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Modeling and simulation of the urban surface impact on boundary layer structure*

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Abstract. This study attempts to formulate an improved model for the turbulent atmospheric boundary layer (ABL). The present model employs three new ingredients: 1) an updated expression for the pressure–velocity correlation, 2) an updated expression for the pressure–temperature/concentration correlation, and 3) deduced fully explicit anisotropic expressions for the turbulent fluxes of momentum, heat/concentration. A parameterization scheme is used to represent the impact of urban buildings on the airflow in mesoscale atmospheric models. The buildings are not explicitly resolved in this model, but their effect on the grid-averaged variables is parameterized as extra terms in the transport equations of momentum, heat, turbulent kinetic energy and its dissipation rate. This improved model gives a more realistic picture of the impact of the urban surfaces on the airflow as compared to the one-parametric turbulence models.

1. Meso-scale RANS-model for the turbulent ABL

For the 2D case, the basic equations can be written down in the form

$$U_x + W_z = 0, \tag{1}$$

$$U_t + UU_x + WU_z = -\frac{1}{\rho_0} P_x - \langle wu \rangle_z + fV + D_u, \tag{2}$$

$$V_t + UV_x + WV_z = -\langle wv \rangle_z - fU + D_v, \tag{3}$$

$$W_t + UW_x + WW_z = -\frac{1}{\rho_0} P_z - \langle ww \rangle_z + \beta\,\Theta g, \tag{4}$$

$$\Theta_t + U\Theta_x + W\Theta_z = -\langle u\theta \rangle_x - \langle w\theta \rangle_z + D_\theta. \tag{5}$$

The dependent variables in (1)–(5) are the mean velocities U, V, and W along the x, y, and z axes, respectively; Θ is the mean deviation of the potential temperature from the standard value T_0; f is the Coriolis parameter, β is the volume expansion coefficient of the air (3.53×10^{-3} K^{-1}); ρ_0 is the mean air density. The extra terms of D_u, D_v and D_θ describe the impact of the urban roughness on the air flow. The fully explicit algebraic models for the Reynolds shear stresses and the turbulent heat flux are formulated in the following subsection.

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The fully explicit algebraic Reynolds stress and scalar flux models. The coupled algebraic equations system for the traceless Reynolds tensor and the turbulent scalar fluxes (temperature/concentratin) can be solved in the 2D case using the symbolic algebra. Below we represent the equations for turbulent momentum and heat fluxes, only, which are used in the numerical tests for the solution to equations (1)–(5):

$$\big(\langle uw\rangle, \langle vw\rangle\big) = -K_M\left(\frac{\partial U}{\partial z}, \frac{\partial V}{\partial z}\right), \tag{6}$$

$$\langle w\theta\rangle = -K_H\frac{\partial \Theta}{\partial z} + \gamma_c, \tag{7}$$

$$K_M = E\tau S_M, \quad K_H = E\tau S_H, \tag{8}$$

$$S_M = \frac{1}{D}\left\{s_0\big[1 + s_1 G_H(s_2 - s_3 G_H)\big] + s_4 s_5(1 + s_6 G_H)(\tau\beta g)^2\frac{\langle\theta^2\rangle}{E}\right\}, \tag{9}$$

$$S_H = \frac{1}{D}\left[\frac{2}{3}\frac{1}{c_{1\theta}}(1 + s_6 G_H)\right], \tag{10}$$

where

$$\gamma_c = \frac{1}{D}\Big(1 + \frac{2}{3}\alpha_2^2 G_M + s_6 G_H\Big)\alpha_5(\tau\beta g)\langle\theta^2\rangle, \tag{11}$$

where γ_c is a countergradient term, which is absent in the 2nd and 2.5-order closure models [1]. Here

$$\begin{gathered} G_H \equiv (\tau N)^2, \quad G_M \equiv (\tau S)^2, \\ N^2 = \beta g\frac{\partial\Theta}{\partial z}, \quad S^2 \equiv \left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2, \quad \tau = E/\varepsilon. \end{gathered} \tag{12}$$

All the parameters in equations (6)–(12) are expressed though the three constants of modeling expressions for the pressure-velocity and the pressure-temperature correlations that can be found in [2, 3]. The three-parametric turbulence model E–ε–$\langle\theta^2\rangle$ is used for the closure of expressions (6)–(7) for the turbulent fluxes.

Numerical test. The new meso-scale model ABL is tested for a simple 2D case. The horizontal extension of the domain is 120 km with 1 km resolution. The vertical resolution is 10 m in the first 50 m above the ground and then it is stretched up to 1 km at the top (6 km). The topography is flat with a 10-km wide city (10 ‘urban’ points) surrounded by a rural area. The ground temperature is the only unsteady boundary condition. This thermal boundary condition simulates a 24 hour cycle of heating by the sun on a land mass located from 45 to 55 km. In our study, the urban heat island effect is specified by an urban-rural temperature difference. The meteorological initial conditions are a geostrophic wind from the West of 3 and 5 m/s, and the atmospheric thermal stratification being equal to 3.5 K/km in potential temperature.

2. Results

Impact on the meso-scale flow. Figure 1 illustrates the vertical distribution of the scaled frictional velocity, computed by the numerical model and the observational data [4–8]. As is seen in the figure, the computed frictional velocity increases with the height from the ground surface, reaches a maximum at the roof level and then slightly decreases with height. This is in a reasonable agreement with observations [8, 9].

Figure 2 shows the vertical distribution of the vertical velocity variance. In addition, the calculated results shown in Figures 3, 4 allow us to estimate the effect of the longitudinal turbulent heat diffusion (the term $\langle u\theta\rangle_x$ in

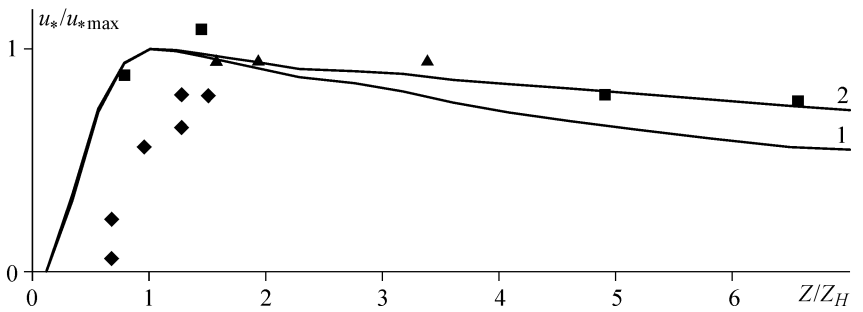

Figure 1. Vertical profiles of "local" friction velocity u_* (defined as $(\langle uw\rangle^2 + \langle vw\rangle^2)^{1/4}$), averaged and normalized by its maximum value. Solid lines are the results of the present model: 1 — for simulation with 3 m/s wind speed, 2 — for simulation with 5 m/s wind speed. Squares are data of [4], diamonds are data of [5–7], and triangles are data of [8]

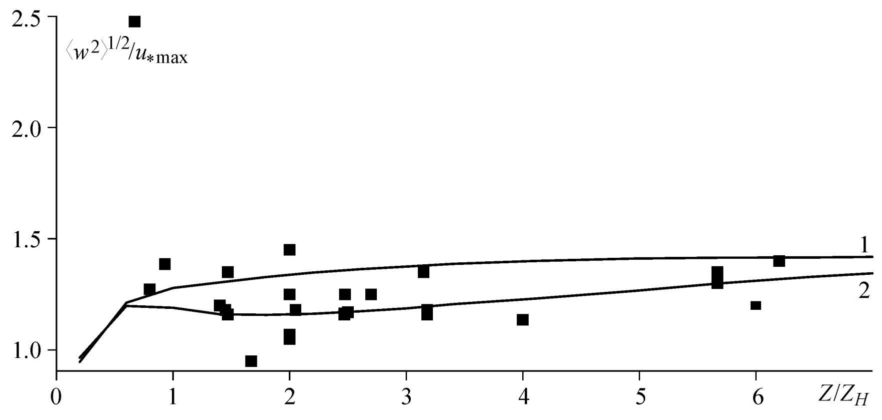

Figure 2. Vertical profiles of normalized vertical velocity variance at the center of the urbanized area. Solid lines are results of the present model: 1 — for simulation with 3 m/s wind speed, 2 — for simulation with 5 m/s wind speed. Squares are the measurement data [10]. The vertical coordinate is normalized on the average height of buildings of the urbanized area Z_H

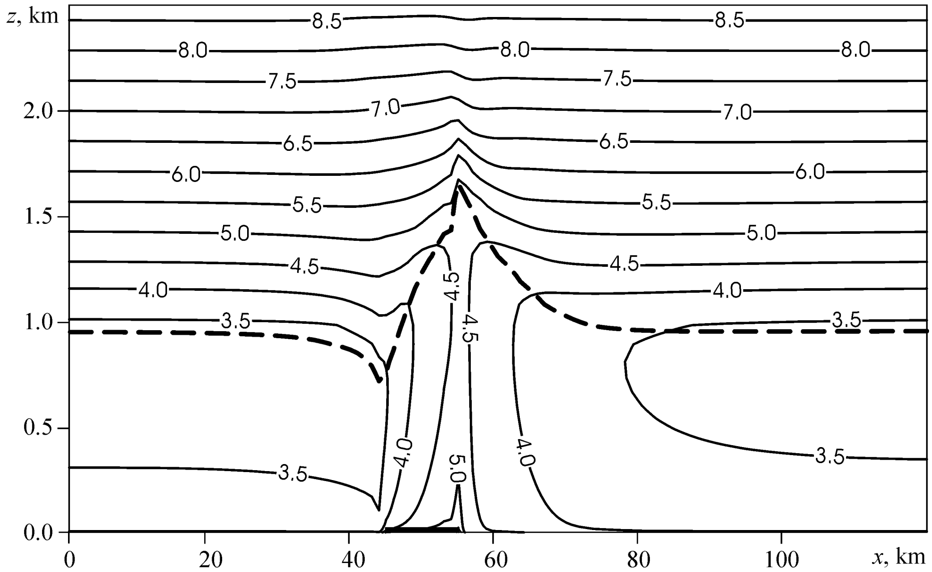

Figure 3. Vertical section of a potential temperature deviation calculated taking into account the longitudinal turbulent heat diffusion at 12:00 a.m. for simulation with 5 m/s geostrophic wind. The dashed line on the potential temperature plots represents the boundary layer height (defined as level, where the turbulent kinetic energy becomes less than 0.01 m^2/s^2)

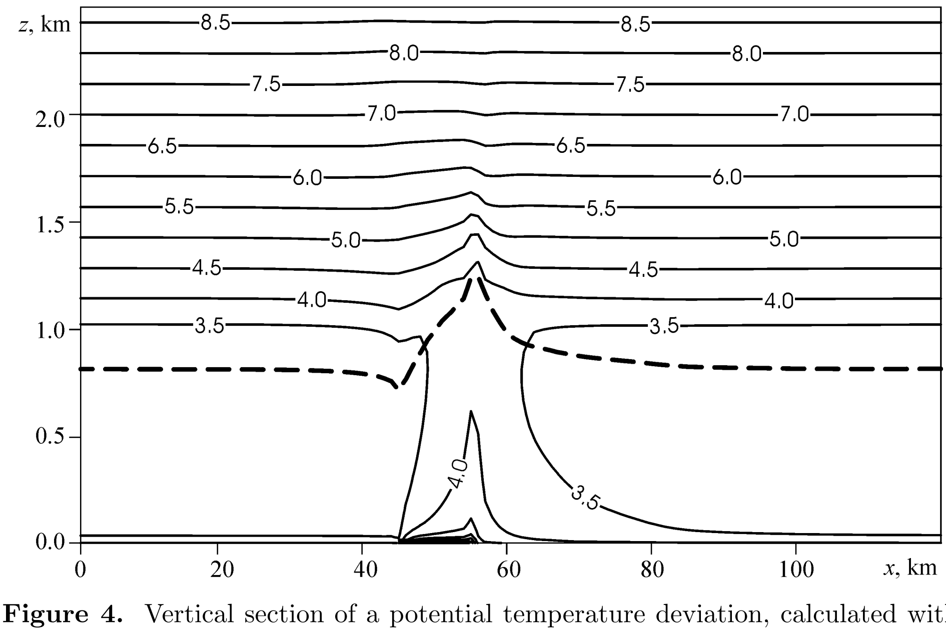

Figure 4. Vertical section of a potential temperature deviation, calculated with neglecting the longitudinal turbulent heat diffusion at 12:00 a.m. for simulation with 5 m/s geostrophic wind. The thick line on the abscissa between 45 and 55 km indicates to the city location

the right-hand side of equation (5)) on the urban boundary layer (UBL) characteristics. It is seen from Figures 3, 4 that the height of the UBL (marked with a dashed line)in the presence of diffusion is higher than in its absence.

Impact on the dispersion of a passive tracer. One of the objectives of the study of the urban boundary layer is linked with pollutant dispersion.

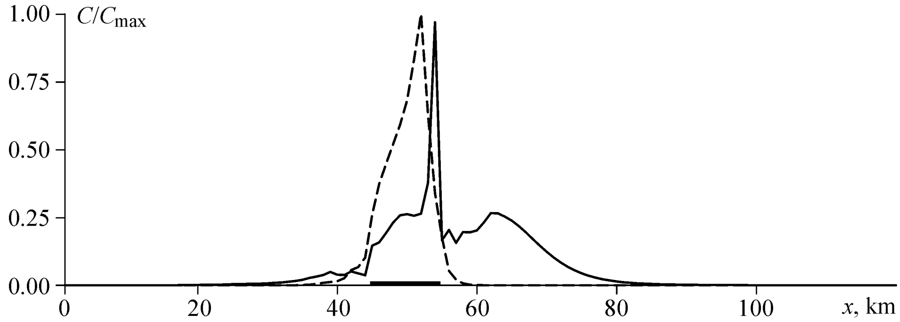

Figure 5. The passive tracer concentration at the lowest level at 13:00 of the second day. The thick line on the abscissa between 42.5 and 55.5 km indicates to the city location. Results are obtained for the case with low (3 m/s) geostrophic wind

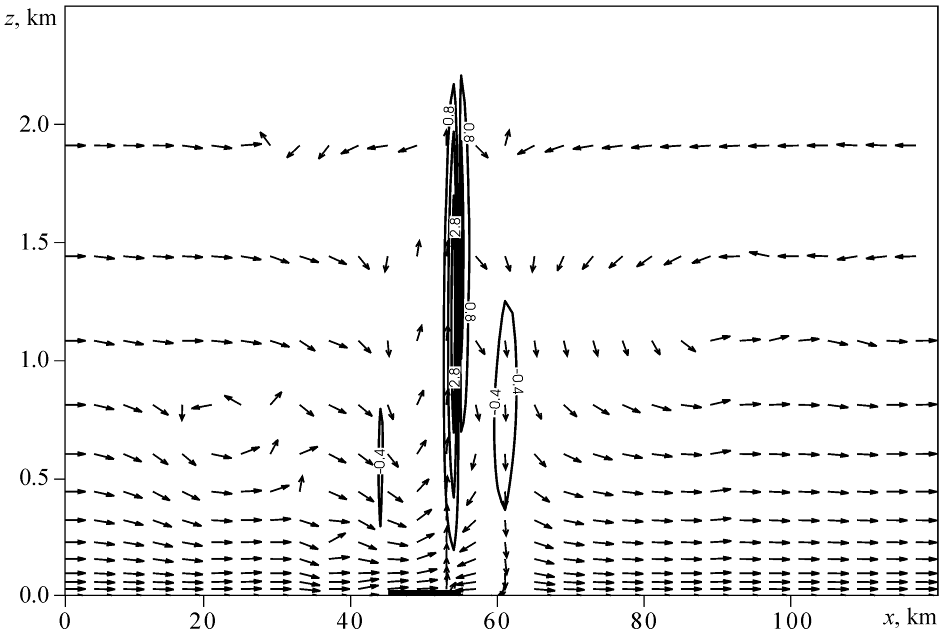

Figure 6. Velocity vectors and isotachs (m/s) for the vertical velocity above the city for 13:00 (the second day)

According to it, it is interesting to study the impact of the city on the pollutant dispersion. With this aim, the computation of the transport of a passive tracer has been added to the model (the same numerical grid, the same advection scheme and the same algebraic anisotropic model for the turbulent scalar fluxes as those used in this improved meso-scale model). In order to have realistic profiles the passive tracer is emitted in the city at ground with a time variation typical of traffic emissions (high values in the morning and low values during the night hours). The impact of the city on the daytime pollutant concentration far from the city is shown in Figure 5. The analysis of the ground-level distribution of concentration shows that the second peak computed at 1300 (the next day) in the rural area, around 10–15 km downwind of the city, is the result of the tracer accumulated in the city during night and early morning and then advected downwind. Such a behavior of concentration is linked to the thermal circulation on the left side of a city shown in Figure 6, as isotachs of the vertical wind speed (arrows show the vector field of the wind speed).

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