On the influence of internal gravity waves on the intensity of turbulence in the atmospheric boundary layer

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Abstract. To date experimental data concerning the impact of internal gravity waves on the intensity of turbulence in a stably stratified atmospheric boundary layer are scarce. The paper presents the results of the analysis of the degree of influence on turbulence characteristics of wave-like motions of two classes: Kelvin-Helmholtz billows (KHBs) and horizontally propagating buoyancy waves (BWs). For this purpose the data of long-term sodar measurements carried out in the suburban area of Moscow were used. The passage of 30% of KHB trains and 90% of BW trains was accompanied with increase of turbulent kinetic energy and both heat and momentum fluxes. The relative increase in values of these characteristics was higher during BWs passage. Nevertheless the magnitude of turbulence characteristics were similar for both IGWs classes. In general the difference between characteristics calculated in the presence and in the absence of wavelike motions was smaller than between those in strongly and weakly stable boundary layers.

1. Introduction

The atmospheric boundary layer (ABL) plays an important role in the dynamics of the atmosphere. The exchange of energy, heat and impurities between the earth’s surface and the free atmosphere takes place through the ABL. The exchange processes in the stably stratified boundary layer (SBL) have not been sufficiently studied so far, although the SBL is regularly observed during nighttime surface cooling. In cold winter months it can persist for long periods of time.

Non-turbulent motions occur simultaneously on a variety of scales, and their interactions complicate the dynamics of the SBL. Notwithstanding the suppression of the turbulence by the temperature stratification, various processes may result in turbulence intensification. For example, significant vertical wind shear in frequently observed low-level jets results in non-periodic vortex motions that generate turbulence [1]. Internal gravity waves (IGWs) are also supposed to be one of the sources of the turbulence in the SBL [see, e.g., 2]. Field studies of non-turbulent processes and turbulent exchange in the SBL, the development of theoretical schemes and comparison of experimental and model results are of a current interest since they are necessary to improve the results of numerical modeling of the SBL [see, e.g., 3, 4].

IGW modes associated with the shear instability are referred to as Kelvin-Helmholtz billows (KHBs), and those associated with temperature gradients are referred to as buoyancy waves (BWs). [5] theoretically investigated some of the properties of these two classes of waves and the possibility of their separation. They pointed out that these two solutions have different phase speeds if scales of wind shear and density gradient are different. The critical level of KHBs was found near the inflection point in the wind speed profile, and that of BWs in the vicinity of high temperature gradients. Both BW
and KHB classes can reach significant amplitudes within the same general time span. Consequently, their nonlinear interaction is possible and it can result in excitation of disturbances with parameters very different from the initial waves.

The cumulative duration of wavelike motion registration ranges from a few percents of the full measurement time when using visual analysis of sodar echograms [6, 7] and of time series of the near-surface wind speed [8] to nearly full time when using automatic registration of coherent pressure pulsations with the help of microbarographs [9, 10].

Experimental studies of the effect of IGWs on the intensity of turbulent exchange in the SBL are few, but they indicate that wavelike motions influence the overall state of the SBL. The passage of wave trains is accompanied by temperature gradient and wind shear alterations, by bursts of turbulence [11, 12], and also by changes in the low-frequency part of momentum flux [13]. Quantitative estimates of the degree of influence of IGWs on turbulence vary. Some measurements show that the wave contribution to wind speed variances reaches tens of percent [8, 14]. In contrast, [15] found that the vertical wind speed variance in the wave layer was several times higher when the KHB train was passing than when there was no apparent wave activity. Experimental estimates have also shown that the contribution of waves can alter both the value and sign of the heat and momentum fluxes. At the same time, the changes in fluxes during the passage of the BW train turned out to be much higher (more than ten times) than during the passage of the KHB trains (no more than three times) [16].

The published papers partially shed light on the complex picture of the interaction between IGWs and turbulence. However, quantitative estimates of variance and flux changes have been obtained only for a small number of episodes. Our work is aimed at obtaining quantitative estimates of the degree of influence of IGWs of different classes on the turbulence intensity on a base of a fairly extensive array of experimental data. The usage of long-term continuous measurements allowed us to make uniform estimates of changes in turbulent kinetic energy and heat and momentum fluxes for several dozens of cases of wave activity.

2. Measurements and data processing
Continuous year-round measurements of ABL characteristics have been carried out since 2008 at the Zvenigorod Scientific Station (ZSS) of A.M. Obukhov Institute of Atmospheric Physics RAS (IAPh) in the suburban area of Moscow. The ZSS is located 50 km west of Moscow (55° 42′ N, 36° 47′ E) in a wooded countryside at an elevation of 150 m above sea level. The landscape around the station is mostly flat, sloping gently (∼1°) to the Moskva River with smooth hills. Registration of IGWs and measurements of wind speed profiles were carried out with the help of the research 3-component Doppler sodar LATAN-3 developed at IAPh [17]. The sodar has been operated at a carrier frequency of 2000 Hz with 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 temperature profiles were evaluated with a scanning microwave radiometer MTP-5 [18] and were used for a basic control of the stratification. To calculate the turbulence characteristics we used data from an ultrasonic thermometer-anemometer (sonic) METEK USA-1, which was located next to the sodar on the mast, at a height of 56 m.

Episodes of wave activity were identified by visual analysis of sodar echograms, as is usual [see, e.g., 19]. Despite some subjectivity of this approach, to date visual identification of periodic structures seems to be simpler and more reliable than the published methods of automatic identification [e.g., 20].

Remote acoustic sounding has a number of disadvantages that complicate the registration of waves, among which the main ones are: low time resolution (from a few seconds) and lack of data at low turbulence [see, e.g., 20]. Since periodic structures are identified as oscillations of the temperature structure parameter CT2, rather than that of meteorological quantities, the physical interpretation of the observed motions becomes more complicated. However, ground-based remote sounding has an important advantage: it makes possible to visualize the vertical structure of the wavelike motions and to determine their shape and location.

Since the vertical and time resolution of the sodar we used was not high, only fairly large IGWs
were registered. For identification of periodic structures on echograms, we used criteria close to those developed in the work [7]:

1. The minimum period of wavelike patterns $T$ was $> 2$ min.
2. The depth of the wave layer was $> 60$ m.
3. The depth of modulation of the background return signal level by a wave structure exceeded 4 dB.

**Figure 1.** Two examples of KHB observation. (a) and (c) panels present return signal $I$ in height–time coordinates (echograms), colors show the relative intensity of $I$. Black dots indicate wind speed profiles. The speed scale is shown at the top of each panel. (b) and (d) panels present temperature profiles. Both wind and temperature profiles calculated with 30 minutes averaging.

We classified periodic structures into KHBs and BWs. The discrimination was based on the analysis of the vertical structure of observed oscillations of the $C_n^2$ and of the vertical velocity.

Periodic structures observed in the $C_n^2$ field in the form of inclined stripes, billows or braids we attributed to the class of KHBs, as, e.g., in [11]. Such waves appear at a strong vertical wind speed shear. Changes in the vertical wind speed at different heights inside the wave layer does not occur synchronously [21]. Examples of sodar echograms with KHBs are shown in figure 1.

Synchronous oscillations of the altitude of one or more turbulized layers or of the boundary of the surface layer we referred to as the BWs. The vertical wind speed oscillates more or less synchronously at different heights inside the layer occupied by BW [e.g. 22]. The presence of a noticeable wind shear is not a necessary condition for the occurrence of BWs. Examples of sodar echogram with BW is shown in figure 2.
Figure 2. Example of BW observation. (a) and (b) is the same as figure 1. (c) vertical wind speed in time-height coordinates.

In the work we used episodes which could be unambiguously classified. A number of cases were classified as a mixed class and were excluded from the statistics.

We calculated the following characteristics using data obtained with the help of the sonic:

1. Turbulent kinetic energy $TKE = \langle u^2 + v^2 + w^2 \rangle$, where $u, v, w$ are fluctuations of wind speed components;

2. Momentum flux $MF = \rho \langle uw \rangle$;

3. Heat flux $HF = c_p \rho \langle tw \rangle$, where $t$ is fluctuations of acoustic temperature measured by the sonic.

A double rotation of sonic axes was applied so that the one of horizontal wind components was aligned with the main flow [23].

For each episode, the ensemble-average of turbulence characteristics were calculated for both period of the passage of the wave train and 30-60 minute period before the episode. After that, the ratio $R$ of these average values was calculated. $R > 1$ indicates that the characteristic was higher during the episode and $R < 1$ indicates the opposite.

A minimum of energy in the spectrum of the turbulence (the so-called gap) separates turbulent eddies from larger-scale motions. The position of the gap can vary or be absent in the presence of stable stratification [24]. To assess the position of the cospectral gap we calculated momentum and heat cospectra with the help of multiresolution flux decomposition for each episode [e.g., 25]. These gaps ranged from tens of seconds to tens of minutes. In some cases it was absent. If only true turbulence is required, the use of a constant averaging time is undesirable. To overcome this difficulty,
wave oscillations identified by means of a spectral analysis are usually filtered out of time series of meteorological quantities [e.g., 8, 14].

To make the results comparable with those obtained by means of the traditional approach we calculated the turbulence characteristics for four constant averaging times - 1, 5, 15 and 30 minutes. While the first of these periods in most cases included only small-scale turbulent fluctuations, the others could include both turbulent and wave oscillations. Note that the passage of wave trains recorded by the sodar was not always recorded by the sonic.

In the previous paper [16] only 15-minute averaging was used. Thus both waves and turbulence contributed to calculated characteristics. These results are in qualitative agreement with those presented below.

3. Results

We analyzed 7.5 years of measurements and assessed the frequency of appearance of both KHB and BW trains on sodar echograms. The number of episodes and the fraction of time occupied by wave activity of both classes varied greatly both from month to month and from year to year. Nevertheless, episodes of KHBs, on average, were observed in 25-35% of measurement days regardless of the season. At the same time, BWs were observed mainly from March to August in 4-8% of days. KHBs occupied 1-3% of the total measurement time, and BWs <1%. These data show that observation of IGWs of both classes are not scarce at the ZSS.

Figure 3. An example of the behavior of turbulent characteristics during the passage of the KHB train. (a) echogram in height-time coordinates. (b), (c) time series of heat and momentum fluxes, calculated with averaging times of 1, 5 and 15 minutes. (d), (e) cospectra of heat and momentum fluxes for time intervals before the KHB passage (22:30-23:25) and during the episode (23:30-00:25).

Figure 3 shows an example of the behavior of turbulence characteristics during the passage of a KHB
train. Before the beginning of the episode, the smallest time scales at which the heat and momentum cospectra attained zero were \(\sim 100\) seconds and \(\sim 50\) seconds, respectively. During the episode, the momentum cospectrum was negative on all scales, and had increased sharply at \(\sim 50-100\) s. At the same time the heat cospectrum had undergone a sharp increase at \(\sim 25-50\) s, but had crossed the zero-line only at \(\sim 400\) seconds. Before and during the episode, the wind shear under the maximum of the wind speed profile was \(\sim 0.05-0.06\) s\(^{-1}\). The temperature gradient in the lower 100 meters (not shown) during the hour prior to the passage of KHB train was \(\sim 1.0-1.2\) K per 100 m, and by the end of the episode it decreased to \(\sim 0.2\) K per 100 m.

Figure 4 shows an example of the behavior of turbulent characteristics during the passage of a BW train. During the episode heat and momentum fluxes averaged over 1 minute oscillated with a period close to that of the BW. Before the episode both heat and momentum cospectra attained zero-line at \(\sim 40-50\) s. During the passage of the BW, the heat cospectrum crossed zero-line at \(\sim 70\) s, and momentum cospectrum had increased to nearly zero at \(\sim 40-50\) s. With the arrival of the wave, bulk shear decreased from \(\sim 0.07\) s\(^{-1}\) to \(\sim 0.05\) s\(^{-1}\). By the beginning of the episode, the difference in air temperatures between the surface layer and 100 meters (not shown) was \(\sim 2.5\) K, and by the end \(\sim 1.4\) K.

![Figure 4](image-url)

**Figure 4.** Same as figure 3 for a train of BW.

We have chosen the most distinct episodes of IGWs to analyze their impact on turbulence characteristics. They comprise 28 KHB trains and 10 BW trains. For each episode, the mean values of turbulence characteristics were calculated for three averaging times: 1, 15 and 30 minutes. The largest difference of these values for each KHB episode did not exceed 0.7 m\(^2\)s\(^{-2}\), 40 Wm\(^{-2}\), and 0.1 Nm\(^{-2}\) for TKE, HF, and MF, respectively. So these changes ranged from tens to hundreds of percent. In general, the differences for TKE and HF are consistent with the data published by [26]. However, differences we calculated for MF are almost double of that presented. And [14] gave even smaller estimates which are 2-3 times lower than ours. During the passage of BWs these differences were even greater: up to 7.3
$m^2 s^{-2}$, up to $300 W m^{-2}$, and up to $0.8 N m^{-2}$.
So these changes ranged from hundreds percent to one thousand percent. The large differences are most likely to result from wind speed and temperature oscillations recorded with the help of the sonic during the passage of BWs. As a consequence, turbulence characteristics averaged over 15 and 30 minutes (more than periods of BW trains) were greatly higher [e.g., 26].

Only 10 of 28 KHB trains seemed to increase turbulence characteristics. During other episodes of KHB changes were either absent or masked by other processes, such as gradual alteration of temperature stratification and wind shear. In contrast, 9 of 10 BWs exerted an influence on the turbulence intensity.

For comparison of the degree of intensification of turbulence during the passage of waves of different classes, only episodes that influenced the turbulence characteristics were used. We calculated mean values of the characteristics and of their ratios $R$ for all these cases. They are presented in the table 1. Median values of $R$ are listed in brackets. They are presented in the table 1. Median values of $R$ are listed in brackets. For KHB trains average and median $R$ generally differed slightly, and for BW trains some values greatly varied. The possible explanation of these differences was mentioned above.

$R$ show that, in general, BW trains exerted stronger influence than KHB trains. However, 1-minute averages of the turbulence characteristics turned out to be close for both classes of waves. Partly it is the result of episode selection: the most distinct BWs were usually observed on echograms in the SBL with weak winds.

### Table 1. Average and median (in brackets) characteristics of turbulence during the passage of KHB and BW trains and the grade of intensification $R$.

|           | KE $m^2 s^{-2}$ | R      | MF $N m^{-2}$ | R      | HF $W m^{-2}$ | R      |
|-----------|----------------|--------|---------------|--------|---------------|--------|
| KHB       | 0.5            | 3.4 (2.4) | -0.07        | 5.6 (3.6) | -12           | 2.3 (2.2) |
| BW        | 0.7            | 6.8 (5.7) | -0.06        | 108.5 (4.6) | -14           | 4.0 (4.5) |

|           |               |        |               |        |               |        |
|-----------|----------------|--------|---------------|--------|---------------|--------|
| KHB       | 0.7            | 2.6 (2.4) | -0.08        | 9.4 (3.2) | -15           | 2.1 (2.0) |
| PBW       | 3.7            | 8.7 (6.5) | -0.13        | 18.5 (4.5) | -8            | 4.7 (5.7) |

|           |               |        |               |        |               |        |
|-----------|----------------|--------|---------------|--------|---------------|--------|
| KHB       | 0.8            | 1.9 (1.9) | -0.07        | 2.3 (2.2) | -14           | 1.9 (2.0) |
| PBW       | 4.1            | 8.2 (3.6) | -0.18        | 14.6 (3.2) | -24           | 607.5 (1.2) |

Turbulence characteristics vary, especially for SBLs with weak and strong turbulence. They can range from very small values up to several $m^2 s^{-2}$, tens of $W m^{-2}$ and to several of $N m^{-2}$ for TKE, heat and momentum fluxes, respectively. [e.g., 27, 28]. Thus, turbulence characteristics we obtained fall into the ranges of commonly measured values. Note, that due to the limited resolution of the sodar, we studied only the largest wave motions. It is possible that large differences in values are associated with the passage of waves with amplitude and period being too small to be registered by our sodar.

### 4. Conclusions

Analysis of long-term continuous sodar measurements carried out in the suburban of Moscow showed that wave-like motions are often registered on sodar echograms in the stably stratified atmospheric boundary layer. It was found that Kelvin-Helmholtz billows were observed on average in 30% of days.
regardless of the season, and buoyancy waves - on average 4-8% of days from March to August and <1% of days in other months. For 38 episodes of wave activity, the behavior of the turbulence characteristics was analyzed. Only 10 of 28 KHB trains seemed to increase turbulence characteristics. In contrast, 9 of 10 BWs exerted an influence on the turbulence intensity. In general, BW trains exerted a stronger influence than KHB trains. However, the absolute values of the turbulent characteristics turned out to be close during the passage of waves of both classes. This can be partly explained by the choice of episodes: the most distinct episodes of BWs were usually observed in the light-wind SBL.

Acknowledgments
This study was supported by the Russian Foundation for Basic Research (project no. 19-05-01008) and the Russian Science Foundation (project no. 21-17-00021).

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