Evidence of Very Shallow Summertime Katabatic Flows in Dronning Maud Land, Antarctica

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ABSTRACT

The three-axis “Latan-3” Doppler sodar was operated near the Finnish Antarctic station Aboa in Dronning Maud Land (73.04°S, 13.40°W) in the austral summer of 2010/11. The measuring site is located at a practically flat, slightly sloped (about 1%) surface of the glacier. The sodar was operated in multiple-frequency parallel mode with 20–800-m sounding range, 20-m vertical resolution, and 10-s temporal resolution. To reveal the wind and temperature profiles below the sounding range as well as turbulent fluxes at 2 and 10 m, the data from a 10-m meteorological mast were used. During the measurements, the atmospheric boundary layer was within the sounding range of the sodar most of the time. Despite a large variety of observed sodar echo patterns and wind speed profiles, several cases of clear steady katabatic flows were observed. Practically all of them were easterly, whereas the uphill direction is southern. The thickness of the katabatic flow varied from a few tens to several hundreds of meters; the wind speed maximum could be as low as 5 m. Thin katabatic flows had lower wind speed and much stronger temperature gradients (up to 1 K m⁻¹) but had smaller surface heat flux than did the thicker ones.

1. Introduction

Katabatic winds are airflows that occur above a cold sloped surface. They are driven by gravity that causes colder and more dense air masses to move downhill. As velocity increases, the Coriolis force declines the flow from the downhill direction. As was done in Vihma et al. (2011), we define the katabatic wind as a downslope wind initially generated by surface cooling.

The katabatic winds occur near a surface in the stably stratified atmospheric boundary layer (ABL) and have maxima in a range from a few meters (Barry 2008) to a few hundreds of meters (Argentini et al. 1996). This makes a sodar a convenient tool to observe them.

Below we show a few examples of katabatic flows observed with a sodar and a meteorological mast near the Finnish Antarctic station Aboa during the summer campaign in December 2010–January 2011 and discuss the features of the flows and their implications for meteorological modeling. The paper is an extended version of the authors’ contribution to the 2012 International Symposium for the Advancement of Boundary Layer Remote Sensing (ISARS-2012; Kouznetsov et al. 2012).

2. Measuring site and equipment

The Aboa station is located at Basen nunatak in west Dronning Maud Land (Fig. 1). The measurements were...
carried out at a practically flat snow surface about 10 km southeast of the station (73.11°S, 13.17°W). The inclination of the surface around the measuring site is about 10 m km\(^{-1}\). The surface is practically homogeneous for more than 100 km in the southeastern sector of the measuring site; therefore, the katabatic flows (mostly from the east) can be considered to be undisturbed. The measuring site was equipped with a sodar, a meteorological mast, a snow-temperature profiling system, and a tethered balloon system. Also, various snow measurements were carried out. Only the data of the sodar and of the meteorological mast are used for this study.

### a. Mast

A 10-m meteorological mast was erected at the measuring site to provide the measurements in a surface layer. The mast was equipped with Campbell Scientific, Inc., 107-type temperature probes at five levels (0.5, 1.2, 2.4, 4.7, and 10 m); 2D Gill Instruments, Ltd., WindSonic anemometers at the same five levels; a Kipp and Zonen, Inc., model CNR4 radiation budget probe at 2 m; a Vaisala, Inc., HMP45AC temperature and humidity probe at 2 m, and two Campbell Scientific model CSAT3 3D sonic anemometers at 2 and 10 m.

The data of the temperature, humidity, and radiation sensors were acquired, preprocessed, and stored by means of a Campbell Scientific model CR3000 datalogger with 10-min averaging time. The raw data from anemometers were acquired by the sodar computer and were processed offline. The 2D anemometers were sampled at 4 Hz, and the 3D anemometers were sampled at 20 Hz. The turbulent statistics in this study are made with 10-min block averages. The turbulent fluxes were calculated in streamwise coordinates obtained with the double-rotation method (see, e.g., Rebmann et al. 2012). The momentum flux was calculated as a component of the Reynolds stress in the direction of the mean velocity vector. No corrections for the effect of humidity fluxes were applied in this study. We estimated them to be less than about 15%, which we consider to be insignificant for the qualitative consideration below.

### b. Sodar

We used the 3-component Doppler sodar “Latan-3m” developed at the A.M. Obukhov Institute of Atmospheric Physics in Moscow, Russia (Kouznetsov 2007). The sodar was operated nearly continuously from 17 December 2010 to 22 January 2011. During the operation time, most of the data losses were due to strong winds causing noise and also to power failures. No major problems caused by sound attenuation, experienced with a single-antenna version of Latan-3m in Antarctica earlier (Kouznetsov 2009a), were found because of the lower frequencies used and the higher humidity.

The sodar was operated with three 1.2-m dish antennas at sounding frequencies of 1.6–2.2 kHz. The operating mode with frequency-coded sounding pulse (Kouznetsov 2009b) and the parallel operation of the antennas were used to achieve high temporal resolution. The different frequency codings were used for the antennas to avoid cross talk: each antenna used an individual set of six frequencies emitted as a series of 100-ms pulses, which resulted in 20-m vertical resolution. The antennas were mounted on wooden stands drilled into the hard snow surface, one vertically pointing and three inclined to 30° off zenith with azimuths 190° and 275°. The sounding interval was 10 s, and the sounding range was 20–800 m. Acoustic shields, needed to suppress the side lobes of the antennas and to protect the transducers from the wind-induced noise, were constructed from snow blocks (Fig. 2).

In Latan-3 sodars, the echo signal from each sounding is processed separately. The information on instantaneous signal and noise intensities and an along-beam velocity component are stored for each range gate. During the campaign, the raw echo signals were stored as well for further reprocessing, should it be necessary.

### 3. Results

During the measurements, the net radiation flux under clear sky had a pronounced diurnal cycle from about \(-60\) W m\(^{-2}\) during nighttime to \(+200\) W m\(^{-2}\) at solar noon (1300 UTC). The steady katabatic flows were observed practically every cloudless night and lasted typically from about 2200 until 1000 UTC. Thus,
the appearance of katabatic flow had about 3 h of hysteresis with respect to the radiative forcing.

The thickness of the katabatic flows varied from 5 to 100–200 m above the surface. In most cases, the katabatic flows were interacting with synoptic-scale phenomena, producing a complex and variable structure of the ABL (Fig. 3). Echograms show a qualitative pattern of the mixing intensity within the sounding range. The majority of wind profiles and corresponding sodar echogram patterns observed during the campaign could hardly be classified into a small number of simple types. The example in Fig. 3 shows the echogram and wind profiles during the passage of a warm microfront (at 0245 UTC).

Below we consider three of about a dozen clear cases of steady katabatic flows observed during the campaign (Fig. 4). All three cases were observed under clear sky and very weak wind in the free troposphere (<2 m s⁻¹) but showed different heights of a jet core and different thicknesses of a mixed layer above the core.

When the katabatic layer is deep enough it clearly appears in the sodar data. In the case of 0200–0300 UTC 31 December 2010, when the stratification turned stable after a cloudy midnight, the core was formed at the height of 200 m. Then the core height decreased until 0600 UTC. After then the conditions remained steady for about 5 h (Fig. 4a). The wind speed increases with height at the ground and then gradually decreases to nearly zero above the flow core. The turbulent mixing occurs both below and above the wind speed maximum, resulting in a strong return signal that decreases with height above the jet core as well. At the jet core the mixing is much weaker, which is seen as a reduction of sodar backscattering around the velocity maximum. The echogram also reveals an oscillating pattern with a period of 3–5 min after 0930 UTC that indicates an unsteadiness of the flow before its break up. A directional shear can be noted above the jet core; it can be attributed to the transition to the free flow above the jet. The sensible heat flux is practically the same at the heights of 2 and 10 m, whereas the magnitude of the...
momentum flux decreases with height by less than 30% on average. The nearly constant warming rate was accompanied by a linear change of the surface heat flux, weakening the stability of the near-surface layer. The flow persisted for several hours and broke up when the period of stable stratification at the surface was over.

The second case (15 January; Fig. 4b) is a shallower katabatic flow with a core height of about 10–20 m. The parameters of the core were practically steady for a few hours. The sodar echogram indicated a mixing in the upper part of the flow. The decrease of the echo intensity around the core is practically undetectable, probably because of the insufficient resolution of the sodar. As in the previous case, the mast temperature profile is nearly linear with height, with a lapse rate of about \(2.1 \text{ K m}^{-1}\). The sensible heat flux is practically the same at 2 and 10 m, whereas the momentum flux is 2 times as strong at 2 m. Assuming a linear decrease of the momentum flux with height, one can conclude that the jet core is at 20 m, which agrees with the wind data.

The third case (16 January; Fig. 4c) is a very shallow katabatic flow. It can hardly be detected by the sodar data, since it was well below the sounding range, but is clearly seen in the mast wind records. As in the previous case, the flow was fairly steady within a few hours (0230–0530 UTC). The wind speed was about one-half of that in previous cases and had a maximum at around 5 m. The directional shear is clearly seen within the mast range; as in the first case, it is caused by the transition to the flow above the jet. The temperature profile has a sharp increase around the jet core with a lapse rate of at least \(-1 \text{ K m}^{-1}\). The turbulent fluxes drastically differ between 2 and 10 m. The heat flux, despite a large temperature gradient, is weaker than in the previous case and nearly vanishes at 10 m. The momentum fluxes are very small and have opposite signs above and below the flow core.

4. Discussion and conclusions

Several general features of the observed katabatic flows can be noticed. First, the direction of the katabatic winds is eastern, whereas the uphill direction is southern. Such behavior can be clearly attributed to the Coriolis force that acts as an equilibration factor providing a feedback that maintains a steady jet speed (e.g., Mahrt 1982). This situation is analogous to the pressure-gradient-driven winds that tend to turn along the isobars. Also, friction plays a role in both cases.
Second, the heat flux ceases at very high temperature gradients. This effect is caused by suppression of turbulence under strong static stability and has been pointed out in many studies (e.g., van de Wiel et al. 2007; Vihma et al. 2009).

Third, the vertical structure of heat and momentum fluxes is different. This makes traditional definitions of the planetary boundary layer (PBL) inapplicable for the considered flows. The PBL height would be very different depending on the turbulence parameter at which we are looking. The sodar data reveal steady wind profiles lasting for up to 10 h, which indicates the equilibrium state of the flow. Since there is no sink of momentum above the jet core, one can conclude that the momentum flux there is much smaller than below the core. Thus the PBL height in terms of the momentum flux would be at the jet core height. However, the sodar echograms and the heat flux time series clearly show that the heat flux is still significant above the jet core. The observed vertical variations in turbulent fluxes within the mast range clearly indicate that meteorological models that use the constant-flux assumption up to heights above a few meters are inapplicable over slightly sloping terrains.

Fourth, the observed cases of katabatic winds show that the same radiative cooling might result in different thickness of katabatic flow depending on the flow history. Thinner katabatic flows have lower wind speed and weaker near-surface mixing, which results in stronger near-surface temperature gradients but smaller heat fluxes.

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REFERENCES


