Lidar visualization of internal gravity waves

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Abstract: the results of observation of the atmospheric internal waves (AIWs) in the boundary layer of atmosphere on the coast of Lake Baikal with the use of Halo Photonics pulsed coherent Doppler wind lidar Stream Line are presented. A total of six AIW occurrences have been revealed from wind lidar measurements. This always happened in the presence of one or two (in 5 of 6 cases) narrow jet streams at heights of approximately 200 and 700 m. The parameters of the observed AIWs were determined.

Keywords: Coherent Doppler wind lidar, atmospheric internal waves

1. Introduction

Atmospheric gravity waves (AGWs) are an important feature of motions present in the atmosphere. Study of the gravity waves is carried out with the help of space images of the cloud fields in the visible and microwave regions [1, 2] and radar images of the sea surface [3, 4]. Experimental investigations of AGWs in the ionosphere from the scattering of radio waves are carried out by different methods [5]. The first results of lidar observations of the inertia gravity waves in the stratosphere and mesosphere with the use of the Doppler Rayleigh lidar are reported in [6]. However, the data of AGW observations in the lower atmosphere, in particular, in the atmospheric boundary layer (ABL) are few and far between. As a rule, they are based on the aerological data or on sodar data for the atmospheric lower 300-400 m layer.

Below we present the results of lidar observations of the coastal-mountain lee waves on the coast of Lake Baikal. Lee AIWs are one of the types of AGWs, which arise on leeward of obstacles at the stable stratification of an incoming flow.

2. Observations and analysis

Experimental investigations of AIWs in the atmospheric boundary layer of Lake Baikal were carried out with the use of the Halo Photonics CDWL Stream Line. The measurements were conducted in August 14-28 of 2015 on the western coast of Lake Baikal (52ºN, 105ºE), Russia. The wind in the atmospheric surface layer during the measurements was mostly directed from the north through the mountainous terrain toward Lake Baikal. The obtained lidar data have revealed several AIW occurrences. Formation of one and often simultaneously two narrow jet streams at heights of the atmospheric boundary layer were observed as well. In all the cases, AIWs were formed in the presence of low-level jet streams.

The lidar was set at a distance of 340 m from Baikal at a height of 180 m. The measurements cover heights from 280 to 1180 m above the Lake Baikal level. Conical scanning by a probing laser beam around the vertical axis allowed reconstruction of the vertical wind profile from wind velocity projections onto the axis of the probing beam estimated from the raw lidar data. During the measurements, the elevation angle of probing beam $\varphi = 60°$ was fixed, while the azimuth angle $\theta = \omega_s t$ of the beam axis position varied with time *t* and with the rate ω_s. The recorded lidar signal received from the distance R_k at the azimuth angle θ_n, where $k, n = 1, 2, 3, \ldots$, is then processed to reconstruct the wind vertical profile [7]. The time for one scan around the vertical axis $T_{\text{scan}} = 2\pi / \omega_s$ varied and was 2 min, 1 min, and 36 s in dependence on atmospheric conditions.

Figure 1 shows the results of lidar visualization of the wind field during the longest observations of a gravity wave for about 4 hours starting from 12:00 Local Time (LT) on August 23 of 2015. Two jet streams were observed simultaneously at heights of about 250 and 750 m.

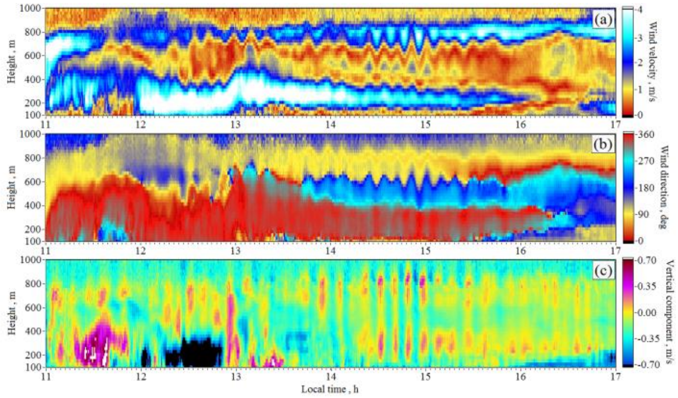

Figure 1. Spatiotemporal distributions of the wind speed (a), the wind direction angle (b), and the vertical component of the wind vector (c) obtained from measurements with the Stream Line lidar on August 23 of 2015. The height is given relatively to lidar position height.

Figures 2 and 3 show the temporal profiles at a height of 636.5 m and vertical profiles at 14:31 LT of wind taken from data in Fig. 1. From these figures, we can see oscillations of the wind parameters in both height and time. They are especially marked in the period from 13:30 to 15:30, when the amplitude of oscillations of the wind direction is approximately 45°.

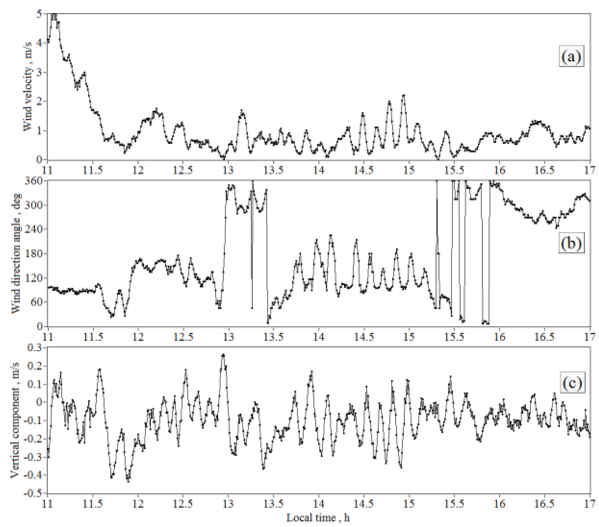

Figure 2. Temporal profiles of the wind speed (a), the wind direction angle (b), and the vertical component of the wind velocity (c). Data of Fig. 1 (measurement height of 636.5 m)

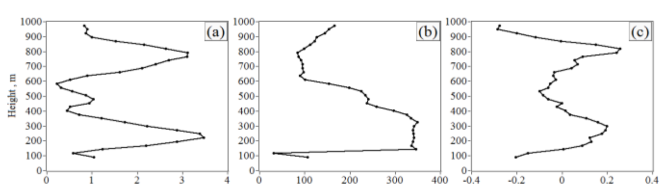

Figure 3. Vertical profiles of the wind speed (a), the wind direction angle (b), and the vertical component of the wind vector (c). Data of Fig.1 (measurement time 14:31 LT).

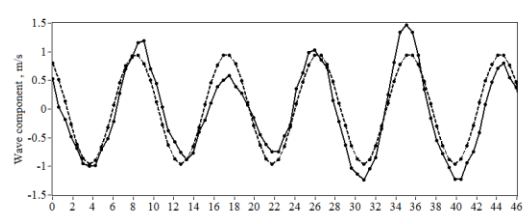

Figure 4. Time dependence of the wave addend of the longitudinal wind velocity.

Neglecting the wind turbulence, we use the model of a plane wave for the component of the wind velocity vector V_α (subscript $\alpha = z$ for the vertical component, $\alpha = x$ for the longitudinal component, and $\alpha = y$ for the transverse component) in the form [8]

$$V_\alpha(\mathbf{r},t) = \langle V_\alpha \rangle + \tilde{V}_\alpha(\mathbf{r},t) . \tag{1}$$

In Eq.(1) $\mathbf{r} = \{z, x, y\}$ is the radius vector, t is time, $\langle V_\alpha \rangle$ and $\tilde{V}_\alpha$ are the regular and wave addends of the α-th component of the wind velocity, respectively,

$$\tilde{V}_\alpha(\mathbf{r},t) = A_\alpha(z)\sin\left[\psi_\alpha(\mathbf{r}) - 2\pi t / T_v\right] , \tag{2}$$

A_α is the wave amplitude, ψ_α is the wave phase, and T_v is the wave period. If the wind direction coincides with the direction of propagation of the internal wave, then A_y = 0, $\psi_x = 2\pi x / \lambda_v$, and $\psi_z = 2\pi x / \lambda_v + \pi / 2$. Here, λ_v is the wavelength of the wave propagating with the speed $c_v = \lambda_v / T_v$.

Model (1), (2) was applied in the analysis of data in Fig.1 for a height of 766.4 m and 47-min time interval starting from 14:20. From these data, with allowance made for the linear trend, we found the wave addends $\tilde{V}_\alpha(\mathbf{r},t)$ for the three components of the wind velocity vector. In Fig. 4, the solid curve shows the dependence of $\tilde{V}_x$ on t. To determine the wave frequency $f_v = 1/T_v$, we have calculated the spectral density of experimental function $\tilde{V}_x(t)$. From the position the obtained of spectrum maximum we have determined the frequency f_v to be equal to 0.00185 Hz. Consequently, the wave period is T_v = 9 min. Using the least-square fitting of model (2) for $\tilde{V}_x(t)$ to the wave addend of the wind velocity component measured by the lidar (solid curve in Fig. 4), we have determined the phase ψ_x and the amplitude A_x. The amplitude of wave addend for the longitudinal component of the wind velocity vector turned out to be 0.96 m/s. The modeled temporal profile $\tilde{V}_x(t)$ calculated by Eq. (2) with the use of experimental values of A_x, ψ_x, and T_v is shown as a dashed curve in Fig. 4.

Parameters of the wave addend of the vertical wind velocity $\tilde{V}_z(t)$ were found in the same way. The estimates of periods of the internal wave for the longitudinal and vertical components coincided fully (T_v = 9 min), amplitude A_z = 0.3 m/s is approximately 3 times less than the amplitude of wave addend of the longitudinal component of the wind velocity vector, and $\psi_z - \psi_x = \pi / 2$. Since the amplitude $A_y \neq 0$ (see Fig. 1(b) and Fig. 3(b)), the direction of propagation of the internal wave did not coincide with the wind direction.

In addition to this AIW occurrence, we succeeded in observation of this phenomena five times more for the period of measurements. Thus, the period of oscillations of other AIW on August 23 at 19:24 LT was 6.5 min. The wind velocity oscillations with amplitude of 1 m/s were observed for 45 min in presence of a single jet stream at a height of about 700 m. On August 19 since 5:30 LT, the atmospheric internal wave was observed for about 40 min. The period and amplitude of the wave were, respectively, 9 min and 0.9 m/s. Two jet streams were observed simultaneously: one at a height of approximately 200 m, and another at a height of 600 m.

On August 25 in the predawn time (04:30–05:06), two jet streams and AIW with the period $T_v \approx$ 9 min and the amplitude $A_x \approx$ 1 m/s at a height of 402.7 m were observed in the atmospheric boundary layer. On August

26, the internal wave with the period $T_v \approx 18$ min and the amplitude $A_x \approx 0.7$ m/s at the same height 402.7 m, passed from 16:22 to 19:00 LT. In the same day, the AIW with the halved period ($T_v \approx 9$ min) and the amplitude $A_x \approx 0.4$ m/s at the height 402.7 m was observed 50 min later from 19:50 to 20:35 LT.

3. Summary

Thus, the results of the experimental campaign in the coastal zone of Lake Baikal in August of 2015 show that the raw data of measurements by the Stream Line lidar allow us to visualize the spatiotemporal structure of the wind field in the atmospheric boundary layer and reveal the presence of low-level jet streams and atmospheric internal waves.

A total of six cases of AIW formation have been revealed, which always occurred against the background of one or two (in 5 of 6 cases) narrow jet streams at heights of about 200 and 700 m. When two jet streams were formed, the period of oscillation of the wave addend of the wind vector components was 9 min. In only one case it was about 18 min. In presence of a single jet stream (at a height of 730 m), the period of oscillations of the wind vector components during AIW was about 6.5 min. The amplitude of oscillations of the horizontal wind components most often was about 1 m/s, while the amplitude of oscillations of the vertical velocity was tree times less. In the most cases, the internal waves were observed for 45 min (5 oscillations with the period $T_v = 9$ min). Only once the lifetime of the atmospheric internal wave was about 4 hours.

4. Acknowledgments

The authors are thankful to A.V. Falits and A.A. Sukharev for the measurements. The authors are grateful to the Institute of Solar-Terrestrial Physics SB RAS for the possibility of using the territory of the Baikal Observatory for the measurements.

This study was supported by the Russian Scientific Foundation for Maintenance and Development, Project No. 14-17-00386.

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