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Research Paper

Six Years Observations ond Analysis of Radiation Parameters and Surface Energy Fluxes on Ice Sheet Near 'Maitri' Research Station, East Antarctica

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In the present study, radiation parameters incoming shortwave radiation flux, reflected shortwave radiation flux, albedo have been observed on ice sheet near 'Maitri' research station, East Antarctica. Surface energy fluxes have been estimated using snow-meteorological parameters. Air temperature, surface temperature, relative humidity, wind speed, atmospheric pressure, incoming shortwave radiation flux, reflected shortwave radiation flux, albedo were recorded using automatic weather station installed on ice sheet about 1 km from 'Maitri' research station. Radiation parameters and energy fluxes were obtained for six years from March 2007 to January 2013. Mean incoming shortwave radiation flux, reflected shortwave radiation flux and albedo were observed to be 124 Wm^{-2}, 80 Wm^{-2} and 0.64, respectively, during six years. Daily average air temperature at the observation site varies from 4.6°C to –28.6°C with six years mean of –10.2°C. High katabatic winds are observed at the site with six years mean wind speed of 8.4 ms^{-1}. Net shortwave radiation flux and sensible heat flux were observed to be heat source for the ice sheet with mean values of 44 Wm^{-2} and 28 Wm^{-2}, respectively, while net long wave radiation flux and latent heat flux were observed as heat sink with mean values of –49 Wm^{-2} and –62 Wm^{-2}, respectively. Sublimation of the ice sheet at the rate of 0.017 cm/day has been observed. Results of the present study were also compared with other studies in Antarctica. It has been observed that present study site near 'Maitri' research station has comparatively warmer temperatures, low relative humidity, high wind speed and low albedo compared to other coastal stations in Antarctica. High sublimation rate of the ice sheet at the present study location may attribute to high katabatic winds and warmer temperatures.

Keywords: Radiation Flux; Cryosphere; Transfer Coefficient; Katabatic Winds; Diurnal Variation

Introduction

Solar radiation is the driving force for weather and climate on planet Earth. Absorption, reflection, scattering, evaporation, sublimation, melt, freezing, condensation and other physical phenomena at the earth's surface drives the interaction between earth's surface and atmosphere. These physical processes exchange energy between earth's surface and atmosphere above. The surface energy balance is an essential element of the climate in any region of the world. It has an added significance in the snow/ice covered cryospheric regions, as small changes can affect cryospheric regions largely. In order to study the long term effect of the climate on the snow/ice fields, it is important to understand the variability of radiation parameters and different surface energy fluxes on temporal and spatial scales. The components of the surface energy fluxes are net shortwave radiation flux, net longwave radiation flux, sensible heat flux, latent heat flux and sub-surface conductive heat flux (Paterson 1994, Vihma 2011). These energy fluxes at the surface determine the ablation and accumulation processes (Lewis *et al.*, 1998). Quantification of these fluxes can contribute to better understanding of the mass exchange at the surface and subsequently the health of the glacier/ice sheet (Gusain *et al.*, 2009). Incoming and reflected shortwave radiation fluxes, down welling and upwelling longwave radiation fluxes are components

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of the radiative energy flux (King and Turner 1997) while sensible and latent heat fluxes are turbulent energy fluxes.

Many studies have been conducted all over the globe on estimation of surface energy fluxes of snow cover (Gustafsson *et al*., 2001; Fierz *et al*., 2003; Datt *et al*., 2008), glaciers (Wagnon *et al*., 2003; Giesen *et al*., 2008; Sicart *et al*., 2008; Azam *et al*., 2014), ice sheet (Reijmer and Oerlemans 2002; Van den Broeke *et al*., 2004a; Van As *et al*., 2005; Town and Walden 2009; Gusain *et al*., 2011), sea ice (Vihma *et al*., 2009) and lake ice (Doran *et al*., 1996) using *in situ* observations. Different components of surface energy flux differ in contribution to the net surface energy balance. The relative contribution of these energy fluxes strongly depends on the prevailing meteorological, topographical and surface conditions. Radiative energy fluxes are generally observed directly using pyranometers or pyrgeometers. A few parametrization schemes (Berliand 1960, Laevastu 1960, Zillman 1972, Maykut and Church 1973, Brutsaert 1975, Jacobs 1978, Moritz 1978, Marks and Dozier 1979, Dozier 1980, Idso 1981, Bennett 1982, Iqbal 1983, Plüssand Ohmura 1996, Prata 1996, Dilley and O'Brien 1998,Niemelä 2001a, 2001b) are also in vogue to estimate different radiative energy fluxes using *in situ* meteorological observations. Turbulent energy fluxes can be measured directly using eddy covariance system or scintillometers. However, in most of the studies, these energy fluxes have been estimated using bulk transfer technique (Oke 1970, Moore 1983; Schneider 1999; Wagnon *et al*., 2003; Munneke *et al*., 2009; Gusain *et al*., 2014; Azam *et al*., 2014). Bulk transfer equations use meteorological variables over the surface and at screen level height above the surface as input to estimate turbulent energy fluxes (Deardorff, 1968; Oke, 1970; Moore, 1983). Contribution of sub surface heat flux in net energy balance is generally very low compared to radiative and turbulent energy fluxes and can be estimated using temperature measurements at different vertical levels inside the snowpack or ice. Sub-surface heat flux can also be measured directly using heat flux sensors placed inside snow/ice. Present study focuses on estimation of long term surface energy fluxes of the ice sheet near 'Maitri' research station and analyses the temporal variation of energy fluxes during different months of the year.

Study Area and Data

'Maitri' research station is situated in Schirmacher oasis which lies between the latitude S 70º44′ to 70º46′ and longitude E 11º24′ to 11º54′. Schirmacher oasis is located about 70Km inland from Prinsesse Astrid Kyst in Dronning Maud Land, East Antarctica. Continental ice sheet south of Schirmacher oasis is known as Schirmacher glacier. An automatic weather station (AWS) of make Sutron was installed on ice sheet at 70º46′05.1″S, 11º42′12.2″E, at an altitude of 142m. AWS site is about 1 km from 'Maitri' station. Figure1 shows the location of 'Maitri' research station in East Antarctica and automatic weather station installed on ice sheet. Automatic weather station was equipped with the following calibrated sensors:

1. AT/Rh sensor to measure air temperature and relative humidity. It measures air temperature in the range of +50ºC to –50ºC with an accuracy of ±0.3ºC and relative humidity with an accuracy of ±3% from 0% to 90% and ±4% from 90% to 100%.
2. Wind speed and wind direction 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 ±0.3 ms^{-1} and gust survival of 60 ms^{-1}. Sensor can measure wind direction with accuracy of ±3 degrees and range 360 degrees.
3. Pressure transducer located in the enclosure can measure atmospheric pressure from 400mb to 1100mb with an accuracy of 0.5 mb.
4. Upward and downward looking pyranometers of make Kipp and Zonen measures incoming and outgoing shortwave radiation in the wavelength range of 305-2800nm with cosine error of ±1% from 0 to 70º zenith and ±3% from 70º to 80º zenith angle.
5. IR-based snow surface temperature sensor measures snow surface temperature in the range of +50ºC to –50ºC with an accuracy of ±0.3ºC.

The automatic weather station record hourly observations of air temperature, relative humidity, wind speed and direction, incoming and reflected shortwave radiation, atmospheric pressure and snow

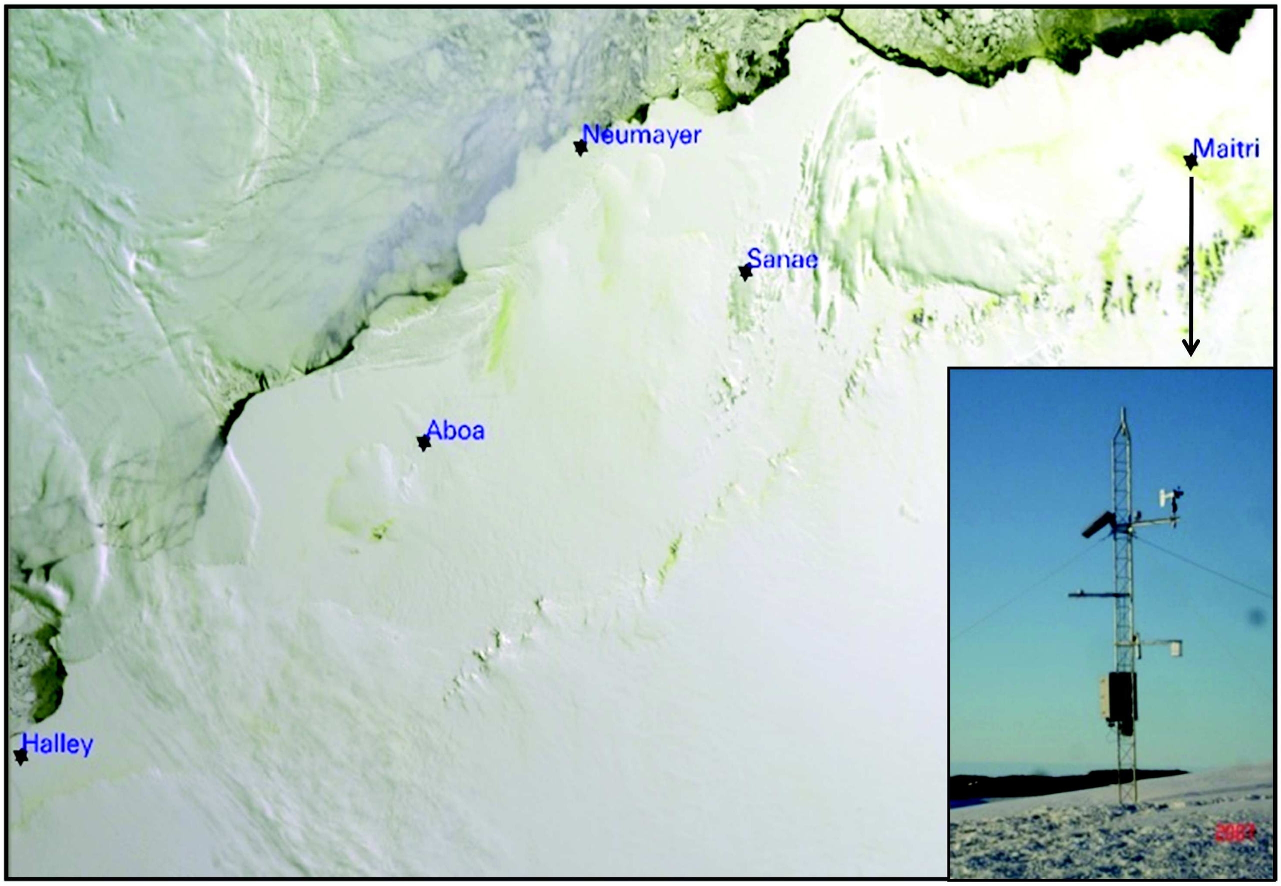

Fig. 1: Study area near 'Maitri' research station

surface temperature. All the sensors of AWS were powered by 100 Ampere-Hour battery and recharged from solar panel. Calibrated heat flux plates were also used to measure sub surface heat flux during summer period. Cloud amount and type had been observed conventionally at 'Maitri' research station.

Methodology

Detailed methodology of estimation of surface energy fluxes are given in Gusain *et al*. (2009) and Gusain *et al*. (2014) and summarized here. Net shortwave radiation flux was estimated using following equation,

$$SHW_{net} = SHW\downarrow - SHW\uparrow \quad (1)$$

Where, SHW↓ is incoming shortwave radiation flux and SHW↑ is reflected shortwave radiation flux. These fluxes were recorded directly using pyranometer sensor.

Net longwave radiation flux was estimated using following equation,

$$LW_{net} = LW\downarrow - LW\uparrow = \varepsilon_m \sigma T_a^4 - \varepsilon_s \sigma T_s^4 \quad (2)$$

Where, T_a is atmospheric temperature, T_s is ice surface temperature, ε_m is emissivity of the air, ε_s is emissivity of the ice surface and σ is the Stephan Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}). Air emissivity was calculated using the model given below (Prata, 1996),

$$\varepsilon_m = 1 - (1+w)\exp\{-(1.2+3.0w)^{1/2}\} \quad (4)$$

Where, w is precipitable water content and estimated using air temperature and vapourpresuure as,

$$w = 46.5\,(e_a/T_a) \quad (5)$$

Clouds affect the net longwave radiation flux significantly (Ganju *et al*., 1999). In the presence of clouds, net longwave radiation flux was estimated by the following equation,

$$LW_{net} = (\varepsilon_m \sigma T_a^4 - \varepsilon_s \sigma T_s^4)(1-rN) \quad (6)$$

Where, r is coefficient and depends on type and height of clouds. Experimental values reported by US Army Corps of Engrs (1956) are r = 0.76 for low clouds, r = 0.52 for medium clouds and r = 0.26 for high clouds. N is the amount of cloudiness in terms of fraction of sky covered.

Sensible heat flux (SHF) and latent heat flux (LHF) was estimated using bulk aerodynamic method and given as,

$$SHF = (C_p\, \rho_0/P_0)\, K_n\, P\, u\, (T_a - T_s) \quad (7)$$

$$K_n = k^2 / [\log(z_a/z_0)]^2 \quad (8)$$

Where ρ_0 is the density of air (1.29Kg m^{-3}) at the standard atmospheric pressure P_0 (1.013x10^5Pa), K_n is a dimensionless transfer coefficient, P is mean atmospheric pressure at the measuring site, and u and T_a are measured wind speed and air temperature.k is von Karman's constant (0.41), z_a is sensor height above ground and z_0 is aerodynamic roughness length and a value of 0.001m is adopted for an ice surface (Van de Wal and Russell 1994; Bintanja1995; Konzelmann and Braithwaite 1995).

$$LHF = L_v\, (0.623\rho_0/P_0) K_n\, u\, (e_a - e_s) \quad (9)$$

Where L_v is the latent heat of vaporization, e_a is the atmospheric vapour pressure and e_s is the saturation vapour pressure at the glacier surface. The latter is a function of the surface temperature and is 611Pa for a melting surface (Paterson, 1994). For distinguishing sublimation and condensation, guidelines given by Ambach and Kirchlechner (1986), and Greuell and Konzelmann (1994), has been followed. For condensation Lv = 2.514 $MJKg^{-1}$, and for sublimation L_v = 2.849 $MJKg^{-1}$. When $(e_a - e_s)$ is positive, and T_s = 0deg, water vapour condenses as liquid water on the melting glacier surface with Lv = 2.514$MJKg^{-1}$, when $(e_a - e_s)$ is negative, there is sublimation with Lv = 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 Lv = 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 Richardson number (Ri). For unstable conditions (Ri<0) transfer coefficient is given by Kw2 = K_n.(1-10R_i). For Ri = 0, Kw2 = K_n; and for stable conditions (Ri>0), Kw2 = K_n/(1+10R_i) (Price and Dunne, 1976). Sub surface heat flux was observed directly using sub surface heat flux plates. Heat flux plates was placed inside the ice sheet at a depth of 10 cm from the surface to record the flow of heat from surface to ground below as well as from ground to the surface (Datt *et al*., 2015).

Results and Discussion

Figures 2 and 3 show daily average surface temperature and daily average air temperature, respectively. Strong annual cycle has been observed for the surface temperature and air temperature during the data period. Large short term variation can also be seen during the annual cycles for these parameters. Daily average surface temperature varied from –30.0°C to 0°C and 6 years average was observed to be –11.3°C. Lowest daily average surface temperature was recorded for 26-July-2012. Daily average air temperature varied from –28.6°C to 4.6°C and 6 years average was observed to be –10.2°C. Lowest and highest daily average air temperature was recorded for 25-July-2009 and 8-November-2007, respectively. In the annual cycle higher temperature was observed during summer season due to radiative heating and temperature dips down during winter in the absence of shortwave radiation. Temperature remains low till the month of September as ice sheet continuously losses heat due to longwave radiation. October onwards as incoming shortwave radiation flux increases, air and surface temperature also increase till the summer months January and February. February onwards again temperature starts decreasing and annual cycle was repeated for each year. Short term variations in the annual cycle are due to change in daily weather and cloud conditions.

Figure 4 shows daily variation in relative humidity (RH) during 6 years. Annual cycle with large short term variations can be observed in the figure. Daily average relative humidity (RH) varied from 26% to 97% and 06 years mean was observed to be 50.8%.Relative humidity was observed high during summer months January and February while low during winter months July, August and transition period from winter to summer September, October. Days with average relative humidity more than 80% corresponds to snowfall days and such events are frequent in coastal region of Antarctica. High relative

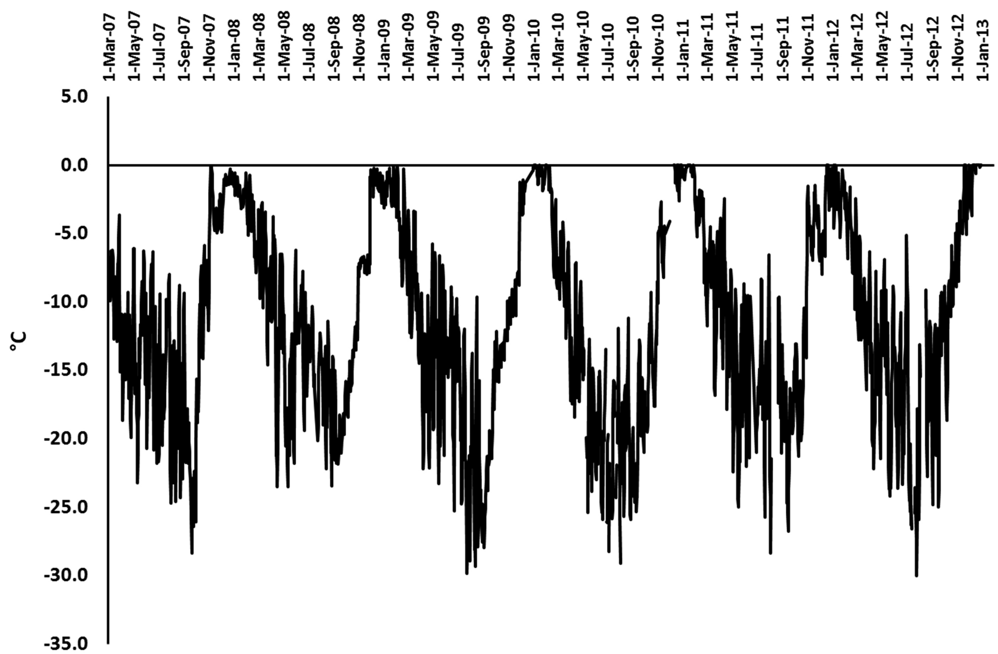

Fig. 2: Daily average surface temperature

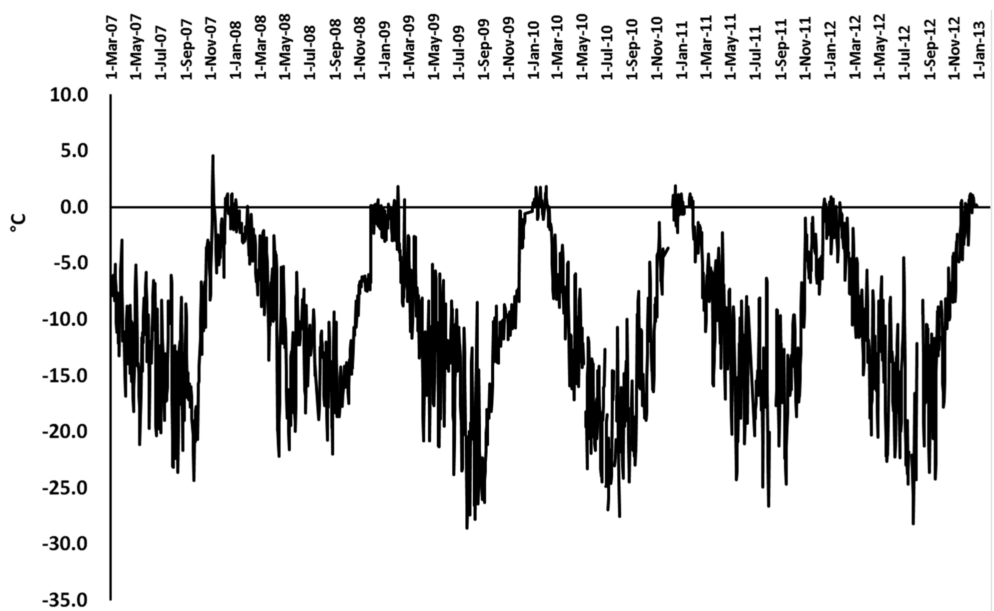

Fig. 3: Daily average air temperature

humidity during summer months is because of warm air advection.

Figure 5 shows daily average wind speed. Daily average wind speed varied up to 32 ms^{-1}. Annual cycle was observed in wind speed with higher winds during winter season and low winds during summer. Strong katabatic winds are observed at the study location with six years mean of 8.4 ms^{-1}. High katabatic winds are due to steep slope at the location from the Antarctic Plateau. Katabatic winds are gravity driven winds blowing down the slope towards periphery of Antarctic continent from the inland high Antarctic plateau. Major wind directions observed at the locations are East, South-East and South. The wind is characterized by short period of light wind followed by a period of high wind. High wind events

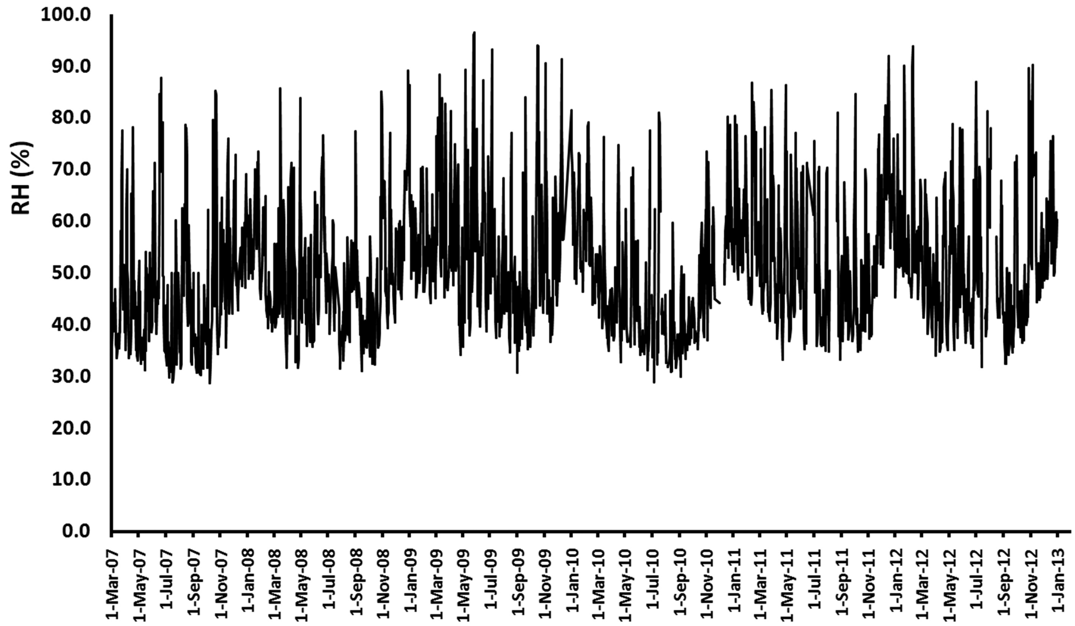

Fig. 4: Daily average relative humidity

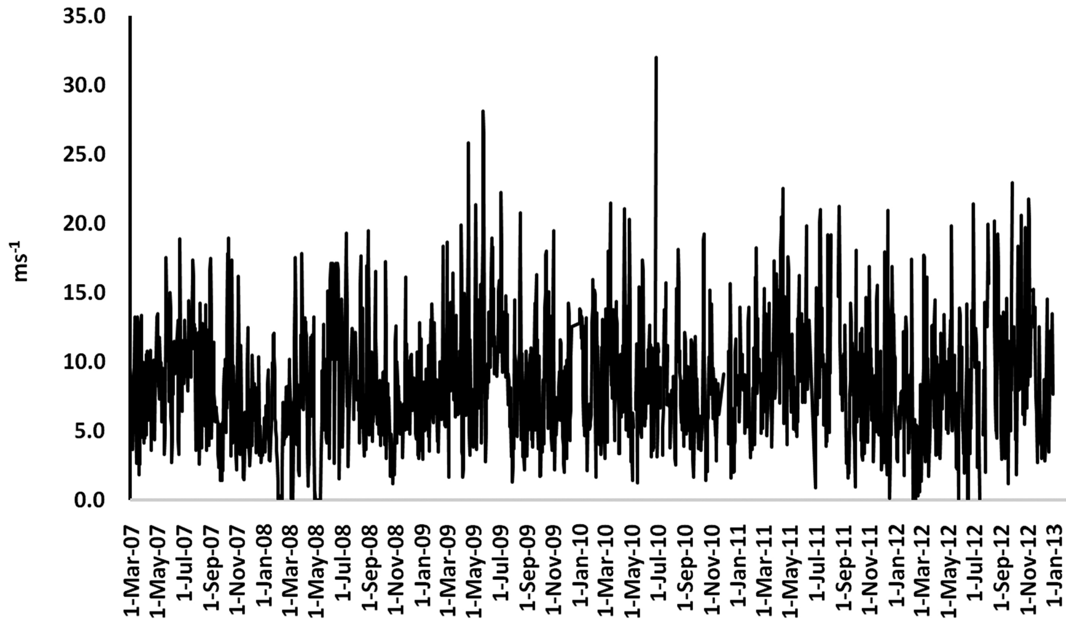

Fig. 5: Daily average wind speed

are generally correspond to passage of low pressure systems at the observation site (Tyagi *et al*., 2007). Low pressure systems are frequent in the coastal Antarctica due to proximity of Antarctic sea.

Figures 6 and 7 shows the incoming shortwave radiation flux and outgoing shortwave radiation flux. High annual and seasonal variability was observed in the incoming and outgoing shortwave radiation fluxes. Incoming shortwave radiation flux is observed highest during summer, it gradually decreases during transition period from summer to winter and then become zero during peak winter months. Again after winter months, incoming shortwave radiation flux increases during transition period from winter to summer and reaches at highest during peak summer months. The cycle

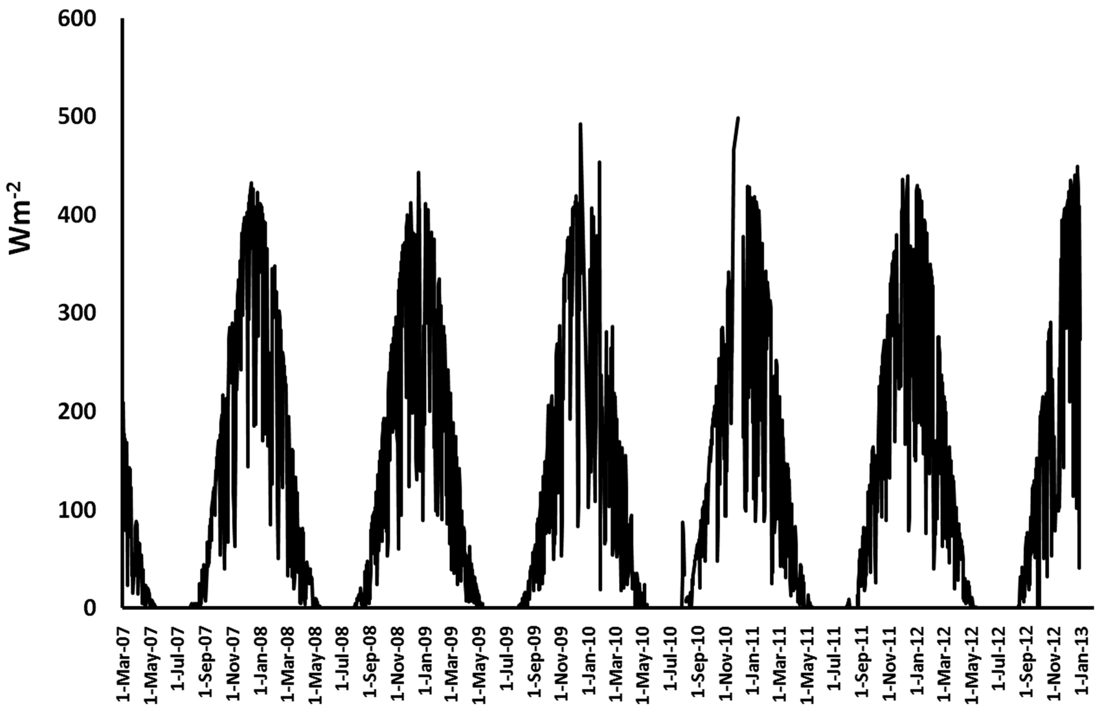

Fig. 6: Daily average incoming shortwave radiation flux

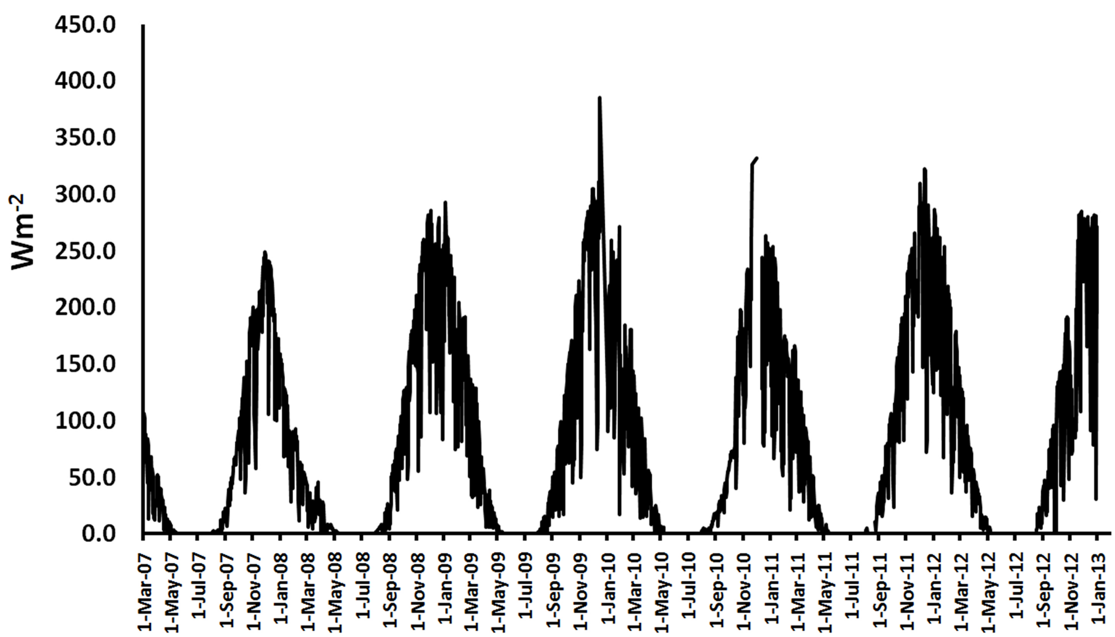

Fig. 7: Daily average outgoing shortwave radiation flux

repeats every year. Seasonal variation in incoming shortwave radiation flux is mainly due to variation in solar zenith angle. Mean solar zenith angle varies from 52° to 88° during summer days while solar zenith angle is ~90° during winter days. For the days of transition period, e.g. March, April, September and October months, solar zenith angle varies between 67.8° to 90°. Daily mean incoming shortwave radiation flux at the observation site was observed up to 500 Wm^{-2}. Six years mean incoming shortwave radiation flux was observed to be 124 Wm^{-2}. Daily average outgoing shortwave radiation flux was observed up to 385 Wm^{-}

^{2} and six years mean was obtained 79.7 Wm^{-2}. Inter-diurnal variation in incoming and outgoing shortwave radiation flux was due to frequent passage of frontal systems and clouds (Van den Broeke *et al*., 2004b). Daily mean albedo of the glacier surface varied from 0.19 to 0.93 with mean albedo of 0.64 during 6 years.

Temporal variation of net shortwave radiation flux, net longwave radiation flux and net radiation flux. Daily average net shortwave radiation flux varied from 0 Wm^{-2} during winter to 272 Wm^{-2} during summer.As surface temperature approaches 0°C during summer, pronounced melting of the ice sheet was observed. Water layer over ice reduces the albedo of the surface and net shortwave radiation flux increases. Net shortwave radiation flux for the summer months of 2007-08 was high compared to other years. During this particular summer season albedo values observed were low compared to other summer seasons. A rise in daily average air temperatureup to 4.6°C during first week of November 2007 started early melting of the ice sheet and triggered a positive feedback loop of albedo causing excessive melting during the season (Gusain *et al*., 2009). Net shortwave radiation flux was observed to be the source of heat for the ice sheet with 06 years average of 44.3 Wm^{-2}. Daily average net longwave radiation flux varied from –12 Wm^{-2} to –86 Wm^{-2} during the data period. Antarctic ice sheet continuously losses heat in the form of longwave radiation. Clouds affect longwave radiation flux significantly and less loss of heat from ice sheet is observed during cloudy days. Net longwave radiation flux was observed to be heat sink with 06 years mean of –49.2 Wm^{-2}. Net radiation flux varied from –86 Wm^{-2}during winter to 198 Wm^{-2} during summer and 06 years mean was obtained –4.9 Wm^{-2}. Net radiation flux was observed to be positive during summer months and negative during winter months. During summer net radiation flux act as heat source to the ice sheet while during winter it becomes heat sink. During transition months from summer to winter e.g. March, April, Net radiation flux changes from positive to negative. Similarly, during transition months from winter to summer e.g. September, October, net radiation flux again changes from negative to positive. Net radiation flux line in Fig. 8 cuts the x-axes (representing 0 Wm^{-2}) twice a year. At these points net radiation flux is zero and net shortwave radiation flux equals the net longwave radiation flux. Above these points net shortwave radiation flux dominates net longwave radiation flux and glacier surface absorbs radiation. Absorbed radiation increases the glacier surface temperature and melting start when the surface temperature reaches 0°C. Below these points net longwave radiation flux dominates the net shortwave radiation flux and the glacier surface loses energy, tending to decrease the surface temperature.

Figure 8 shows temporal variation in sensible heat flux and latent heat flux. Strong seasonal and annual cycle was observed in the sensible heat flux during the data period. Sensible heat flux was low during the summer months November, December, January and February as the difference in surface and air temperature was obtained low for these months, resulting into less flow of heat from air to surface or vice versa. Sensible heat flux was comparatively higher during the months March, April, May, June, July and August. Higher values attributed to high rate of heat transfer from air to surface or surface to air due to higher difference in temperature and comparatively high wind speed. Highest sensible heat flux was obtained during the September and October months as air temperatures are much higher compared to surface temperatures during these months. Daily average sensible heat flux varied from –208 Wm^{-2} to 309 Wm^{-2} with 06 years average of 28 Wm^{-2} and act as source of heat to the ice sheet throughout the year.

Latent heat flux has also shown seasonal variation. Lowest values were obtained for winter months and transition period from winter to summer, i.e. during September and October months. Highest values were obtained for summer months, i.e. November, December, January and February. Highest latent heat flux during summer attributed to high rate of sublimation of ice at higher temperatures. Sublimation and evaporation processes slow down due to low temperatures, which attributed to low latent heat flux during winter and transition period. Wind also plays an important role in sublimation and evaporation process. High wind accelerates the process, resulting into higher latent heat flux during windy days. Daily average latent heat flux varied from –260.4 Wm^{-2} to 41.3 Wm^{-2} with 06 years mean of –62.1 Wm^{-2}. Latent heat flux was observed as heat sink to the ice sheet throughout the year and sublimation at the rate of 0.017cm/day is observed at

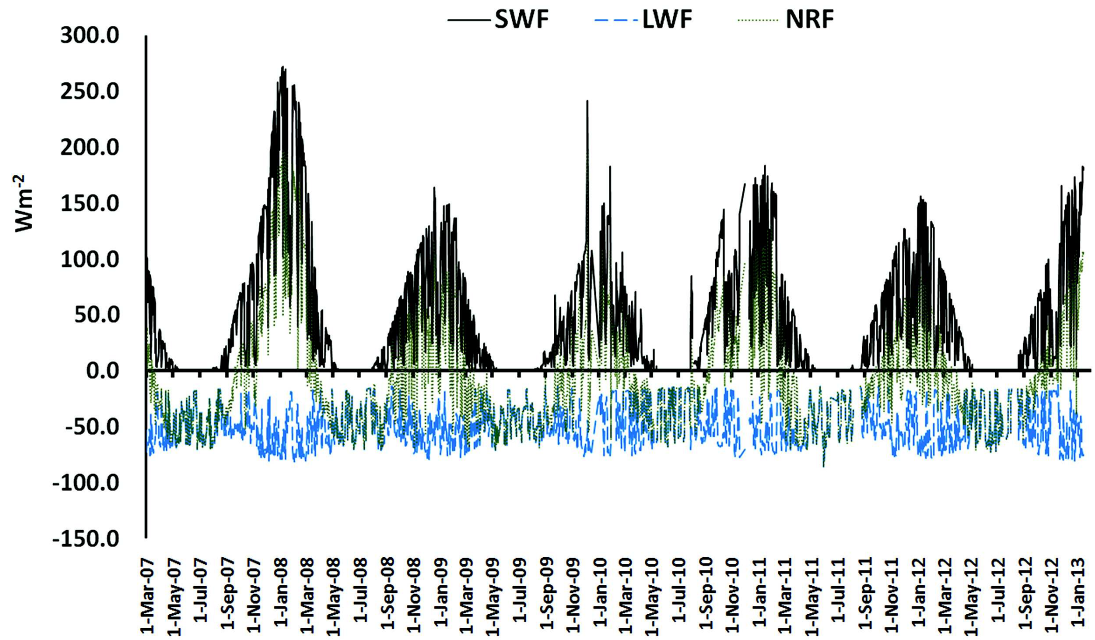

Fig. 8: Daily average sensible and latent heat flux

the observation site.

Figure 9 shows diurnal variation in net radiation flux and net sub surface heat flux at the observation site during summer. Net subsurface heat flux varied from –11.5 Wm^{-2} to 11.3 Wm^{-2}in diurnal variation with mean value of –0.12 Wm^{-2}. Net subsurface heat flux was observed to be less than 1% of net radiation flux during summer.

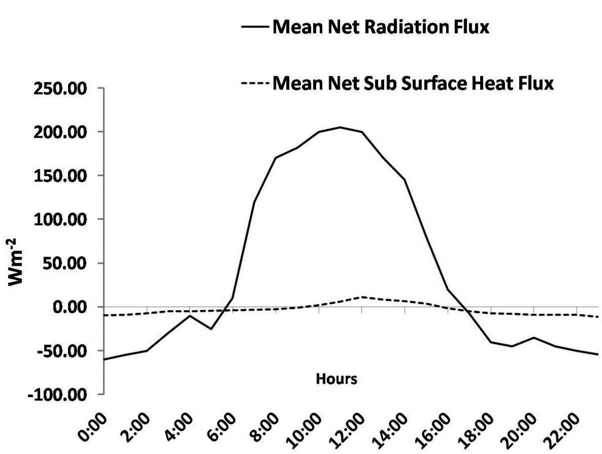

Fig. 9: Diurnal variation in net radiation flux and net sub surface heat flux at observation site during summer

Conclusion

In this paper we have reported 6 years observations and analysis of radiation parameters and surface energy fluxes of ice sheet near Indian research station 'Maitri' in East Antarctica. Daily average air temperature varied between 4.6°C to –28.6°C and 6 years mean air temperature obtained was –10.2 °C. Mean relative humidity at the site was 50.8% and mean wind speed was 8.4 ms^{-1}. Frequent low pressure systems were observed at the site, as site is located in the coastal region of Antarctic continent and has proximity to Antarctic sea. Daily average incoming shortwave radiation flux varied from 0 to 500 W m^{-2} with 06 years mean of 124 W m^{-2}. Similar values of incoming shortwave radiation flux has been reported in other coastal region of Antarctica. Albedo at the site varied from 0.19 to 0.93 and mean albedo was 0.64. Albedo value of 0.19 corresponds to melting glacier during summer while 0.93 corresponds to fresh snow over ice surface. Mean albedo obtained at the present site is low compared to other glacier site of Antarctica reported earlier. Low values of outgoing shortwave radiation flux (6 years mean 79.7 W m^{-2}) obtained at the site were due to low albedo values. Strong seasonal cycle was obtained in different surface energy fluxes, which attributed to seasonal cycle in solar radiation and meteorological parameters at the site. Seasonal cycle in solar radiation attributed to seasonal variation in solar zenith angle. Net shortwave radiation flux obtained was the main source of heat to the ice sheet during summer while net longwave radiation flux and latent heat flux were the main heat sink, as ice sheet continuously losses heat due to longwave radiation and sublimation process. Sensible heat flux became main heat source to the ice sheet during winter and transition period. Mean net sub surface heat flux was obtained –0.12 W m^{-2} during summer and contributed less than 1% of the net radiation flux to the net energy balance of the ice sheet. Mean values of net shortwave radiation flux, net longwave radiation flux, sensible heat flux and latent heat flux were obtained 44.3 W m^{-2}, –49.2 W m^{-2}, 28 W m^{-2} and –62.1 W m^{-2}, respectively during 6 years. Latent heat flux observed at the site is equivalent to the sublimation rate of 0.017cm/day. Mild temperature, low relative humidity and high katabatic wind compared to other Antarctic coastal locations cause high latent heat flux of the ice sheet near 'Maitri' research station.

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