Height of layer of intense turbulent heat exchange under conditions of stable atmospheric stratification

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ABSTRACT

In the work, we consider estimates of the height of layer of intense turbulent heat exchange in stably stratified atmospheric boundary layer, made with the use of meteorological acoustic radar (sodar). Dependence of this height on temperature gradient is analyzed. Current temperature stratification of the atmosphere in the layer with height up to 1 000 m was determined with the help of MTP-5 meteorological temperature profiler.

Keywords: atmospheric boundary layer, temperature profiles, stable stratification, turbulent heat exchange

Turbulent heat exchange between different layers is substantially complicated in the stably stratified atmosphere. Nonetheless, numerous experimental works demonstrate that, in the case of stable stratification, there are regions with increased variance of air temperature. Meteorological acoustic radar (sodar) is one of rare instruments, capable of diagnosing the microstructure of turbulent component of temperature field. Sodar signals are proportional to, among other things, the variance of air temperature in atmospheric boundary layer.

How the gradient of temperature field in stably stratified atmospheric boundary layer (ABL) influences the height of the layer of intense turbulent heat exchange (layer extending from underlying surface level to the height H_M) in cold period of the year still remains incompletely understood. This is especially true for urbanized territory, and just what our work was devoted to. We note that similar studies had already been performed by us earlier [1, 2], though with no emphasis on analysis of cases with stable stratification. The results, presented below, were obtained according to measurements over urbanized territory in winter season (Tomsk, Akademgorodok, January 23–February 13, 2015; instruments were installed on the roof of laboratory building of Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences, at height of 12 m above underlying surface level).

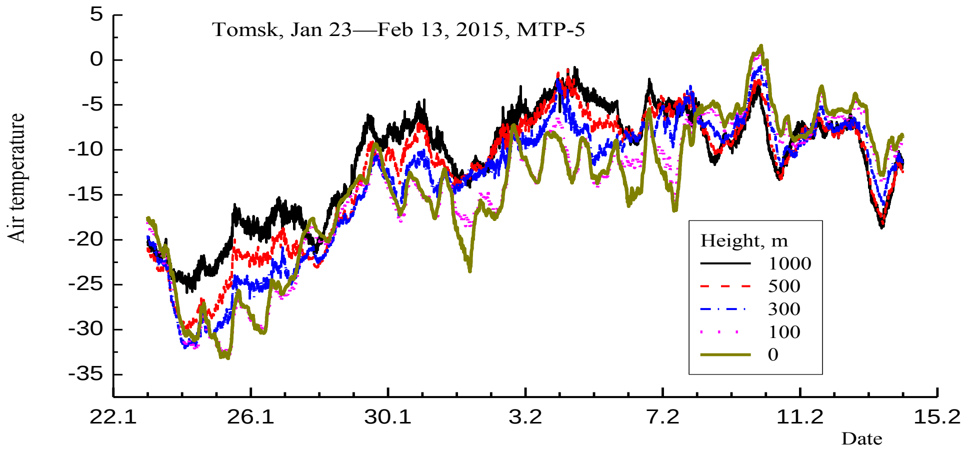

Figure 1 – Air temperature at a few heights.

The altitude-temporal profiles of air temperature were obtained using MTP-5 meteorological temperature profiler [3], which measures temperature in layer with thickness of 1 000 m (from the level where instruments were located) with

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steps of 5 min in time and 50 m in height. Temperature variations in ABL in time interval, chosen for analysis, are presented in Fig. 1. This figure presents temperatures at just a few heights, which is sufficient to gain an idea of the general pattern of temperature variations, both on the whole over the period analyzed and in separate days.

The MTP-5 instrument retrieves air temperatures $T(H_i, t_j)$ in degrees Celsius in the form of time series discrete in height (H_i) and time (t_j). In fact, $T(H_i, t_j)$ corresponds to the "average" temperature of air layer between heights H_i and H_{i-1}. Time t_j corresponds to the end of procedure of measurement of current temperature profile.

The ABL stratification type was characterized using potential air temperature $\Theta(H_i, t_j)$, calculated from simplified formula $\Theta(H_i, t_j) \approx T(H_i, t_j) + 273.15 + 0.01 \cdot H_i$. A stable stratification is characterized by positive gradients of potential temperature $\Gamma_\Theta = \partial\Theta(H)/\partial H > 0$, i.e., the potential temperature grows with increasing height. The "discrete" gradient of potential temperature was calculated using formula $\Gamma_\Theta(H_i,t_j) \approx \dfrac{T(H_i,t_j) - T(H_{i-1},t_j)}{50}$, $i = 1 \ldots 21$. No procedures of smoothing and/or interpolation of $\Gamma_\Theta(H_i,t_j)$ were applied.

The temperature turbulence in ABL was diagnosed using "Volna-4M" sodar, which controlled the altitude range up to 700 m. Sodar was located near MTP-5 and operated only in period from 08:00 to 21:00 Local Time (LT). A total of 254 hours of observations in period of simultaneous sodar and MTP-5 measurements had been analyzed. The determination of the height H_M on the basis of sodar observations was performed with the use of the method described in [1].

The current state of the near-ground atmospheric layer was estimated using data of "Meteo-2" ultrasonic meteorological station (UMS) [4], located close to MTP-5 and sodar. We made it possible to determine not only average wind velocities and air temperatures, but also different turbulence characteristics, including measurements of vertical turbulent heat flux.

The purpose of the work was to estimate how the height $H_M(t_j)$ is related to the "degree" of ABL stability, characterized by the gradient $\Gamma_\Theta(H_i,t_j)$. The main task was to analyze the "boundary" values of $\Gamma_{\Theta,B}(H_M, t_j)$, corresponding to the height H_M. We note that the "step" of gradient $\Gamma_\Theta(H_i,t_j)$ was 50 m in altitude, while the height $H_M(t_j)$ was determined with uncertainty up to a few meters. Therefore, as "boundary" gradients, we specified those calculated for height closest to H_M : $\Gamma_{\Theta,B}(H_M, t_j) = \Gamma_\Theta(H_i \approx H_M, t_j)$.

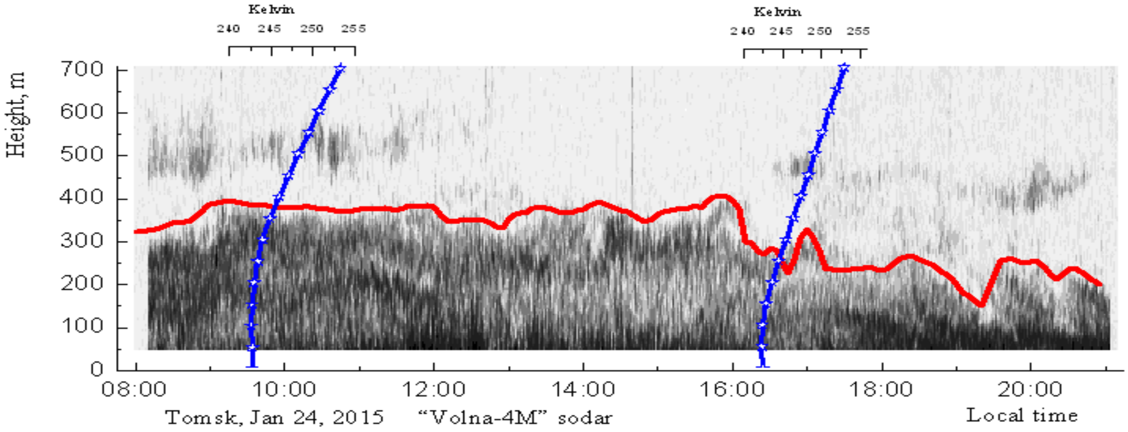

Figure 2 – An example of sodar echogram, height H_M (solid line), and altitude profiles of potential air temperature (lines with symbols) for two time intervals.

Figure 2 presents an example of sodar echogram, with superimposed plot of $H_M(t_j)$ and profiles of potential air temperature for two 5-min time intervals. We note that the solution of this problem is somewhat complicated by two factors. Firstly, under the conditions of stable stratification, there may be internal gravity waves ("buoyancy waves"), the propagation of which leads to "modulation" of temperature-wind fields in ABL and to formation of thin (usually 20-50 m thick) layers with increased level of temperature turbulence, even in the case of stable stratification. In echograms, these layers have "undulating" shape in $\{H, t\}$ coordinates and may introduce certain uncertainties in $H_M(t_j)$ estimates. Moreover, the "buoyancy waves" may "modulate" the temperature profiles as well. Secondly, "multilayer" structure of temperature turbulence is quite often fixed on sodar echograms in the case of stable ABL stratification (especially under winter conditions). These layers may be from several ten to several hundred meters apart in altitude, thus obscuring the decision as to what are the heights above the underlying surface to which the layer with intense turbulent heat exchange may extend. Our method assumes that if the height of this "elevated" layer is more than 50 m above the "near-ground" layer, this "elevated" layer is excluded from consideration. Otherwise, it is just the height of this layer that will give the $H_M(t_j)$ estimate. This just explains why the $H_M(t_j)$ plot in Fig. 2 does not "encompass" the layers with increased temperature variance at heights above 400 m.

As a result of per-day processing of experimental data, we identified three types of relation between $\Gamma_{\Theta,B}$ and H_M. First type is characterized by a decrease of the height H_M with increasing gradient $\Gamma_{\Theta,B}$. The second type demonstrates the absence of a unique relation between $\Gamma_{\Theta,B}$ and H_M. The third type refers to the case when height H_M grows with increasing gradient $\Gamma_{\Theta,B}$. Examples of identified types are presented in Fig. 3. In the case when $\Gamma_{\Theta,B} > 0.01$ (K/m), temperature (either near-ground or elevated) inversion and "invasion" of turbulent heat exchange into the inversion take place in ABL. We note that the third type of the dependence $H_M \propto \Gamma_{\Theta,B}$ was most often encountered (with different manifestation degrees of this relation).

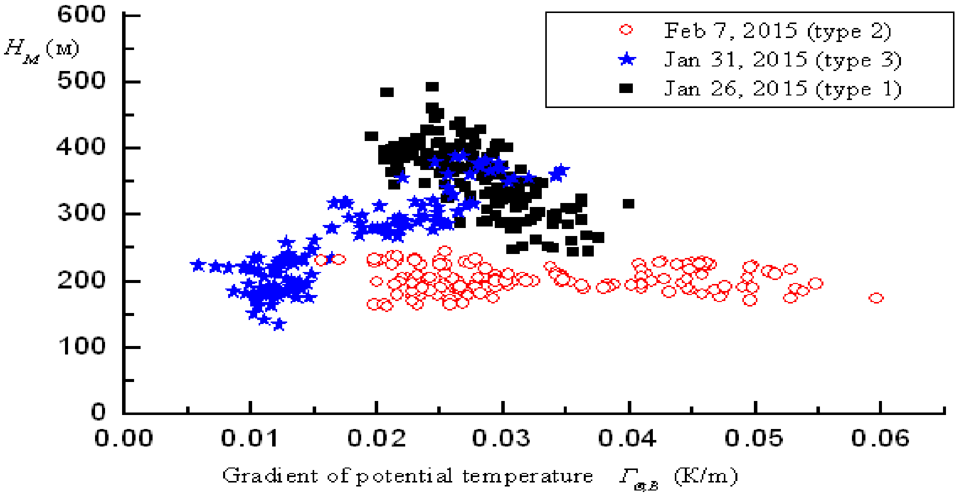

Figure 3 – Examples of dependence of the height H_M on the gradient $\Gamma_{\Theta,B}$.

The statistics of the "boundary" gradient $\Gamma_{\Theta,B}$ shows that its values did not usually exceed 0.04 K/m (up to 97% of cases), indicating that, under stable stratification conditions, the turbulent heat exchange between underlying surface and atmosphere could be mainly in those regions only where the gradient $\Gamma_{\Theta}(H_i, t_j) \leq 0.04$ (K/m). It should be stressed that, in time period considered here (January 23–February 13, 2015), and in the controlled altitude range, the values of the gradient $\Gamma_{\Theta}(H_i, t_j)$ in excess of 0.04 (K/m) were rarely encountered and only within the layer of 0–300 m at morning hours (recall that analysis was performed for the interval of 08:00–21:00 LT). Of course, all conclusions above are only true for experimental data, obtained in above-indicated period of time.

No obvious factors, influencing the relation between H_M and $\Gamma_{\Theta,B}$ and determining any specific type of the relation $H_M(\Gamma_{\Theta,B})$, could be found. It is usually assumed that the size (height H_M) of the region of significant heat exchange in stably stratified ABL (though also valid for other types of stratification) is "regulated" by structure of wind and air temperature fields, as well as by turbulent heat fluxes. To verify these statements, we plotted the diagrams of the dependences $H_M(\Gamma_{\Theta,B}, V_h)$ and $H_M(\Gamma_{\Theta,B}, Q)$, where V_h and Q are respectively the average wind speed and vertical turbulent heat flux, measured by ultrasonic meteorological station near the underlying surface.

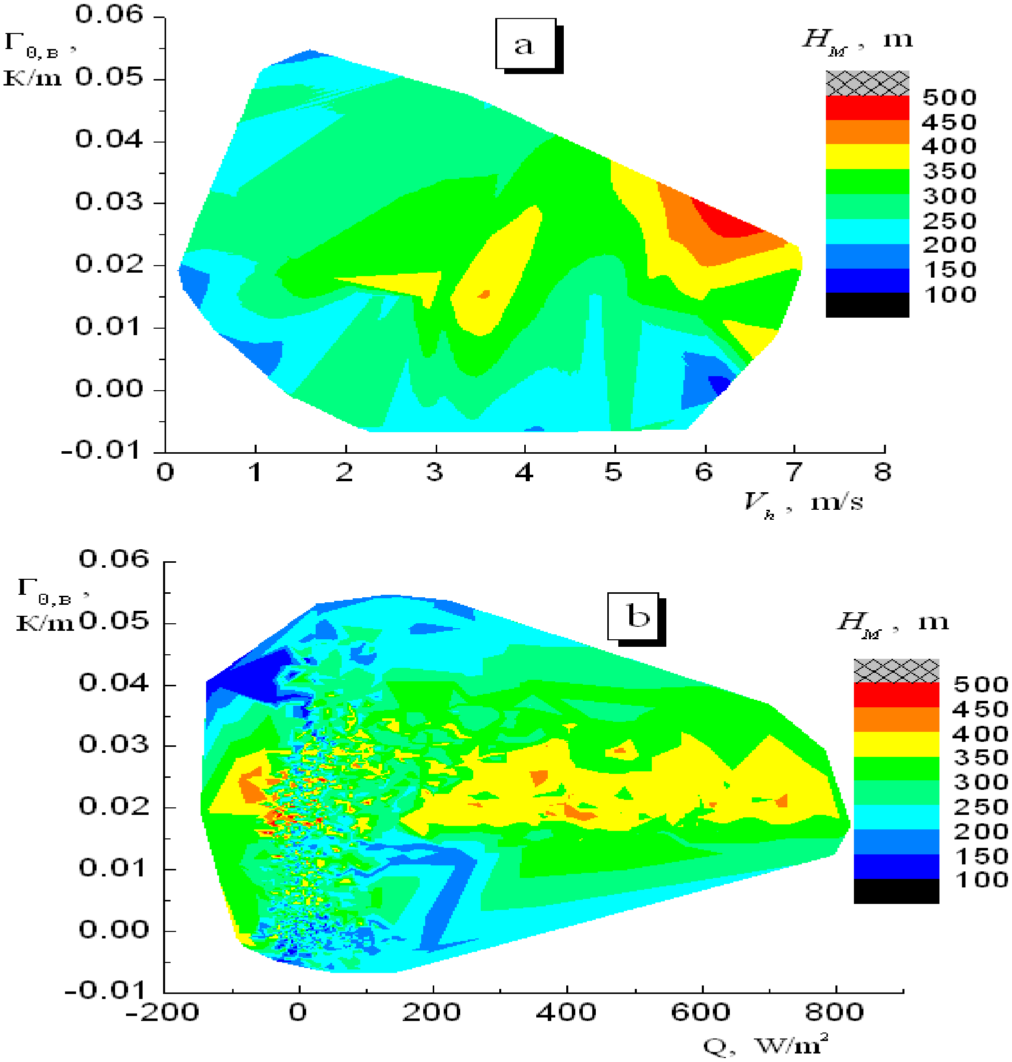

Figure 4 – (a) Diagram of the dependence $H_M(\Gamma_{\Theta,B}, V_h)$; and (b) diagram of the dependence $H_M(\Gamma_{\Theta,B}, Q)$

These diagrams are presented in Fig. 4. According to Fig. 4a, the near-ground wind speed V_h is correlated, in a specific way, with the height H_M : as V_h increases, so too does H_M . However, no well-defined relation between H_M and "boundary" gradient $\Gamma_{\Theta,B}$ exists. Consequently, some other factors, and not wind (at least not near-ground wind) speed, determine the types of the dependences $H_M(\Gamma_{\Theta,B})$, examples of which are presented in Fig. 3.

The vertical turbulent heat flux Q in the near-ground layer is also not among the factors determining a specific type of the relation $H_M(\Gamma_{\Theta,B})$, as analysis of Fig. 4b shows. It is noteworthy that H_M values are mainly elevated when $0.015 \le \Gamma_{\Theta,B} \le 0.03$ (K/m). We also note that large positive Q values are associated with anthropogenic factor, i.e., they are due to local heat fluxes from vent shafts on the roof of the building where the ultrasonic meteorological station was located. We may conjecture that these same values of the flux Q are also characteristic for other buildings, surrounding the observation point and creating local ABL properties. Therefore, these cases were not considered as "unique" features of the observation point and, as such, were not excluded from consideration. We only note that the values $Q > 200$ (W/m2) took place for about 8% of observation time, mainly in the coldest period (January 24-26, 2015). The median value of the positive (negative) Q values had been approximately 42 W/m2 (-20 W/m2).

We will conclude by formulating the main conclusions concerning the material discussed. Analysis of relations between the height of the layer of intense turbulent heat exchange H_M and gradient of potential temperature at this height $\Gamma_{\Theta,B}$ revealed no generalizing regularity. There may be both the case $H_M \propto \Gamma_{\Theta,B}$ and inverse dependence $H_M \propto 1/\Gamma_{\Theta,B}$. It is noteworthy that most of experimental material obeys neither of these regularities. The statistical analysis of $\Gamma_{\Theta,B}$ values makes it possible to conclude that $\Gamma_{\Theta,B} \le 0.04$ (K/m) in majority of realizations. We estimated how wind speed and vertical turbulent heat flux in the near-ground atmospheric layer influence the relation $H_M \Leftrightarrow \Gamma_{\Theta,B}$ and found no significant effect of these parameters. Seemingly, for a more detailed analysis of the relation $H_M \Leftrightarrow \Gamma_{\Theta,B}$, we should perform additional observations under the conditions of stable stratification and employ the data on wind speed above the near-ground layer and other parameters such as estimates of the second derivatives of the air temperature gradient.

Experimental data were obtained with employment of instrumentation at "Atmosfera" Center for Collective Use, Institute of Atmospheric Optics, Siberian Branch, Russian Academy of Sciences.

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