Nineteenth Indian Expedition to Antarctica, Scientific Report, 2004
Department of Ocean Development, Technical Publication No. 17, pp 47-64

Albedo Studies in Antarctica

Mahender Kumar
Snow & Avalanche Study Establishment, Manali

Introduction

In polar region, 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 winds) and global (upper westerlies) atmospheric circulation. 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 modeling 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 requires a detailed understanding of ground Albedo measurements and its seasonal variation, with various meteorological parameters for snow.

The Albedo, (i.e. ratio of reflected to the incident short wave solar radiation) of any surface, controls the amount of radiative energy being reflected backward thereby
Snow is the brightest substance of considerable extent on the surface of our planet and because of its high Albedo compared to other natural surfaces, seasonal and perennial snow cover plays significant role in the global energy balance. The connection between snow Albedo and climate has long been recognized as an important feedback mechanism. The snow Albedo feedback mechanism is looked upon as a positive feedback that occurs when warmer temperatures reduce the snow covered area, revealing a darker substrate and promoting increased radiative heating.

To the human eye, the vast Antarctic ice sheet gives the impression of homogeneity. However, large seasonal fluctuations in surface climate at these high latitudes create substantial changes in surface energy balance.

Although snow/ice Albedo has been identified as a sensitive boundary condition in general circulation models (GCMs), most of the current GCMs have been using simplistic representation of Albedo that vary only as functions of latitude and air temperature. The more physically based treatment of snow/ice Albedo takes into account changes in snow grain size and type, age of snow pack, liquid water content, solar zenith angle, cloud amount and type and light absorbing impurities in the snow. These parameters are coupled with each other and individual factor quantification has not yet been achieved. The current study aims at bridging these gaps as well as estimating the changes in surface energy balance in different snow/ice media. Keeping this in view, attention was focused on studying the variation in snow-met parameters, radiative fluxes, short-wave reflectance (Albedo) and surface energy balance over a part of the Dronning Maud Land, East Antarctica. This report examine and compares physical processes and the factors controlling Albedo over the continental shelf covered with thick layer of high density snow with that over the blue-ice (continental ice).

Aim of Albedo Studies in Antarctica

The Albedo studies were aimed at the following objectives:

(a) To Albedo dependence of snow Albedo on the following parameters:

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

(b) Determinations of Albedo distribution over various parts of ice shelf, continental ice & snow medium .

(c) To determine the magnitude of energy exchange in different snow/ice medium.

Theory of Radiative Energy Exchange Between Snow/Ice Surface and Atmosphere

Consider a snow/ice-covered surface. If there'is no horizontal transport of heat, conservation of energy requires that, at any point on the surface-at any instant.

$$B = S + L + H + LE + Qg + Qp - dU/dt$$

Where

B = net flux into or out of the surface
C = net short-wave energy absorbed by surface
L = net long-wave energy radiated / absorbed by the surface
H = sensible heat flux to the air
LE = latent heat flux to the air
Qg = heat flux absorbed by the surface from ground through snow/ ground interface
Qp = heat energy added to the surface due to precipitation in the form of rain
DU/dt = change in the internal energy of the surface layer

All these terms are measured/calculated in W/m2 and positive for flux toward the surface, negative for fluxes away from the surface. For this study the last three terms are negligible components in daily energy balance of a surface when compared to the other terms. Therefore, neglecting those terms we get

$$B = S + L + H + LE$$

The first two terms on the right hand side of the equation are net radiation budget components. They are estimated as follows :

Short-wave radiation:

The short-wave radiation reflected from the surface S_{out} (↑) depends on the amount of incident radiation S_{in} (↓) and the surface Albedo a. Considering the fact that snow surface is opaque to short-wave radiation, the portion of S_{in}(↓) that is not reflected is absorbed; so the net short-wave radiation (S) is given as

$$S = S_{in}(\downarrow)(1-\acute{\alpha})$$

Long-wave radiation :

Net long-wave radiation is the difference between incoming radiation from the atmosphere and emitted radiation from the snow surface. The snow-surface is considered almost a black body, as Dozier and Warren (1982) have noted, "in the infrared wavelengths, snow is one of the blackest substances on earth". Thus, outgoing long wave radiation, L_{out}, can be calculated using the Stefan-Boltman low ;

$$L_{out} = \epsilon_S \sigma T_S^4$$

Where ϵ_s is the emissivity of the snow/ice surface with a value close to one; σ is the Stefan-Boltzman constant and T_s is the surface temperature.

Incoming long-were radiation will depend on the temperature and composition of the overlying atmosphere and is calculated following a model developed by Prata (1996). This model computes emissivity of the atmosphere depending on perceptible water content and performs well in the limit of a dry atmosphere.

$$L_{out} = \{l-(l+w) \exp(-(1.2 + 3.0w)l/2\} \ \sigma T_a^4$$

If N is the amount of cloudiness, then

$$L_{out} = \sigma[\{l-(l+w) \exp(-(1.2 + 3.0w)l/2\} \ T_a^4 - \epsilon_s \sigma T_s^4]$$
$$[l-kN/8]$$

Where k is a constant and depends on type and height of cloudiness.

K = 0.76	for	low and thick clouds
= 0.52	for	medium clouds
= 0.26	for	high clouds

Turbulent energy exchanges :

Transportation of heat and moisture in the atmospheric surface sub-layer are governed primarily through turbulent motion. This transport gives rise to two forms of energy flux between the air and the snow/ice surface : Sensible heat flux (H) which is the direct transport of heat energy and Latent heat flux (LE) which is the transport of heat through the phase change of water. These fluxes play an important role in determining the rate of sublimation/melt form the surface. Turbulent fluxes are estimated using the bulk transfer approach with corrections for atmospheric stability.

The Sensible and latent hear flux are given by

$$H = C_p D_p u(T_a \ T_s)$$
$$LE = (0.622 \ p/P) L_v U(e_a \ e_s)$$
$$D = k^2/[In(z_a/z_0)]^2$$

Where

p = density of air

C_p = specific heat of air

L_v = latent heat of vaporization

z_a = height above the snow surface where measurement is made

z_0 = surface roughness parameter

D = bulk transfer coefficient for sensible and latent energy transport
T_a & T_s = temperatures of air and surface and at measurement height respectively
e_a & e_s = vapour pressures at the surface and at measurement height respectively
u = wind speed at measurement height
k = von Karman's constant

The bulk transfer equations are valid only for neutral atmospheric conditions. However, in actual case the atmosphere is seldom neutral. In that case appropriate stability corrections are applied for the transfer coefficient d. One of the common form of correction that is applied is based on Price and Dunne, 1976, using the Richardson number R. Based on theory, for stable conditions (R_1>0), transfer coefficient is

$$Ds = D/(1+\ 10R_i)$$

Under unstable conditions (R_1>0), the transfer coefficient can be modified by

$$Du = D/(1+\ 10R_i)$$

These correction factors have been used by other workers (Hong 1992) with reasonable accuracy. Hence it has been decided to use these correction terms in this work. All the required snow-met (nine in all) are given as input in the form of an input file (hourly basis and a program executes them.

Instrumentation and Location of Measurements Sites

For recording the continuous radiation data, Automatic weather stations were installed during austral summer of the 18^{th} expedition. The AWS were set up at locations 70°05'S, 12°E over continental shelf and 70°45'52"S, 11°44'3"E over the blue ice. But during the 19^{th} expedition, the AWS at continental shelf was not functioning; so manual data was recorded there. At both the locations the surrounding topography is almost flat and measurement sites are completely unshaded, so the affect of slope and aspect on the topoclimate are minimized.

The Sutron 8210 series data logger was used in the AWS, which has a wide range of inputs, designed to support the most common snow and met data collection applications. The system consists of Data Collection Platform (DCP) and various snow and meteorological sensors. The DCP acquires data after a predefined interval from different sensors. At the end of every hour, this data is processed and stored locally. All the electronic components of the DCP are capable of operating up to ~40°C under extreme weather conditions. Salient features include ;

- **PCMCIA** memory card slot for data of programming storage.
- Dedicated external **RS-232** serial port for programming and data retrieval.
- Field programmable flash **EPROM's** via the use of **PCMCIA** port.

The AWS is equipped with the following sensors :

- Ambient temperature
- Relative humidity
- Wind direction and wind speed
- Atmospheric pressure
- Snow depth
- Albedometer (upward and downward looking pyranometers)
- Snow surface temperature

Power is supplied by a solar panel combined with heavy-duty low temperature batteries. The entire assembly including the data logger, sensors, battery and solar panel are mounted on a triangular mast over the snow or ice surface.

Results and Discussion

Meteorological Conditions

Figure 1(a) shows the daily variation of ambient temperature and surface temperature over blue ice for the period of February to April 2000. The measured average ambient temperature was -9.9°C and the average surface temperature was -10.1°C. The variation pattern shows that a sharp rise in average air temperature corresponds to fair weather, followed by a drop in air temperature corresponding to bad weather days. Average surface temperature was lower than average air temperature for all months except February 2000. This is because of longer period of unstable stratification caused by strong radiative heading of ice surface during month of Feb.

Figure 1(b) shows the daily variation of average relative humidity and average wind speed for the period of February to April 2000. The average relative humidity for this period was 55.1%, maximum RH was 85.4% and minimum RH was 38.6%. the average wind speed for the period of Feb. to April 2000 was 6.57 m/sec and the highest average wind speed was 7.1 m/sec in the month of April.

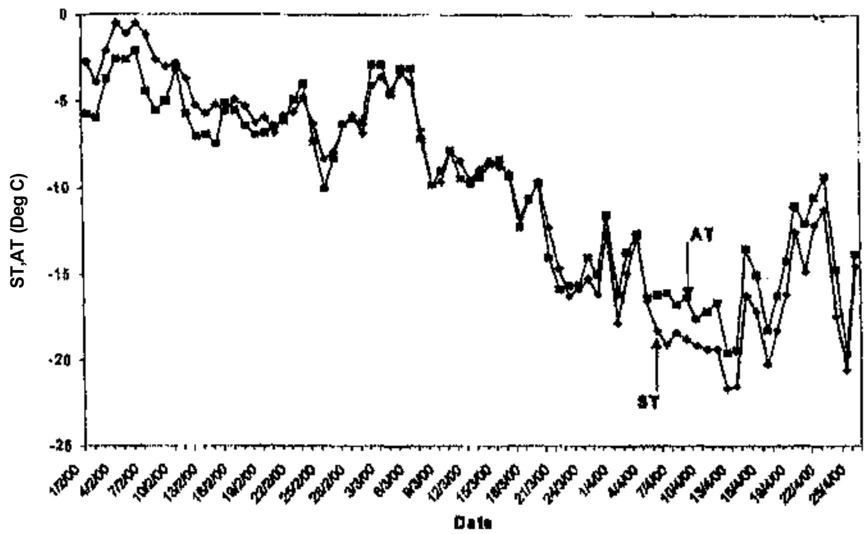


Fig. 1 (a): Daily average variation of ambient temperature & surface temperature over blue ice for the period of Feb-Mar-Apr 2000

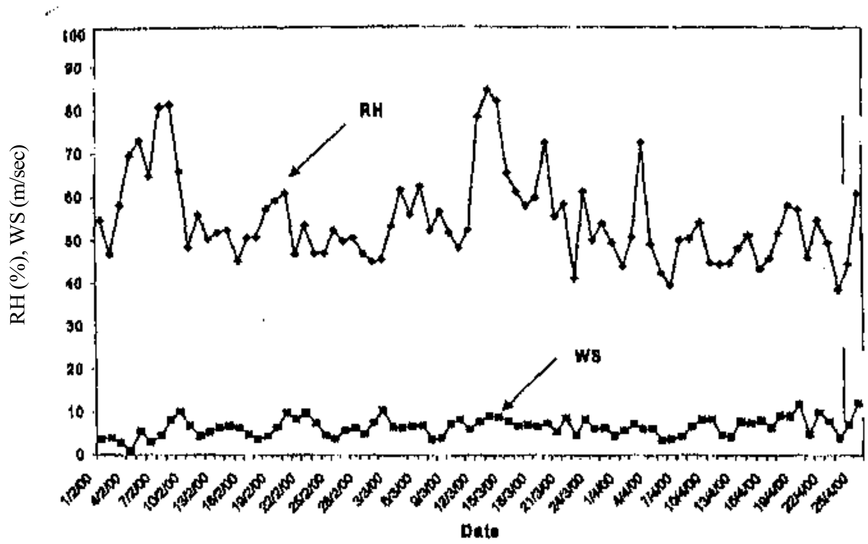


Fig. 1(b): Daily average variation of relative humidity & wind speed over blue ice for the period of Feb-Mar-Apr 2000

Radiation Characteristics

We define an effective transmissivity of the atmosphere (T_{err}) as the ratio of daily totals of incoming short wave radiation and extraterrestrial radiation I on a horizontal surface:

$$\tau_{err} = S_{in} (\downarrow)/1$$

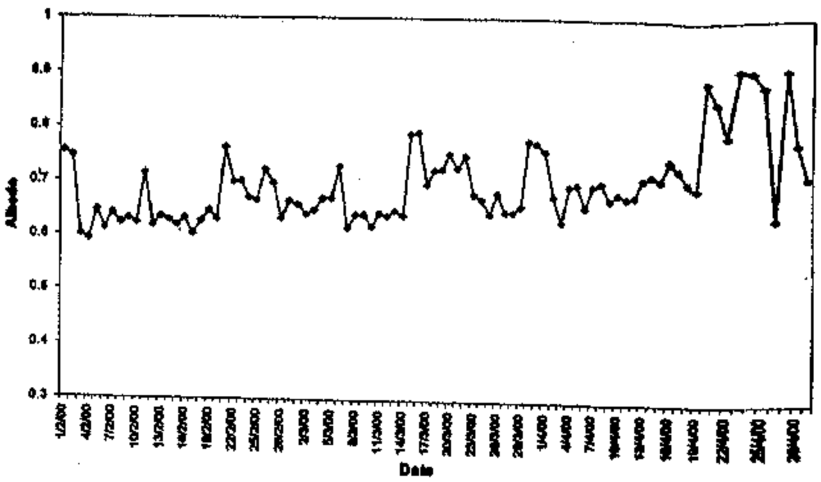


Fig. 2 (a): Daily albedo variation over blue ice for the period of Feb-Mar-Apr 2000

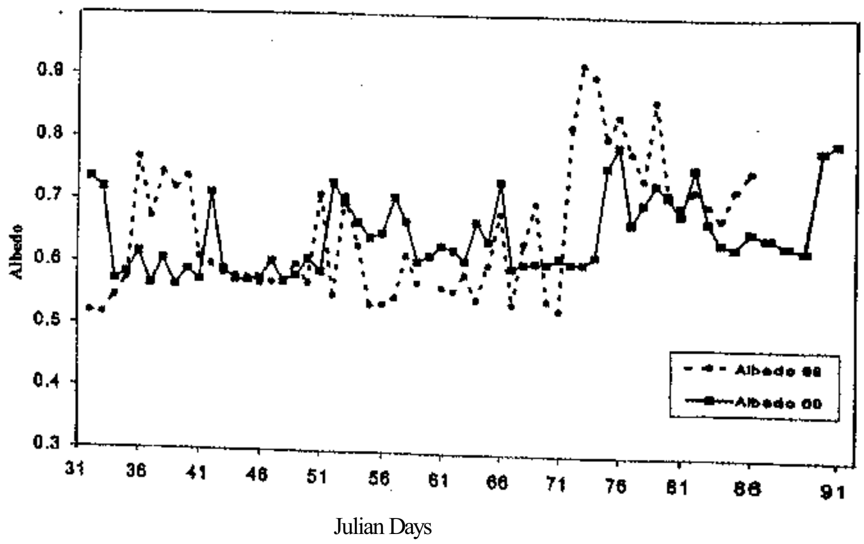


Fig. 2(b): Comparison of daily albedo variation over blue ice for the period of Feb-March 1999 & 2000

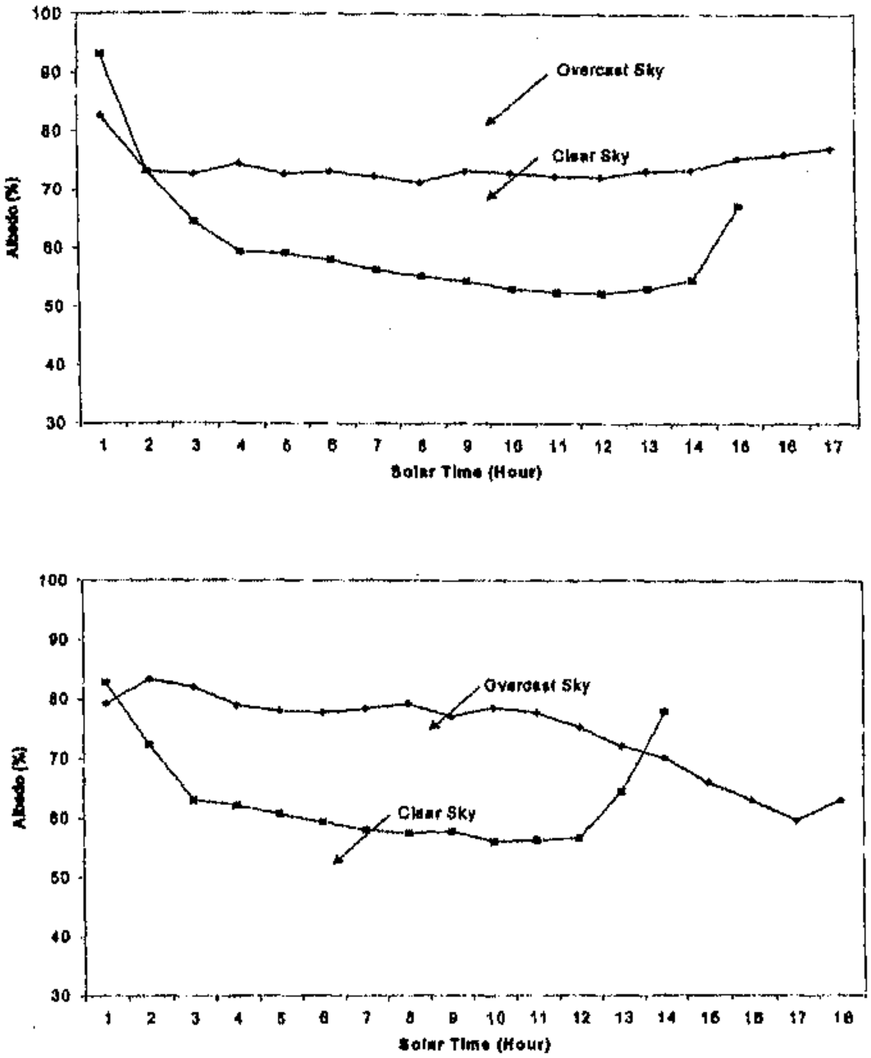


Fig. 3: Mean daily variation of albedo values over blue ice for clear sky (0 to 1 acta) conditions and complete overcast conditions (7 to 8 octa)

The result of number of atmospheric processes, that is scattering and absorption of solar radiation by air, aerosol and cloud is included in Ten-Comparison of daily mean values of S_{in} (↓) for Feb. and March 1999 & 2000 over blue ice are plotted in Figure 5, together with extraterrestrial irradiance, I. τ_{err} varies between 0.2 to 0.87, having a mean value of 0.64 (Figure 6).

Albedo Over Continental Ice

Albedo is defined as the ratio of daily amount of reflected solar radiation to the daily insolation. This differs from the daily mean Albedo, which mean of all instantaneously determined Albedo values over during day light. However, when the solar elevation angle is very low, this quantity may be influenced greatly by instrumental errors. In view of this we will concentrate on daily Albedo for analyzing measurements.

Figure 2(a) shows the daily Albedo variation over blue ice for the period February to April 2000. While the Fig. 2(b) shows the comparison of daily Albedo variation over blue ice for the period of February-March 1999 & 2000.

Albedo Variation with Cloud Amount

The Albedo values are found to increase with the increase in the cloud amount, as shown in the Figure 3. The increase in Albedo can be attributed to the fact that cloud absorbs a larger part of infrared than visible radiation. Thus, a relatively larger portion of visible radiation reaches the surface under cloudy condition. Since the Albedo in the visible range is very high compared to near IR Albedo, an increase in surface Albedo is to be expected during overcast conditions. Figure 4(b) shows the variation for daily Albedo with mean daily cloud amount (values are averaged as a function of cloud amount).

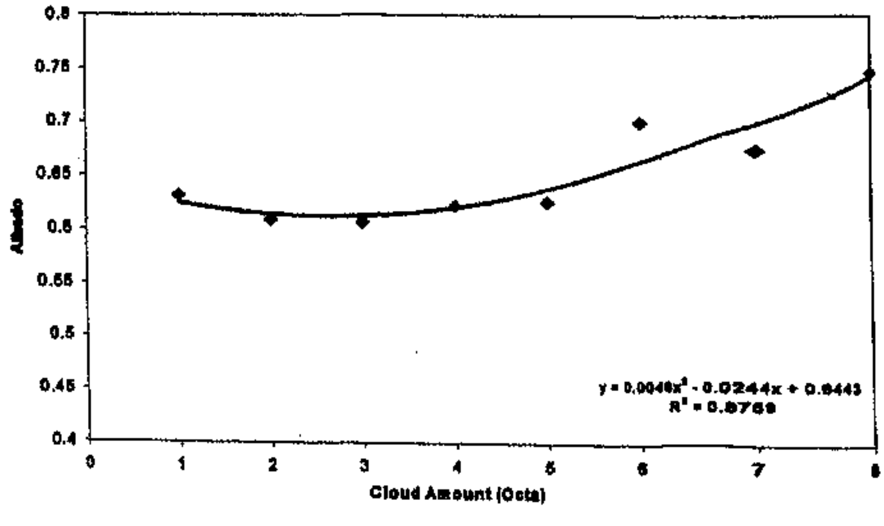


Fig. 4(a): Albedo variation with cloud amount over blue ice. Feb-March 2000 values are averaged as a function of cloud amount

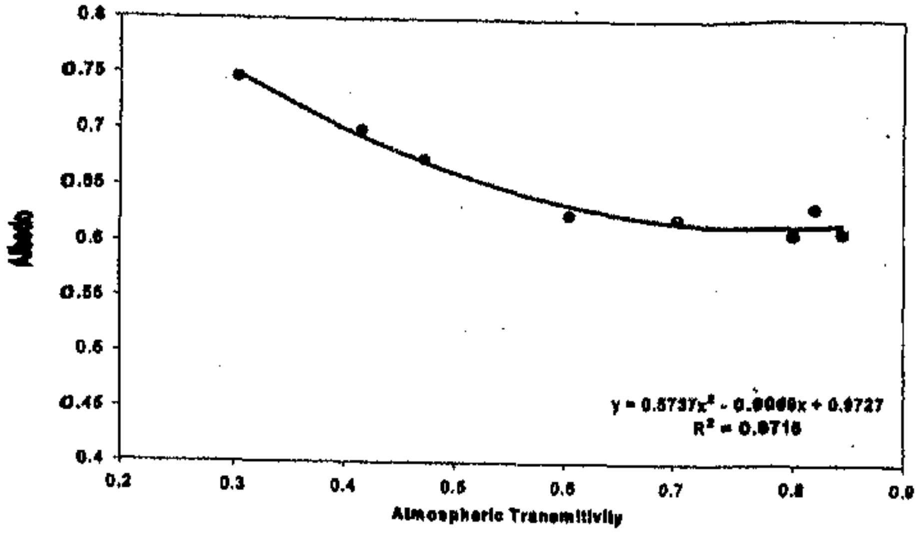


Fig. 4(b): Albedo variation with atmospheric transmitivity. Feb-March 2000 values are averaged as a function of atmospheric transmitivity

Figure 4(b) shows the Albedo variation with atmospheric transmissivity (values are averaged as a function of atmospheric transmissivity).

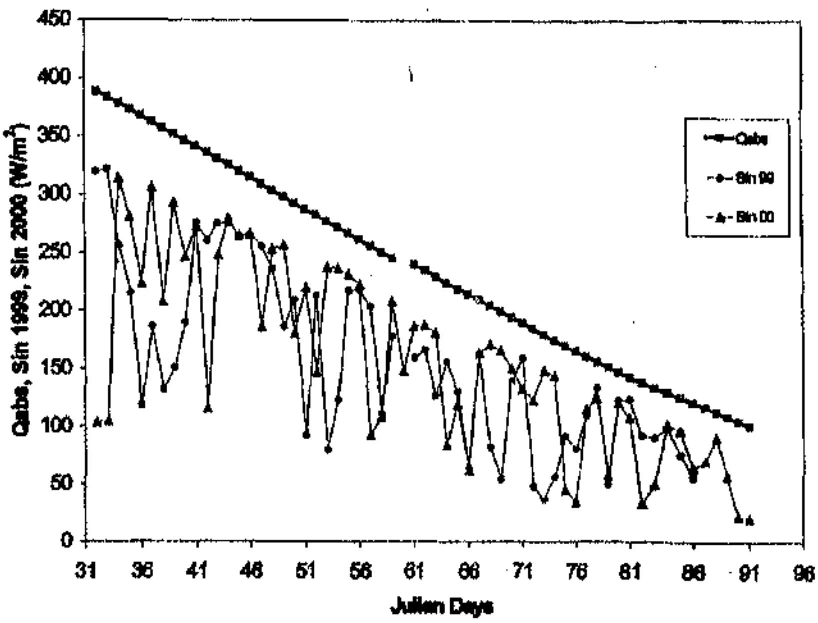


Fig. 5: Daily mean values of insolation and extra terrestrial radiation over blue ice during Feb-March 1999 & 2000

Surface Energy Balance

The full energy balance was calculated on an hourly basis. Aside from being physically more correct than a daily calculation, the hourly calculation of the turbulent fluxes has a hidden bonus. This is because the temperature sensors show a clear sign of radiation heating; temperatures

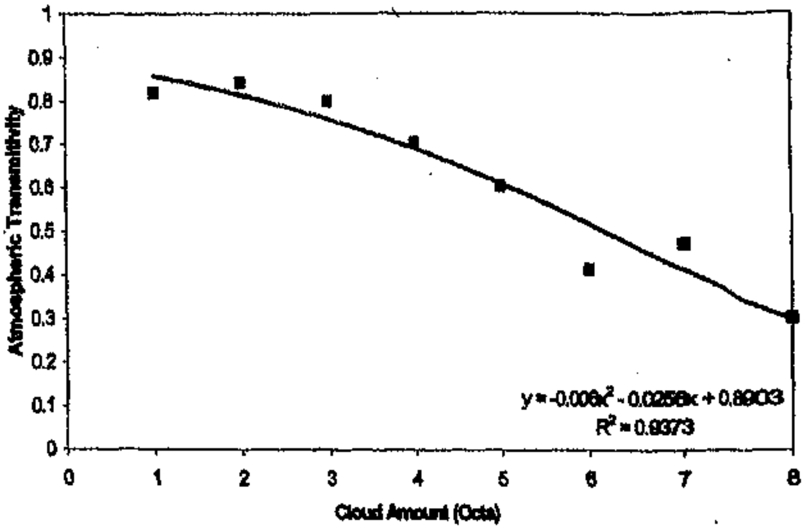


Fig. 6: Atmospheric transmitivity variation with cloud amount. Feb-March 2000 values are averaged as a function of cloud amount

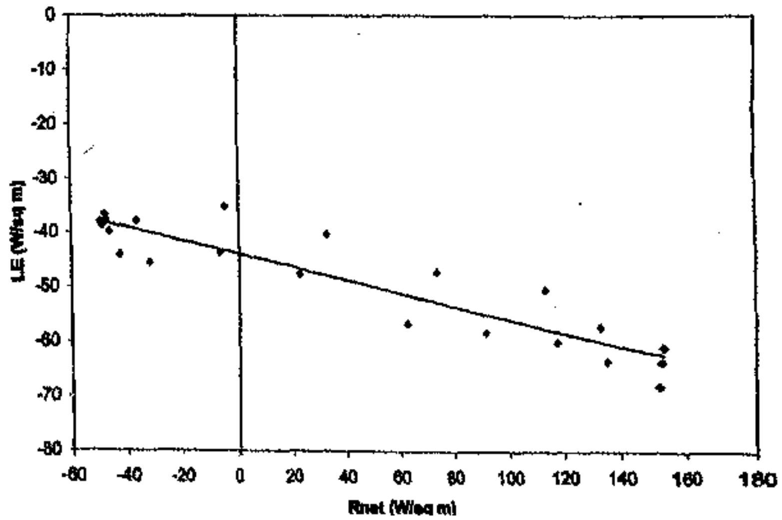


Fig. 7: The relationship between net radiation and estimated latent heat flux (sublimation) based on average diurnal values for February 2000

rise quickly if wind speed drop below 1.5 m/sec. This caused some concern until it was realized that, even if the temperature is erroneously high for a particular hour, it is multiplied by a correspondingly low wind speed for the same hour so that the resulting error in sensible heat, averaged over the day will be small because the largest contributions come from hours with relatively high wind speeds. The hourly values of computed energy balance are summed into daily totals and averaged for the period February to April 2000.

Table 1 shows the values of the energy balance components for the period of Feb. to March, April and average. Table 2 shows the comparison of the energy balance components for the period of February & March 1999 & 2000.

Table 1: Energy balance results over blue ice
(Analysis period: February to April 2000)

Energy balance components	Feb	March	April	Average
Qsw (W/sq m)	85.77	41.94	10.64	47.54
Qlw (W/sq m)	-52.32	-39.60	-31.81	-41.64
Rnet (W/sq m)	32.66	1.0	-22.92	4.63
H (W/sq m)	-13.84	1.15	29.20	4.72
LE (W/sq m)	-47.8	-25.35	-22.37	-32.48
B (W/sq m)	-28.97	-23.19	-16.50	-23.12

Table 2: Comparison of energy balance components over blue ice
(Analysis period-February & March 1999 & 2000)

Energy balance components	1999	2000
Qsw (W/sq m)	60.4	64.6
Qlw (W/sq m)	-43.9	-46.2
Rnet (W/sq m)	16.5	17.4
H (W/sqm)	-6.3	-6.6
LE (W/sqm)	-59.3	-37.0
B (W/sqm)	-49.2	-26.2

Time series of net short wave and net long wave fluxes for **the** period of Feb. to April are shown in Figures 8a and 8b respectively. It can be clearly seen that short wave budget steadily decrease from 85.77 Wm^{-2} in Feb to 41.94 Wm^{-2} in March and 10.64 Wm^{-2} in April with average values of 47.54 Wm^{-2} for the period of Feb to April. There is a decreasing trend in long wave budget. In Feb it was -52.32 W^{-2} decreased to -39.60 Wm^{-2} in March and -31.81 Wm^{-2} April with average value of -41.64 Wm^{-2} the period of Feb to April 2000.

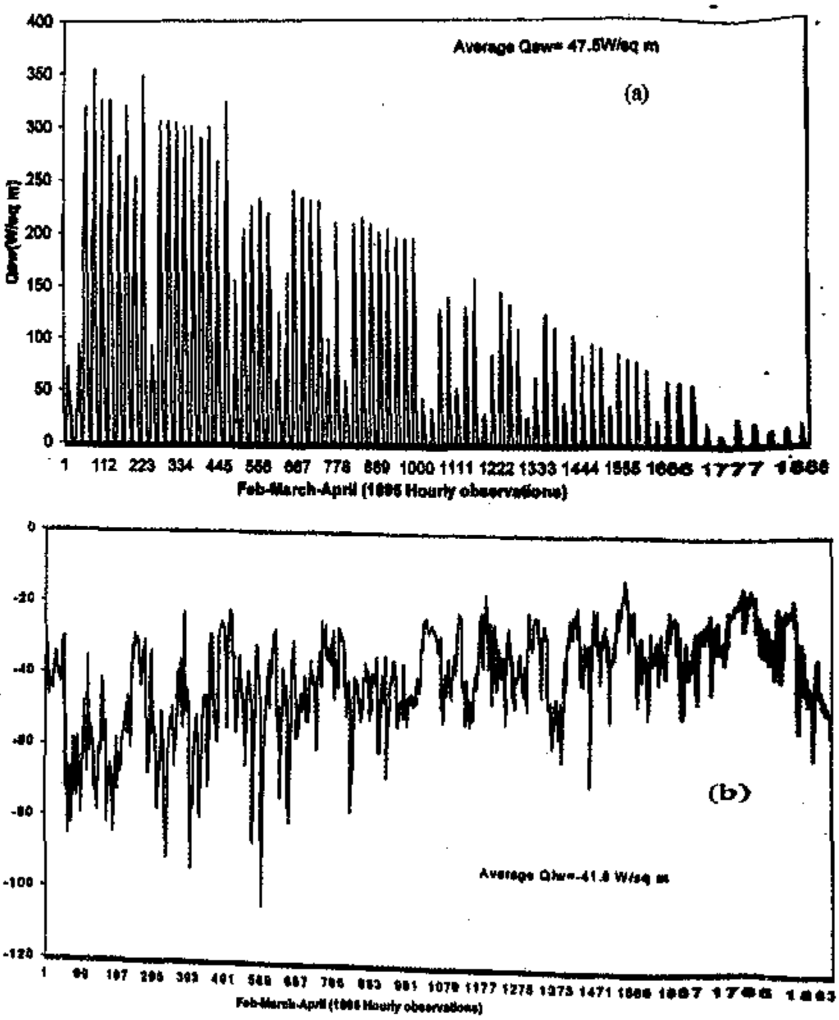
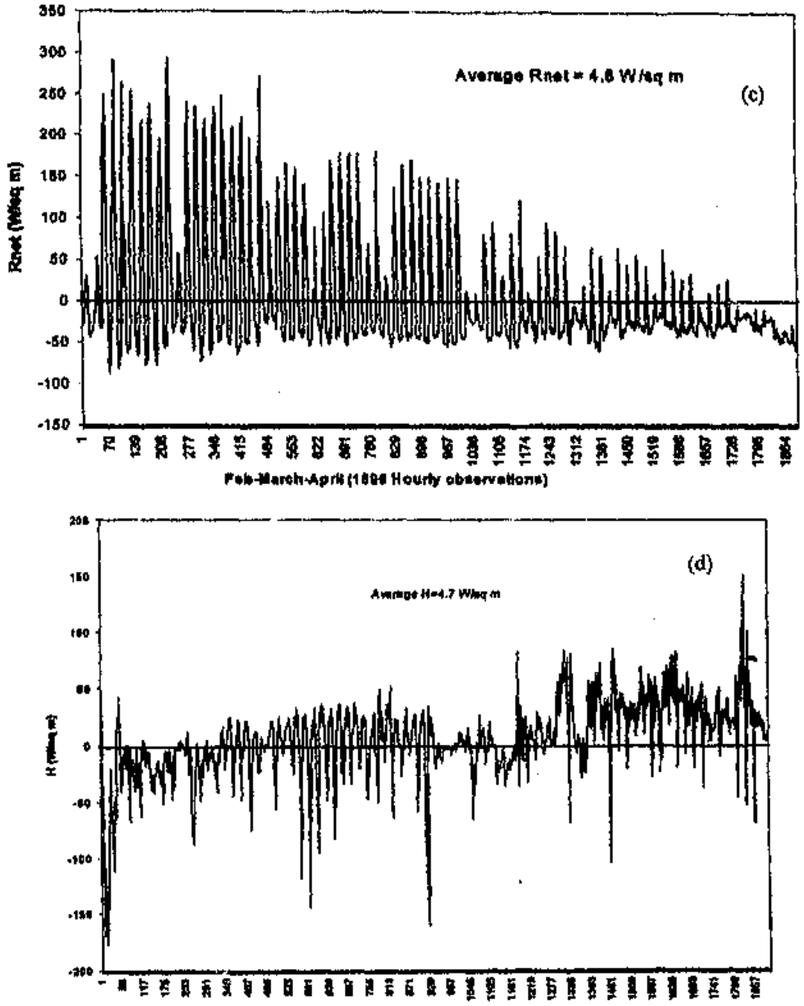


Fig 8: Time series of surface energy budget components-la) Net short wave radiation, (b) Net long wave radiation for the period of February, March and April 2000

The average net radiation was positive (flux towards the surface) during the late summer period and changes sign in the month of April. The time series of net radiation for the period of Feb to April is shown in Figure 8c. The average value for February was 32.66Wm^{-2}, it was reduced to 1.0 Wnr^{-2} in March and -22.92Wm^{-2} in April with the average value of 4.63Wm^{-2} for the period of Feb to April.

The sensible heat flux also changes sign and shows an increasing trend between seasons. The time series of heat flux for the period of Feb to April is shown in Figure 8d. In Feb average value was-13.84 Wm^{-2} (flux



Feb-March-April (1896 Hourly observation)

Fig. 8: Time series of surface energy budget components— (c) Net radiation, (d) Sensible heat flux for the period of February, March and April 2000

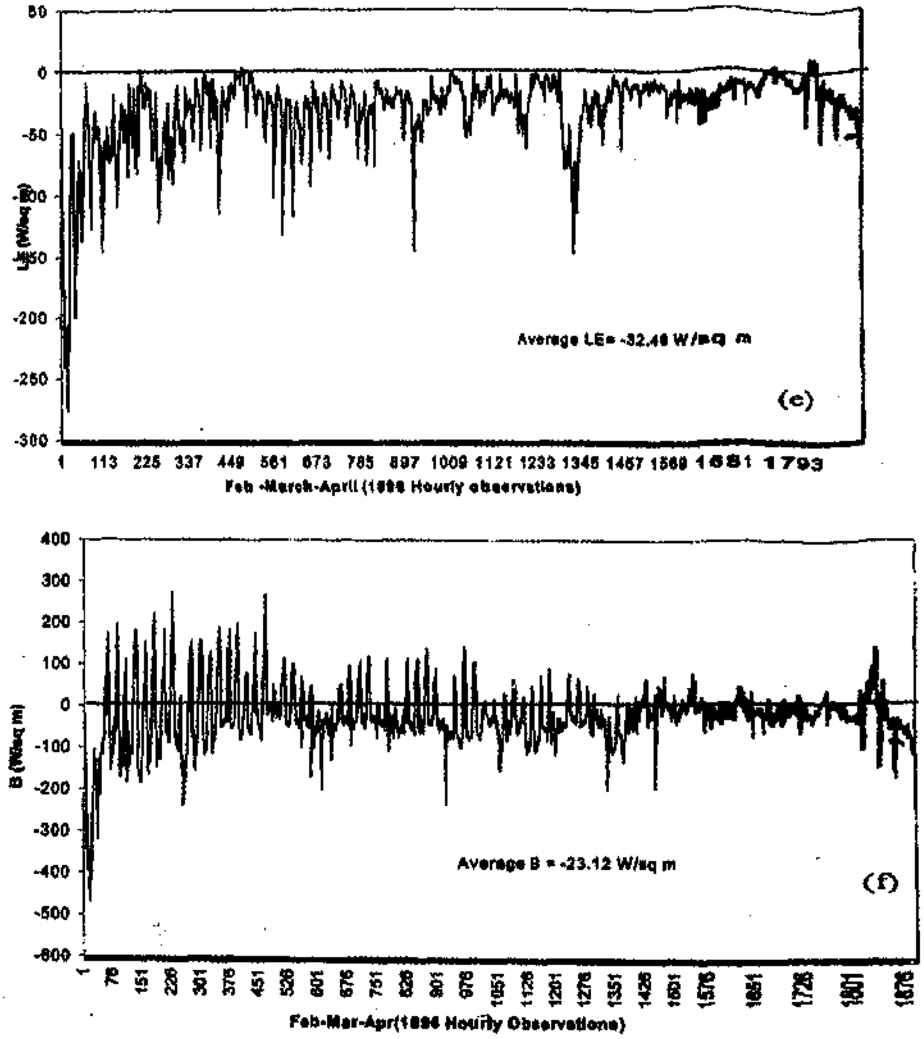


Fig. 8: Time series of surface energy budget components—(e) Latent heat flux, (f) Net surface energy budget for the period of February, March and April 2000

away from the surface) while in March it was slightly positive; 1.15 Wm^2 and increased to 29.20 Wm^{-2} (flux towards the surface) with the average value of 4.42 Wm^{-2} for the period of Feb to April. The plot show a large positive as well as negative fluctuations, still the average values were small compared to fluctuations. Larger surface heating causes a longer period of unstable stratification, which is indicated by a negative heat flux in February.

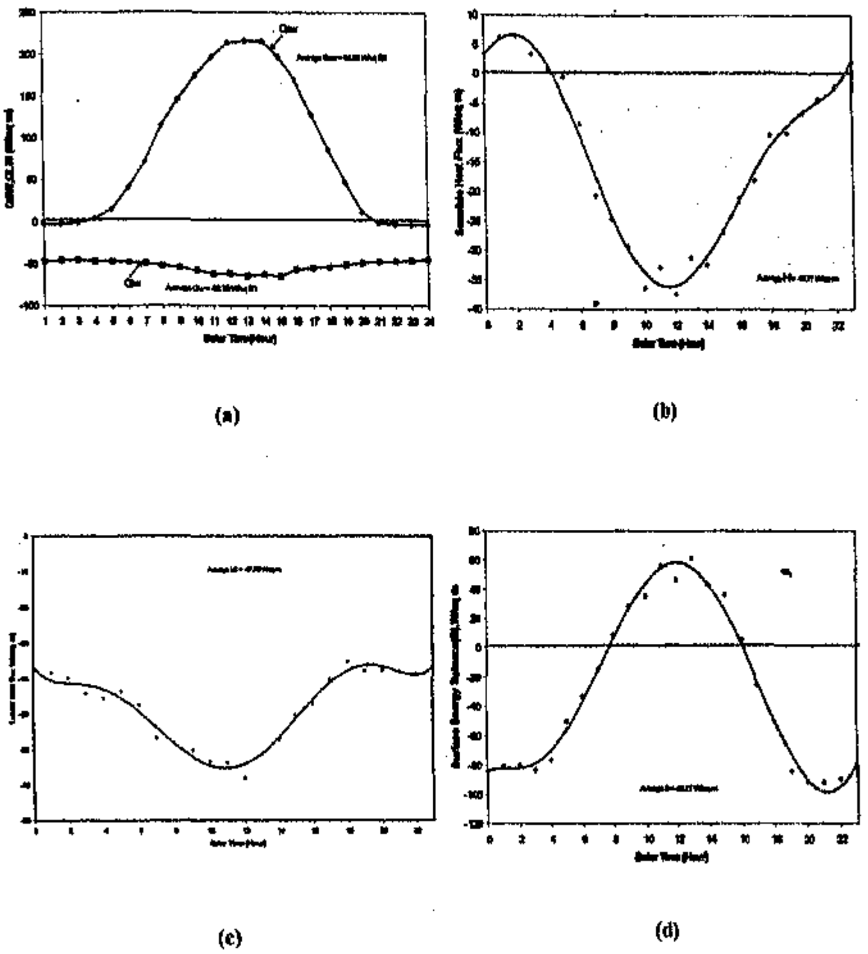


Fig 9: Mean daily cycle of ice cap surface energy balance components (a) Net short wave and net long wave, (b) Sensible heat flux, (c) Latent heat flux, and (d) Net surface energy balance for the month of Feb 2000

The surface gains latent heat when atmospheric water vapour condenses on it and loses heat when moisture evaporates from it. Process of sublimation/ evaporation was found to play an important role over blue ice in suppressing summer ablation/melting. Latent heat flux is one of the dominant components of the energy balance. The time series of latent heat flux for the period of Feb to April. Latent heat flux was found to be negative for the whole period (i.e. fluxes are away from the surface) with the average value of-32.48 Wm^{-2}.

The surface energy budget is the net flux into or out of the snow/ice surface. It might be used for phase change (melting or sublimation) or storage change (change of temperature of ice sheet or snow). The time series variation of the net surface energy budget is plotted in Figure 8f. The values are positive as well as negative with the average value of -23.12 Wm^{-2} for the period of Feb to April.

The mean daily variation in each of the energy balance component is large and can vary considerably. The average diurnal cycle of short wave and long wave radiation, sensible heat flux, latent heat flux and surface energy budget for the month of Feb 2000 over blue ice is plotted in Figure 9. The peak value of the short wave radiation is nearly 217 Wm^{-2} at 1300 hours and then drops to minimum at about 2000 hours. This is the driving force for the latent and sensible heat fluxes, which shows similar diurnal cycles. Latent heat varies from -35 to -70 Wm^{-2} with the greatest flux at solar noon when air temperature is greatest and therefore can drive the greatest vapour exchange. The surface energy budget was positive between 0800 hours to 1600 hours UTC i.e. surface was gaining energy between this period, for the remaining part of the day surface was loosing the energy continuously. The surface energy budget was found to fluctuate between 60 to -100W m^{-2}.

Acknowledgements

I would like to thank National Centre for Antarctic and Ocean Research (NCAOR) for providing the opportunity to participate in the expedition. I am grateful to the expedition Leader, Shri Arun Chaturvedi, and all members of 19th expedition for providing the logistic support and co-operation during the expedition. I also express my sincere gratitude to Maj. Gen. SS Sharma, KC VSM, (Retd.) Director SASE, Shri D.K. Prashar, Shri E.N. Sethi, Sh Ashwagosha Ganju, Dy. Directors, SASE and Sh. Praveen Srivastava, Scientist `C` for their kind encouragement and constant guidance during the course of project.