MAUSAM, **62**, 4 (October 2011), 557-566

551.521 : 551.511.62 (99)

# Comparative study of the radiative and turbulent energy fluxes during summer and winter at the edge of the Antarctic ice sheet in Dronning Maud Land - East Antarctica

H. S. GUSAIN, V. D. MISHRA and AVINASH NEGI

*Snow and Avalanche Study Establishment,*

*Research and Development Centre, DRDO, Chandigarh (U.T.) – 160036, India*

**e mail : gusain_hs@yahoo.co.in**

**सार** – इस शोध पत्र में पूर्वी एंटार्कटिका के ड्रॉनिंग मटलैंड में ग्रीष्म एवं शरद ऋतु के दौरान एंटार्कटिक पर जमी हुई बर्फ के किनारे पर अनुमानित विकिरणी एवं प्रक्षुब्ध ऊर्जा फ्लक्सों की तुलना की गई है। हिमनद (ग्लेशियर) की सतह पर लगे हुए स्वचालित मौसम स्टेशन (ए.डब्ल्यू.एस.) का उपयोग करके वर्ष 2007 में सर्दी के महीनों (मई, जून, जुलाई, अगस्त) तथा वर्ष 2007–08 में गर्मी के महीनों (नवम्बर, दिसम्बर, जनवरी और फरवरी) के दौरान बर्फ – मौसम विज्ञान प्राचलों को अभिलेखित किया गया और उनका विश्लेषण किया गया। बर्फ मौसम विज्ञान प्राचल अर्थात वायु तापमान, सापेक्षिक आर्द्रता, पवनगति, पवन दिशा, आगमी सौर विकिरण, निर्गमनी सौर विकिरण, वायुमंडलीय दाब और हिमनद सतह के तापमान ए.डब्ल्यू.एस. द्वारा अभिलेखित किए गए है। ग्रीष्म तथा सर्द ऋतु के दौरान अभिलेखित मौसम विज्ञान मात्रकों से सतह ऊर्जा फ्लक्सेस की गणना करने के लिए एक ऊर्जा संतुलन मॉडल का उपयोग किया गया है। ग्रीष्म ऋतु के दौरान मुख्य ऊष्मा स्रोत से कुल विकिरणी फ्लक्स प्राप्त किया गया है जिसका ऋतुनिष्ठ औसत 98 वाट प्रति मी.$^2$ है जबकि शरद ऋतु के दौरान मुख्य ऊष्मा स्रोत से संवेदी ऊष्मा फ्लक्स प्राप्त किया गया है जिसका ऋतुनिष्ठ औसत 30 वाट प्रति मी.$^2$ है। दोनो ही ऋतुओं में गुप्त ऊष्मा फ्लक्स में मुख्य ऊष्मा में कमी होती देखी गई है इसमे ग्रीष्म ऋतु में ऋतुनिष्ठ औसत –86.7 वाट प्रति मी.$^2$ और शरद ऋतु में –65.4 वाट प्रति मी.$^2$ देखा गया है। शरद ऋतु की अपेक्षा ग्रीष्म ऋतु में ऊर्ध्वपातन अधिक देखा गया है।

**ABSTRACT.** Present study compares the estimated radiative and turbulent energy fluxes at the edge of the Antarctic ice sheet during summer and winter in Dronning Maud land, East Antarctica. Hourly snow meteorological parameters were recorded and analysed during winter months (May, June, July and August) of the year 2007 and summer months (November, December, January and February) of the year 2007-08 using Automatic Weather Station (AWS) on the glacier surface. Snow-meteorological parameters air temperature, relative humidity, wind speed, wind direction, incoming solar radiation, outgoing solar radiation, atmospheric pressure and glacier surface temperature were recorded by the AWS. An energy balance model was used to evaluate the surface energy fluxes from measured meteorological quantities for the summer and winter. Net radiative flux was observed the main heat source during summer with seasonal average of 98Wm$^{-2}$ while sensible heat flux was observed main heat source during winter with seasonal average of 30 Wm$^{-2}$. Latent heat flux was observed the main heat sink during both the season with seasonal average values of -86.7 Wm$^{-2}$ for summer and -65.4 Wm$^{-2}$ during winter. Sublimation was observed high during summer compare to winter.

**Key words** – Turbulent energy flux, Radiative flux, Albedo, Latent heat, Solar radiation, Polar cryosphere.

## 1. Introduction

Snow and Avalanche Study Establishment (SASE) are contributing to the Indian Polar Research by taking up the scientific work on Antarctic ice sheet. SASE is continuously participating in the Indian Scientific Expedition to Antarctica (ISEA) since 25$^{th}$ expedition. Polar regions are very important to the climate of the Earth as most of the solar energy reflected back by these regions and only a small proportion of the energy is absorbed. The surface energy balance of the Polar Region is of great significance and small changes in the surface energy balance can lead to changes in the Polar cryosphere. The glacier surface energy balance is the study of net radiative flux, turbulent fluxes and sub-surface conductive heat flux at the glacier surface. These energy fluxes are directly related with the accumulation and ablation processes of the glacier. Quantification of these processes can provide the information about the health of the glacier. In the past researchers had studied

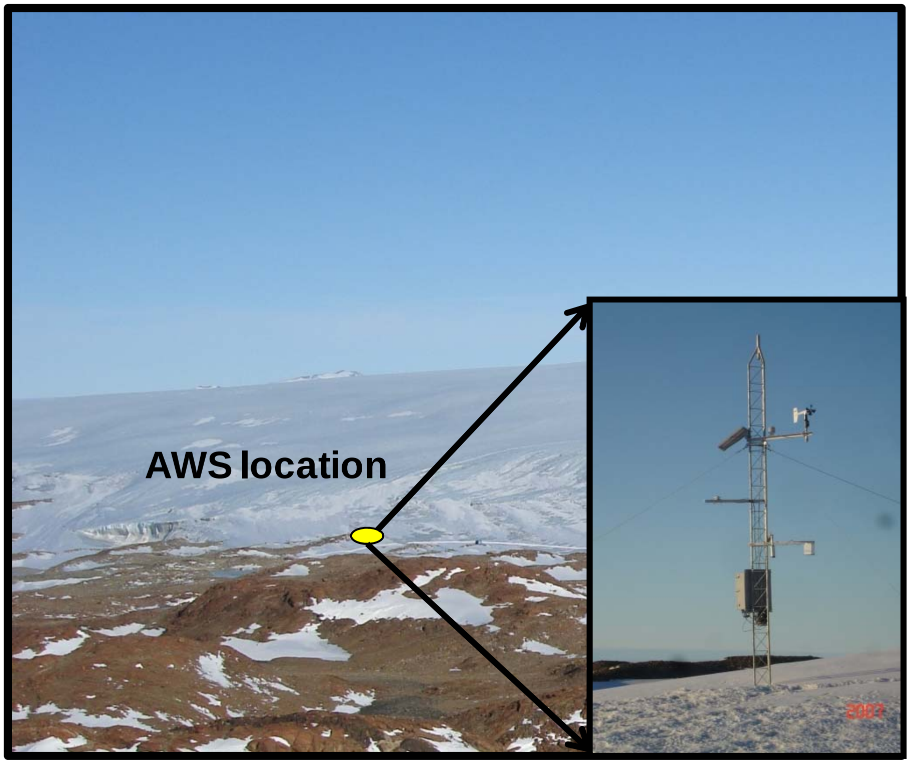


**Fig. 1.** Data observation site and automatic weather station

the surface energy balance of the Antarctic ice sheet in different parts of Antarctica during summer and winter period. Lewis *et al*. (1998) calculated surface energy balance to estimate sublimation and melt on the surface and terminus of Canada Glacier, Taylor Valley, Antarctica during the 1994-95 and 1995-96 austral summers. Christoph (1999) presented the energy balance estimates of the Antarctic Peninsula glaciers during the austral summer of 1994/95. Bintanja *et al.* (1997) presented the annual cycle of the surface energy balance of Antarctic blue ice area in Dronning Maud Land, Anatrctica. Bintanja (1999) also studied the glaciological, meteorological and climatological significance of Antarctic blue ice areas. Reijmer and Oerlemans (2002) studied the temporal and spatial variability of the surface energy balance in Dronning Maud Land, East Antarctica using the data of nine automatic weather stations. Van den Broeke *et al*. (2004) presented the 4 years near surface radiation balance along a traverse line in Dronning Maud Land, connecting the coastal ice shelf and the inland plateau in East Antarctica. Van Den Broeke *et al*. (2006) presented the summertime daily cycle of the Antarctic surface energy balance (SEB) and its sensitivity to cloud cover using data of four major Antarctic climate zones: the coastal ice shelf, the coastal and interior katabatic wind zone and the interior plateau. Hoffman *et al*. (2008) studied the surface energy balance and melt thresholds over 11 years at Taylor glacier, McMurdo Dry Valleys, Antarctica. Town and Walden (2009) presented the surface energy budget over the South Pole. Very few studies contributed in the past to the energy exchange processes of Antarctic ice sheet close to the Schirmacher oasis. Gusain *et al.* (2009) studied energy and mass balance at the edge of Antarctic ice sheet close to the non-glaciated area of Schirmacher oasis during summer period, while in the other study Gusain *et al.* (2008) presented the annual variability of the surface energy fluxes of Antarctic ice sheet approximately 8 km South of the Indian research station, Maitri. In the present study a comparison of the meteorology and surface energy fluxes of the ice sheet close to the Schirmacher oasis during summer and winter is presented.

## 2. Data and methodology

An Automatic Weather Station (AWS) of make Sutron was installed on the ice sheet at 70° 46′ 5.1″ S and 11° 42′ 12.2″ E, at an altitude of 142 m a.s.l., close to the

Schirmacher oasis (observation site shown in Fig. 1). The AWS was equipped with the following calibrated sensors.

(*i*) Wind direction and wind speed sensor (propeller vane type) of make RM YOUNG for measuring wind speed and direction. Sensor is capable of measuring wind speed in the range of 0-50 $ms^{-1}$ with an accuracy of $\pm$0.3 $ms^{-1}$ and gust survival of 60 $ms^1$. Sensor can measure wind direction with accuracy of ± 3 degrees and range 0-360 degrees.

(*ii*) AT/RH sensor to measure air temperature and relative humidity. It measures air temperature in the range of +50° C to –50° C with an accuracy of ± 0.3° C and relative humidity with an accuracy of ± 3% from 0% to 90% and ± 4% from 90% to 100%.

(*iii*) Pressure transducer located in the enclosure can measure atmospheric pressure from 400 hPa to 1100 hPa with an accuracy of 0.5 hPa.

(*iv*) Upward and downward looking pyranometers of make Kipp and Zonen measures incoming and outgoing radiation and measures short wave radiation in the wavelength range of 305 - 2800 nm with cosine error of ± 1% from 0 to 70° zenith and ± 3% from 70° to 80° zenith angle.

(*v*) IR-based snow surface temperature sensor measures snow surface temperature in the range of + 50° C to –50° C with an accuracy of ± 0.3° C.

The AWS records hourly observations of air temperature, relative humidity, wind speed, wind direction, incoming solar radiation, reflected solar radiation, atmospheric pressure and glacier surface temperature. The data was recorded for the winter and summer of the year 2007-2008. All the sensors of AWS were powered by 100 Ampere-Hour batteries, which were recharged by solar panel. Cloud amount and type were observed manually from conventional surface observations for each hour.

Radiative and turbulent energy fluxes at the glacier surface were estimated using the recorded meteorological parameters by AWS. The radiative component, incoming and reflected solar radiation are directly measured by the upward looking and downward looking pyranometer mounted in AWS, while incoming and outgoing longwave radiation at the glacier surface are estimated using a model developed by Prata (1996), US Army Corps of Engrs (1956) and Stefan Boltzmann Law. Net radiative flux in the model is computed by the following equation:

$$R_{net} = \mathrm{SHW}\downarrow(1-\alpha)+\left(\varepsilon_m \sigma T_a^4 - \varepsilon_s \sigma T_s^4\right)(1-\mathrm{K}N) \qquad (1)$$

Where, SHW↓ is incoming shortwave radiation, α is albedo of the glacier surface, $\varepsilon_m$ is emissivity of the atmosphere, σ is Stefan Boltzmann constant, $T_a$ is absolute temperature measured approximately at 2.0 m height above surface, $\varepsilon_s$ is glacier surface emissivity, $T_s$ is absolute temperature of the glacier surface, $N$ is the amount of cloudiness in terms of fraction of sky covered and K is the coefficient and depends on type and height of the clouds.

Sensible heat flux and latent heat flux are the turbulent energy fluxes. The vertical turbulent sensible heat flux is expressed in terms of wind speed and temperature (Ambach & Kirchlechmer, 1986 and Paterson, 1994) as follows:

$$\mathrm{SHF} = \left(\frac{\mathrm{C_p}\rho_0}{\mathrm{P_0}}\right)\mathrm{K_n}\mathrm{P}u(T_a - T_s) \qquad (2)$$

$$\mathrm{K_n} = \mathrm{k}^2 / \left[\log\left(\frac{\mathrm{z_a}}{\mathrm{z_0}}\right)\right]^2 \qquad (3)$$

Where $\rho_0$ is the density of air (1.29 $kgm^{-3}$) at the standard atmospheric pressure $P_0$ ($1.013 \times 10^5$ Pa), $K_n$ is a dimensionless transfer coefficient, P is the mean atmospheric pressure (Pa) at measuring site, $u$ and $T_a$ are the measured wind speed ($ms^{-1}$) and air temperature (K) at a height of 2 m above the glacier surface respectively. k is von Karman's constant (0.41), $z_a$ is the sensor height above ground (2 m) and $z_0$ is aerodynamic roughness length.

Latent heat flux is an important component of the surface energy budget and carried by turbulent transport in the atmospheric boundary layer. By analogy with the sensible heat flux, the latent heat flux is given by:

$$\mathrm{LHF} = \mathrm{L_v}\left(0.623\frac{\rho_0}{\mathrm{p_0}}\right)K_n u(\mathrm{e_a} - \mathrm{e_s}) \qquad (4)$$

Where $L_v$ is the latent heat of vaporization, $e_a$ is the vapour pressure at height z above glacier surface and $e_s$ is the saturation vapour pressure at the glacier surface. Later is a function of the surface temperature and is 611 Pa for a melting surface (Paterson, 1994). Ambach & Kirchlechner

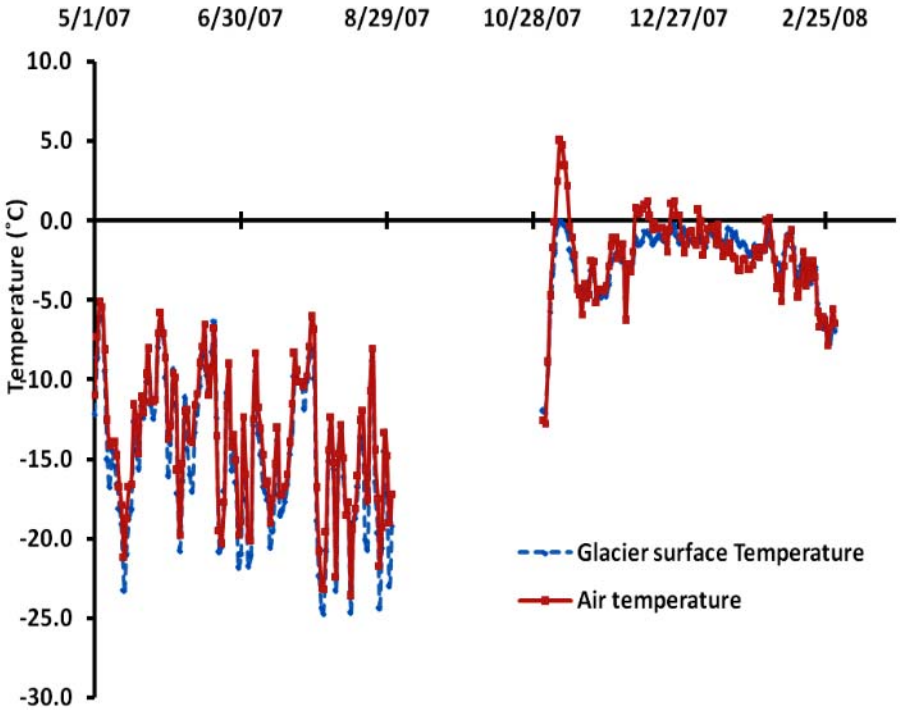


**Fig. 2.** Daily mean air temperature and glacier surface temperature

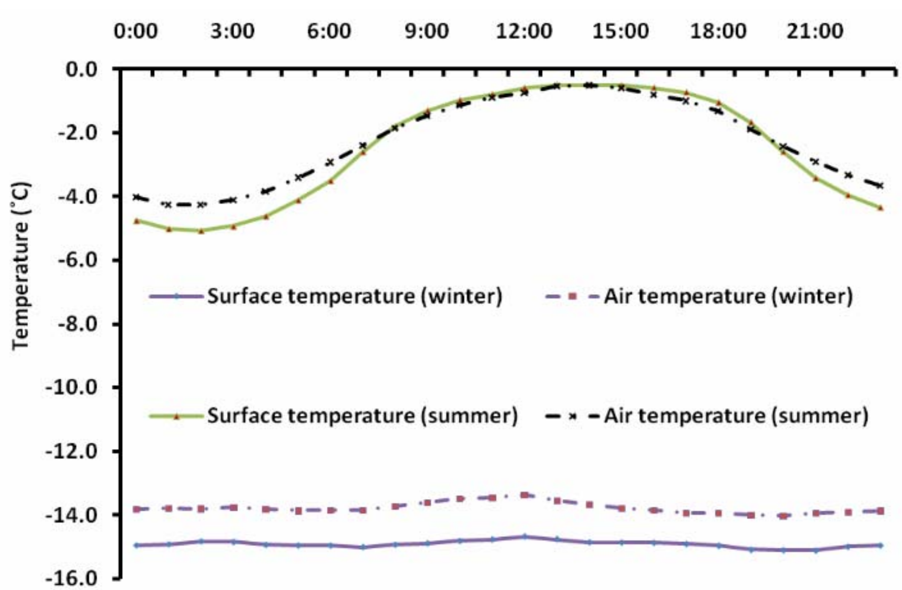


**Fig. 3.** Diurnal variation of glacier surface temperature and air temperature during summer and winter season

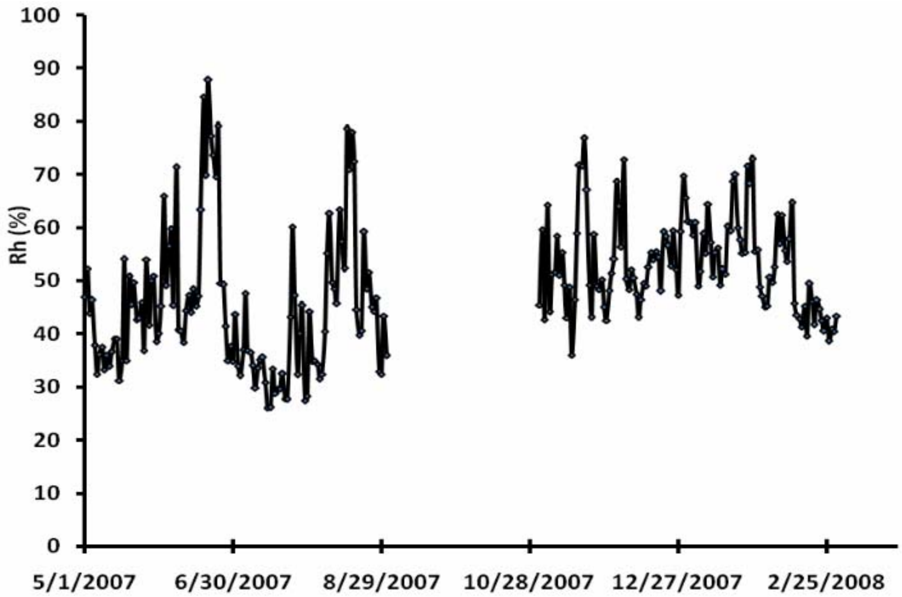


**Fig. 4.** Daily averaged relative humidity during winter and summer

(1986), and & Konzelmann (1994), has been followed for distinguishing the sublimation and condensation *e.g.*, when ($e_a$ - $e_s$) is positive, and $T_s$ = 0°, water vapour condenses as liquid water on the melting glacier surface with $L_v$ = 2.514 MJkg$^{-1}$, when ($e_a$ - $e_s$) is negative, there is sublimation with $L_v$= 2.849 MJkg$^{-1}$. Also, when ($e_a$ - $e_s$) is positive and $T_0$ < 0 deg, there is deposition from vapour to solid ice with $L_v$ =2.849 MJkg$^{-1}$.

The equations of sensible and latent heat fluxes are applicable for neutral atmospheric conditions. In Antarctica the atmospheric conditions above ice sheet are rarely neutral and so the equations can be applied with stability corrections for the transfer coefficient $K_n$ in terms of bulk Richardson number ( $R_i$ ). For unstable conditions ( $R_i$ <0) transfer coefficient is given by $Kw2 = K_n(1-10R_i)$. For $R_i$ = 0, $Kw2 = K_n$ ; and for stable conditions ( $R_i$ >0), $Kw2 = K_n(1+10R_i)$ (Price and Dunne, 1976).

## 3. Results and discussion

A contrast was observed in the summer and winter meteorological condition of the ice sheet at the observation point. Daily mean air temperature and glacier surface temperature are shown in Fig. 2. Daily mean air temperature varied from -5° C to -24° C during winter with seasonal average of -13.8°C while during summer, daily mean air temperature varied from -13° C to 5° C with seasonal mean of -2.2° C. The reason for the temperature contrast is obvious as the average sun shine hours during winter is nil while during summer it is more than 12 hours. The daily average glacier surface temperature during winter was as low as -25° C and the seasonal average was observed -14.9° C. Fig. 3 shows the diurnal variation of glacier surface temperature and air temperature during the summer and winter. During winter season the diurnal variation in the glacier surface temperature and air temperature are not much observed and the temperature are almost constant and very low compared to the summer. During summer, diurnal variation observed in the glacier surface and air temperature due to absorption of shortwave radiation. The temperatures are comparatively higher during 0800 hours to 2000 hours as solar radiation is maximum during these hours. During these hours the surface temperature is close to air temperature.

Daily averaged relative humidity (RH) during summer was observed between 36% & 77% with seasonal average of 53% while daily averaged relative humidity during winter was observed between 26% & 88% with mean seasonal value of 45%. Daily averaged relative humidity during summer and winter is shown in Fig. 4. July was observed the least humid month with monthly mean relative humidity of 36%. The wind speed was observed high during winter compare to summer. Daily mean wind speed was observed between 2.6 ms$^{-1}$ &

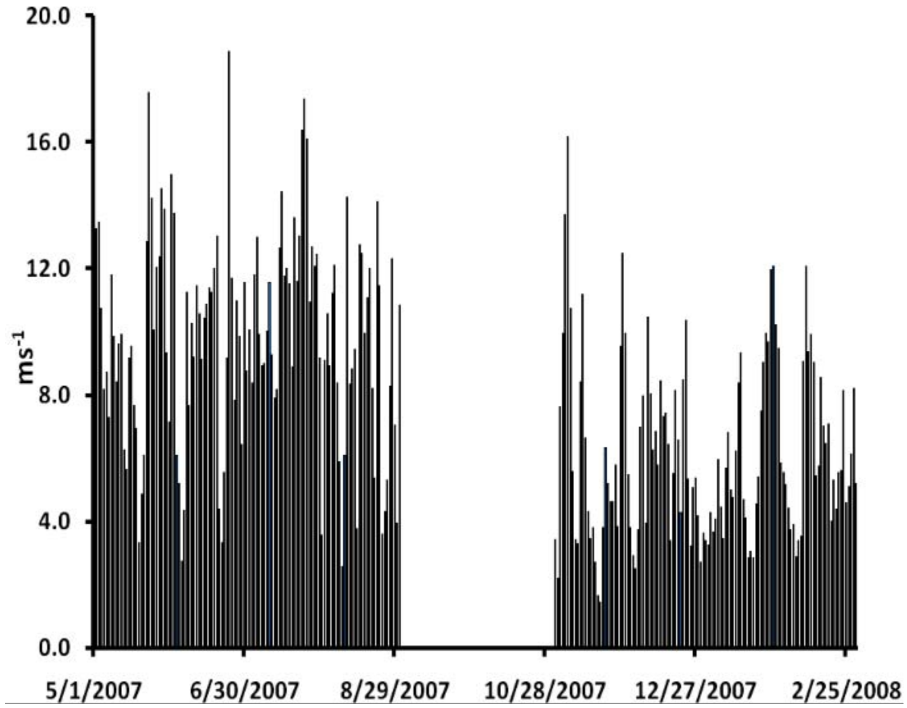


**Fig. 5.** Daily averaged wind speed during winter and summer

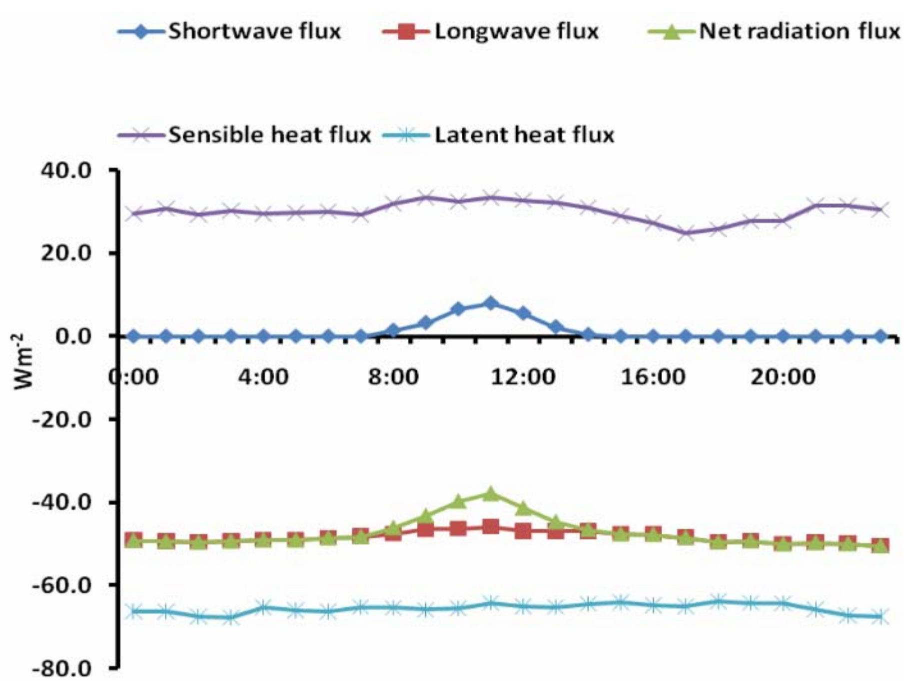


**Fig. 6.** Diurnal variation of the radiative and turbulent fluxes during winter

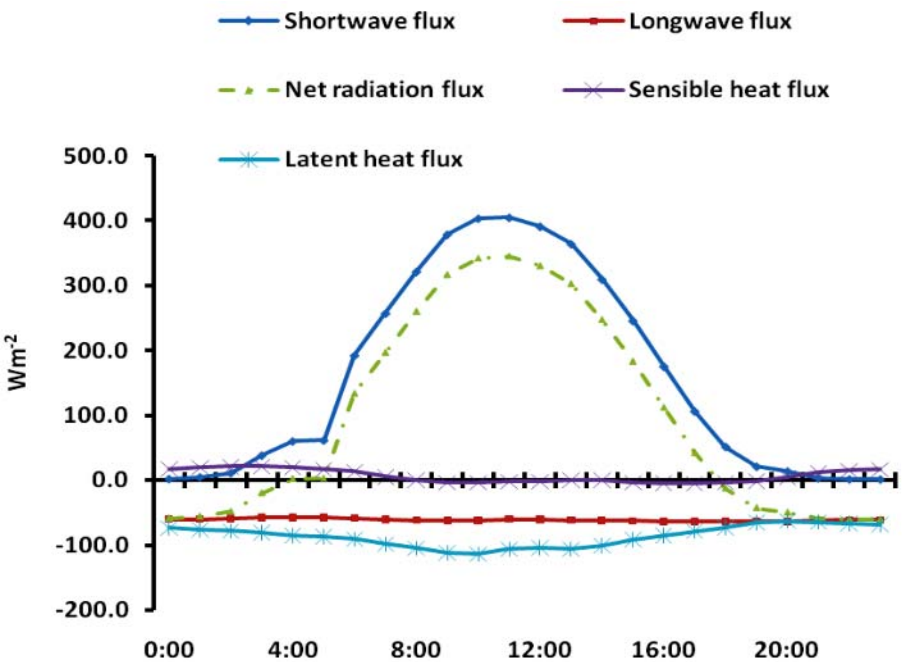


**Fig. 7.** Diurnal variation of the radiative and turbulent fluxes during summer

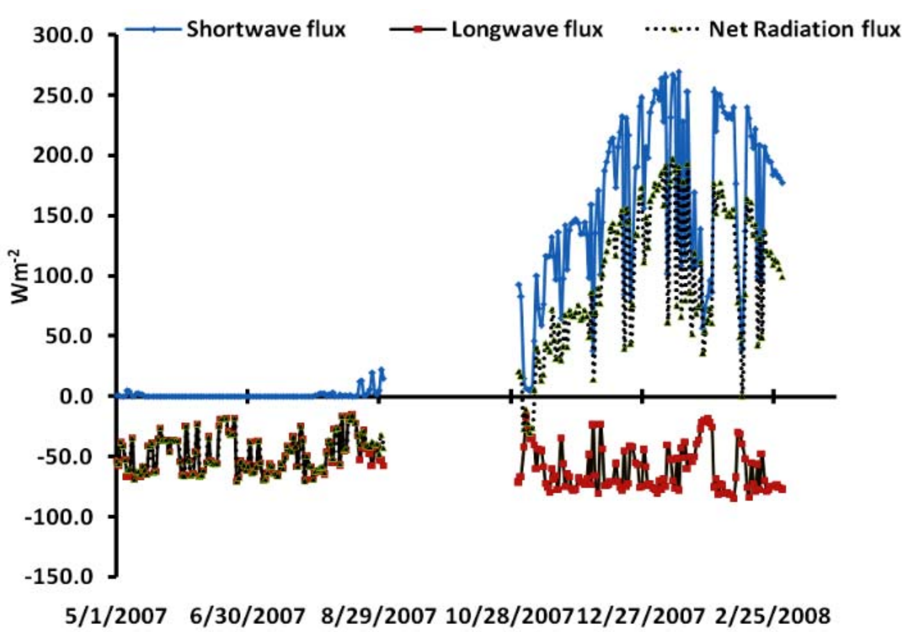


**Fig. 8.** Daily averaged radiative fluxes during winter and summer

18.9 ms$^{-1}$ during winter with seasonal average of 9.8 ms$^{-1}$ while during summer the seasonal average was observed 6.2 ms$^{-1}$ (Fig. 5). June and July were observed the months with highest wind with monthly mean of 10 ms$^{-1}$ and 11.4 ms$^{-1}$ respectively. Most of the days of the summer and winter season were observed partly cloudy to cloudy. Winter season were observed cloudier with average cloud amount of 4.1 octa compared to summer season with cloud amount of 3.3 octa.

Large temporal variability was observed in the short wave radiation. During winter months May, June and July,

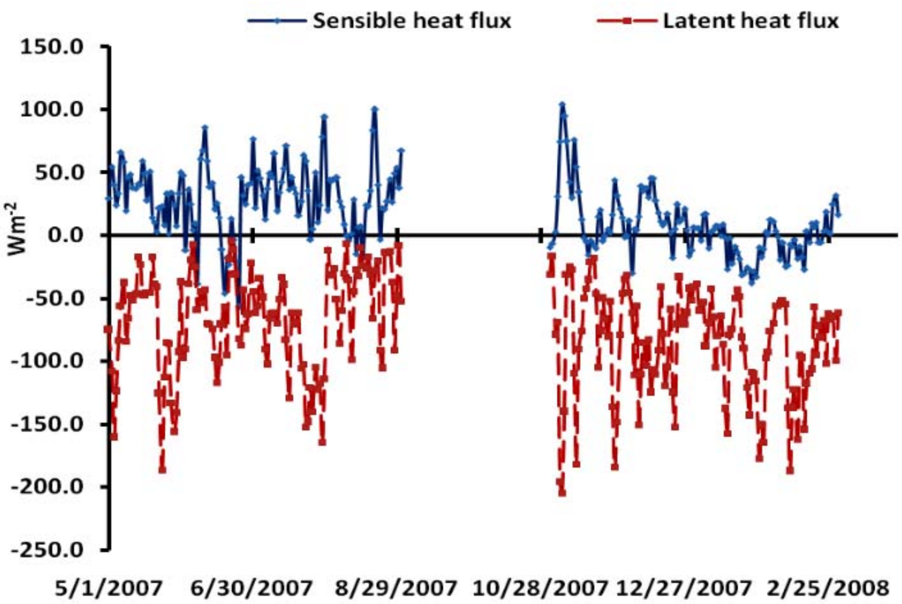


**Fig. 9.** Daily averaged turbulent fluxes during winter and summer

no shortwave radiation received by the glacier surface as solar disc remain below horizon. August onwards the glacier surface starts receiving shortwave radiation from the Sun as the solar disc appear above horizon and shortwave radiation gradually increases with increasing sun shine hours. Mean seasonal incoming short wave radiation were 2.7 Wm$^{-2}$ during winter season with main contribution from the month of August. Mean daily incoming solar radiation reaches to 432 Wm$^{-2}$ during peak summer. Summer averaged incoming shortwave radiation was observed 291Wm$^{-2}$ and outgoing shortwave radiation was observed 129 Wm$^{-2}$.

Albedo of the glacier surface also varied as the surface conditions varied from snow free to snow covered after blizzards and again snow free after melting of snow during summer period. Average albedo of the glacier surface was observed 0.45 for the summer season. The glacier surface condition determine the amount of short wave radiation actually absorbed at the glacier surface and played a crucial role in energy balance of the glacier.

A large difference was observed between summer average (159 Wm$^{-2}$) and winter average (1.2 Wm$^{-2}$) net shortwave radiation. Net shortwave radiation was observed the main source of energy for the glacier surface during summer and daily averaged value varied up to 269 Wm$^{-2}$. During winter the diurnal shortwave radiation cycle shows that the radiation was above zero between the 0800 hours to 1400 hours (mainly during August month) and nil for the rest of the hours while for summer the shortwave radiation was above zero between 0100 hours to 2100 hours showing long radiation period (Figs. 6 & 7). Maximum radiation was observed between 0900 hours to 1300 hours of the diurnal cycle during summer. Daily averaged net long wave radiation varied from -16 Wm$^{-2}$ to -85 Wm$^{-2}$ during summer with seasonal mean of -61 Wm$^{-2}$ while during winter daily averaged net long wave radiation varied from -16 Wm$^{-2}$ to -70 Wm$^{-2}$ (Fig. 8) with seasonal mean of -48 Wm$^{-2}$. It was observed that glacier surface loses more energy in the form of long wave radiation during summer compared to winter as the surface temperature is high during summer. Long wave radiation flux was observed as one of the major heat sink for the glacier surface during both the season. Daily averaged net radiation flux varied from -70 Wm$^{-2}$ to -16 Wm$^{-2}$ during winter and -30 Wm$^{-2}$ to 197 Wm$^{-2}$ during summer. Mean net radiation flux was observed negative during winter and positive during summer with seasonal mean values of -47 Wm$^{-2}$ and 98 Wm$^{-2}$.

Sensible heat flux was the main heat source to the glacier during winter with mean seasonal value of 30 Wm$^{-2}$ and daily averaged value varied between -56 Wm$^{-2}$ & 101 Wm$^{-2}$. During summer daily averaged sensible heat flux varied from -38 Wm$^{-2}$ to 104 Wm$^{-2}$ (Fig. 9) with seasonal average value of 6.5 Wm$^{-2}$. During winter months sensible heat flux was observed higher compared to summer months as the glacier surface temperature was observed quite low compared to air temperature throughout winter. During summer period, glacier surface temperature also observed higher compared to air above during day hours after absorption of sufficient short wave radiation, so glacier surface loses energy and sensible heat flows from surface to air for those hours. In the seasonal diurnal variation, the sensible heat flux was observed low between the hours 0800 hours to 2000 hours during summer. Latent heat flux was observed the main heat sink for the glacier surface during summer and winter. Daily averaged latent heat flux varied from -4.3 $Wm^{-2}$ to -186 $Wm^{-2}$ during winter with seasonal average of -65 $Wm^{-2}$ while it varied from -24 $Wm^{-2}$ to -205 $Wm^{-2}$ with the seasonal mean of -86.7 $Wm^{-2}$ during summer (Fig. 9). High latent heat flux during summer compared to winter indicates high sublimation rate of ice sheet in summer at the observation location.

## 4. Conclusions

Present study reported on meteorological conditions, radiative and turbulent energy fluxes during summer and winter at the edge of the Antarctic ice sheet close to Schirmacher oasis in Dronning Maud land, East Antarctica. Mean air temperature was observed -2.2° C during summer and -14.9° C during winter, mean relative humidity 53 % during summer and 45% during winter and mean wind speed 6.2 m/s during summer and 9.8 m/s during winter at the observation site. Net radiative flux was the main heat source for the glacier during summer with 98 $Wm^{-2}$ seasonal average and drive the summer melting. Large temperature difference between air and glacier surface during winter season leads to higher sensible heat flux in winter. High latent heat flux during summer indicates high rate of sublimation compared to winter at the observation site.

*Acknowledgements*

Authors are thankful to Shri Ashwagosha Ganju, Director, Snow and Avalanche Study Establishment (SASE) for providing encouragement and extensive support to the Antarctic study. Authors are grateful to National Centre for Antarctic and Ocean Research (NCAOR), Goa, for logistic support in Antarctica. We express our sincere thanks to all the members of Antarctic expedition from SASE for their sincere efforts in data collection in Antarctica.

**References**

Ambach, W. and Kirchlechner, P., 1986 "Nomographs for the determination of meltwater from ice and snow surfaces by sensible and latent heat", *Wetter Leben*, **38**, 4, 181-189.

Bintanja, R., Jonsson, S. and Knap, W. H., 1997, "The annual cycle of the surface energy balance of Antarctic blue ice", *J. Geophys. Res.,* **102** (D2), 1867-1881, doi:10.1029/96JD01801.

Bintanja, R., 1999, "On the glaciological, meteorological, and climatological significance of Antarctic blue ice areas", *Reviews of Geophysics*, **37**, 337-359.

Christoph, S., 1999, "Energy balance estimates during the summer season of glaciers of the Antarctic Peninsula", *Global and Planetary Change*, **22**, 117-130.

Gusain, H. S., Singh, K. K., Mishra, V. D., Srivastava, P. K. and Ganju, A., 2009, "Study of surface energy and mass balance at the edge of the Antarctic ice sheet during summer in Dronning Maudland, East Antarctica", *Antarctic Science*, **21**, 4, 401-409, doi:10.1017/S0954102009001989.

Gusain, H. S., Negi, H. S. and Kumar, M., 2008, "Temporal variability of the snow meteorological parameters over Antarctic continental ice sheet and estimation of surface energy budget, in Dronning Maud Land, East Antarctica", *Proceedings International workshop on Snow, Ice, Glacier and Avalanches*, IIT Mumbai, India, 95-107.

Greuell, W. and Konzelmann, T., 1994, "Numerical modelling of the energy balance and the englacial temperature of the Greenland ice sheet", Calculation for the ETH-camplocation (West Greenland, 1155 m a.s.l.), *Global and Planetary Change*, **9**, 91-114.

Hoffman, M. J., Fountain, Andrew G. and Liston Glen E., 2008, "Surface energy balance and melt thresholds over 11 years at Taylor Glacier, Antarctica", *J. Geophys. Res.*, **113**, F04014, doi: 10.1029/2008JF001029.

Lewis, K. J., Andrew, G. F. and Gayle, L. D., 1998, "Surface energy balance and meltwater production for a Dry Valley glacier, Taylor Valley, Antarctica", *Annals of Glaciology*, **27**, 603-609.

Paterson, W. S. B., "*The Physics of Glaciers*", Third Edition, Oxford etc., Elsevier, 1994.

Prata, A. J., 1996, "A new long wave formula for estimating downward clear-sky radiation at the surface", *Q.J.R. Meteorol. Soc*., **122**, 1127-1151.

Price, A. G. and Dunne, T., 1976, "Energy balance computation of snowmelt in a Sub Arctic Area", *Water Resource Research*, **12**, 4, 686-694.

Reijmer, C. H. and Oerlemans, J., 2002, "Temporal and spatial variability of the surface energy balance in Dronning Maud Land, East Antarctica", *J. Geophys. Res.,* **107**(D24), 4759, doi:10.1029/2000JD000110.

Town, M. S. and Walden, V. P., 2009, "Surface energy budget over the South Pole and turbulent heat fluxes as a function of an empirical bulk Richardson number", *J. Geophys. Res.*, **114**, D22107, doi:10.1029/2009JD011888.

U. S. Army Corps of Engineers, 1956, "Snow Hydrology, Summary report on the snow investigations", North Pacific Division, Corps of Engg., Portland, Oregaon.

Van den Broeke, M., Reijmer, C. and van de Wal, R., 2004, "Surface radiation balance in Antarctica as measured with automatic weather stations", *J. Geophys. Res*., **109**, D09103, doi:10.1029/ 2003JD004394.

Van den Broeke, M., Reijmer, C., Van As, Dirk. and Wim, B., 2006, "Daily cycle of the surface energy balance in Antarctica and the influence of clouds", *International Journal of Climatology*, Published online in Wiley Inter Science (www.interscience. wiley.com). DOI: 10.1002/joc.1323.