Observation of Kelvin-Helmholtz and propagating buoyancy waves in the Antarctic with the help of sodar and microbarograph

D V Zaitseva¹ and R D Kouznetsov¹,²
¹ A.M. Obukhov Institute of Atmospheric Physics RAS, Moscow, Russia
² Finnish Meteorological Institute, Helsinki, Finland
E-mail: zaycevadv@gmail.com

Abstract. Internal gravity waves of different types are frequently observed in the stable atmospheric boundary layer. The most common way to study the waves is analysis of pressure records. Remote sensing techniques also can be used to observe the waves and to estimate their parameters. We used synchronous sodar and microbarograph records obtained during austral summer at the Antarctic Finnish station Aboa (73.04° S, 13.40° W). Among six wave episodes of different types visible on sodar echograms there was only one in which corresponding pressure oscillations with nearly constant amplitude were present. For three episodes there were pressure oscillation with varying amplitude seemed to be associated with the waves visible on the echograms. For two cases corresponding pressure oscillations were absent.

1. Introduction
Internal gravity waves (IGWs) are frequently observed in the atmospheric boundary layer (ABL). IGWs can be divided into two types by the mechanism of generation: internal gravity-shear waves (IGSW) and horizontally propagating buoyancy waves (PBW) (Gossard and Hooke 1975).

Ground-based remote sounding of the atmospheric boundary layer by acoustic and electromagnetic waves makes it possible to observe IGWs in the refractive index and/or wind speed field. IGSWs in the field of $\frac{\partial n}{\partial z}$ are often observed as periodic structures embedded into inversion layer (e.g. Blumen et al. 2001, Lyulyukin et al. 2015, Petenko et al. 2016). PBWs manifest themselves in the refractive index field in the form of undulation of boundary of inversion layers and in the field of the wind speed in the form of periodic upward and downward air currents (e.g. Petenko et al. 2012, Banakh et al. 2016). Remote sounding techniques allow not only to register IGWs and distinguish between IGSWs and PBWs, but also to estimate depth, arrangement and temporal evolution of the wave layer and calculate the period of waves.

At the same time the most common way to study IGWs in the ABL is analysis of microbarograph records (e.g. Anderson et al. 1992, Essex and Love 1978). Microbarograph data allow to calculate period and amplitude of pressure variations associated with the waves passing above the measuring point. Also the pressure variations can be used as a reference oscillator to separate wave and turbulent fluctuations of wind and temperature (Finnigan 1988). Array composed of at least three microbarographs allows to calculate speed and direction of propagation of wave trains.
Joint analysis of remote sensing and microbarograph records to study IGWs in the ABL was presented in a number of papers (e.g. Gossard et. al. 1970, Hooke et. al. 1972, Hooke et. al. 1973, Einaudi and Lalas 1978, Einaudi and Finnigan 1993, Reddy and Kumar 1998). This approach allows to obtain more information about IGWs.

The aim of this work is to compare a vastness of information about IGWs in the ABL obtained by sodar and microbarograph. The examples of simultaneous sodar and microbarograph records during passage of waves of different types are presented in the next Section.

2. Measurements and Results

Synchronized network of Doppler sodars (Kouznetsov 2009) and microbarographs was operating for 1.5 months during antarctic summer at Finnish station Aboa (73.04° S, 13.40° W), 2014-2015 (Kouznetsov et al. 2015). The station is located at practically flat slightly sloped surface of glacier in Queen Maud Land at about a hundred kilometers from the coast (Kouznetsov et al. 2013).The network consisted of 3-axis Latan-3 sodar and 3 vertically pointed 1-axis Latan-3M sodars. Each of vertical sodars was supplemented with a microbarograph. The vertical sodars were placed in a vertices of a triangle, each of them was located at a distance of 200 meters from 3-axis sodar. The 3-axis sodar was providing the data on the wind speed and the return-signal intensity with temporal and vertical resolution respectively 6 seconds and 20 meters, up to altitude of 720 meters. The vertical sodars were providing data on the vertical wind speed and the return-signal intensity with temporal and vertical resolution respectively 3 seconds and 10 meters for altitudes up to 340 meters.

Echograms with wave episodes found on them were analyzed jointly with barograms. Identification of a wave type was based on both vertical structure (visible on echograms) and character of vertical profiles of the wind speed. For each episode we present data of only one of vertical sodars and corresponding microbarograph. Since vertical sodars were providing only vertical component of the wind speed, there are presented the wind speed profiles obtained by 3-axis sodar on the figures.

We divided episodes into two types according to those mentioned above. Episodes I-IV (Fig.1 and 2) were referred as IGSWs. In all of these cases vertical wind shear had absolute values in the range 0.04-0.1 s$^{-1}$. These episodes are alike waves presented in Zaitseva et al. 2018, but have another vertical structure visible on echograms. Episodes V(Fig.3) and VI(Fig.4) are clearly visible on echograms as undulation of layers of increased backscatter intensity, so they were referred as PBWs. In both cases wind varied with the height only slightly.

During episodes 1 and 2 the stratification of the ABL was stable, the sky was clear, and synoptic wind blew from NEE. Episode 3 was accompanied with anticyclonic weather and weak synoptic wind. During episode 4 there was active cooling and southern synoptic wind. Episodes 5 and 6 were accompanied with small cloudiness and weak synoptic wind.

An episode I shown on the Fig. 1a occurred between 5 and 6 a.m. on 24 December, 2014. Periodic structures in the form of ”breaking waves” were observed within the layer of approximately 150 meters depth. The time period of these motions varied from 3 to 2 minutes. Also there are seen corresponding pressure variations with magnitude varying from 2-3 to 10 Pa on the barogram. The vertical wind shear within the wave layer was near 0.04 s$^{-1}$.

Fig. 1b shows an episode II observed later on the same day, 24 December 2014, which also resembles ”breaking waves”. The depth of the wave layer varied from 100 to 180 meters. At least 5 cycles of the wave train with slightly varying time period (2 minutes) are clearly seen on the echogram. Correspondent oscillations of pressure were not so apparent, and those that may be connected with this wave train did not exceed 5 Pa. Vertical wind shear during the episode had values up to 0.06 s$^{-1}$.

Periodic structures in the form of inclined strips embedded into the inversion layer (episode III) observed at about 3 oclock in the morning on 29 December, 2014, are shown on the Fig.
Figure 1. Episodes I (a) and II (b). Panels from top to bottom: 1) echogram obtained by vertically pointed minisodar in time-height axis, color denotes intensity of echosignal I, dB; 2) barogram obtained by microbarograph located near corresponding minisodar, Pa; 3) vertical profiles of wind speed (green) and direction (purple and blue) obtained by 3-axis sodar, averaged over 10 minutes.

2a. From 2:50 to 03:10 the period of the wave was about 2 minutes. Although these periodic structures are slightly less apparent than those shown on the Fig.1, it is still possible to discern them on the echogram. Nevertheless there are not apparent pressure oscillation on the barogram. In the layer occupied with the wave train wind shear was about $-0.04 \ \text{s}^{-1}$ (wind speed decreased with the height).

Due to indiscernible vertical structure, an example shown on the Fig. 2b is ambiguous for its type identification. Although wind shear within the wave layer was up to $0.09 \ \text{s}^{-1}$, the wave train resembles undulating of the top of the inversion layer. Amplitude (peak to peak) did not exceed 120 meters. The period was less than 1 minute, oscillations lasted for many periods. There are apparent pressure oscillations with magnitude of 3-5 Pa corresponding to layer undulations on the barogram.

Fig. 3 shows part of PBW train, episode V. This wave is seen on the echogram as an oscillation of the altitude of the layer arranged above convective plumes. Period of the PBW was about 10 minutes. There are only 4 periods visible on the echogram. Although magnitude of variations of the layer altitude attained 100 meters, there are only two discernible cycles of pressure variations which seem to be connected with PBW train. Convective plumes being present under the undulating layer can result in the absence of distinct oscillations of pressure with corresponding period. Wind shear within the wave layer was less than $0.02 \ \text{s}^{-1}$.

Another example of PBW is shown on the Fig. 4. The episode VI is manifested in the form of the undulating layer of the 30-50 meter thickness. The magnitude of oscillations of the height of arrangement of this layer was from 40 to 70 meters. While period of the layer arrangement oscillations was near 7 minutes, the only apparent oscillations of pressure had period of 15 minutes with amplitude (peak to peak) up to 5 Pa. We cannot surely state the cause of these pressure oscillations. Wind shear within the wave layer was less than $0.02 \ \text{s}^{-1}$. 
3. Conclusions
This study was aimed at the comparison of a vastness of information about internal gravity waves in the stable atmospheric boundary layer obtained by sodar and microbarograph. For this purpose we preformed joint analysis of sodar and microbarograph data obtained at Antarctic station during austral summer in 2014-2015. There are presented six wave episodes in the Section 2. Four of these episodes were accompanied with the large vertical wind shear and
Figure 4. Episode VI. The panels are the same as on the Fig.1

resembled "breaking waves", "inclined strips" or had indiscernible structure in the refractive index field. These were referred to episodes of internal gravity-shear wave type. Also two cases of horizontally propagating buoyancy wave type manifested themselves as undulating layers were presented. Both of them were accompanied by the vertical wind shear less than 0.02 $^{-1}$.

Only for one case with indiscernible structure there were corresponding pressure oscillations with almost constant amplitude and time period. For two cases of "breaking waves" the pressure variations persisted only for several cycles and had varying amplitude. For one case of propagating buoyancy wave there also seemed to be correspondent pressure variations. During other two cases including "inclined strips" and buoyancy waves there were not corresponding pressure oscillations at all. Also for two cases of six (with indiscernible structure and inclined strips) there were pressure fluctuations with period less than 1 minute. Meantime during other episodes there were not pressure variations with high frequency.

We see that the period of waves observed by sodar and microbarograph may differ, moreover, waves registered on echograms not always visible on barograms. Therefore microbarograph records should be supplemented with remote sounding data for investigation waves in the ABL, otherwise it will reduce the amount of registered waves.

Acknowledgments

The work was supported by Russian Foundation for Basic Researches, Grant NoNo 16-05-01070 and 19-05-01008. Authors thank M.A. Kallistratova for her attention to the work and useful discussions.

References

[1] Anderson P S, Mobbs S D, King J C, McConnell I and Rees J M 1992 Antarctic Science 4 241-8
[2] Banakh V A and Smalikho I N 2016 Atmos. Meas. Tech. 9 5239-48
[3] Blumen W, Banta R, Burns S, Fritts D, Newsom R, Poulos G and Sun J 2001 Dynam. Atmos. Oceans 34 189-204
[4] Einaudi F and Finnigan J J 1993 J. Atmos. Sci. 50 1841-64
[5] Einaudi F, Lalas D P and Perona G E 1978 G.E. PAGEOPH 117 627-63
[6] Essex E A and Love G B 1978 Journal of Geophysical Research 83 1883-8
[7] Finnigan J J 1988 J. Atmos. Sci. 41 2409-36
[8] Gossard E E and Richter J H 1970 Journal of Geophysical Research 75 3523-36
[9] Gossard E E and Hooke W H 1975 Waves in the Atmosphere: Atmospheric Infrasound and Gravity Waves Their Generation and Propagation (Elsevier)
[10] Hooke W H, Young J M and Beran D W 1972 Boundary-layer Meteorol. 2 371-9
[11] Hooke W H, Hall F F and Gossard E E 1973 Boundary-Layer Meteorol. 5 29-41
[12] Kouznetsov R D 2009 Meteorologische Zeitschrift 18 169-73
[13] Kouznetsov R, Tisler P, Palo T and Vihma T 2013 Journal of Applied Meteor. and Climatology 52 164-8
[14] Kouznetsov R D, Tisler P and Vihma T 15th EMS Annual Meet., 0711 Sept 2015, Sofia, Bulgaria. Paper EMS2015. 281.
[15] Lyulyukin V S, Kallistratova M A Kouznetsov R D 2015 et al. Izv. Atmos. Ocean. Phys. 51 193
[16] Petenko I, Mastrantonio G, Viola A, Argentini S and Pietroni I 2012 Boundary-layer Meteorol. 143 125-41
[17] Petenko I., Argentini S, Casasanta G, Kallistratpva M, Sozzi R and Viola A 2016 Boundary-Layer Meteorol. 161 289-307
[18] Reddy K K, Kumar T R V, Rao S V B, Kishore P and Rao D N 1998 Indian Journal of Radio and Space Physics 27 247-59
[19] Zaitseva D V, Kallistratova M A, Lyulyukin V S, Kouznetsov R D and Kuznetsov D D 2018 Izv. Atmos. Ocean. Phys. 54 173-81