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An experimental study of atmospheric turbulence characteristics in an urban canyon

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Abstract. This article presents the first results of an experimental study of turbulent heat exchange between a surface surrounded by buildings and the atmospheric boundary layer. Heat and momentum fluxes are measured at three levels in the first part of the experiment and three points in the second part of the experiment by an eddy covariance (EC) technique. The presence of wind-shear effects is supported in our measurements by the fact that the momentum flux increases with height from the surface. The sensible heat flux increases with height in the daytime. The distributions of the dimensionless proportionality coefficients between the third and second moments thus obtained indicate the presence of coherent structures in the surface layer.

1.Introduction

For mathematical modeling of climate and numerical weather prediction, information on turbulent heat and momentum fluxes between the atmosphere and the underlying surface is needed. Moreover, the traditionally applied parametrizations are based on the conclusions of the Monin–Obukhov similarity theory (MOST), which assumes an underlying surface with a uniform distribution of aerodynamic and temperature roughness, as well as stationary turbulent flows horizontally and in the surface layer of the atmosphere [1]. Over inhomogeneous landscapes, the condition of horizontal statistical flow homogeneity is violated, which requires specialized experiments to establish the limits of applicability and accuracy of MOST, as well as to study both the vertical and horizontal turbulence patterns in the surface layer of the atmosphere [2, 3,4]. Also, the presence of spatial inhomogeneities can cause non-closure of the heat balance, an effect revealed in many field experiments [5].

Conventionally, the surface heterogeneities can be divided into three groups that can act in combination: a step of different heights and lengths, which causes the separation of the wind flow (forest edge, seashore, cliff), areas with sharply different roughness (forest glades surrounded by forest lakes, urban squares), and long tunnels (river beds, mountain gorges, city canyons). Full-scale measurements of atmospheric turbulence characteristics under such terrain conditions are few, and estimates of the spatial distribution of the turbulence characteristics in this case are mainly based on the results of LES modeling and laboratory experiments [6, 7].

It is well-known that one of the most important tasks of statistical hydromechanics is to find the relationships between the statistical moments of thermohydrodynamic quantities. The Monin-Obukhov similarity theory can be interpreted as one of the most famous examples in geophysics of the diagnostic relationship between the first and second moments. At the same time, in a heterogeneous landscape the so-called coherent structures have a significant role in the formation of the turbulent regime, in the presence of which a closer connection can be demonstrated by the second and third moments [4, 8]. The authors suggest that in one-type heterogeneous landscapes (for example, in canyons) there are universal forms of dependences between statistical moments in which dimensionless constants can be associated with the geometrical parameters of a particular locality.

Revealing of such dependences will contribute to the development of new methods for parameterizing the exchange between the inhomogeneous surface and the atmosphere by the momentum and scalar characteristics.

The study of the turbulent structure of the atmospheric boundary layer (ABL) within urban development is a particularly important task. Assessment and prediction of the microclimate and air quality in cities and their environs comes down to the task of determining the statistical characteristics of stratified turbulent currents with spatial detail down to scales comparable to individual buildings and streets. It is well-known that the accumulation of pollutants in an urban environment is determined not only by the location of pollution sources, but also by the development structure [9]. Urban canyons significantly change the wind regime in the surface layer of the atmosphere [10], creating inhomogeneities in the deposition of pollution and wind tunnels. This factor leads to significant heterogeneity of the pollution field of the urban environment. Also, the study of the dynamics of the wind flow inside an urban canyon is important for modeling the effects of the urban "heat island", especially in winter and at night under conditions of stable stratification [11].

2. Relationships of statistical moments in the boundary layer in the presence of coherent structures

For the case when a large part of the dispersion of thermohydrodynamic fields falls on large (comparable to the boundary layer thickness) structures in which ordered ascending and descending jets are distinguished, the authors of [9, 12] proposed a so-called bimodal model. In the bimodal model, the temperature dispersion flux $\overline{w'\theta'\theta'}$ is associated with the potential temperature flux $\overline{w'\theta'}$ and, accordingly, with the heat flux through the relation:

$$\overline{w'\theta'\theta'} = C_\theta S_\theta \left(\overline{\theta'^2}\right)^{\frac{1}{2}} \overline{w'\theta'}, \tag{1}$$

where $S_\theta = \dfrac{\overline{\theta'^3}}{\overline{\theta'^2}^{\frac{3}{2}}}$ is the asymmetry coefficient of the temperature distribution, and C_θ is the

dimensionless constant. The potential temperature flux is similarly related to the heat flux

$$\overline{w'w'\theta'} = C_w S_w \left(\overline{w'^2}\right)^{\frac{1}{2}} \overline{w'\theta'} \ . \tag{2}$$

If the values of C_θ and C_w from the data of pulsation measurements turn out to be of the order of 1, this indicates the presence of coherent structures (large eddies) and their determining contribution to the vertical turbulent flows. Thus, using equations (1) and (2) in [4] it was shown that turbulent flows over a small lake surrounded by a forest, with the transverse direction of the wind, are formed due to large structures not described by the Monin–Obukhov similarity theory.

3. Experiment setup

This paper presents an experiment in which all-weather monitoring of the temporal variability and spatial structure of atmospheric turbulence is carried out under conditions close to the conditions of an urban canyon. The measurements are carried out at the geophysical observatory of the Institute of Monitoring of Climatic and Ecological Systems (IMCES) SB RAS, Tomsk. The observation platform is located at an altitude of 167 m above sea level inside a multi-story building with building heights from 11 to 21 m (Figure 1). In the southeast of the site there is a forest with a tree height of at least 30 m. On average, southern and southwestern winds prevail over the year, that is, from the open side. The measuring scheme includes seven AMK-03 acoustic anemometers, which allow measuring pulsations of the three components of wind speed and temperature with a frequency of up to 80 Hz (http://meteosap.ru/catalog/amk-03/), a joint production of IMCES SB RAS and LLC "Sibanalitpribor "(Russia). Five anemometers are located on the ground: three AMKs at a height of 2 m, one at a height of 10 m, and another one at the edge of the forest at a height of 28 m. Two anemometers are located on the buildings surrounding the site. The general arrangement of the devices is shown in Figure 1. The data collected by the geophysical observatory are used to analyze the state of the atmosphere and the

underlying surface: standard weather data, snow depth, surface and soil temperatures, and components of the radiation balance.

The location scheme of the sensors of the ground site was previously tested when measuring the structure of turbulence over a lake surrounded by forest [2]. It allows one to estimate the terms of the balance equations of statistical moments and, accordingly, the contribution of horizontal and vertical transport to the formation of turbulent flows.
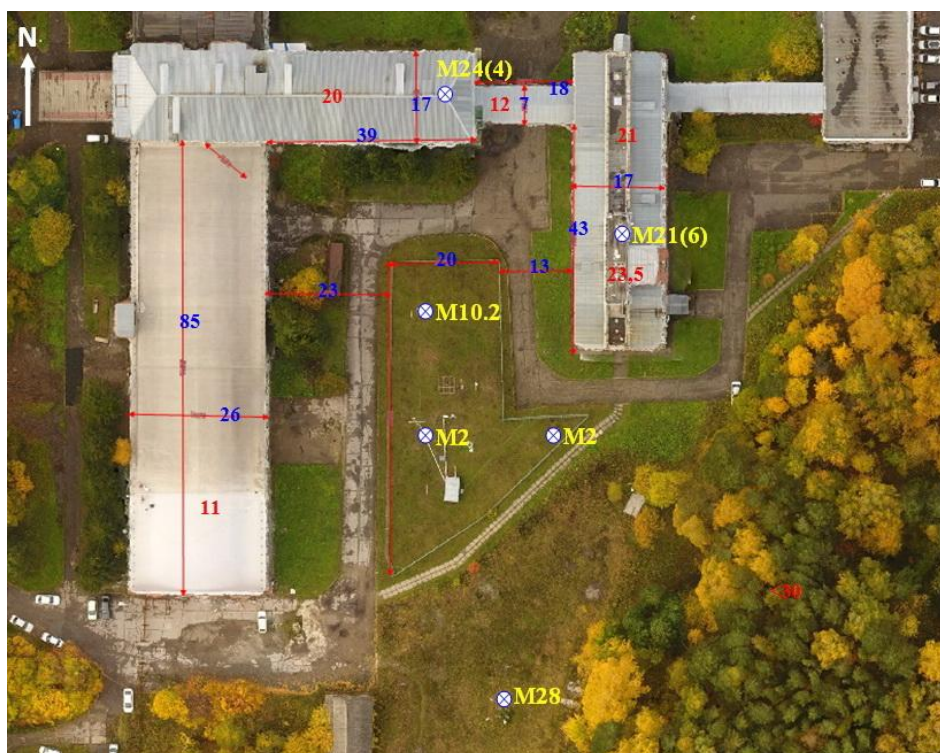

Figure 1. Layout of the masts of the geophysical observatory of IMCES SB RAS. The heights of buildings are shown by red color and horizontal dimensions, by blue one. Masts are denoted by blue circles with crosshairs on a white background with a yellow "M" signature with numbers that indicate the heights of acoustic hot-wire anemometers. For appliances located on the roof, the height above the roof is in brackets. The scheme is oriented to the north.

4. Measurement results

For the consideration, the measurement data of three acoustic hot-wire anemometers located at heights of 2 m and 10 m (mast M10.2) and 28 m (M28), from March 9 to 12, 2019, were selected. Figures 2 and 3 show values with 20-minute averaging; local time (UTC + 7). The temperature with a daily amplitude of about 7°C during the day and in night hours was below zero. The temperature difference between the devices does not exceed 0.4°C, i.e., stratification is close to neutral. Over the entire period the cloud cover was 10 points, and the snow depth was 77 cm. The horizontal wind speed increases with height: the characteristic values at a height of 2 m are in the range of 1-2 m/s, at 10 m in the range of 2-3 m/s, and at 28 m in the range of 3-5 m/s. A pronounced diurnal course of the speed module was not noted. In the wind direction, two modes can be distinguished:

  1) wind from the side of the free southern corridor: direction 190˚;
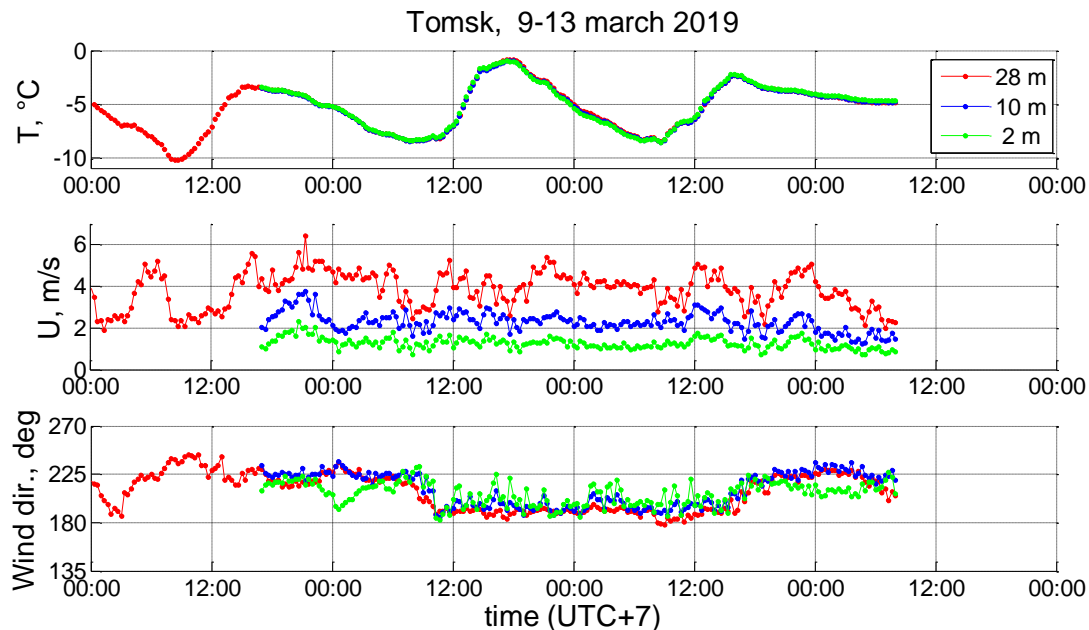 2) through the western wing of the building: direction 225˚.

Figure 2. Flow parameters with 20-minute averaging: air temperature, horizontal wind speed, wind direction.

Figure 3 shows the time course of the turbulent flow of sensible heat. The diurnal flow course at heights of 10 m and 28 m stands out clearly. During the day, the positive flow from the surface to the atmosphere at a height of 28 m reaches 200 W/m^2, at a height of 10 m it reaches 80 W/m^2, and at a height of 2 m the flow is close to 0. At night at all levels the flow is close to 0, but at a height of 2 m the flow is directed downward. At night, when the wind blows from the side of the free corridor, the flow at a height of 2 m is directed down to -30 W/m^2, and when the wind blows through the building it is close to 0.

In the daytime, there is no layer of constant flows under both regimes distinguished in the direction of the wind. The heat flow increases with height. This is especially pronounced in the daytime. This can be explained by the fact that the influence area ("footprint") for the device located at a height of 2 m covers an adjacent relatively cold surface covered with snow, for a height of 10 m the part of this area falls on the walls of buildings heated during the day. At a height of 28 m, the presence of nearby mixed forest, which also warms up during the day, can affect the nearby snow. The average value of the pulse flux in the presented segment of recording of the time course of three acoustic hot-wire anemometers also grows with height: at 2 m – 0.27 H/m^2, at 10 m – 0.43 H/m^2, and at 28 m – 0.46 H/m^2. An increase in the momentum flux, as well as the modulus of the heat flux with height during the flow behind the "step", is noted in measurements in natural landscapes [3, 4, 13]. An increase in the pulse flux with height was obtained in similar flows in laboratory experiments [14] and in eddy-resolving modeling [7].

Consider the dimensionless coefficients C_θ and C_w presented in Figure 4 and calculated by equations (1) and (2). On the probability distribution C_w, a shift of the distribution maximum to the right from zero is noticeable: for heights of 2 m and 28 m the maximum frequency falls in the interval from 0 to 2, and for a height of 10 m the maximum is less pronounced and falls in the interval from -1 to 3. The maximum of C_θ for distribution for all three heights falls in the interval from 0 to 2. Note that in [12] $C_\theta = C_w = 1$, while with a less rigorous approach having a wider range of applicability [9] this equality is true in the order of magnitude. Thus, in the city canyon under consideration, one can assume the presence of large vortices and their decisive role in the formation of vertical turbulent

flows. At the same time, a significant fraction of the values of C_θ and $C_w \gg 1$ means the need for further study of the conditions favorable for the development of coherent structures.
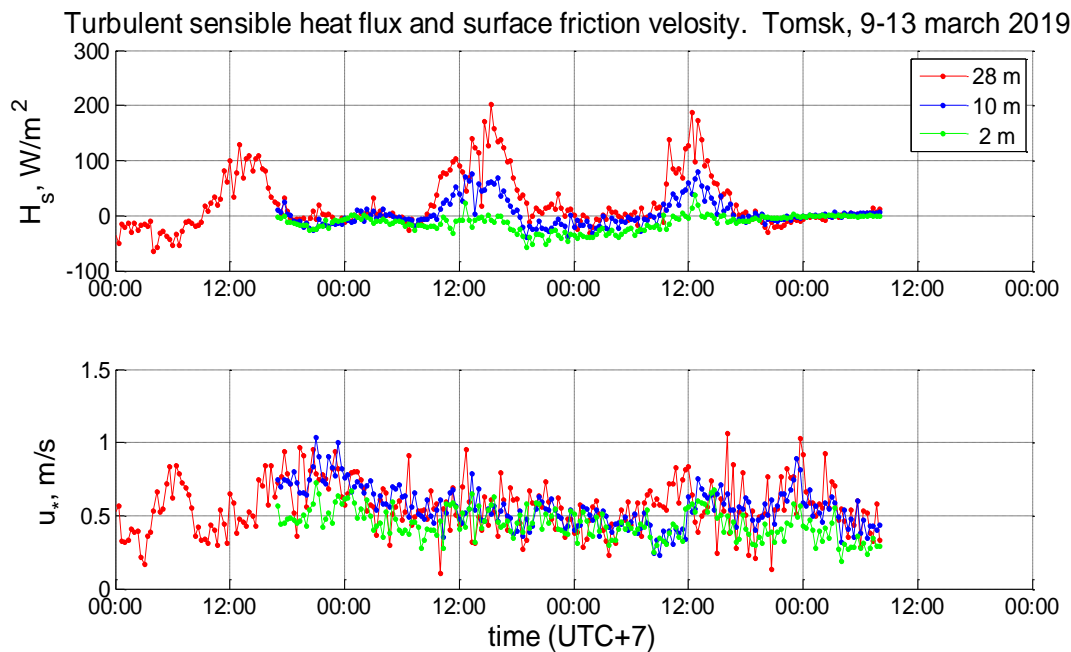

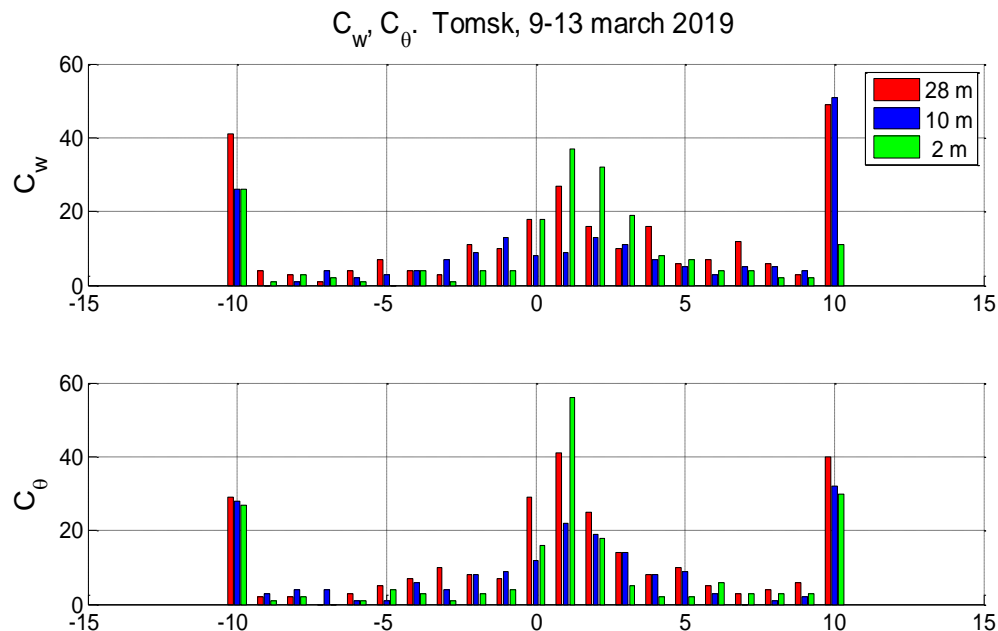**Figure 3.** Turbulent sensible heat flux and surface friction velocity.

Figure. 4. Diagram of the probabilistic distribution of the coefficients C_θ and C_w (in the extreme columns all values that are beyond the boundaries shown in the figure are accumulated).

5. Conclusions

The measurements and calculations with the turbulent pulsation method in the conditions of an urban canyon have not shown a layer of constant fluxes at heights from 2 m to 28 m in the daytime. The

above-obtained distributions of C_θ and C_w (the dimensionless proportionality coefficients between the third $\overline{w'\theta'\theta'}$, $\overline{w'w'\theta'}$ and second $\overline{w'\theta'}$ moments) do indicate the presence of coherent structures in the surface layer.

It is planned to collect observational data in the different seasons and find dependences of the turbulence characteristics on wind direction under various atmospheric stratifications.

Acknowledgments

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