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Summertime turbulent heat fluxes at East Antarctica over neighbouring rocky and ice shelf sites

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सार - अंटार्कटिक के नौवें भारतीय वैज्ञानिक अभियान के दौरान वर्ष 1990 में प्रायोगिक आधार पर दक्षिणी गंगोत्री (70°7'द. 11°7'पू.) की चट्टानी तराई में हिम-शेल्फ के निकटवर्ती क्षेत्र मैत्री (70°द.,12°पू.) में एक सूक्ष्म मौसम विज्ञान टॉवर की स्थापना की गई थी। किए गए अध्ययनों से पता चला है कि ध्रुवीय शीर्ष से चलने वाली अवरोही पवनों तथा/अथवा समुद्र की ओर से चलने वाली उत्तरी निम्न स्तरीय उष्ण और आर्द्र पवनों को वहाँ की सिनॉप्टिक आवृत्तियाँ गम्भीर रूप से प्रभावित करती हैं। इन प्रवाहों के कारण सूर्यातपन की क्रमशः न्यूनतम और अधिकतम अवधियों के दौरान हिम शेल्फ तथा चट्टानी तराई में धरातल पर आधारित प्रबल प्रतिलोमन और प्रबल संवहनी स्थितियाँ उत्पन्न होती हैं। इस शोध पत्र में अंटार्कटिका के तटीय क्षेत्र के निकट दो विपरीत धरातलों पर बाह्य परत की संरचना का अध्ययन किया गया है तथा इसमें अंटार्कटिक की चट्टानी तराई में ऊर्जा विनिमय की प्रक्रियाओं के महत्व और प्रबल प्रतिलोमन संवहनी स्थितियों वाले धरातलों पर प्रक्षोभ फ्लक्सों के प्राचलीकरण पर विचार किया गया है। इस शोध-पत्र में प्रक्षोभ के उन प्रकार्यों का उपयोग किया गया है जो पनोफस्काई ओर डयूटन (1984) द्वारा बताए गए परम्परागत प्रकार्यो से भिन्न हैं।

ABSTRACT. During the ninth Indian Scientific Expedition to Antarctica, in the year 1990, a micro-meteorological tower was installed at Maitri (70° S, 12° E) on the rocky terrain and on an experimental basis, on the nearby ice-shelf at the location of Dakshin Gangotri (70° 7′ S, 11° 7′ E). The synoptic features strongly influencing over the sites are the southeasterly katabatic winds from the polar cap and/or northerly low level warm and humid winds from the sea. These flows are responsible for the formation of strong surface based inversion and strong convective conditions at the ice shelf and rocky terrain during the minimum and maximum insolation periods, respectively. This paper presents a study of surface layer structure over two contrasting surfaces on near-coastal Antarctica and deals with the significance of the energy exchange processes over the rocky Antarctic region and the parameterization of turbulent fluxes over surfaces having strong inversion/convection conditions. The paper makes use of turbulence structure functions which are different from the conventional one given by Panofsky and Dutton (1984).

Key words – Near-coastal Antarctic stations, Rocky and ice shelf terrain, Katabatic winds, Inversion, Convection.

1. Introduction

The Indian Antarctic station Dakshin Gangotri (70° 7′ S, 11° 7′ E) was a typical Antarctic ice-shelf site, which was abandoned after sinking of the station in the shelf ice at Antarctica in 1990. It was situated at a distance of about 20 km from the sea in the north. The other Indian Antarctic station Maitri (70° S, 12° E) is situated on a rocky terrain of Schirmacher range (Wastard and Singh, 1988) at a height of about 120 m above mean sea level and at a distance of about 80 km from the sea (Naithani, 1995).

Main flow features over this region are either katabatic winds from the inside plateau which are found to be responsible for snow drift and blizzard condition in the region (Parish, 1988; King, 1990) or cyclonic wind flow from the sea in the north, which influences the Schirmacher range in experiencing cloudy conditions and the formation of fog or/and snowfall over it. Few clear

TABLE 1

Instrumentation at Maitri and Dakshin Gangotri, Antarctica

Sensors	Height at Maitri	Height at Dakshin Gangotri	Parameter measured	Instrumental error
Platinum resistance thermometers	0.15 m, 1 m, 3 m and 9 m	0.15 m, 1 m and 3 m	temperature	0.5° C
Cup-anemometer	0.15 m, 1 m, 3 m and 9 m	0.15 m, 1 m and 3 m	wind speed	0.2 $\mathrm{ms^{-1}}$
Sensitive rotating arm wind vane	0.15 m, 1 m, 3 m and 9 m	0.15 m, 1 m and 3 m	wind direction	2°

sunny days are also observed at the region when neither the katabatic flow from the southern sector nor the influences of the cyclonic disturbances significantly affecting the local weather conditions occurred.

In this note are presented the turbulent heat fluxes and modelled net radiation fluxes [Carroll and Fitch (1981)] computed by the meteorological measurements made over the Maitri and Dakshin Gangotri stations with a 9 m/3 m micrometeorological tower during the second and fourth week of January 1990, respectively. The paper makes use of turbulence structure functions, which are different from the conventional one given by Panofsky and Dutton (1984). Other objective of the present study is to understand the role of winds in the thermal structure of the surface layer during clear sunny days in the Antarctic summer.

2. Instrumentation, measurements and data analysis

2.1. *Instrumentation*

A 9m meteorological tower was erected at the rocky terrain of the Maitri station during the second week of January, 1990. Details are given in Table 1 for Maitri and Dakshin Gangotri station (DG).

This is to clarify that the Maitri station is located upwind of the prevailing mesoscale air motion with respect to the Dakshin Gangotri station. The roughness length over the smooth snow and rocky terrain of the Dakshin Gangotri and Maitri stations are 0.0001 m and 0.05 m, respectively. The meteorological data for the study, though collected continuously, was later scanned and checked for quality and for clear sunny days. The data reported in this note was collected by two of the authors (PKP and RS) during the 9th Indian scientific expedition to Antarctica (Pasricha *et al*. 1991).

2.2. *General weather*

The 'day' and 'night' conditions over the Indian Antarctic stations have been considered as 0900-1500 and 2100-0300 hr respectively on the basis of occurrence of maximum and minimum solar insolation, since there is no total darkness during the entire 24 hr period of the summerday at Antarctica. Therefore, for the purpose of calculating turbulent heat fluxes in the present study, an averaged value of temperature over all the observations in the 6-hour period as well as over all the clear days has been utilized. Mean wind speeds are roughly 1, 1.5, 1.7 $\mathrm{ms^{-1}}$ at 15 cm, 1m and 3m respectively, during the two periods at both the stations. The winds predominantly from the north during daytime are considered. The katabatic winds from the south, however, dominate during the nighttime. Representative values of wind direction at the Maitri and Dakshin Gangotri stations are 60° and 160° during day and night, respectively.

3. Method

3.1. *Evaluation of turbulent heat flux*

The turbulent heat flux H_S ($\mathrm{Wm^{-2}}$) due to atmospheric turbulence in the surface layer, under severe convection/inversion conditions, is given by (Lettau, 1979)

$$H_s \cong \rho C_p\, u^* \,(\delta T/\delta z)(1/\phi_h)\, z \tag{1}$$

Where,

z = mean layer height (= 1 m)

δT = temperature change across a layer thickness of δz (~ 1 m at the rocky terrain of Maitri, ~ 1m at the ice shelf of Dakshin Gangotri during day and ~2 m at the ice shelf of Dakshin Gangotri during night)

ρ = air density = 1250 ($\mathrm{gm^{-3}}$)

C_p = air specific heat = 0.24×4.185 ($\mathrm{Jg^{-1}K^{-1}}$)

k = von Karman constant = 0.35 (Stull, 1989)

Frictional velocity

$$u^* = \mathrm{k}\,(\delta u/\delta z)(1/\phi_m)\,\mathrm{z}\ (\mathrm{ms^{-1}}) \qquad (2)$$

where,

δu = wind speed change across a layer thickness of δz (~ 1 m or ~ 2 m) ($\mathrm{ms^{-1}/m}$)

ϕ_m = dimensionless wind shear function

$$\phi_m = \phi_m(z/L) = (1 - 15\ z/L)^{-0.25} \quad R_i < 0 \qquad (3a)$$

$$= (1 + 5\ z/L)^{0.75} \quad R_i > 0 \qquad (3b)$$

ϕ_h = dimensionless temperature gradient function

$$\phi_h = \phi_h(z/L) = (1 - 22.5\ z/L)^{-0.33} \quad R_i < 0 \qquad (4a)$$

$$= (1 + 5\ z/L)^{1.5} \quad R_i > 0 \qquad (4b)$$

$1/L$ = 1/Obukhov length ($\mathrm{m^{-1}}$)

$$= (R_i/z)(\phi_m^2/\phi_h) \quad R_i < 0 \qquad (5a)$$

$$= R_i/z \quad Ri > 0 \qquad (5b)$$

R_i = dimensionless bulk Richardson number

$$R_i = \mathrm{g}/T\,(\delta T/\delta z)\,[1/(\delta u^2/\delta z)] \qquad (6)$$

g = acceleration due to gravity = 9.8 $\mathrm{ms^{-2}}$

T = mean air temperature = 273° K

It may be noted that the expression $\phi_m = (1+5\ z/L)^{0.75}$ for $R_i > 0$ in Eqn.3(b) over Antarctica replaces the commonly used expression $\phi_m = (1+5\ z/L)$ given in Panofsky and Dutton (1984). Similarly, the expressions for ϕ_h in Eqns 4(a,b) over Antarctica are different than those commonly used. These improved forms of the functions ϕ_m and ϕ_h have been derived from refined similarity theory (Lettau, 1979, King, 1990). It may be further noted that $1/L = R_i/z$ for $R_i > 0$ in Eqn.5(b), since $\phi_h = \phi_m^2$. Whereas, it is common to use $1/L = R_i/z$ for $R_i < 0$ (Panofsky and Dutton, 1984; $\phi_h = \phi_m^2$ still holds good). Similarly, the expression for $1/L$ for $R_i < 0$ in Eqn. 5(a) is different than the commonly used expression of $1/L = (R_i/z)(1 - 5\ R_i)$. The latter expression is true, since $\phi_h = \phi_m = 1+5\ z/L$.

The expression for $1/L$ in Eqn 5(a) over Antarctica is evaluated numerically in the following manner. An initial value of $z/L=0.001$ is taken and the ϕ_m and ϕ_h are evaluated. Then, R_i in Eqn 5(a) is evaluated. This value of R_i is compared with the value of R_i obtained from the measurements in expression (6). The procedure is repeated with an increment in z/L of 0.001, such that the values of R_i in Eqn 5(a) and Eqn 6 suitably match.

The turbulent heat flux values for the temperature and wind speed gradients made at the ice shelf and rocky terrain of the Dakshin Gangotri and Maitri stations, respectively, are given in Table 2. The turbulent heat flux at the rocky terrain during day time is extremely high (880 $\mathrm{Wm^{-2}}$). It mainly reflects a rather large vertical temperature gradient over the rocky terrain and is interpreted in terms of an energy flux in the present study.

3.2. *Evaluation of net radiation flux*

The net flux of radiation RNo ($\mathrm{Wm^{-2}}$) at the surface, in the wavelength region 0.35-100 µm, is given by

$$\mathrm{RNo} = (1 - \mathrm{a}_s)\,\mathrm{Q} + (1 - \mathrm{a}_l)\,I - \mathrm{s_r}\,\mathrm{T_{s4}} \qquad (7)$$

where,

a_s = surface albedo of shortwave solar radiation (0.35-4 µm)

a_l = surface albedo of radiation (4-100 µm)

TABLE 2

Atmospheric turbulence related parameters and turbulent heat flux (H_s) over Dakshin Gangotri (DG; ice-shelf) and Maitri (rocky terrain) stations

Stations	Periods (hrs)	Temperature gradient (^{0} C)	Wind speed gradient (ms^{-1})	U^* (ms^{-1})	R_i	ϕ_h	ϕ_m	K_h (m^{2}s^{-1})	RNo (Wm^2)	H_s (Wm^2)	δH_s (Wm^2)
DG	0900-1500	-0.35	0.85	0.23	-0.04	0.82	0.90	0.089	-30±12	+43±64	±64
DG	2100-0300	+0.55	1.85	0.09	0.14	2.18	1.48	0.021	-107±5	-10±09	±09
Maitri	0900-1500	-3.3	0.85	0.31	-0.34	0.51	0.66	0.166	+407±50	+880±177	±177
Maitri	2100-0300	0.82	0.85	0.22	-0.09	0.71	0.82	0.070	+70±35	+128±93	±93

Q = downward global or hemispheric shortwave solar radiation flux (Wm^{-2}, 0.35 - 4μm)

I = downward counter radiation flux due to atmospheric constituents such as water vapour, *etc*. (Wm^{-2}, 4-100 μm)

r = Stefan-Boltzman constant = 5668 × 10^{-11} (Wm^{-2} K^{-4})

T_s = surface temperature (°K)

s = surface emissivity = (1 - a$_l$)

$s_r\, T_{s4}$ = upward longwave terrestrial radiation flux (Wm^{-2}, 4-100 μm)

Model estimate of downward counter radiation flux (I) at the 70° south latitude is based on Fig 14 of Sellers (1965). Empirical relations relating (I) to meteorological parameters such as temperature, water vapour pressure, *etc*. are given by Sellers (1965).

Model estimates of Q for the day and night time are based on Robinson (1966) and Carroll and Fitch (1981). The calculations of Q were performed for 14 January and 25 January for the rocky terrain and ice shelf of Maitri and Dakshin Gangotri stations respectively. Their Q values, in general, indicate that the solar radiation flux has a maximum/minimum during day/night time.

The net radiation flux (RNo) at the ice shelf and rocky terrain of the DG and Maitri stations, respectively, are given in Table 2.

3.3. *Comparison of experimentally measured turbulent heat fluxes and modelled net radiation fluxes*

The energy balance at the air-snow (rock) interface is symbolically given by

$$\text{RNo} = H_S + H_L + F_S \tag{8}$$

where RNo is the net flux of radiation, H_S is the turbulent heat flux, H_L is the latent heat flux and F_S is the flux of heat into the snow/rock surface. However, for the kind of model study being pursued in the present study, both H_L and F_S may be neglected.

During day hours over the ice shelf of DG, convection is maintained in the surface layer of the ice shelf by radiative cooling of the ice-covered surface. The advection of 'relatively warmer' air from the nearby sea is, however, not warmer enough to cause thermal stratification of the air in the surface layer over the ice shelf (Table 2).

The resultant downward flux of turbulent heat (= 10 Wm^{-2}) during night over the ice shelf of Dakshin Gangotri (Table 2) implies the presence of surface-based inversions during night time over the ice shelf. The formation of strong surface-based inversions during night is caused by the combination of radiative cooling of the ice surface and the flow of katabatic winds. The katabatic flow is strongly suggested from the direction of the winds, which in the present case is always from the southeast. It may be noted that the katabatic winds of higher magnitude (> 10 ms^{-1}) tend to weaken the surface-based inversions due to enhanced turbulent mixing.

However, the resultant upward flux of turbulent heat (= 880 Wm^{-2}) during day time over the rocky terrain of Maitri (Table 2) implies strong convection. The formation of strong convection during day time is due to the combination of radiative heating and the advection of the now 'relatively cooler' air from the nearby sea to cause turbulence in the air in the surface layer over the rocky terrain. The persistence of large heat fluxes over longer periods over the rocky terrain are likely to be due to the existence of a large number of water bodies over Maitri (Naithani, 1995). The large flux is maintained due to overturning in the water column providing the energy necessary to balance the surface energy budget.

Convection during night over the rocky terrain of Maitri is maintained due to radiative cooling. The 'relatively cooler' katabatic wind over the rocky terrain is, however, not cooler enough to cause additional turbulence in the surface layer.

4. Conclusion

The present study is of specialized significance for the climate of Antarctic ice-free, *i.e.*, rocky regions. There is generally a lack of knowledge about the energy exchange processes occurring over the rocky Antarctic regions. The study may also be considered of a more generalized significance for the parameterizations of turbulent fluxes over surfaces having strong inversion and convection conditions. The turbulent parameterization has been adopted from Lettau (1979) and is entirely different as suggested by Panofsky and Dutton (1984).

Convection during the maximum insolation, in the summer period, over the ice shelf at Antarctica is maintained by radiative cooling of the ice-covered surface. The katabatic winds, from the polar cap in the southeast, induce the formation of strong surface-based inversions over the ice shelf during the minimum insolation period. The advection of relatively cooler air from the northern sea induce the formation of strong convection over the rocky terrain at Antarctica during the maximum insolation period in the summer. Convection during the minimum insolation over the rocky terrain is maintained by radiative cooling.

It is instructive to view the occurrence of strong convection over the rocky terrain of the Maitri station during the maximum solar insolation and the consequent enhanced evaporation from the surface of the lakes in Schirmacher range.

Geographically, Maitri station is located near one of the biggest lakes, Zublake. It is like most of the lakes in the Schirmacher range, directly fed by the melting polar glacier. During the maximum solar insolation, the quantity of cool water from the glacier to the lake increases, thus maintaining much lower temperature of the lake water than the surrounding rocky area. This also reduces the evaporation from the water surface of the lake, maintaining low humidity in the environment over the Schirmacher range as suggested by Naithani (1995). In fact, it is just possible to observe a closed air circulation around the big lakes in the Schirmacher range during intense solar heating; in which, the warmer air over the rocky terrain would be replaced by the relatively cooler air from the lakes. This type of study would require much more sophisticated instrumentation, and is beyond the scope of the present paper.

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