The Composite Shape and Structure of Braid Patterns in Kelvin–Helmholtz Billows
Observed with a Sodar

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ABSTRACT
The structure and dynamic characteristics of the Kelvin–Helmholtz billows (KHB), observed with a sodar in the stable atmospheric boundary layer, are studied by means of composite analysis, which consists in the averaging of samples selected according to certain criteria. Using a specific kind of this method allowed the authors to obtain the fine structure of the perturbation velocity fields from the sodar data. The events of most pronounced KHB were visually selected from echograms of continuous sodar measurements in the Moscow region over 2008–10. The composite patterns of KHB have been constructed for a few cases of clear inclined-stripe echogram patterns to derive a typical finescale structure of billows and a spatial distribution of wind speed and shear within them. The interconnection between echo intensity and wind shear variations within such patterns is shown. The typical distributions of velocity perturbation within various forms of billows are found.

1. Introduction
Over the last years, an interest in theoretical and experimental studies of gravity–shear waves, such as Kelvin–Helmholtz billows (KHB), has increased because of their role in the generation of turbulence and vertical exchange of mass and heat in a stably stratified atmosphere. Ground-based remote sensing gives a visual two-dimensional picture of the wave motions in the fields of refractive index and/or wind velocity, providing valuable information on wave activity in the atmosphere. KHB are revealed by sodar, radar, and lidar under conditions of statical stability in the presence of strong vertical shear of wind velocity. Examples of KHB observations in the lower and middle atmosphere can be found in the monograph Gossard and Hooke (2003), as well as in reviews in DeSilva et al. (1996) and Fukao et al. (2011) and references therein.

Radar observations of KHB in the free atmosphere are numerous, but in the lowest atmosphere only a small number of KHB events (a little more than a dozen) have been observed (Newsom and Banta 2003; Fukao et al. 2011). The scarcity of the observations is caused by the fact that, unlike the radar monitoring of the upper troposphere and stratosphere, remote sensing of the atmospheric boundary layer (ABL) is conducted irregularly, and therefore only a small part of such episodes is registered. However, in the ABL KHB are particularly important for heat and mass transfer. Continuous monitoring of a stable ABL by a sodar is much simpler and more cost effective than by a scanning lidar or radar. In the Moscow region, continuous sodar monitoring of the ABL since 2008 (Kallistratova and Kouznetsov 2012; Lyulyukin and Kuznetsov 2012) yielded quite extensive statistics: several hundred well-pronounced KHB patterns over 4 years.
The fine structure of the wave-induced perturbation of the velocity field is of great interest for understanding the processes of vertical mixing in a stable ABL. A rough estimate of the two-dimensional perturbation velocity vector field, which was made by Newsom and Banta (2003) for a single realization of KHB, revealed the vorticity of the velocity field. The preprocessed sodar data (instantaneous radial velocity profiles) give little information on the eddy perturbations due to large measurement error and strong variability of instantaneous profiles, which is caused by statistical uncertainty. The time interval required to obtain sufficiently smooth-averaged profiles is comparable with the period of KHB, and therefore such averaging destroys the information on the wave process. In this connection, a conditional averaging is needed.

The present work aims to develop a specific kind of composite analysis to obtain the fine structure of the perturbation velocity fields from the sodar data and evaluate the influence of the mean profiles of wind speed and the air temperature on the character of vortex disturbances in the KHB layer.

2. Measurement site, equipment, and dataset

We used data from the year-round sodar measurements at the Zvenigorod Scientific Station (ZSS) of the A.M. Obukhov Institute of Atmospheric Physics in 2008–10. ZSS (55.70°N, 36.78°E) is situated in a weakly inhomogeneous rural area 45 km west of Moscow. The three-antenna monostatic Doppler sodar Latan-3, which is used at the station, has a carrier frequency of 1700 Hz, vertical resolution of 20 m, and an altitude range from 40 to 200 to 500 m, depending on the stratification and the level of acoustic noise (Kouznetsov 2007). The sodar was operated in one of two modes: parallel mode with a time resolution of 10 s and sequential mode with a time resolution of 20 s.

About 200 cases of the occurrence of the billows were identified by visual inspection of the echograms. The frequency distribution of the time periods of the billows is close to the normal distribution and 80% of the cases fall in the range between 2 and 4.5 min (Lyulyukin and Kuznetsov 2012). Most identified billows are around the resolution limit of sodar. Also, many of the cases include billows with highly varied amplitudes and shapes, for example, during the lifting of the inversion layer at the morning a billow amplitude can rise from 50 to 200 m. To select samples suitable for analysis we use the following criteria:

(i) The train includes more than five well-pronounced billows of similar shape.
(ii) The time period of the billows is more than or equal to 5 min.
(iii) The amplitude of the billows varies within the limits of 20%.
The amplitude of modulation of the echo signal with the billow structure is more than or equal to 10 dB.

There were totally 15 cases in the dataset satisfying the specified criteria. Examples of sodar echograms with clear KHB in the shape of braids or inclined stripes are presented in Fig. 1.

3. Data processing

Preprocessed data of the sodar echo signal provide the values of signal intensity, noise intensity, and radial velocities. Using data on the radial velocities from three antennas we can formally calculate instantaneous horizontal wind speed, but such data will have no physical meaning because in reality various sodar antennas measure radial velocities at different volumes of flow and at different times. Temporal averaging provides the average wind speed profile but not the spatial distribution of velocities.

a. Composite analysis

To obtain the space–time distributions of wind velocity, we have adopted the method of constructing a composite shape and structure, similar to the one used by Williams and Hacker (1992) for convective structures. The method consists of the averaging of samples, selected according to certain criteria and normalized in scale, which contain the event of interest. Composite analysis is admirably suited to study quasi-periodic processes.

The process of normalization of billows of various scales would require resampling because the resolution of sodar data is comparable to space–time scales of the billows. The composites are built separately for each of the selected events, and so the waves included in the averaging were similar in scale and wave periods. We used a visual selection of the position and amplitude of each billow in the echograms to determine the locations of samples for averaging. Preprocessed data of the echo signal from each of the three antennas (the intensity of sodar echo, noise, and radial velocity) for the selected periods of KHB were averaged. The parameters of the averaging (position and number of selected periods, width, height, location of the data samples for averaging, and the critical signal-to-noise ratio) were selected in order to construct the clearest composite shape of the echo signal. As a result we obtain an average shape of billow for the analyzed episode and an average space–time...
distribution of radial velocities, echo signal intensities, and noises for three antennas within a composite billow. The process of constructing a composite shape of the braid pattern is presented in Fig. 2.

b. Correlation analysis

Composite structures convey the real picture of the distribution of KHB parameters only if the time shift between the braid structures in the echo signals from vertical and tilted antennas does not exceed the temporal resolution of the sodar. The time shift is connected with the distances between scattering volumes, which depend on the height and zenith angle, time delay between signals sending, and horizontal wind velocity profile. Correlation functions of signals of the vertical and tilted antennas show the significance of this time shift. For processing with composite analysis we have used samples where the time shift does not exceed the resolution of the sodar.

4. Results

Using the selection criteria described in sections 2 and 3b, 10 KHB episodes, with typical braid-shaped
structure and with periods of 5 min and more, were selected. The duration of the episodes ranged from 1 to 3 h. The composite shape and velocity perturbation structure of the braid patterns were obtained for each sample. Basic features of the composites are discussed for the example observed on the 29 January 2010.

a. Vertical velocity distribution

A typical composite shape of space–time distribution of the vertical velocity within KHB is presented in Fig. 3 (top). The left picture shows a color representation of the velocity, and the right one shows a composite time series of vertical velocity superimposed on a composite distribution of echo intensity. The picture shows a correlation between the vertical velocity distribution and the braid structure. The maximum velocity is on the backward face and minimum velocity on the forward face of the wave.

b. Horizontal velocity distribution

Composite structures of horizontal velocity within the billows were obtained using composite values of radial velocity from three antennas. Composite profiles of wind speed, presented in Figs. 3d, 4a, and 5a,c, were constructed by averaging the wind profiles on all billows selected in the sample. Values of speed in the maximums of profiles obtained by the composite method significantly exceed those obtained by time averaging, and the profile of the low-level jet (LLJ) is also less smooth (Fig. 4).

Figure 3c shows a color representation of the composite perturbation of horizontal speed, obtained as a deviation from the average profile. A clear braid structure, similar to the structure of the echo signal, can be seen in the perturbation field. The maximum deviation is positive on the backward face and negative between the billows.

c. Perturbation direction field

The 2D field of directions of wind perturbations was obtained for each sample. The fields are superimposed on the composite distributions of the echo intensity from the vertically directed antenna. The perturbation direction fields were obtained by changing in the ratio between the vertical and horizontal scales of perturbation vectors \((u' + w)\) with a factor

\[ k = \frac{\Delta t}{\Delta h} \langle V \rangle, \]

where \(\Delta t\) is the time resolution, \(\Delta h\) is the height resolution, and \(\langle V \rangle\) is the average wind speed. For \(u'\) we used the deviation from the flow speed averaged over the layer with the braid structure. An example is given in Fig. 5b. The clear vorticity structure of the wind field can be seen: velocity is higher than the average speed of flow at the crest of billow and lower at the bottom. Such structure of perturbations is typical for Kelvin–Helmholtz instability and was demonstrated in laboratory and numerical experiments (Thorpe 1973).
d. Influence of the wind profile

The velocity distributions show that the structure of the wind velocity within KHB is strongly connected with the average wind profile. Figure 5b shows the shape and structure of braids in cases when the altitude of the LLJ maximum is located above the KHB layer and the wind profile is monotonic in the layer. The turbulent structure has the shape of a braid. The vortex located within the billow is seen in the velocity field.

In the case of an LLJ with the speed maximum located within the KHB layer, the wind field looks different. A counterrotating vortex pair in the wind structure can be seen in Fig. 5d. Therefore, the turbulent structure at the echogram looks more like a series of inclined stripes than like a braid. Such structures were also obtained in laboratory experiments and numerical simulations of KHB in jet-type flow (Patterson et al. 2006).

e. Influence of the mean temperature profile

Many of the selected cases with clear KHB occur in the morning hours (0700–1200 LT) and in the evening hours (1900–2200 LT). The major changes in the
temperature gradient usually occur during these time periods. A collation of the temperature profiles with the echograms shows that KHB arises in a narrow range of vertical temperature gradients. For example, if the value of the wind speed shear is about $0.05 \text{s}^{-1}$, then KHB arises in the range of the temperature gradient between $3 \times 10^{-3}$ and $6 \times 10^{-3} \text{km}^{-1}$. These conditions are consistent with the known Richardson number criterion $Ri \approx 0.25$ that is necessary (but not sufficient) for instability to occur (Miles 1961; Howard 1961; Gossard et al. 1970). Figure 6 demonstrates composite shapes of KHB and related direction fields in cases when the wave crest is less visible and when the wind vortexes are shifted vertically relative to turbulent structures in the echograms.

5. Conclusions

A large number of KHB events has been identified by the visual inspection of the sodar echograms obtained during a continuous 4-yr monitoring of the ABL in the Moscow region. Trains of KHB lasting from 30 min to several hours were regularly observed in the lower part of low-level jetstreams forming in a statically stable ABL. However, the effectiveness of the KHB study by sodars is limited by insufficient temporal and spatial resolution of conventional sodars that are comparable with the time period and amplitude of the smallest billows observed. This deficiency noticeably complicates the processing of the primary data about the field of wind speed within the KHB: only a few episodes of KHB were suitable for analysis, and this may bias the results presented in this manuscript.

Nonetheless, the application of a composite analysis has allowed us to construct vector fields of the wind speed perturbations within the KHB layers, using a particular method to select the billows for the composite averaging. The two-dimensional direction fields of velocity perturbations, superimposed on the images of the echo signal intensity that visualized the billows in the coordinates $(z, t)$, have clearly demonstrated the fine eddy structures that are typical for the Kelvin–Helmholtz instability.

Composite averaging gives a less smooth profile of LLJ than the usual time averaging, because the altitude of the maximum wind speed in the presence of KHB in the flow changes periodically in accordance with the structure of the braids. Moreover, the value of the maximum composite wind velocity can significantly exceed the time-averaged velocity. Comparison of the observed KHB with the form of vertical profiles of mean temperature and wind speed shows an effect of the latter on the shape of the KHB (either braids or tilted strips). Hence, the shape of KHB depends on meteorological conditions.

Note that the method of sodar echo signals processing with the help of the composite analysis proposed in this paper might be useful for the lidar and radar studies of KHB as well.

Our results allow for direct comparisons with the results of the linear stability analysis based on the numerical solution of the Taylor–Goldstein equation (Baas and Driedonks 1985; Newsom and Banta 2003). Such comparisons could clarify the contribution of coherent perturbations of velocity to the variance of velocity fluctuations, which is usually measured in experiments and serves as a measure of the intensity of turbulent mixing.

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