MEASUREMENTS OF SENSIBLE HEAT FLUX IN KATABATIC WIND AT MIZUHO STATION, EAST ANTARCTICA

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***Abstract*:** A study was made of transfer of heat under strong surface inversion observed in 1980 at Mizuho Station, East Antarctica. Two sonic anemothermometers were used for direct measurements of eddy heat flux divergence or convergence between the levels of 3 and 30 m above a snow field when skies were clear and weak katabatic winds were blowing at a low level. We obtained the following results:

When the surface cooling is predominant, the air layer between the snow surface and 30 m has a structure in which at the surface a downward sensible heat flux compensates radiative cooling, and at 30 m any sensible heat flux remains insensible until a gravity wave comes about from shear instability.

The sum of values of radiative flux divergence between the snow surface and the top of a 30-m-high tower, and values of sensible heat flux divergence or convergence between the levels of 3 and 30 m, shows a discrepancy in comparison with the actual cooling or warming rate. This discrepancy suggests that the amounts of advection and phase change are not neglegible concerning their effects on the rate of cooling or warming by radiative heat plus sensible heat which accompanies the developments of low katabatic flow.

1. Introduction

Properties of radiation components and the surface boundary layer have been looked into under the program of the Polar Experiment-South (POLEX-South) at Mizuho Station (70°42′S, 44°20′E), as was described by KUSUNOKI (1981). This station is located at a height of 2230 m above sea level on the slope of the East Antarctic ice sheet; its climate is characterized mainly by the katabatic flow at the surface layer which blows continuously with an annual average speed of 11 m/s, and by low air temperature, the annual average of which is below −32°C (OHATA *et al.*, 1981). A number of observations were made in 1979 of the radiation budget and the properties of surface boundary layer by YAMANOUCHI *et al.* (1981) and WADA *et al.* (1981a, b) at Mizuho Station. The present authors, belonging to the 21st Japanese Antarctic Research Expedition, carried out glacial-meteorological observations at this station in 1980 as the second-year program of POLEX-South.

This paper describes especially the preliminary results of measurements of vertical heat mixing through a thin katabatic wind layer in order that the heat balance of the snow surface at this station may be made clear.

2. Measurements

The profiles of air temperature were obtained using seven thermometers of the platinum resistance type manufactured by Toho Electric Co., Ltd. The thermometers, shielded from direct radiation by a shelter made of stainless steel, were mounted, one each, on the seven aluminum pipe arms extending from a high micrometeorological observation tower, 30 m high, their heights being 29.5, 15.5, 7.5, 3.5, 1.5, 1 and 0.5 m above the snow surface. The output of each thermometer was automatically recorded every minute.

The profiles of wind speed were obtained using seven three-cup anemometers manufactured by Makino Instrument Company. They were mounted, one each, on the same pipe arm at the same seven heights. The rotation of each anemometer was optically transformed into electric pulses and recorded automatically every minute.

The amounts of net radiation of short-waves and long-waves were measured using pyranometers and pyrgeometers at a height of 1 m above the snow surface and at the top of the 30-m-high tower. The amount of net radiation, R, was calculated by the following equation:

$$R = S_d - S_u + L_d - L_u \,, \tag{1}$$

where S_d, S_u, L_d and L_u are the global, the reflected short-wave, the downward and the upward long-wave radiation, respectively. More detailed reports on the radiometry used have been given by MAE *et al.* (1981) and YAMANOUCHI *et al.* (1981).

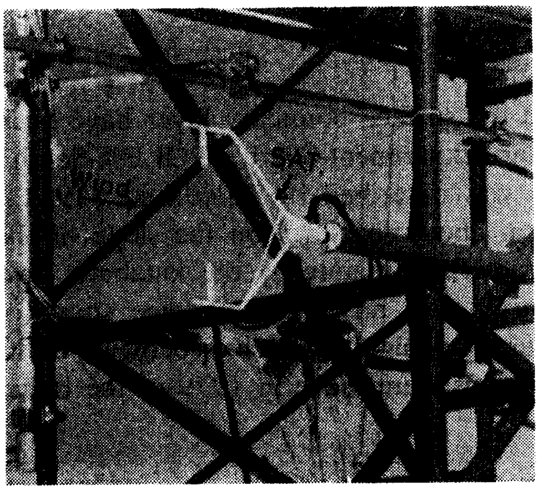


Fig. 1. One-component sonic anemothermometer for measuring sensible heat flux mounted on a 30-m-high tower.

Sensible heat flux was measured using two sonic anemothermometers. Fluctuations in the vertical component of wind speed and in air temperature were simultaneously measured with two sets of sonic anemothermometers (referred to as S.A.T. hereafter) manufactured by Kaijo Denki Co., Ltd. The sensors were mounted, one each, at the respective heights of 3 and 30 m on the tower (Fig. 1). Electric signals from the S.A.T. were recorded on a 2 channel rectigraph passed through a fluxmeter manufactured by Kaijo Denki Co., Ltd. The fluxmeter gave $(\overline{\theta' w'})$, where θ' and w' are the deviations from the average air temperature and the average vertical wind speed, respectively, and the overbar denotes the time average. The sensible heat flux, S, is given in the following equation:

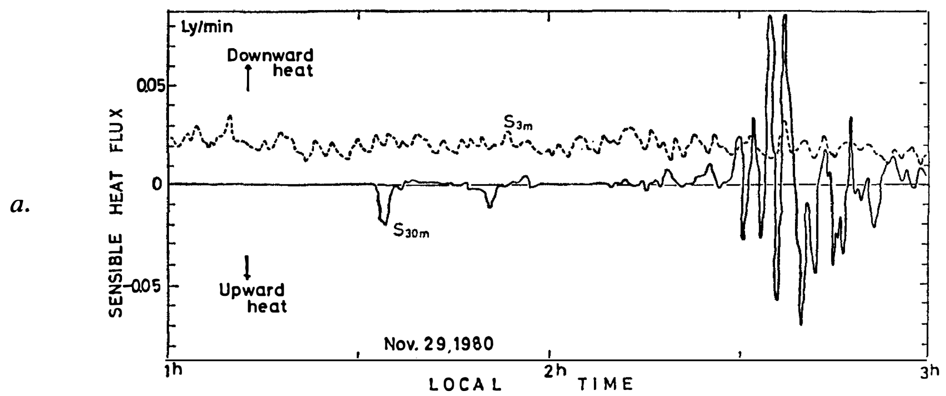
$$S = c_p \rho \overline{\theta' w'} \, , \qquad (2)$$

where c_p ($\sim$0.24 kcal/kg·°C) and ρ ($\sim$1.1 kg/m^3) are the specific heat and density of air, respectively.

3. Results

The surface inversion originates at the surface and ascends upward at an unsteady rate to mid-tower levels when winds are weak and skies are clear, as reported by WADA *et al.* (1981) and KOBAYASHI *et al.* (1982). According to WADA *et al.* (1981), a large temperature fluctuation was measured at the level of 30 m from August 21 to 22, 1979; *i.e.*, the fluctuations of temperature amounted to 15°C per hour at about 2100 LT, August 22. RIORDAN (1979) also described a temperature fluctuation at Plateau Station (79°15′S, 40°30′E, 3625 m above sea level). According to his reports, the fluctuation of temperature, which amounted to 11°C at the surface, decreased to 4°C at the level of 32 m, where a rise in temperature did not begin until about 0800 LT; *i.e.*, it had a phase lag of 5 hours in relation to the surface. Namely, some remarkable advection will occur in the surface layer on Mizuho Station. Plateau Station is located on a higher plateau of the East Antarctic ice sheet, where weak winds blow throughout the year, while Mizuho Station is characterized by stationary katabatic winds which blow continuously at annual mean speed of 11 m/s. Consequently, vertical mixing in the surface layer is larger at Mizuho Station than at Plateau Station.

Figures 2a and 2b show the time series of S_{3m} and S_{30m}: the 10-min averages at the levels of 3 and 30 m, respectively, of sensible heat flux from 0100 to 0600 LT, November 29, 1980. The downward sensible heat transfer from the air to the surface is defined as positive when directed toward the surface. When surface cooling was predominant S_{3m} always showed downward heat flux (Fig. 2a); when surface heating was predominant it changed to show upward heat flux (Fig. 2b). Meanwhile, S_{3m} was zero in the beginning of the development of a surface inversion corresponding to quiet flow with nonturbulence reported in this issue by KOBAYASHI *et al.* (1982). At a place where a wind shear appears to be associated with the upward growth of the inversion, the so-called "intermittency" of atmospheric turbulence occurs and is deformed into a wave-like pattern as shown in Fig. 2a. Propagation of such waves and their breakdowns are considered to play an important role in the mixing between the surface layer (cold) and the free atmosphere



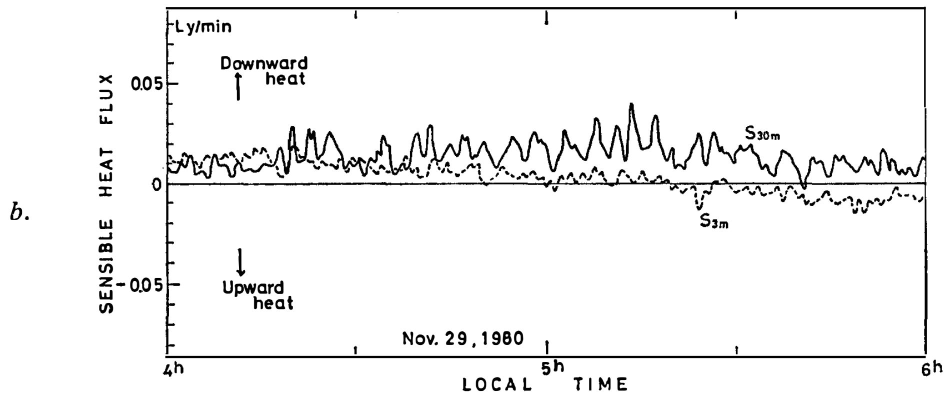


Fig. 2. Times series of S_{3m} and S_{30m}, the 10-min averages at the levels of 3 and 30 m, respectively, of sensible heat flux from 0100 to 0600 LT, November 29, 1980. (a): In the case of transition from quite flow to intermittency of breakdown of flow in wave-like motion. (b): In the case of full turbulent development of flow.

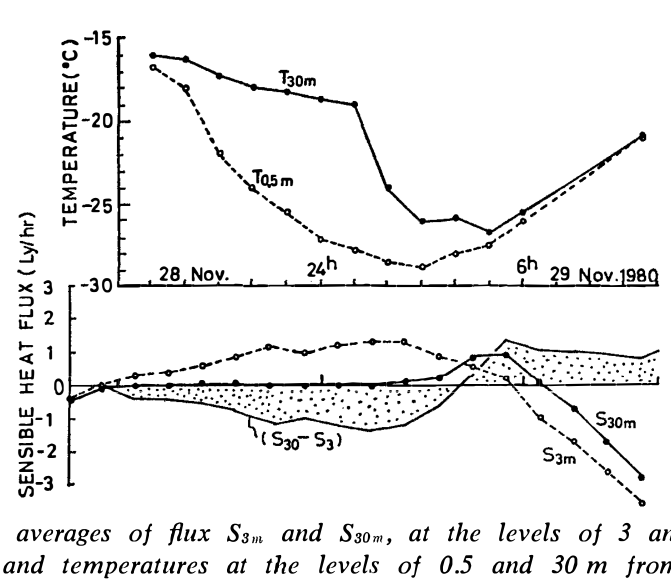


Fig. 3. Hourly averages of flux S_{3m} and S_{30m}, at the levels of 3 and 30 m, respectively, and temperatures at the levels of 0.5 and 30 m from November 28 to 29, 1980.

(warm) above it. Figure 3 shows the one-hour averages of flux at the levels of 3 and 30 m levels, together with temperatures at the levels of 0.5 and 30 m from November 28 to 29, 1980. If $S_{30m}-S_{3m}$ for downward sensible heat is negative, it means that the surface layer in the air progresses in radiative cooling; in the day-time the difference of upward sensible heat becomes positive, which is associated with radiative heating. However, a stationary or high katabatic wind is associated with a thick inversion layer (*e.g.*, KOBAYASHI and YOKOYAMA, 1976); such a thin surface inversion layer as was accompanied by a low katabatic wind occurred from 5 to 10 days per month in 1980, each time after a synoptic scale disturbance.

4. Discussion and Conclusion

Net heat loss by radiation from the surface in initially compensated almost entirely by the downward flux of sensible heat from the air as shown in Fig. 2. In a micrometeorological study it is customary to assume that regardless of a change in height, the vertical flux of momentum or heat is kept constant and effective in a layer extending from a few centimeters to tens of meters in thickness above the surface. Many researches indicate, however, that a change in air temperature under clear sky and weak wind conditions is usually due to the divergence of heat flux, both turbulent and radiative (*e.g.*, FUNK, 1960; ELLIOTT, 1964; OKE, 1970; OKAMOTO and FUNK, 1971; OKAMOTO, 1971; FUGGLE and OKE, 1976; NUNEZ and OKE, 1976; ISHIKAWA, 1977; NKEMDIRIM, 1978; KONDO *et al.*, 1978).

If it is assumed that there is no phase change in water vapor inside an atmospheric column and there is no horizontal advection, then the actual rate of cooling of an atmospheric column between the vertical coordinates Z_1 and Z_2 is given by a combination of the cooling due to divergence of net radiation $\partial R/\partial Z$ and of sensible heat flux $\partial S/\partial Z$ (FUNK, 1960). Consequently, the actual cooling rate $\partial T/\partial t$ is expressed by the following equation:

$$\rho c_p\left(\frac{\partial T}{\partial t}\right)=\left(\frac{\partial R}{\partial Z}+\frac{\partial S}{\partial Z}\right). \tag{3}$$

In general, $C_A=-\partial T/\partial t$ is the actual cooling rate; $C_R=(c_p\rho)^{-1}\times\mathrm{div}\ R$ is the

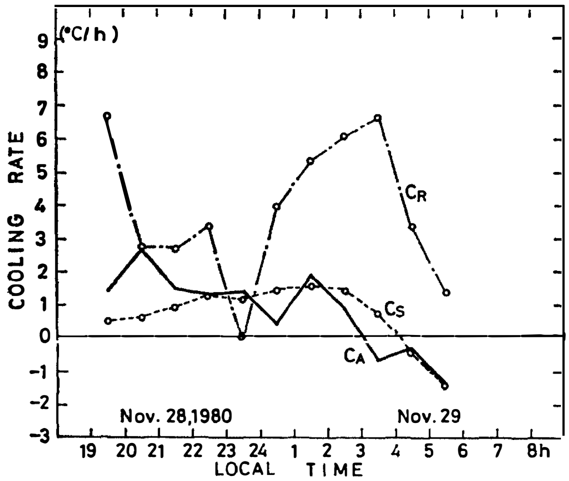


Fig. 4. Hourly averages of C_A (actual cooling rate), C_R (radiation divergence cooling rate) and C_S (cooling rate due to divergence of eddy heat flux) from 1930 LT, November 28 to 0600 LT, November 29, 1980.

radiation divergence cooling rate; $C_s=(c_p\rho)^{-1}\times\mathrm{div}\,S$ is cooling (or heating) due to divergence (or convergence) of sensible heat flux. The downward direction is taken as positive, for both the net radiation flux R and the sensible heat flux S.

Figure 4 shows the hourly averages of the cooling rate components C_A, C_R and C_S from 1930 LT, November 28, to 0600 LT, November 29, 1980. Equation (3) will be satisfied in case of such small amounts that have negligible effects of both net horizontal heat transfer and latent heat, for instance, because of advection in the former and dissipation or no formation of hoar in the latter. In order to investigate the validity of eq.(3), Fig. 5 compares C_A with the sum of C_R and C_S, using data plotted in Fig. 4. In Fig. 5 a straight line shows the relation given in eq.(3). As a result, it appears that horizontal advection and latent heat transfer were not negligible during the development of a low katabatic wind. Another example obtained from October 20 to 21, 1980 is shown in Figs. 6 and 7. The

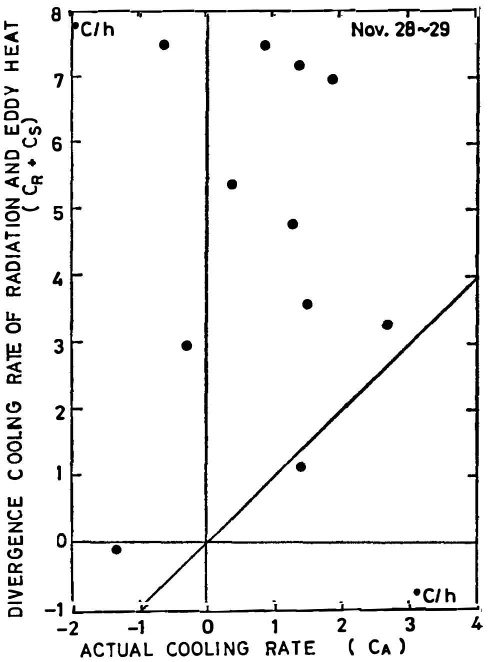


Fig. 5. Relation between C_A (actual cooling rate) and C_R+C_S (sum of radiation divergence cooling rate and cooling rate due to divergence of eddy heat flux) in the same period as in Fig. 4. A straight solid line shows the relation of eq. (3).

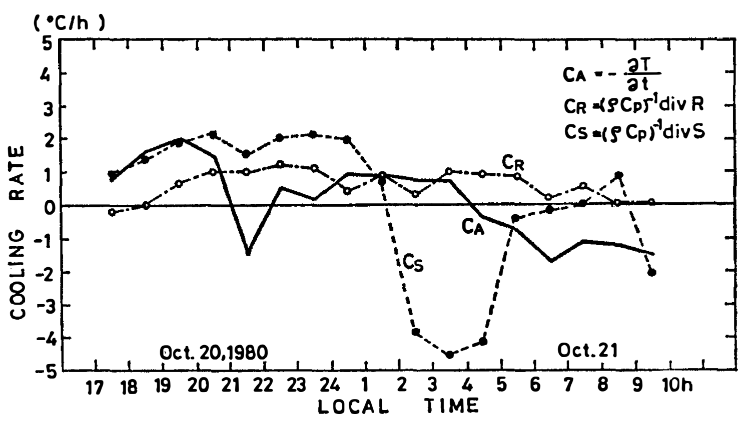


Fig. 6. Same as Fig. 4 from October 20 to 21, 1980.

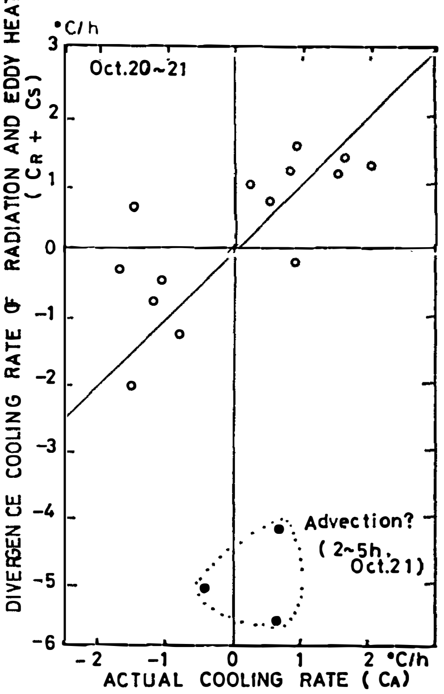


Fig. 7. *Same as Fig. 5 from October 20 to 21, 1980.*

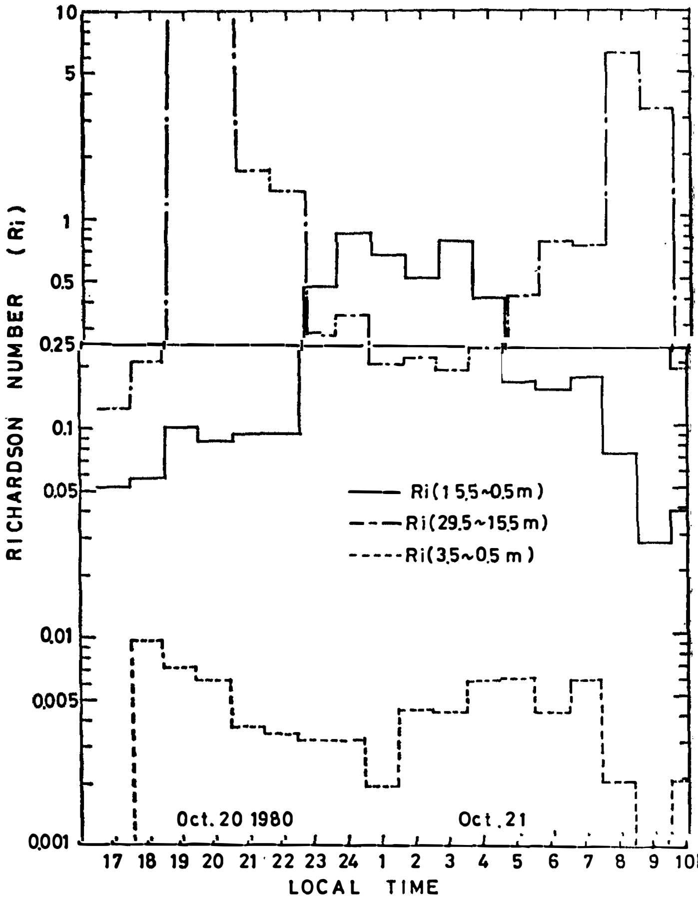


Fig. 8. *Analysis of local Richardson numbers in three layers from October 20 to 21, 1980.*

result roughly agrees with eq.(3) except for a period of remarkable advection taking place from 0200 to 0500 LT, October 21. Periods for which eq.(3) does not hold may correspond to those with small Richardson number ($\lesssim 0.25$). Figure 8 illustrates the local Richardson number calculated over three layers between the levels of 0.5 and 29.5 m from October 20 to 21, 1980. According to the present measurements, an especially unstable layer between the levels of 29.5 and 15.5 m with the Richardson number of less than 0.25 was maintained from 0100 to 0400 LT, October 21.

It is suggested that a nonlinear interaction between the three variables, *i.e.*, C_A, C_R and C_S, is an important mechanism of heat mixing in the first step of the development of a katabatic wind.

Acknowledgments

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