Profiles of Wind Speed Variances within Nocturnal Low-Level Jets Observed with a Sodar

MARGARITA A. KALLISTRATOVA
A. M. Obukhov Institute of Atmospheric Physics, Moscow, Russia

ROSTISLAV D. KOUZNETSOV
Finnish Meteorological Institute, Helsinki, Finland, and A. M. Obukhov Institute of Atmospheric Physics, Moscow, Russia

VALERII F. KRAMAR AND DMITRII D. KUZNETSOV
A. M. Obukhov Institute of Atmospheric Physics, Moscow, Russia

(Manuscript received 1 December 2012, in final form 15 May 2013)

ABSTRACT

Continuous sodar measurements of wind profiles have been carried out at the Zvenigorod Scientific Station of the Obukhov Institute of Atmospheric Physics since 2008. The station is located in a slightly inhomogeneous rural area about 45 km west of Moscow, Russia. The data were used to determine the parameters of wind and turbulence within low-level jets in the stable atmospheric boundary layer (ABL). Along with the mean velocity profiles, the profiles of variances of wind speed components from the sodar and the profiles of temperature from a microwave radiometer have been used to quantify turbulence and thermal stratification. Data from two sonic anemometers were used to get the near-surface parameters.

The typical standard deviation of the vertical wind component $s_w$ within the low-level jet is about 5% of the maximum wind speed in the jet. No noticeable vertical variation of $s_w$ across the jets was detected in several earlier sodar campaigns, and it was not found in the present study. An increase in horizontal variances was detected in zones of substantial wind shear, which agrees with earlier published lidar data.

Quasi-periodic structures in the sodar return signal, which appear in sodar echograms as braid-shaped patterns, were found to emerge preferably when a substantial increase of wind shear occurs at the top of the stable ABL. The braid patterns in the sodar echograms were not accompanied by any noticeable increase of observed $s_w$, which disagrees with earlier data and indicates that such patterns may originate from various phenomena.

1. Introduction

Variances of velocity components can be measured in the atmospheric boundary layer (ABL) with any Doppler device, such as sodar, lidar, and radar. Being the simplest characteristics of turbulence, variances are widely used in the evaluation of wind energy resources and in air pollution meteorology. Experimental data on the variances are especially desired for stable ABLs because of the difficulties in theoretical description and numerical simulations of stably stratified turbulence (Baas et al. 2010).

The low-level jet (LLJ) is a flow, specific to stable ABLs, that has a distinct maximum of wind speed within a few hundreds of meters above ground. LLJs form in stably stratified atmospheres resulting from the small vertical exchange between atmospheric layers that favor the formation of wind shears. LLJs can originate from local circulations because of orography and/or thermal inhomogeneity of the ground surface, from inertial oscillations resulting from the nocturnal ceasing of turbulent exchange, or from the mesoscale baroclinicity.

Because of nonmonotonicity of the wind speed profile, some peculiar vertical profiles of variances of wind
components can be expected. Substantial wind shears within LLJs are subject to shear-flow instability, which can impact the intensity of turbulence and its vertical distribution.

Experimental results on the profiles of wind component variances published by different authors look contradictory. In the last decade, turbulence parameters within the LLJ have been intensively explored with a high-resolution Doppler lidar (HRDL; Banta et al. 2002, 2003, 2006; Banta 2008). The lidar data revealed a local minimum of alongstream velocity variance \( \sigma_u^2 \) in the vicinity of jet stream cores, where the variance drops by a factor of 5–10 with respect to its values below the core. A few papers were published on sodar studies of wind variances within the LLJ (Kallistratova et al. 1985; Coulter 1990; Karipot et al. 2008; Prabha et al. 2008). Unlike the lidar measurements, the data by Kallistratova et al. (1985) and Coulter (1990) did not show any peculiarities in the vertical structure of the standard deviation of alongstream and vertical velocities, \( \sigma_u \) and \( \sigma_w \), respectively, across the LLJ. Moreover, Prabha et al. (2008) reported an increase of both \( \sigma_u \) and \( \sigma_w \) in the vicinity of the LLJ core.

The intensity of sodar return signal in stably stratified ABLs often reveals quite clear quasi-periodic patterns. In plots of the return intensity in time–height coordinates (sodar echograms), these patterns appear as braid shaped or inclined stripes of enhanced echo intensity. In some studies such patterns are associated with Kelvin–Helmholtz billows (Gossard and Hooke 1975). The effect of such structures on variances of wind components in the LLJ has been studied previously, to our knowledge, for only two short episodes of the wave activity: one observed with a sodar (Coulter 1990) and another with a lidar (Blumen et al. 2001; Newsom and Banta 2003). Coulter (1990) reported a doubling of \( \sigma_u \) throughout the whole ABL during wave activity (compared to the preceding quiet period) in a 4-h episode observed over a gently rolling terrain near Chicago, Illinois, on 1 October 1985. Blumen et al. (2001) reported the increase of both streamwise and vertical velocity variances by a factor of 6 or 7 but only within a rather thin layer just below the top of the wave structures. Note that for the mean wind speed in nocturnal LLJs, the statistics obtained by HRDL (Banta et al. 2002) and by a sodar (Kallistratova et al. 2009) are quite similar.

The aim of this work is to study the vertical structure of the velocity variances within LLJs observed with a sodar. The issues to be addressed are as follows:

- The causes of the discrepancies between results of lidar and sodar measurements cited above.
- A connection between wave patterns that appear in sodar echograms and the profiles of variances of the vertical wind component in LLJs.

To address these issues, we have made a classification of the observed LLJ profiles, constructed composite LLJ profiles of wind speed and \( \sigma_w \), and analyzed the vertical and temporal variations of \( \sigma_w \) during the appearance of the braid structures in sodar echograms.

2. Equipment and measurements

For this study we used the data of continuous sodar measurements during 2008–11 at the Zvenigorod Scientific Station (ZSS) of the A. M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences. The ZSS is located in a weakly inhomogeneous rural area 45 km west of Moscow, Russia. The three-axis Doppler sodar Latan-3 (Kouznetsov et al. 2007) has three 1.2-m dish antennas, one vertically pointing and two oblique with zenith-pointing angles of 30° and mutually perpendicular azimuths. The sodar has been operated with a carrier frequency of 2000 Hz, a vertical resolution of 20 m, and the vertical range from 30 to 150–800 m, depending on noise level and weather. The sounding cycle takes 20 s.

The sodar uses pulse-by-pulse signal processing. From each sounding pulse, the along-beam velocity component and the signal and noise levels are evaluated for each range gate. The instantaneous data can be averaged offline to get the horizontal wind speed and direction, and radial wind component variances. The signal-to-noise ratio is used for data plausibility checks and selection of the instantaneous values for averaging.

In this study, we used 30-min averages with less than 75% of the discarded values for mean velocities, and with less than 25% discarded for variances.

The instantaneous values of wind velocity components measured by the sodar are averaged over a large spatial domain (\( \sim 10^3 \) m\(^3\)), so an underestimation of vertical velocity variance can be expected. However, the comparison of 30-min values of sodar Latan-3 and local measurements of \( \sigma_w \) at an altitude of 56 m showed a centralized RMS error of 0.1 m\(^2\) s\(^{-2}\) and a slight positive bias of the same magnitude (Kouznetsov et al. 2007), resulting in a correlation coefficient of 0.94. The bias was found to be a feature of the signal processing routines, thus a corresponding correction is applied for this study.

Despite the fact that the sodar was not calibrated, the return intensity can be used to determine the shapes of vertical profiles of the temperature structure parameter \( C_T^2 \). The latter is a function of eddy dissipation rates for velocity \( \epsilon \) and temperature \( e_T \) [Monin and Yaglom 2007, chapter 8, Eq. (21.87)]:

\[
C_T^2 = \text{constant} \times \epsilon_T \epsilon^{-1/3}.
\]
Thus, profiles of $C_T^2$ provide some information on turbulent mixing. Generally, high values of $C_T^2$ indicate ongoing mixing in the presence of mesoscale temperature inhomogeneities. Below, the range-corrected return intensity, expressed in decibels with respect to some level, is used as a qualitative indicator of mixing.

Auxiliary measurements of ABL temperature profiles were carried out with the Attex meteorological temperature profiler (MTP)-5 microwave radiometer (Kadygrov et al. 2003). The near-surface meteorological and turbulence parameters were measured with two Metek USA-1 sonic anemometers mounted at two masts at heights of 6 and 56 m.

3. Results

The nocturnal LLJ wind speed profiles are rather diverse, and there is no commonly accepted definition of the LLJ. We identified the LLJ by visual inspection of wind profiles according to the following criteria: the maximum wind speed is higher than $3 \text{ m s}^{-1}$, the wind speed decreases above the maximum by at least $1 \text{ m s}^{-1}$, and such a profile is persistent for more than 2 h. Similar criteria were suggested earlier by Banta et al. (2002).

The examples of wind speed profiles measured by the sodar at the ZSS were arranged by the shape and maximum speed. The types are shown in Fig. 1. Note that other kinds of classifications were used in literature as well. Banta et al. (2002) considered the shapes of wind speed profiles regardless of the maximum speed; Baas et al. (2009) classified the LLJs according to the external forcing parameters, whereas we use purely morphological classification.

The types b, f, and j were observed during 68% of winter and 50% of summer nights. They are often, but not always, accompanied by the appearance of distinct
wave patterns in the form of inclined stripes of increased echo signal. In summertime, profiles with a single clearly pronounced maximum (types a, e, and i) were observed in up to 25% of cases. Other cases have more or less the same infrequent occurrence. Profiles of the types c, g, and k occurred in the presence of elevated temperature inversions. The occurrence of the LLJ types for winter and summertime LLJs is summarized in Table 1.

The statistics of the diurnal distribution of LLJs and their heights and speeds were published elsewhere (Kallistratova and Kouznetsov 2012).

### a. Standard deviation $\sigma_w$ within LLJs

The episodes of persistent LLJs with a pronounced maximum (as in Figs. 1a,e,i) were selected by a visual inspection of the sodar echograms. These episodes have been divided into two classes with respect to the bulk Richardson number:

$$
\text{Ri}_B = \frac{g H_{\text{Vmax}}}{\Theta} \left[ \frac{\Theta(H_{\text{Vmax}}) - \Theta(2\text{m})}{V_{\text{max}}^2} \right],
$$

where $\Theta$ is potential temperature; $V_{\text{max}}$ and $H_{\text{Vmax}}$ are the maximum wind speed in the jet and its core height, respectively; and $g$ is acceleration of gravity. The value $\text{Ri}_B = 0.25$ is used to separate classes, as suggested by Banta et al. (2007). The classes are strong deep LLJs with a small temperature gradient and weak shallow LLJs with strong static stability. The example of profiles of these classes is shown in Fig. 2. For both classes, the echo-signal intensity drops by two orders of magnitude at the jet core height, and the temperature profiles remain stable until some height above the jet. The vertical profiles of $\sigma_w$ do not vary much with height within the layer of detectable return signal. No particular features in the $\sigma_w$ profiles appeared at the jet core in either case, as seen in Fig. 2. A similar behavior of $\sigma_w$ in jet profiles was reported by Emeis (2009).

To reveal general features of the vertical profiles of $V$ and $\sigma_w$ for the LLJ cases, we calculated composite profiles, shown in Fig. 3, from the selected 30-min averaged profiles. The 30-min profiles were normalized with $H_{\text{Vmax}}$ and $V_{\text{max}}$. The scaling with friction velocity $u_*,\text{ from a sonic anemometer at 56 m, resulted in much stronger scatter for both } V \text{ and } \sigma_w \text{ profiles, since the decoupling of stable ABL from the surface, which leads}

![Fig. 2. (top) Echograms and (bottom) corresponding mean profiles of wind speed $V$ and $\sigma_w$, acoustic backscattering $I$, and temperature during nocturnal LLJs observed (a) 30 and (b) 4 Aug 2011. Data of sonic anemometers are shown with large symbols. Neutral moist-adiabatic temperature profile $\gamma = -0.005 \text{ K m}^{-1}$ is shown on the temperature profiles at bottom right of (a) and (b).](image-url)
Altitude is normalized on the height of the LLJ core, velocities and standard deviations are normalized by the jet core speed.

to jet formation, makes $u_s$ an inappropriate scaling parameter in such regimes.

For the composite profiles within and above the jet core, $\sigma_w \approx 0.05 V_{max}$. A slight increase of $\sigma_w/V_{max}$ with the scaled height is within statistical uncertainties. We have not noticed any substantial difference in composite profiles between weak and strong stabilities, thus the composite profiles are plotted regardless of stability. Note that Banta et al. (2006) have reported 0.05 for $\sigma_w$ from eight nights in July–August 2011. Altitude is normalized on the height of the LLJ core, velocities and standard deviations are normalized by the jet core speed.

FIG. 3. Composite normalized profiles of $V$ and $\sigma_w$: average of 132 profiles, each 30 min, from eight nights in July–August 2011. Altitude is normalized on the height of the LLJ core, velocities and standard deviations are normalized by the jet core speed.

For the composite profiles within and above the jet core, $\sigma_w \approx 0.05 V_{max}$. A slight increase of $\sigma_w/V_{max}$ with the scaled height is within statistical uncertainties. We have not noticed any substantial difference in composite profiles between weak and strong stabilities, thus the composite profiles are plotted regardless of stability. Note that Banta et al. (2006) have reported 0.05 for $\sigma_w$ from eight nights in July–August 2011. Altitude is normalized on the height of the LLJ core, velocities and standard deviations are normalized by the jet core speed.

b. Wind variances within stable ABLs with braid structures

To reveal the influence of wavelike structures on the wind components' variances, we have selected the sodar echograms with clear braid structures. The structures varied substantially with clarity, amplitude, and temporal scales. Distinct, well-defined braids, such as those seen in Fig. 4, were observed in only several tens of episodes per year. They were usually accompanied by a strong wind shear that occurred in the upper part of the ABL. The shear is defined as $S = [(\partial V_x/\partial z)^2 + (\partial V_y/\partial z)^2]^{1/2}$, where $V_x$ and $V_y$ are two horizontal wind components. For instance, in the case shown in Fig. 4, the direction changed to almost opposite at the height of 400 m. Less distinct braid structures are noticed in about 30% of observed LLJs.

For the case shown in Fig. 4, the patterns in the echogram are most pronounced in the intervals 0200–0230 and 0300–0330 LT. During these events $\sigma_w$ gradually increases with height throughout the ABL from 0.5 to approximately 1 m s$^{-1}$; however, nothing special happens to its profile at the height of a strong wind shear. Some information on the horizontal variances can be inferred from the variances of radial velocities $\sigma_v$ measured with oblique sodar beams (zenith angles of 30°). Normally, fluctuations detected by a tilted beam do not differ much from those measured by the vertical beam. In cases when the corresponding horizontal fluctuations significantly exceed vertical ones, $\sigma_v$ can be used as a proxy of the standard deviation of the corresponding horizontal component.

The profile of standard deviation of the radial velocity $\sigma_1$ in Fig. 4 practically coincides with the profile of $\sigma_w$, except for a local peak at 300 m. The peak is an artifact caused by the fixed-echo suppression algorithm that masks out small velocities for the oblique beams and thus increases the variance when the along-beam wind component $V_1$ is close to zero. The standard deviation of radial velocity $\sigma_2$ in Fig. 4 is up to a factor of 1.5 larger than those of the two other components in the layer 50–300 m, where the corresponding radial velocity has a substantial shear. A drastic increase of $\sigma_2$ around the height of 400 m is clearly connected with the shear of $V_2$. The natural reason for such an increase is the variation of the altitude of the shear zone, so corresponding heights are sampled part time above the shear. The value of $\sigma_2$ gets saturated at the value of 10 m s$^{-1}$, which corresponds to the difference of $V_2$ from below and above the shear.

The coherent vertical motions of the whole LLJ layer cause the contribution of the mean wind into the measured $\sigma$ in the shear zone, since different parts of the mean profile are sampled at the same height. The contribution is proportional to the shear and to the amplitude of the vertical motions. One can expect that in no-shear zones, the vertical motions do not affect the observed $\sigma_w$, resulting in the reduction of its values at the jet core height. A similar situation is likely to cause the minima in the variance of a streamwise component $\sigma_u$ at the jet core height in the observations by Banta et al. (2006).

To check if the appearance of the structures accompanies the increase of $\sigma_w$, we have chosen several short intervals of well-pronounced structures during the periods of more or less uniform echo signal within LLJs, like one shown in Fig. 5. Together with the echogram and wind profiles, we have plotted a 10-min time series of $\sigma_w$ averaged over 100-m layers. The clear braid structures appear in the echogram around 0430–0500 LT. The event caused a noticeable change of wind speed profiles in the upper part of the ABL; however, it did not show any clear signal in the $\sigma_w$ time series. Other selected cases have shown similar behavior of $\sigma_w$. This suggests that the structures are likely to be advected by
the wind rather than developing above the observational point.

4. Discussion and conclusions

The scaling of turbulence parameters from the LLJ with the maximum LLJ speed $V_{\text{max}}$ results in a better collapse of profiles than scaling with the surface-layer friction velocity $u^*$. This inference agrees with Banta et al. (2006) and supports the hypothesis of “upside down” structure of the stable ABL (Mahrt 1999). The increase of $s_w$ with height, observed in the lowest part of the LLJ, also agrees with this hypothesis. No dependence of $s_w$ on altitude across the middle and upper parts of the jet streams was found in our sodar data, while the lidar profiles (Banta et al. 2006) of the standard deviation of downstream velocity $s_u$ had a minimum, and the sodar profiles of $s_w$ and $s_u$ reported by Prabha et al. (2008) have a maximum in the vicinity of a jet core. The typical standard deviation of the vertical speed fluctuations $s_w$ within the middle part of the LLJ was found to be about 5% of the maximum wind speed in the jet $V_{\text{max}}$.

The difference between the values of $s_w/V_{\text{max}}$ observed in various studies can be due to the fact that the
variances of vertical velocity in the stable ABL can be essentially influenced by coherent vertical motions. For such cases, the variances of wind components are not purely turbulent; thus, the traditional relationships between variances of vertical and horizontal components (see, e.g., Banta et al. 2006, their Table 1) are obviously inapplicable.

We have demonstrated an increase of $\sigma_u$ in zones of wind shear. This indicates that vertical motions can significantly affect observed $\sigma_u$. If we assume that a jet slightly moves as a whole in the vertical direction, then the profile of $\sigma_u$ would have a minimum at the height where the vertical gradient of mean velocity turns to zero, as similarly reported by Banta et al. (2006). This mechanism explains the difference between the vertical profiles of $\sigma_u$ and $\sigma_w$ observed in low-level jets.

The study of several episodes of the wave activity, identified within the LLJ from sodar echograms, found no significant influence of the braid structures on $\sigma_w$. This somewhat disagrees with findings of two earlier studies (Coulter 1990; Newsom and Banta 2003), which reported a substantial increase of turbulence during wave activity. Reasons for a discrepancy between the results of the various authors are not yet clear. It could be caused by nonturbulent vertical motions that dominate $\sigma_w$, which is quite large in our measurements. It is also likely that there is more than one phenomenon causing the braid patterns in the echograms.

**Acknowledgments.** We are grateful to Prof. R. Banta from NOAA for fruitful discussions, to Dr. C. R. Wood from the Finnish Meteorological Institute, and to the
anonymous reviewer for the language proof of the manuscript. This study is supported by the Russian Foundation for Basic Research (Projects 10-05-00802, 12-05-31399, and 13-05-00846), by the EC FP7 Project ERC PBLPMES (Grant 227915), and by the Academy of Finland (ASTREX project).

REFERENCES


