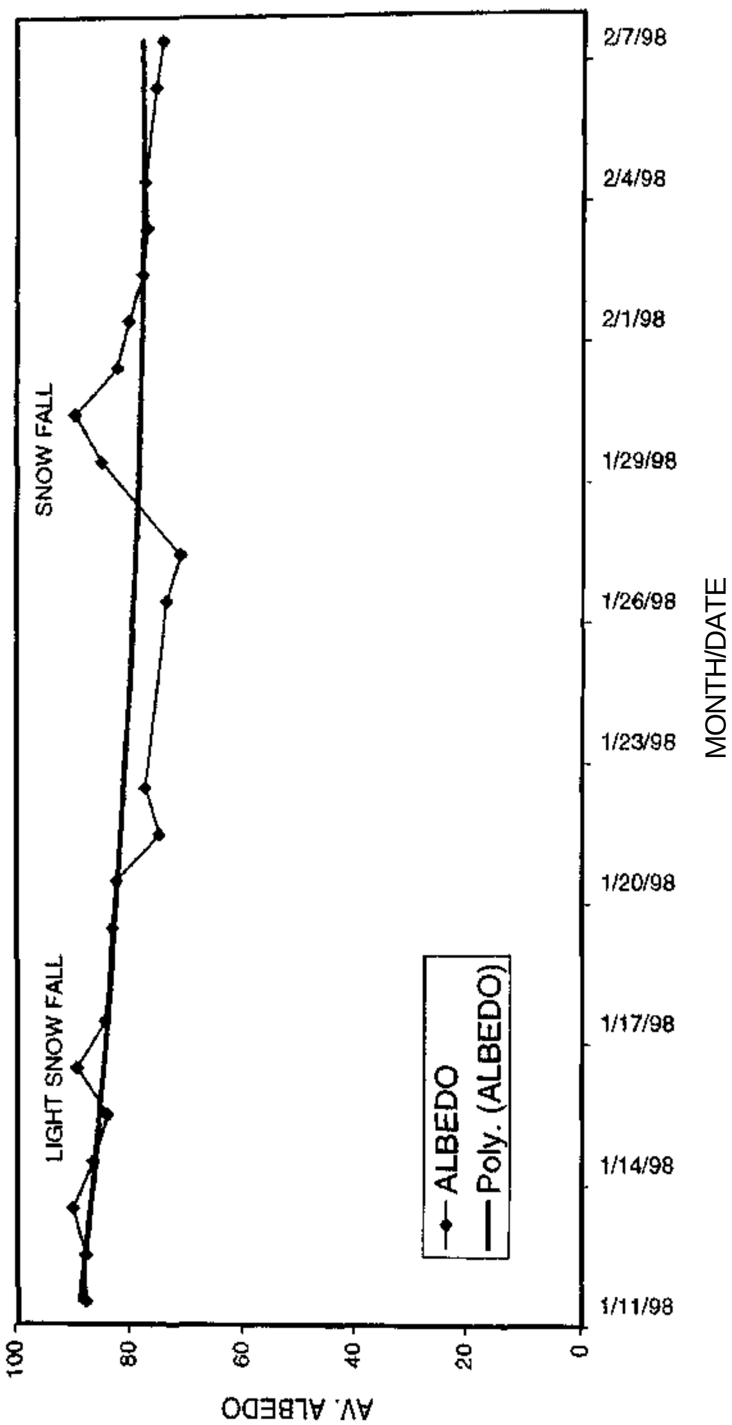


Fig. 4 Albedo variation on the Shelf ice surface

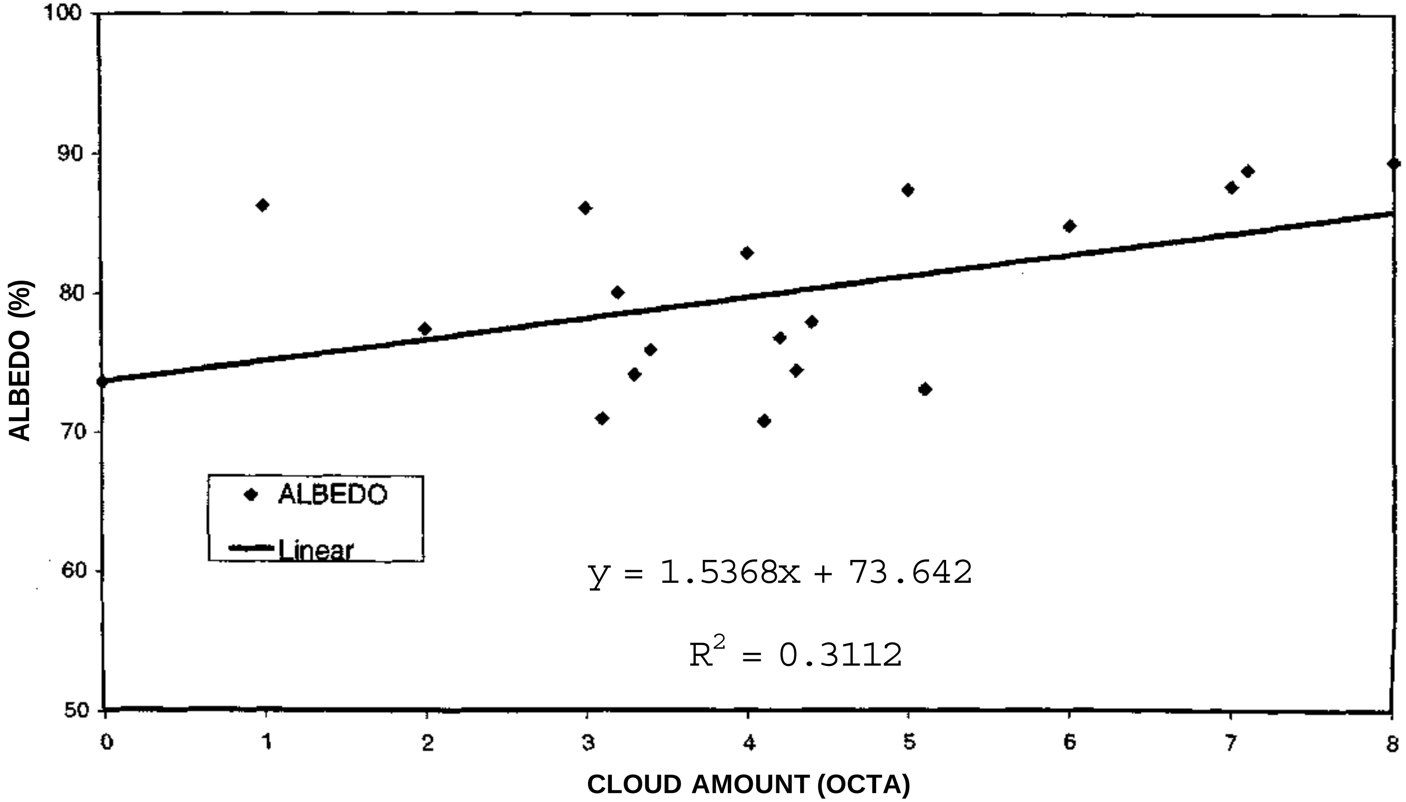


Fig. 5 Albedo variation with cloud amount

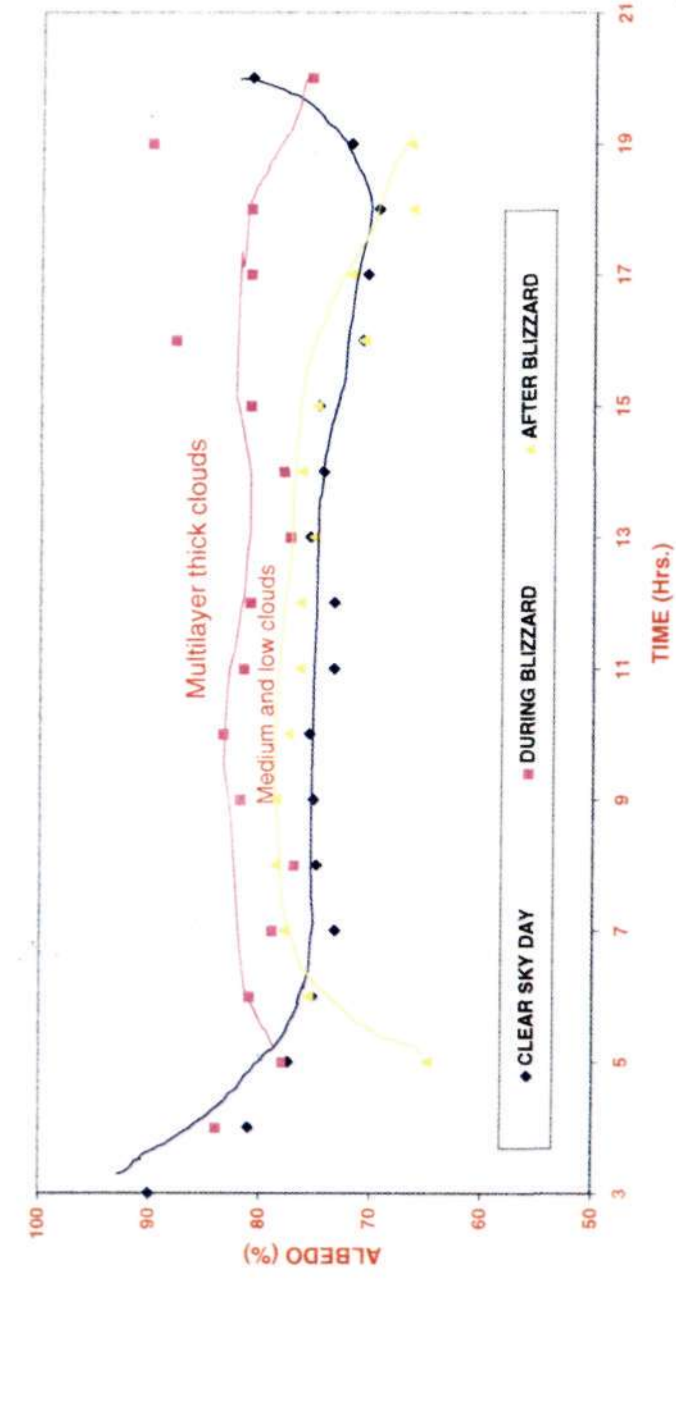
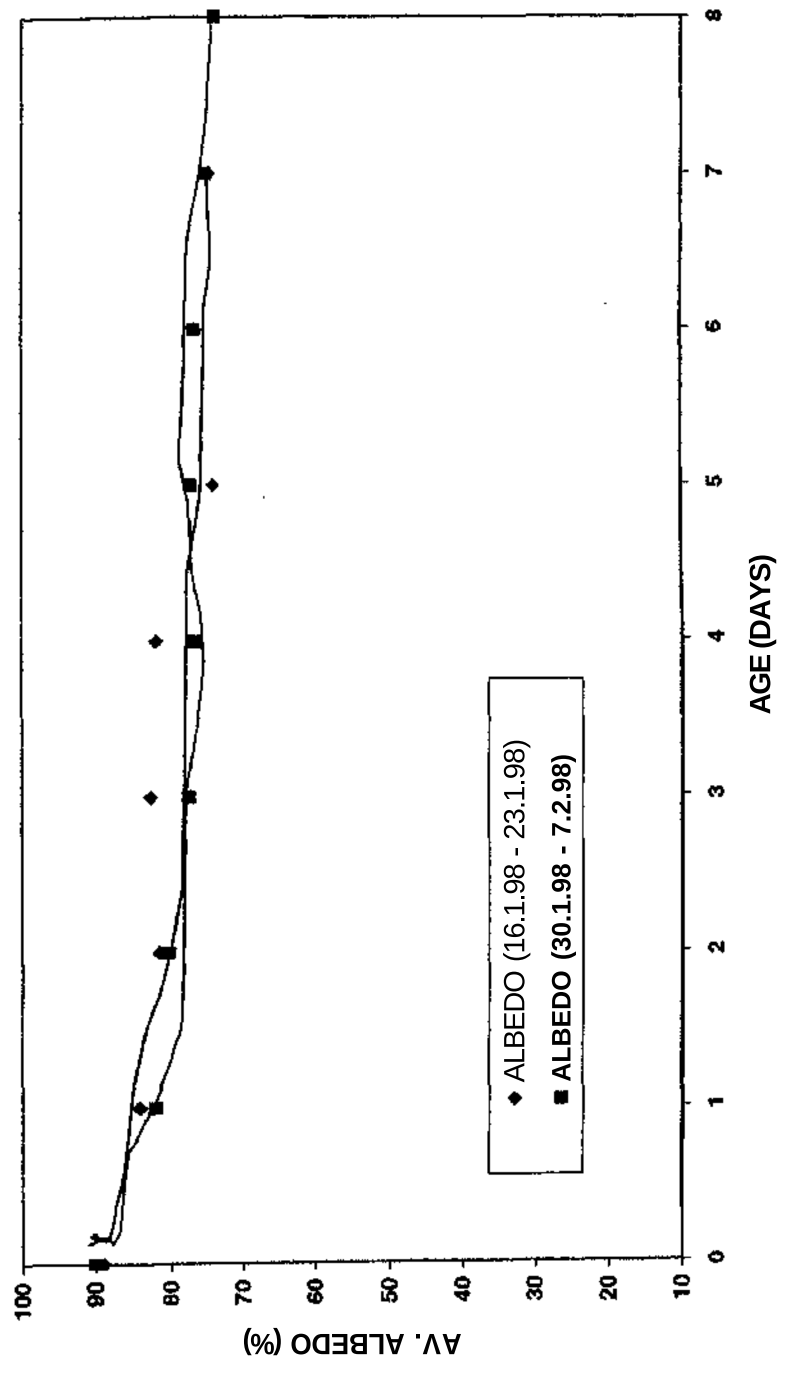


Fig.6: Albedo variation under different cloud conditions



Fig,7 Albedo variation with age of snow pack

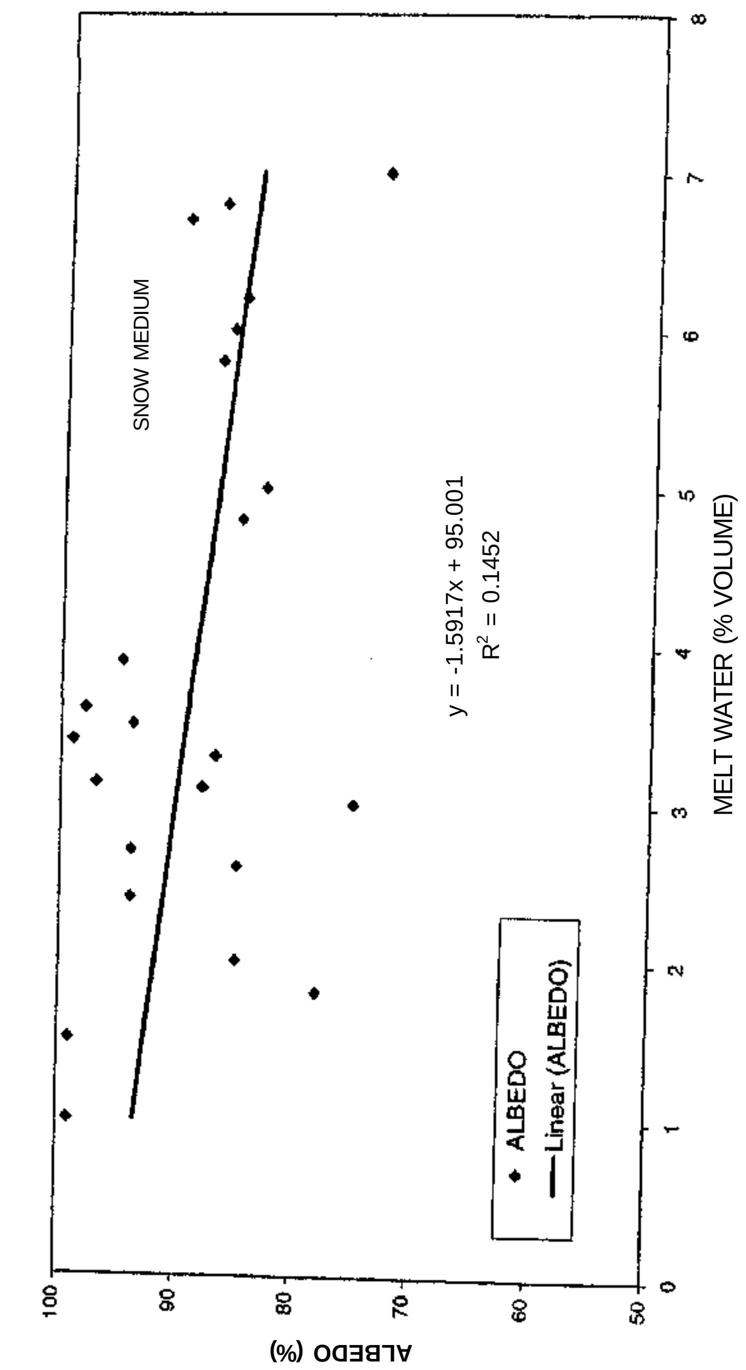


Fig. 8 Albedo variation with natural melt water in snow pack

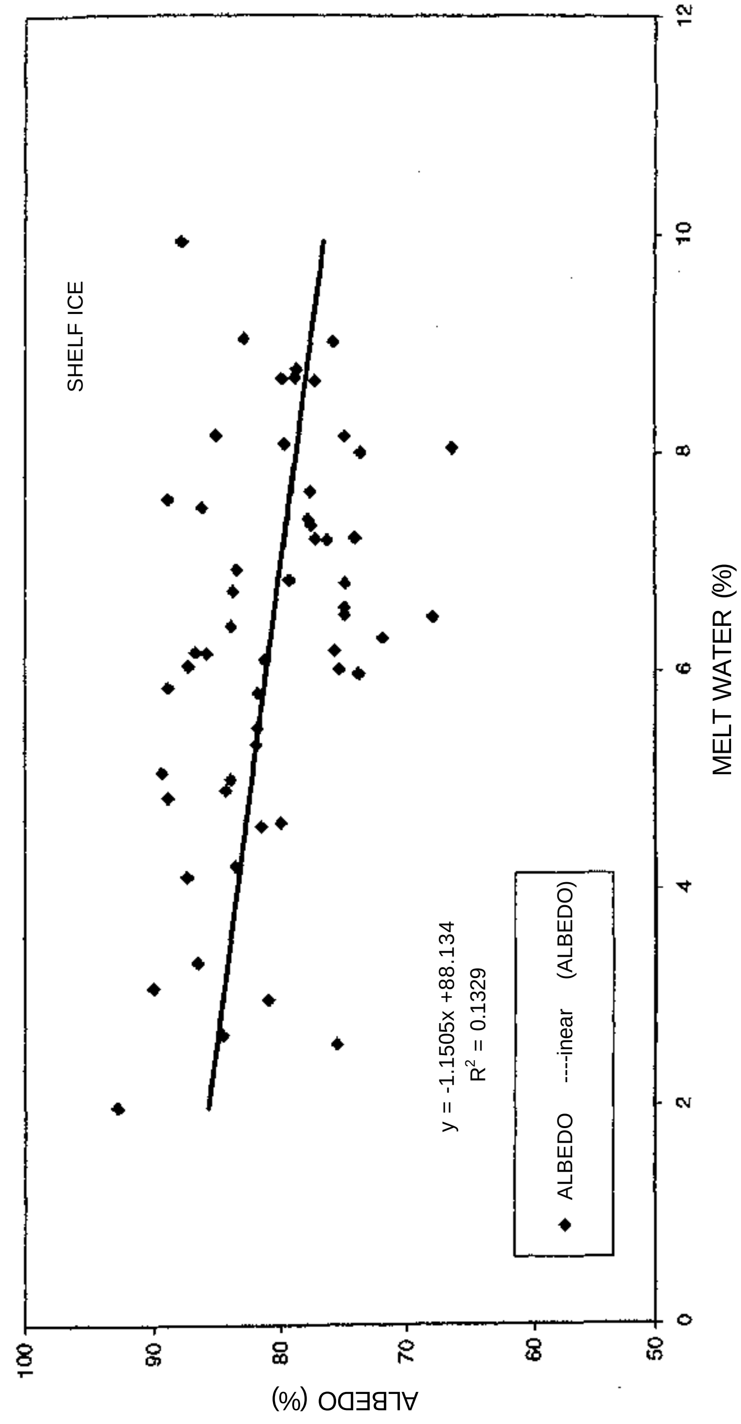


Fig. 9 Albedo variation with natural melt water in Shelf ice

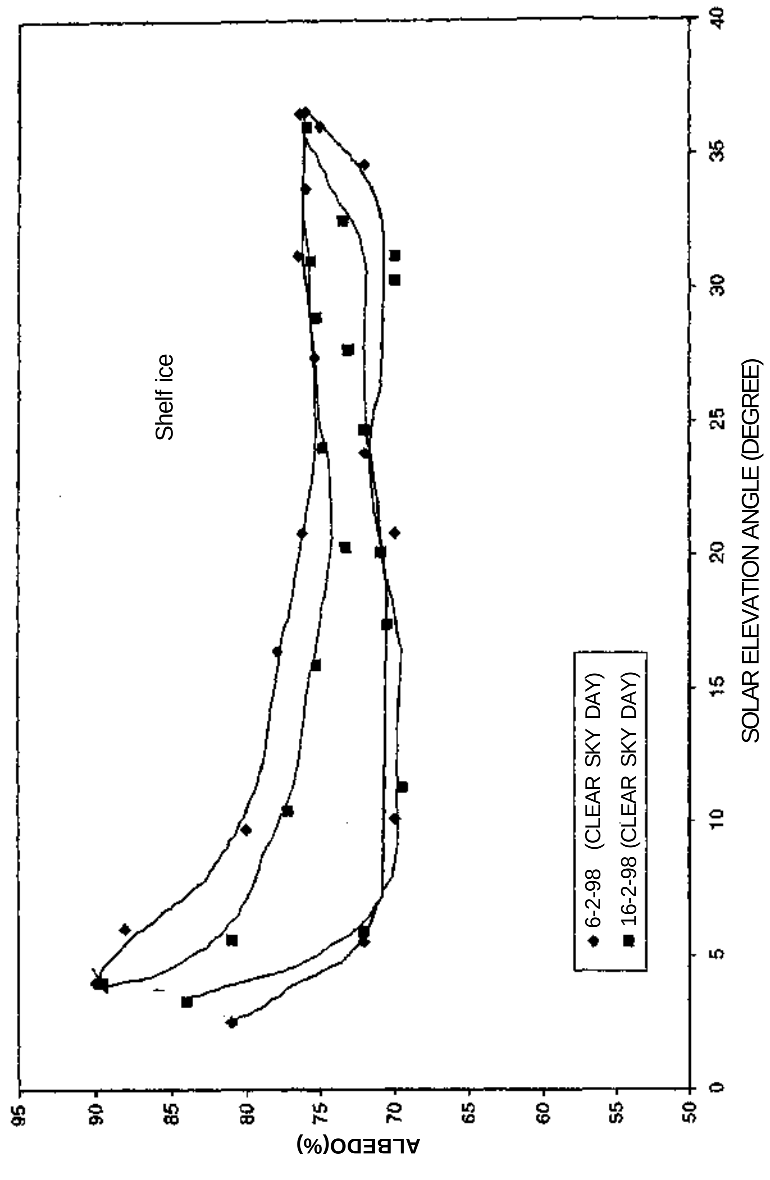


Fig. **10 Diurnal hysteresis of snow albedo**

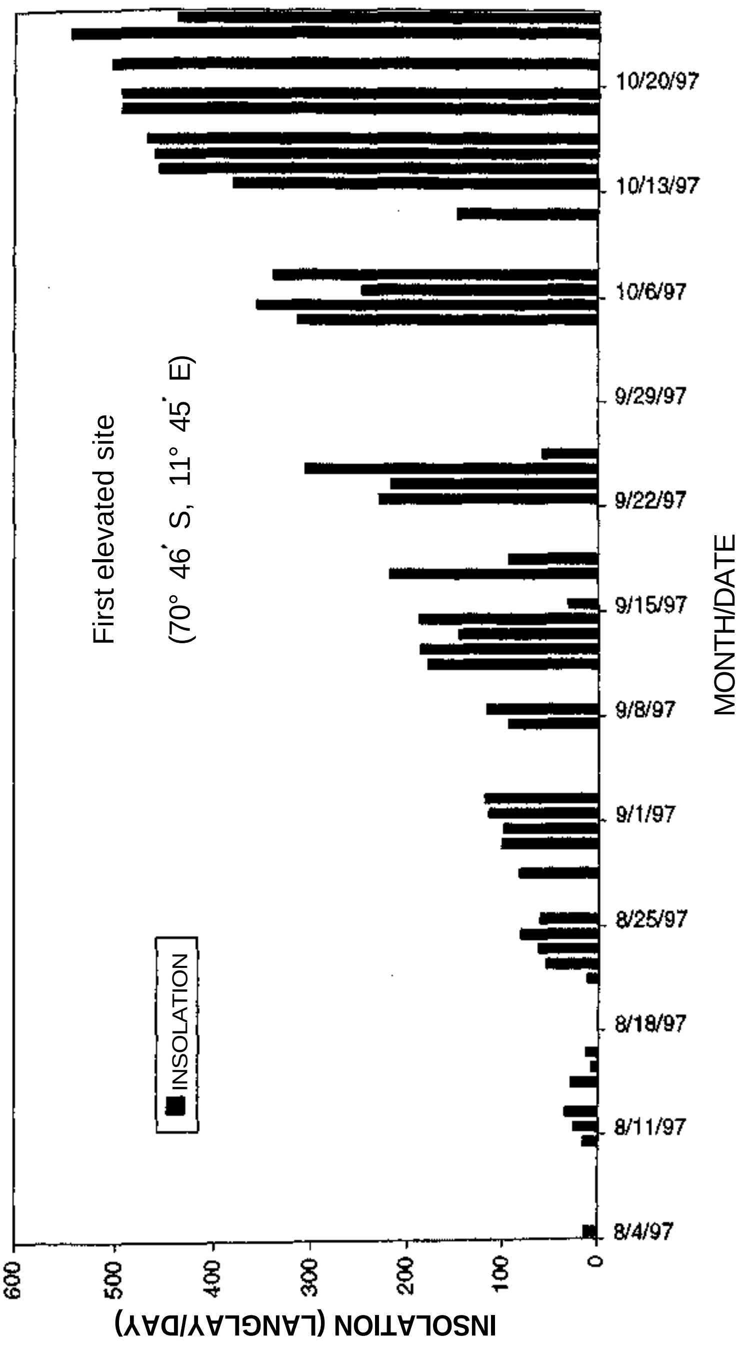


Fig.11 Solar Insolation on snow surface near Maitri station

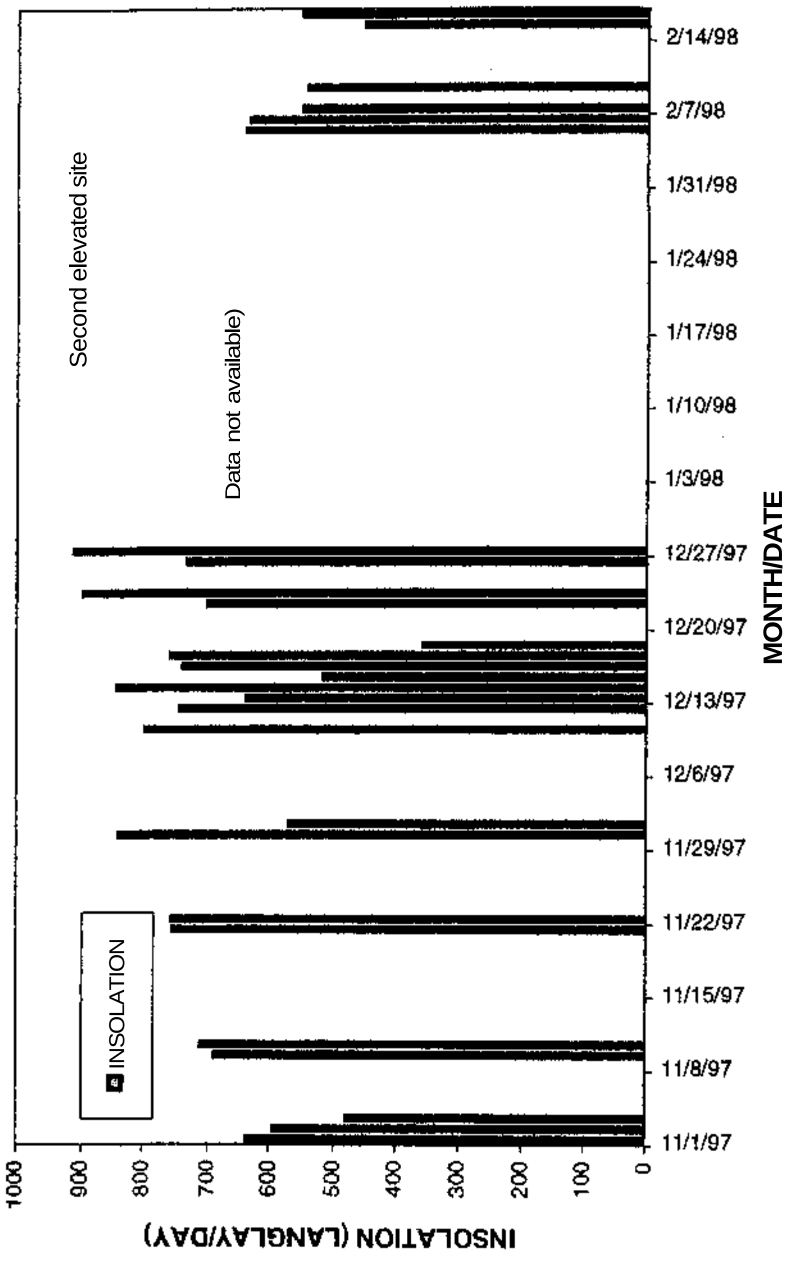


Fig.12 Solar insolation on Continental ice surface

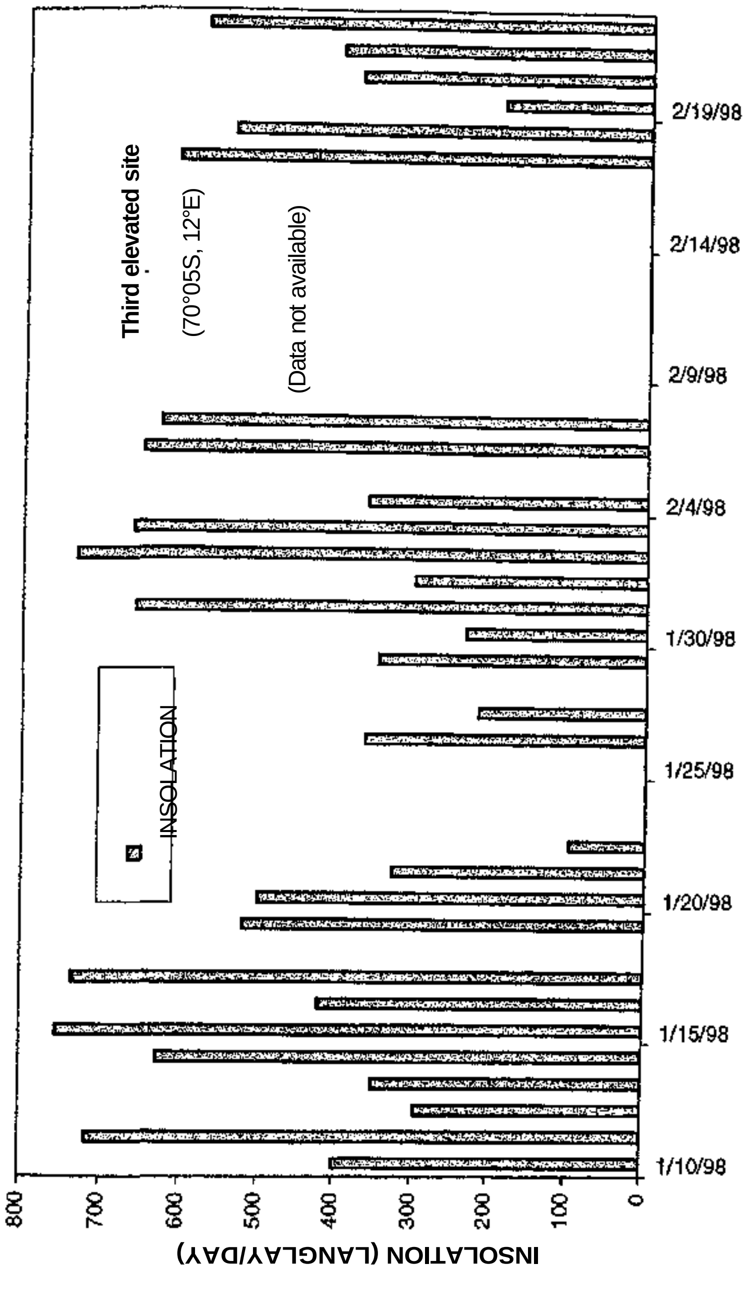


Fig. 13 Solar insolation on the Shelf ice at Dakshin Gangotri

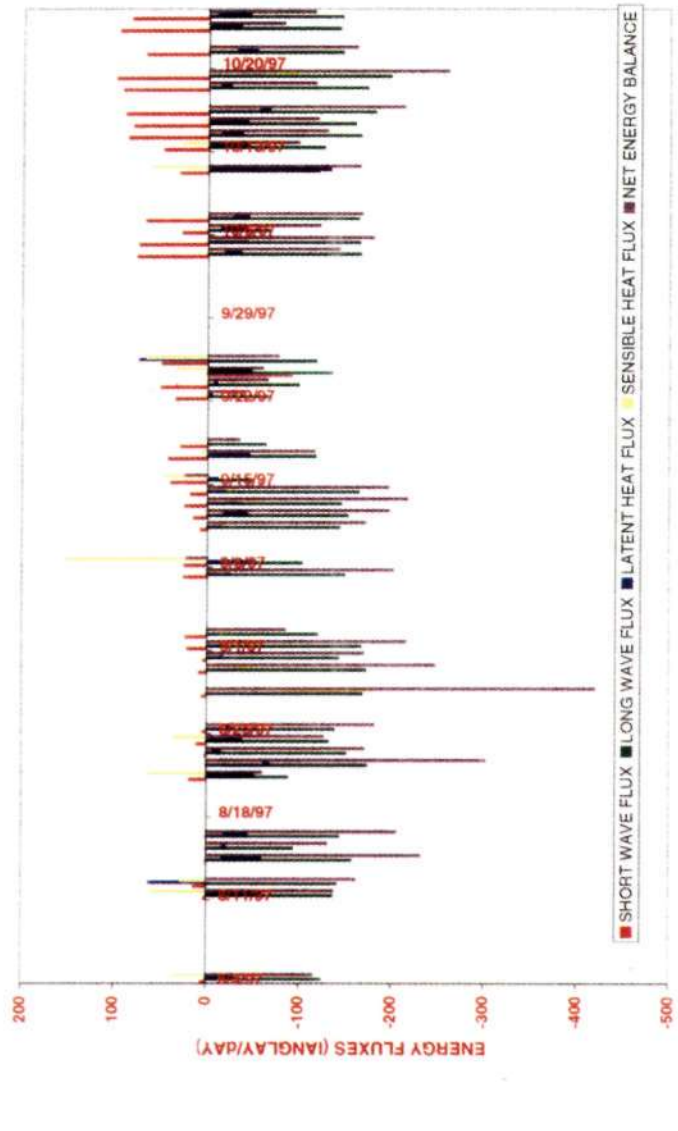


Fig. 14: Various energy fluxes and energy balance on natural snow surface

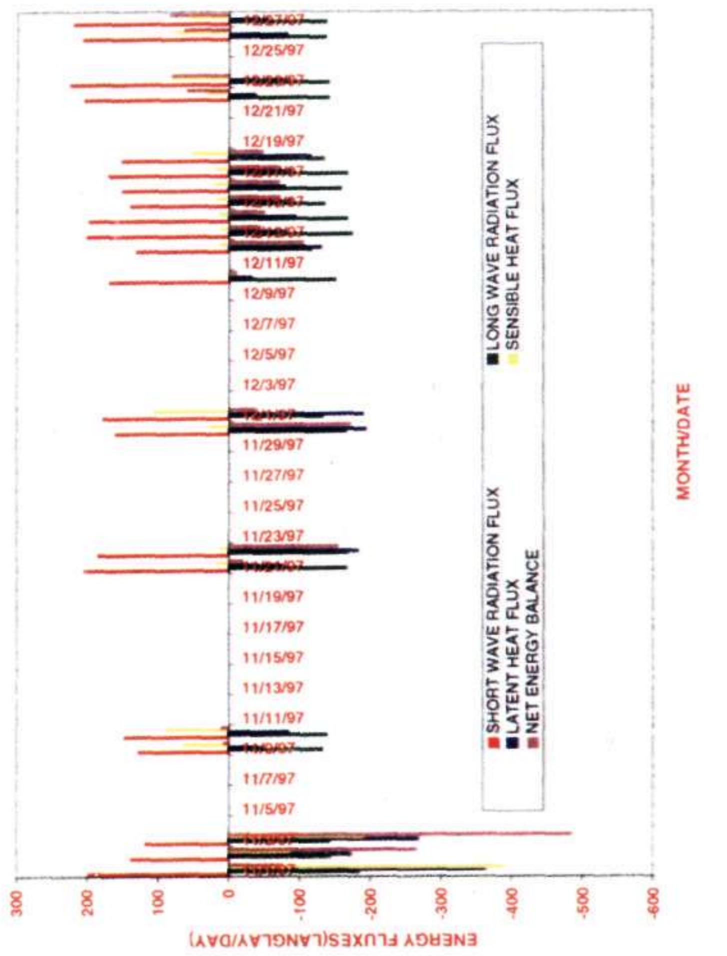


Fig. 15:Various energy fluxes and energy balance on Continental ice surface.

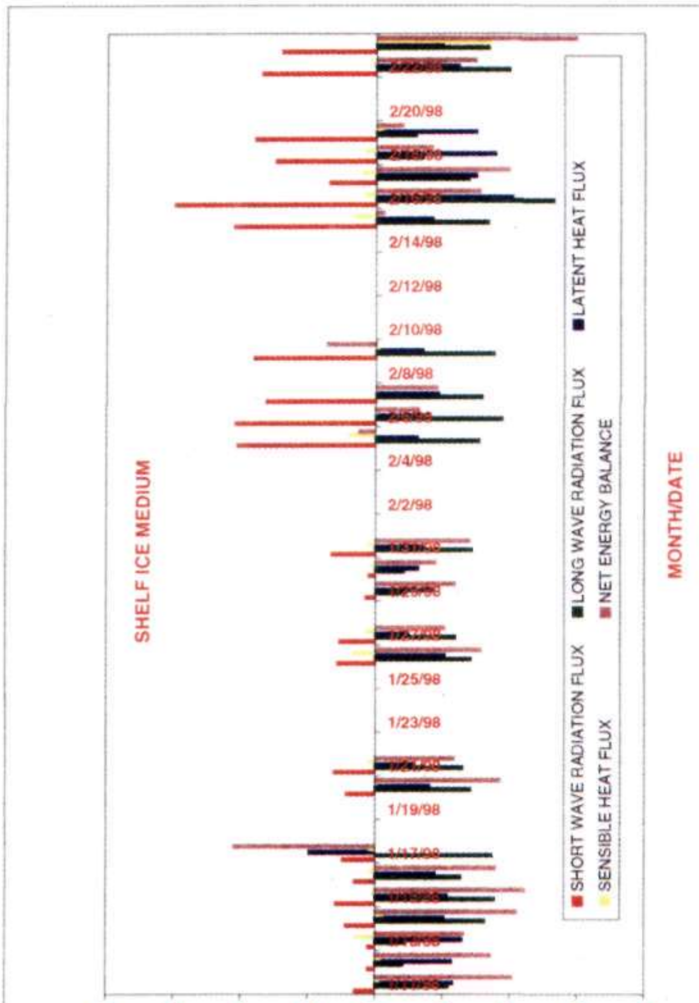


Fig. 16:Various energy fluxes and energy balance on Shelf ice