Antarctic Science 11 (1): 93–99 (1999)

Estimation of turbulent heat fluxes and exchange coefficients for heat at Dumont d'Urville, East Antarctica

S. ARGENTINI*, G. MASTRANTONIO and A. VIOLA

Istituto di Fisica dell' Atmosfera, CNR, via Fosso del Cavaliere, 100, 00133 Roma, Italy
**E-mail: stefania@sung3.ifsi.fra.cnr.it*

Abstract: Simultaneous acoustic Doppler sodar and tethersonde measurements were used to study some of the characteristics of the unstable boundary layer at Dumont d'Urville, Adélie Land, East Antarctica during the summer 1993–94. A description of the convective boundary layer and its behaviour in connection with the wind regime is given along with the frequency distribution of free convection episodes. The surface heat flux has been evaluated using the vertical velocity variance derived from sodar measurements. The turbulent exchange coefficients, estimated by coupling sodar and tethered balloon measurements, are in strong agreement with those present in literature for the Antarctic regions.

Received 24 September 1997, accepted 5 August 1998

Key words: Antarctica, exchange coefficients, heat fluxes, sodar, tethersonde

Introduction

Boundary layer measurements over the Antarctic continent are needed for boundary layer studies as well as for mesoscale and synoptic scale modelling (Pettré *et al.* 1990). Recently it has been well documented that climate simulation studies with General Circulation Models (GCMs) are sensitive to the representation of energy and mass fluxes in the planetary boundary layer (Pettré *et al.* 1990). It is therefore important for studies at all the scales to estimate and to have methods to derive the parameters that characterize the Antarctic boundary layer under different stability conditions. Yague & Cano (1994), using the data from ultrasonic thermo-anemometers in the surface layer during the Antarctic winter at Halley base showed how the stratification in the lower atmosphere influences the eddy transfer of heat and momentum. They evaluated the turbulent fluxes and found a sharp decrease of turbulent exchange coefficients for heat and momentum (of the order of 10^{-3} m^2 s^{-1}) passing from neutral to stable conditions. King & Anderson (1994) determined the similarity functions for momentum and heat for the stable surface layer at the Antarctic station of Halley, pointing that the results they found likely could be used in other situations where similar conditions, stable atmospheric stratification over a snow surface, prevail. Stearns & Weidner (1993) estimated the sensible and latent heat fluxes using the data from the Automatic Weather Stations (AWS) scattered all over the continent. They wanted to determine the direction and magnitude of the latent heat flux on the Antarctic continent to know if the process represents either an annual surface addition or a removal of water mass. The general interest remains to parametrize the observed phenomena over the mostly stable Antarctic boundary layer to understand if these results may be generalized to areas with the same characteristics. Although a condition of inversion prevails over the whole continent, many cases may occur along the coast in which a mixing layer may be found due to free or forced convection. These cases, as shown by Gera *et al.* (1998) are quite common during the summer and alternate with each other depending on the wind intensity. It is interesting then to evaluate the fluxes along the coast to know if they play a significant role in the circulation between the low and high latitudes over Antarctica.

In this paper we describe some aspects of the convective boundary layer at the coastal station of Dumont d'Urville and present an estimation of the turbulent heat fluxes and the turbulent exchange coefficients during free convection using sodar and tethersonde data.

The sodar (sound detection and ranging) has been used successfully in the past to study the Antarctic boundary layer (Argentini *et al.* 1996) and has proven its usefulness in depicting the boundary layer structure and evolution (Gera *et al.* 1998, Naithani & Dutta 1995, Culf 1989). It gives measurements continuously, with little human involvement, for both intensive campaigns and long-term studies (Argentini *et al.* 1996). Although the sodar is used primarily to measure the wind speed profiles in the Planetary Boundary Layer (PBL), data reduction techniques of vertical velocities, w, and variances, σ^2_w, derived by sodar during convective activity have been proposed and utilized in recent years to derive surface heat flux (Weill *et al.* 1980, Greenhut & Mastrantonio, 1989, Melas 1990, Melas 1993, Casadio *et al.* 1996). The derivation of σ^2_w by sodar measurements is less accurate than the wind velocity components, u, v, w. However, it has been shown that in certain situations, particularly over complex terrain, the quantities derived by remote sensors, such as sodars or radars, give a better representation of the spatial-temporal averaged atmospheric parameters, such as mean fluxes, than the in situ measurements. This is because they are less sensitive to surface conditions than a point sensor

(Angevine *et al.* 1994).

The data set we used in this paper was collected during the summer 1993–94 at the French station of Dumont d'Urville (Argentini *et al.* 1996).

Site description, instrumentation and data

The experimental site (140°00'30"E, 66°39'45"S) is located at the French base of Dumont d'Urville on a small island 5 km from the coastline, in Adélie Land, East Antarctica (Fig. 1), at an elevation of about 50 m a.s.l. A sparse distribution of buildings and small rocks characterizes the site. The ground is normally covered with snow throughout the year except during the summer months when some areas become clear of snow.

A Special Observation Period (hereafter SOP) was planned between December 1993 and January 1994 to simultaneously run a Doppler sodar and a tethered balloon. This Multimicro-sodar, similar to that used in other Antarctic campaigns (Argentini *et al.* 1992, Argentini & Mastrantonio 1994), is a monostatic three-axis Doppler system with 1.2 m diameter antennas emitting three acoustic tones, one for each antenna, at 1750, 2000, and 2250 Hz. Two of the antennas were tilted 20 degrees off the vertical, while the third one pointed vertically. The vertical resolution of the system was 27m whereas the 6 s pulse repetition frequency allowed the echo recording up to 1000 m.

Processing of the returning signal includes the harmonic analysis and a two-step procedure to minimize the influence of the noise on the measurements (Mastrantonio & Fiocco 1982, Mastrantonio & Argentini 1997). In addition, the unit provides the facsimile recording of the backscattering intensity due to the thermal inhomogeneities of the atmosphere. The profiles of the radial velocities are derived from the Doppler shift of the acoustic echo. From the radial velocities, with simple trigonometric formulas, the zonal, the meridian and vertical velocities are computed (Mastrantonio & Argentini 1997).

The Air-balloon carrying the tethersonde is shaped to facilitate the orientation upwind. The tethersonde, suspended about 2 m below the balloon, provides measurements of pressure, temperature, humidity, wind speed and wind direction every 6 s. The wind speed is obtained by a three-cup anemometer within an accuracy of 0.5 m s^{-1} whereas the direction is measured with a magnetic compass that relies on the orientation of the balloon within an accuracy of ± 5 degrees. An aneroid barometer gives pressure to an accuracy of 1 hPa, pressure and temperature profiles then provide the altitude at the sensor package above the surface. During the flight the electronics of the sonde scanned the sensors sequentially and transmitted the raw data to the ground station. The data were then transferred to the computer and processed to give the profiles of the potential temperature, the relative humidity, the wind speed and direction.

The SOP lasted 18 days (from 18 December 1993 to 9 January 1994), whereas the sodar data are available for all of 1993 and 1994 (Argentini *et al.* 1996). While the sodar data are available continuously, the tethersonde profiles were generally taken every 2 hours and only when the wind speed was less than 4–6 m s^{-1}.

For this study, the data were carefully selected to satisfy two criteria. First, we selected only those data gathered during quiescent synoptic weather conditions, restricting the analysis to the hours during which the convective regime was well established and the wind shear negligible. Second, we selected only those data where the signal intensity, derived from the signal to noise ratio, was above a predefined threshold (see Mastrantonio & Fiocco 1982). By following these constraints, the data set used in this study was restricted to four days (25 December 1993, 3, 4 and 8 January 1994).

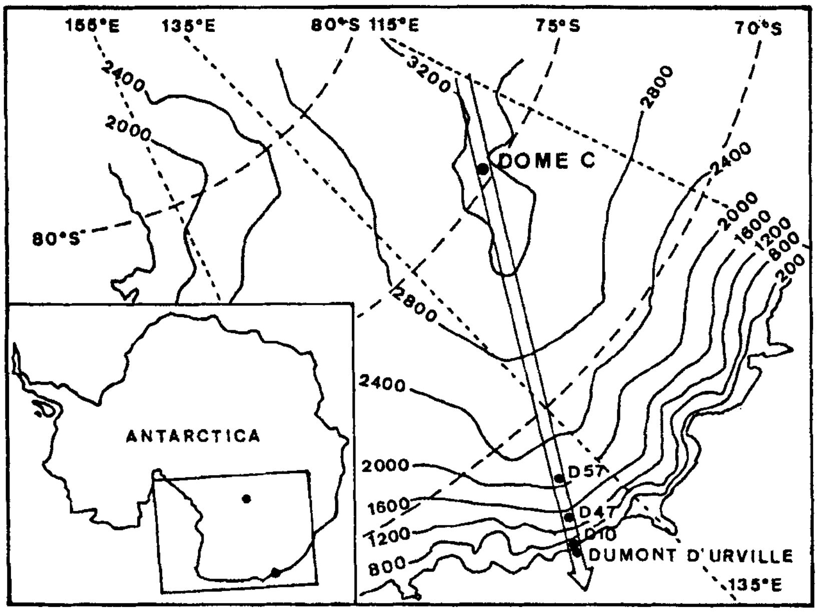

Fig. 1. Topographic map showing the location of the Antarctic station of Dumont d'Urville and the location of the AWS D-10, D-47, D-55 and Dome C.

https://doi.org/10.1017/S0954102099000127 Published online by Cambridge University Press

Characteristics of the convective boundary layer

As pointed out by Gera *et al.* (1998), the forced convection, due to the presence of shear in the lower part of the PBL (the first 200–300 m), prevails most of the year along this coastal region of Antarctica. During the summer, when part of the Dumont d'Urville area is clear of snow and fair weather anticyclonic conditions prevail, episodes of free convection are observed during periods of high insolation. Well organized convective structures may then be observed on the sodar facsimile records for those days with light winds and clear sky conditions when the wind field does not distort the plumes. The free convection episodes are confined to the summer period, between October and the middle of February (Gera *et al.* 1998). Having in mind to study the PBL during free convection, we planned a SOP during the summer. In this study we selected four days from the SOP in which the convective activity lasted for several hours. The convection episodes were selected by visually analysing the sodar facsimile records, which provide a qualitative representation of the thermal structure of the atmosphere. Figure 2 is an example of such an episode for 3 January 1994, the facsimile record shows convective plumes of different intensity, rising from the ground up to 200–300 m that are observed between 12h00 and 17h00 Local Time (LT). The black traces in the upper part of the facsimile are noise due to the presence of the penguins. On rare occasions, convective activity was observed later in the day at 18h00–19h00 LT. In addition the same graph shows the vertical velocity at different heights. As expected, alternate positive and negative vertical velocities in an organized fashion typical of convective activity is recognizable. A similar behaviour is seen on other days. Figure 3 shows the wind speed and direction for 25 December 1993 and 3, 4, and 8 January 1994 respectively, the time corresponding to the free convection hours is between the vertical bars. A feature common to all the examined days is the decrease of the wind speed during the hours of free convection. The winds during the SOP were predominantly easterly, with a few episodes from the S–SW sector. These S–SW cases are associated with low wind speed. Figure 4 is the scatter plot of wind speed versus wind direction for all days during the free convection hours. The data are clustered around 3–4 m s^{-1} and from the east. Other angular sectors are also present in the graph (180 and 270 degrees), but in these cases the wind speed is always lower than 2 m s^{-1}. During the summer, when high pressure and clear sky conditions occur, the wind speed is generally low and the wind blows from the East. At midday the solar insulation is strong and the reduced local albedo enhances radiative warming of the surface preventing the formation of the usual local inversion. Hence free convection is observed to govern the mixing within the boundary layer with a process similar to that observed at mid-latitudes.

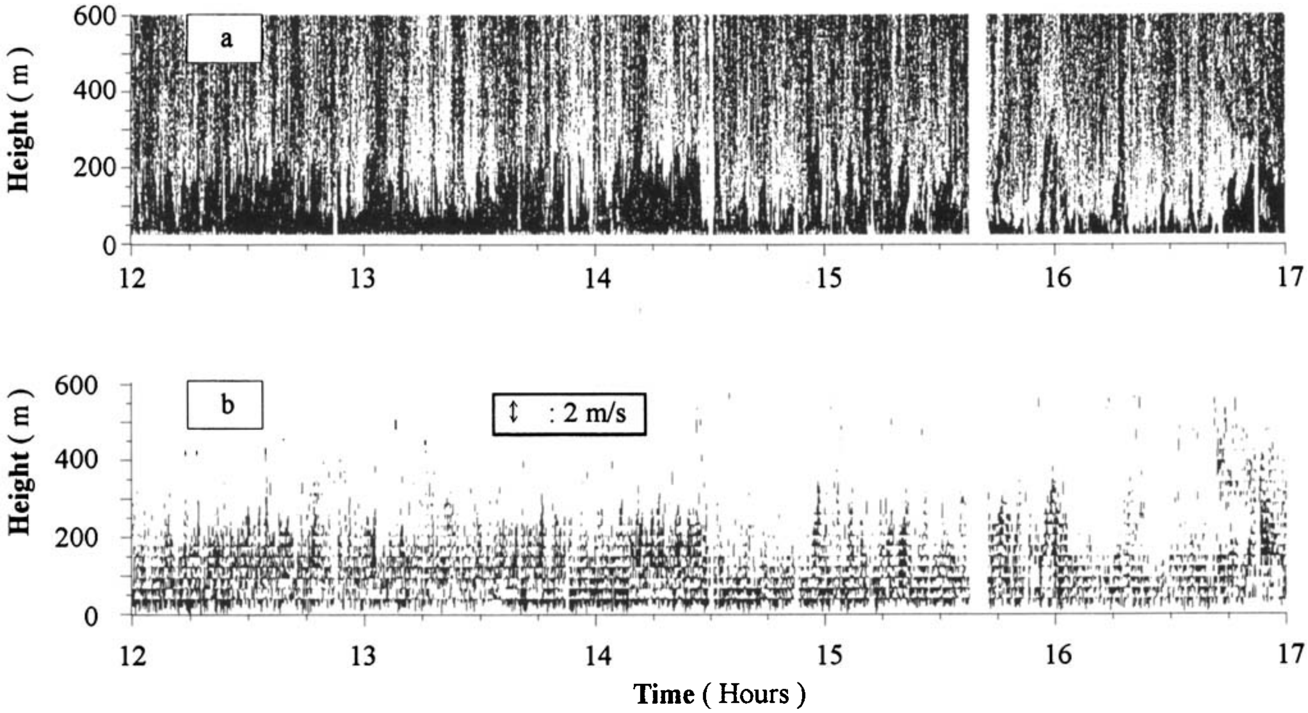

Fig. 2. Facsimile record representation obtained by sodar during convective activity for day 3 January 1994 as a function of height. **a.** convective plumes are shown between 12h00 and 17h00 LT. **b.** Vertical velocity as a function of height for the same period, each level corresponds to a normalization of 2 m s^{-1}.

https://doi.org/10.1017/S0954102099000127 Published online by Cambridge University Press

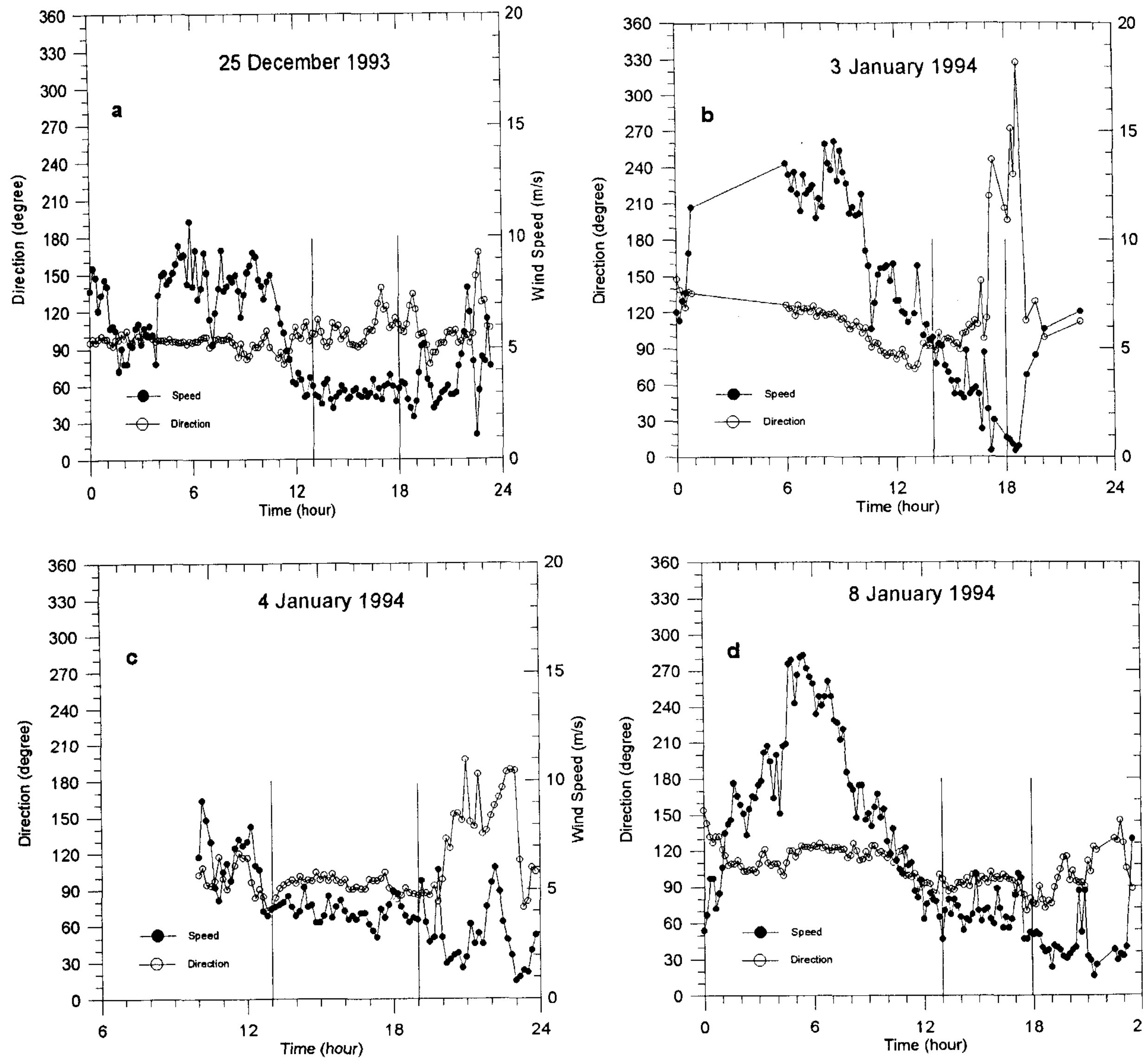

Fig. 3. Wind speed and wind direction as a function of time for days **a.** 25 December, **b.** 3 January, **c.** 4 January, **d.** 8 January. In each day the vertical bar indicates the period during which convective activity was observed.

Heat flux profiles from sodar measurements

To estimate the surface heat flux we used the Turbulent Kinetic Energy (TKE) budget equation. During convection, the most important terms of TKE generation are the shear and thermal production terms. Weill *et al.* (1980), and Greenhut & Mastrantonio (1989) showed that in a well mixed boundary layer, where the shear production may be considered negligible in the TKE budget, the variance of the vertical velocity σ^2_w, is related to the virtual potential temperature heat flux profile by the following:

$$\frac{\sigma_w^3}{z} = \beta \frac{g\left(w'\theta_v'\right)}{\theta_v}, \qquad (1)$$

where $(w'\vartheta_v')$ is the kinematic heat flux, β (= 1.66) is a constant, g is acceleration due to the gravity, ϑ_v the virtual potential temperature, w' and ϑ_v' are the vertical velocity and the virtual potential temperature fluctuations. The kinematic heat flux at the surface $(w'\vartheta_v')_0$ and then the surface heat flux $H_0 = \rho c_p (w'\vartheta_v')_0$ can be derived by extrapolation of the linear part of the $w'\vartheta_v'$ profile given in equation (1).

The vertical velocity variance profiles was derived using the data of the vertical pointing antenna of the sodar. An underestimation in σ^2_w generally occurs due to the inability of sodar to cover all the vertical velocity spectrum and due to the pulse volume filtering of velocities associated with eddies smaller than the pulse volume. However, this underprediction during free convection can be neglected since the large-scale eddies dominate the spectrum (Venkatesan *et al.* 1995, Melas

https://doi.org/10.1017/S0954102099000127 Published online by Cambridge University Press

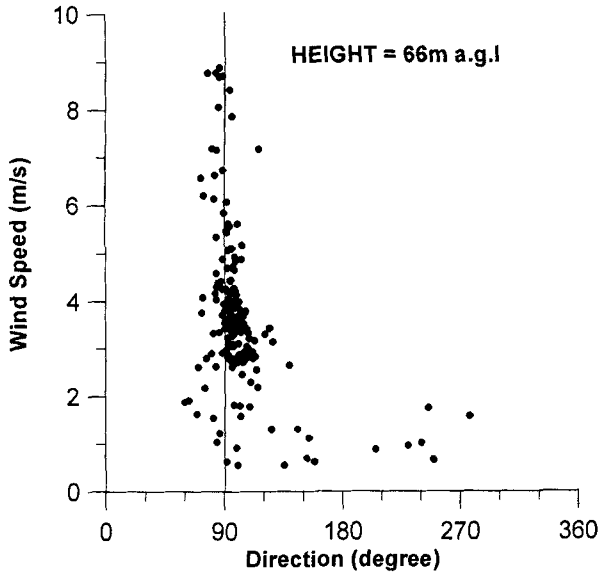

Fig. 4. Scatter plot of wind speed versus wind direction for days 25 December and 3, 4 & 8 January. The wind generally blows from the East and the speed is always lower than 10 m s^{-1}.

1993, Giannini *et al.* 1997). The 1-hour profiles of σ^2_w have been computed for all the range gates in which the number of significant values was greater than 75% for at least the first 4–5 range gates. The evolution of the surface heat fluxes for 25 December and 3, 4 and 8 January are presented in Fig. 5. On these days the surface heat flux ranged between 30 and 90 W m^{-2}, with the maximum reached between 13h00 and 16h00 LT, that is, during the hour of maximum insolation. On 8 January the computation of the fluxes was not possible before 14h00 because of the lack of sufficiently intense convective activity before this time.

Turbulent exchange coefficient derived by combining sodar and tethersonde measurements

The turbulent exchange coefficient for heat K_h was computed from both sodar and tethersonde data. The turbulent heat flux is given by (Stull 1989)

$$H = -\rho c_p K_h \frac{\partial \vartheta_v}{\partial z},$$

where ρ is the density of air, c_p is the specific heat at constant pressure, K_h is the turbulent eddy diffusivity for heat, and $(\partial \vartheta_v / \partial z)$ is the virtual potential temperature gradient.

Using the surface heat flux values of Fig. 5 at the times when the balloon soundings are available, K_h can be estimated from the lapse rate given by the tethersonde. In Fig. 6a K_h is given as a function of the surface heat flux. The value of this coefficient shows only a weak dependence on H.

Plotting H as a function of the $(\partial \vartheta_v / \partial z)$ (Fig. 6b) a regression slope H = -284.676 $(\partial \vartheta_v / \partial z)$ (bold line in the figure) with a correlation coefficient of 0.98 is obtained. The slope gives a value of K_h = 0.23 m^2 s^{-1}, while the standard deviation is σ = 0.03 m^2 s^{-1}. To estimate the error that may occur from an incorrect choice of K_h, the surface heat fluxes in correspondence to K_h = 0.23 m^2 s^{-1} and within ± 1 σ interval (line corresponding to K_h = 0.26 m^2 s^{-1} and K_h = 0.20 m^2 s^{-1}) are shown. In all cases, the uncertainty is less than 25%. The value of K_h found with this method is in agreement with the eddy diffusivity value suggested by Stellers (1965) and by Yague & Cano (1994) for the convective surface layer.

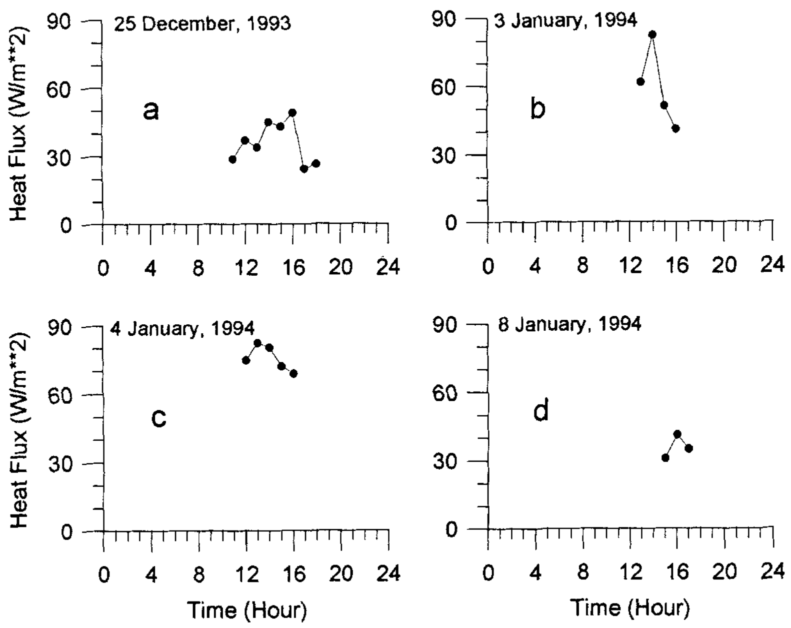

Fig. 5. Surface heat fluxes computed for **a.** 25 December, **b.** 3 January, **c.** 4 January, **d.** 8 January, using the variance method.

https://doi.org/10.1017/S0954102099000127 Published online by Cambridge University Press

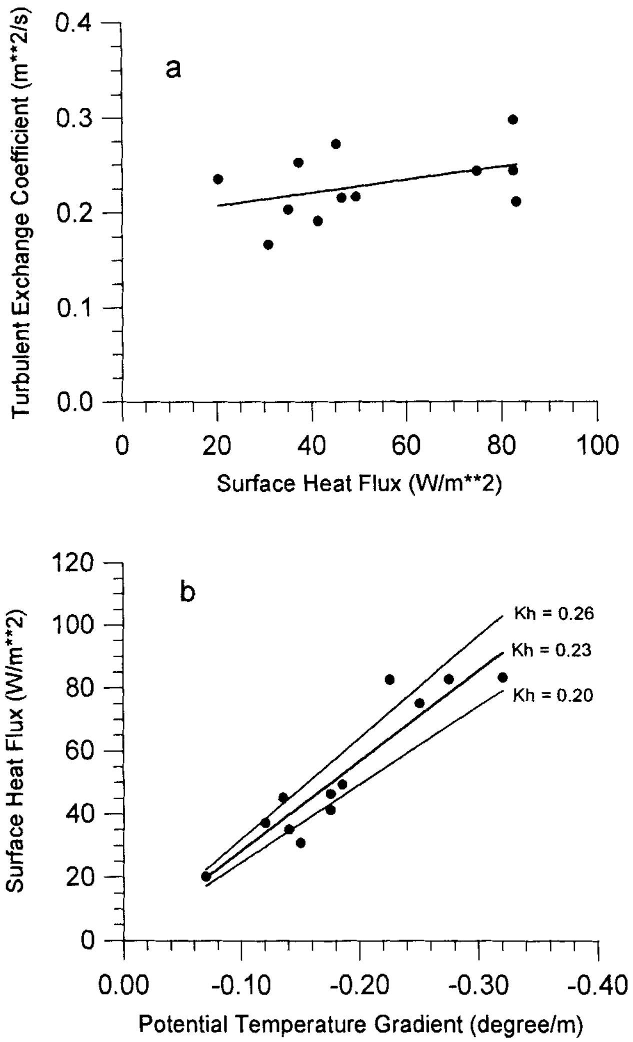

Fig. 6. a. Turbulent exchange coefficients versus surface heat flux. **b.** Surface heat flux versus potential temperature gradient. The experimental data as well as the best fit to these data are given. A value of $K_h = 0.23$ m^2 s^{-1} is obtained from the straight line angular coefficient. The fluxes were computed for $K_h = 0.23 \pm 1\sigma$ m^2 s^{-1}.

Summary and discussion

A description of some characteristics of the convective boundary layer for a coastal region of Antarctica was given. The convection mostly occurs in the summer period when the wind is from the east, the main direction for the circulation in this area when high pressure system dominates and the wind velocity is lower than 5–6 m s^{-1}. Stronger wind speeds distort the convective plumes and we can often observe the rising of "convective like" structures due to the forced convection, i.e. shear in the boundary layer mixing air with different densities. The surface heat fluxes, estimated using sodar data, show a correlation with insulation. The turbulent exchange coefficient, computed using the gradient of the virtual potential temperature and the fluxes estimated by sodar data, gave a value of K_h = 0.23 ± 0.03 m^2 s^{-1}, in agreement with that given by Stellers 1965.

The values of the thermal exchange coefficients we derived cannot be used to evaluate the eddy transfer of heat for the stable regions of the inner Antarctic continent as they were derived for the unstable boundary layer. However it is likely that our results may find general application over other snow surfaces during the summer when in the presence of low wind speeds.

The present work was carried out using the data that were available from our field experiment. It is to be hoped that, if other similar campaigns are funded, direct measurements obtained by eddy correlation techniques will be used for comparison.

Acknowledgements

The authors are thankful to Dr P. Pettré, G. Dargaud of IFRTP and the station personnel of Dumont d'Urville for their collaboration and co-operation during the special observation period. We would also like to thank Dr I. Petenko for providing useful comments to this paper. Special thanks go to Dr P. Anderson for several helpful suggestions that greatly helped in improving this paper. The reviewers provided helpful suggestions for improving the earlier version of this manuscript. The project has been supported by Italian PNRA.

References

Angevine, W.M., Doviak, R.J. & Sorbjan, Z. 1994. Remote sensing of vertical velocity variance and surface heat flux in a convective boundary layer. *Journal of Applied Meteorology*, **33**, 977–983.

Argentini, S. & Mastrantonio, G. 1994. Barrier winds recorded during two summer campaigns and their interaction with the katabatic flows as observed by a triaxial Doppler sodar. *International Journal of Remote Sensing*, **15**, 455–466.

Argentini, S., Mastrantonio, G., Fiocco, G. & Ocone, R. 1992. Complexity of the wind field as observed by a sodar system and by Automatic Weather Stations on the Nansen Ice Sheet, Antarctica, during summer 1988–89: two cases studies. *Tellus*, **44B**, 422–429.

Argentini, S., Mastrantonio, G., Viola, A., Pettré, P. & Dargaud, G. 1996. Sodar performance and preliminary results after one year of measurements at Adélie Land coast, East Antarctica. *Boundary Layer Meteorology*, **81**, 75–103.

Casadio, S., Di, A.S., Fiocco, G., Fuá, D., Lena, F. & Rao, M. 1996. Convective characteristics of the nocturnal urban boundary layer as observed with Doppler sodar and Raman Lidar. *Boundary Layer Meteorology*, **79**, 375–391.

Culf, A.D. 1989. Acoustic sounding of the atmospheric boundary layer at Halley, Antarctica. *Antarctic Science*, **1**, 363–372.

Gera, B.S., Argentini, S., Mastrantonio, G., Viola, A. & Weill, A. 1998. Characteristics of the boundary layer thermal structure in a coastal region of Adélie Land, East Antarctica. *Antarctic Science*, **10**, 89–98.

Giannini, L., Argentini, S., Mastrantonio, G. & Rossini, L. 1997. Estimation of flux parameters from sodar wind profiles during a field experiment in the Tyber valley. *Atmospheric Environment*, **31**, 1307–1313.

GREENHUT, G.K. & MASTRANTONIO, G. 1989. Turbulence kinetic budget profiles derived from Doppler sodar measurements. *Journal of Applied Meteorology*, **28**, 99–106.

KING, J.C. & ANDERSON, P.S. 1994. Heat fluxes and water vapor fluxes and scalar roughness lengths over an Antarctic Ice shelf. *Boundary Layer Meteorology*, **69**, 101–121.

MASTRANTONIO, G. & FIOCCO, G. 1982. Accuracy of wind velocity determinations with Doppler sodars. *Journal of Applied Meteorology*, **21**, 820–830.

MASTRANTONIO, G. & ARGENTINI, S. 1997. A modular PC-based multiband sodar system. *In* SINGAL, S.P., *ed. Acoustic sounding and applications*. New Dehli: Narosa Publishing House, 105-116.

MELAS, D. 1990. Sodar estimate of surface heat flux and mixed layer depth compared with direct measurements. *Atmospheric Environment*, **24A**, 2847–2853.

MELAS, D. 1993. Similarity methods to derive turbulence quantities and mixed layer depth from sodar measurements in the convective boundary layer: a review. *Applied Physics*, **B57**, 11–17.

NAITHANI, J. & DUTTA, H.N. 1995. Acoustic sounder measurements of the planetary boundary layer. *Boundary Layer Meteorology*, **76**, 199–207.

PETTRÉ, P., RENAUD, M.F., DÉQUÉ, M., PLANTON, S. & ANDRÈ, L.J.C. 1990. Study of the influence of katabatic flows on the Antarctic circulation using GCM simulations. *Meteorology & Atmospheric Physics*, **43**, 187–195.

STEARNS, C.R. & WEIDNER, G. 1993. Sensible and latent heat flux estimates in Antarctica. *Antarctic Research Series*, **61**, 109–138.

STELLERS, W.D. 1965. *Physical climatology*. Chicago: University of Chicago Press, 272 pp.

STULL, R. 1989. *An introduction to boundary layer meteorology*. Dordrecht: Kluwer Academic Publishers, 666 pp.

WEILL, A., KLAPISZ, C., STRAUSS, B., BAUDIN, F., JAUPART, C., VAN GRUNDERBEECK, P. & GOUTORBE, J.P. 1980. Measuring heat flux and structure functions of temperature fluctuations with an acoustic Doppler sodar. *Journal of Applied Meteorology*, **19**, 199–205.

VENKATESAN, R., SITARAMAN, V. & MANJU, M. 1995. Estimation of the atmospheric surface layer parameters and comparison with sodar observations. *Atmospheric Environment*, **29**, 3325–3331.

YAGUE, C. & CANO, J.L. 1994. The influence of stratifications on heat and momentum turbulent transfer in Antarctica. *Boundary Layer Meteorology*, **69**, 123–136.