# Modeling and Simulation of Thermal Air Circulation above an Urbanized Area

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*Abstract:* - A numerical model to represent the impact of urban buildings on airflow in meso'scale atmospheric models is presented. In the model, the buildings are not explicitly resolved, but their effects on the grid-averaged variables are parameterized. An urbanized area is characterized by a horizontal building size, a street canyon width and a building density as a function of height. The improved, three-parametric $E-\varepsilon-\overline{\theta^2}$ turbulence model for the computation of the wind field, air temperature and pollutant dispersion was developed. The transport of momentum, heat and mass under density stratification is evaluated from the fully explicit anisotropic algebraic expressions. These expressions are derived based on the assumption of weak-equilibrium turbulence approach where transport effects on the stresses and heat fluxes are negligible. The heating processes at surfaces of buildings and ground are also modeled. The comparison of the computational results obtained with the present model and existing observational data and numerical models shows that the present model is capable of predicting the structure of turbulence in the urban canopy layer under density stratification and of obtaining high-resolution local wind fields. Numerical experiments with the new three-parametric model show that the behavior of the airflow in the urban canopy layer and above urbanized area is strongly affected by the existence of buildings and thermal stratification, including the urban heat island effect.

*Key-Words:* - Thermal convection, turbulence, atmospheric boundary layer, modeling

## 1 Introduction

Urbanization causes drastic changes in radiative, thermal, moisture and aerodynamic characteristics of the land surface, leading to heterogeneities of the airflow. The main reasons for complexity of urban modeling lies in the diversity of spatio-temporal scales over the phenomena occur. In order to compute the mean and turbulent transport, several variables are needed (wind, turbulent coefficients, temperature, pressure, humidity). The numerical models must, indeed, ideally be able to represent the two main scales (the 'urban' and the 'meso') involved. Since the horizontal dimensions of the domain are on the order of the meso'scale (~100 km), to keep the number of grid points compatible with the CPU time cost, the horizontal grid resolution of such (meso'scale) models ranges between several hundreds of meters and a few kilometers. Because is not possible to resolve the city structure in detail (buildings or blocks), but that the effects of the urban surfaces must be parameterized [1]. The most important urban effects on the airflow are: (i) the presence of an intense shear layer at the top of the urban canopy (there, the mean kinetic energy of the flow is converted into turbulent kinetic energy (TKE)); (ii) the development of the turbulent wakes that generated by the roughness elements; efficiently mix and diffuse momentum, heat and mass; (iii) drag due to buildings, i.e. the pressure differences across individual roughness elements; (iv) phenomena of differential heating/cooling of sunlit/shaded surfaces, radiation trapping effects in street canyons and heat storage in buildings can generate the so-called urban heat island effect [2, 3]. (In modeling, the urban heat island effect can be specified by an urban-rural temperature difference. The urban heat island effect may produce major temporal and spatial alterations to the thermodynamics and circulation of the urban airflow).

This study attempts to formulate a three-parametric numerical model for simulation of the air circulation over the urbanized areas. In this model, the turbulent transfer of momentum, heat and concentration in the urban boundary layer is numerically simulated by a time-dependent Reynolds-averaged Navier-Stokes (T-RANS approach). In the present model, two new ingredients are employed:

1) an updated expression for the pressure-strain correlation,

2) an updated expression for the pressure-temperature correlation. The turbulent momentum and scalar fluxes are determined by the full explicit algebraic expressions which are derived from the closed transport equations for turbulent fluxes and simplified using the weak-equilibrium assumption and symbolic algebra. Closure is achieved by solving the evolution equations for the turbulent kinetic energy, its dissipation rate and scalar variance (the three-parametric turbulence model [1, 4]). This improved meso'scale model is able to reproduce the most important features of a wind field above the city.

# 2 The closure model for turbulent ABL

Both mean and turbulent variables are needed to model an ABL. The following system of partial differential equations models the ABL flow over the urban heat island for a full 24 hour cycle. The Boussinesq approximation for density variations is used to include buoyancy effects:

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

$$U_t + UU_x + WU_z = -\frac{\overline{P_x}}{\rho} - \left(\overline{wu}\right)_z + fV + D_U, \tag{2}$$

$$V_t + UV_x + WV_z = -\left(\overline{wv}\right)_z - fU + D_V, \tag{3}$$

$$W_t + UW_x + WW_z = -\frac{P_z}{\rho} - \left(\overline{ww}\right)_z + \beta\Theta g + D_W, \tag{4}$$

$$\Theta_t + U\Theta_x + W\Theta_z = -\left(\overline{u\theta}\right)_z - \left(\overline{w\theta}\right)_z + D_\Theta. \tag{5}$$

The dependent variables in (1)-(5) are the mean flow velocities $U$, $V$, and $W$ in $x$, $y$, and $z$ directions respectively, mean pressure $P$, mean deviation $\Theta$ from a reference temperature $T_0$. The terms $D_U, D_V, D_W$ here represent the forces (e.g., frictional force, drag force etc.) and $D_\Theta$ denotes the impact of the sensible heat fluxes from solid surfaces (ground or buildings) on the potential temperature budget. The parametric quantities in the equations (1)-(5) include gravitational acceleration g (9.8 $\text{ms}^{-2}$), Coriolis parameter f ($0.8\times10^{-4}$ at latitude $35^0$N), volumetric expansion rate of air $\beta$ ($3.53\times10^{-3}$ $\text{K}^{-1}$), and mean air density $\rho$ (1.25 $\text{kgm}^{-3}$). The lower case terms $u$, $v$, $w$, and $\theta$ represent time dependent deviations from their respective mean values, and their products in (1)-(5) give the turbulent Reynolds stresses and heat fluxes. They are modeled by the full explicit anisotropic algebraic expressions which are obtained from the differential closed transport equations for turbulent fluxes by reducing them to the system of algebraic equations using the weak-equilibrium assumption. The system of algebraic turbulent flux equations is solved using symbolic algebra (cf. [4]). Three-parametric turbulence model [1, 5] is used to close expressions for the turbulent momentum and scalar fluxes. The turbulent fluxes expressions are not shown here because of their bulkiness.

## 2.1. Nonlocal expressions for turbulent momentum and heat fluxes

Equations for the turbulent momentum and heat fluxes were solved via symbol algebra. Below, we present expressions for those turbulent momentum and heat fluxes that were used in a numerical test to solve system of equations (1) – (5):

$$\left(\overline{uw}, \overline{vw}\right) = -K_M\left(\frac{\partial U}{\partial z}, \frac{\partial V}{\partial z}\right), \quad \overline{w\theta} = -K_H\frac{\partial\Theta}{\partial z} + \gamma_c,$$

$$K_M = E\tau S_M, \; K_H = E\tau S_H;$$

$$S_M = \frac{1}{D}\left\{\begin{matrix} s_0\left[1 + s_1G_H\left(s_2 - s_3G_H\right)\right] + \\ + s_4s_5\left(1 + s_6G_H\right)(\tau\beta g)^2\frac{\overline{\theta^2}}{E}\end{matrix}\right\}$$

$$S_H = \frac{1}{D}\left\{\frac{2}{3}\frac{1}{c_{1\theta}}\left(1 + s_6G_H\right)\right\};$$

$$\gamma_c = \frac{1}{D}\left\{1 + \frac{2}{3}\alpha_2^2G_M + s_6G_H\right\}\alpha_5(\tau\beta g)\overline{\theta^2}$$

is the countergradient term.

The quantities $G_H$ and $G_M$ are defined as

$$G_H \equiv (\tau N)^2, G_M \equiv (\tau S)^2,$$

$$N^2 = \beta g\frac{\partial\Theta}{\partial z}, \quad S^2 \equiv \left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2,$$

$$D = 1 + d_1G_M + d_2G_H - d_3G_MG_H + d_4G_H^2,$$

$$d_1 = \frac{2}{3}\alpha_2^2, d_2 = \frac{7}{3}\frac{\alpha_3}{c_{1\theta}}, \; d_3 = \frac{2}{3}\alpha_2\frac{\alpha_3}{c_{1\theta\,2}}\alpha_5,$$

$$d_4 = \frac{4}{3}\left(\frac{\alpha_3}{c_{1\theta}}\right)^2, \; s_0 = \frac{2}{3}\alpha_2, \; s_1 = \frac{1}{\alpha_2}\left(\frac{\alpha_3}{c_{1\theta}}\right), \; s_2 = \alpha_2 - \alpha_5,$$

$$s_3 = \alpha_5\left(\alpha_3 / c_{1\theta}\right), \; s_4 = \alpha_3\alpha_5, \; s_5 = \alpha_5 + (4/3)\alpha_2,$$

$$s_6 = \alpha_3 / c_{1\theta}, \; \alpha_1 = (4/3)\frac{1-c_2}{c_1}, \; \alpha_2 = \frac{1-c_2}{c_1}, \; \alpha_3 = \frac{1-c_3}{c_1},$$

$$\alpha_4 = (1 - c_{2\theta}), \; \alpha_5 = (1 - c_{2\theta})/c_{1\theta},$$

($c_1$=2, $c_2$=0. 54, $c_3$=0.8, $c_{1\theta}$=3.28, $c_{2\theta}$ =0.5).

# 3 Numerical Test

The 2D numerical test is carried out. The size of the computational domain is 6x120 km with the resolution of 1 km. The topography is flat with a 10-km wide city surrounded by a rural area. In the model, urban heat island effects are specified by the urban-rural temperature difference. The magnitude of rural-urban temperature difference driving this circulation depends on a variety of factors including the morphology of urban canopy layer. Therefore, the urban roughness parameterization has been incorporated in the improved meso'scale model (Fig. 1). The ground temperature is the only unsteady boundary condition [1]. This thermal boundary condition simulates the 24 hour cycle of heating by the sun on a land mass located from $x = 0$ km to $x = 120$ km. The meteorological initial conditions are geostrophic wind from the west of 1, 3 and 5m $s^{-1}$, and atmospheric thermal stratification equal to 3.5 K $km^{-1}$ in potential temperature.

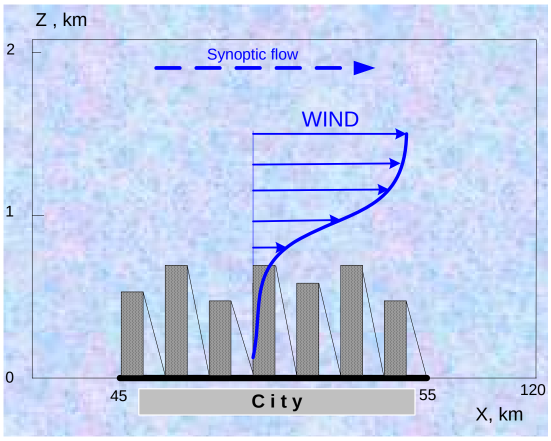



Fig. 1. The concept incorporated of urban canopy layer. The thick line on abscissa between 45 km and 55 km indicates the city location.

# 4 Simulation Results

Results of numerical modeling of the urban boundary layer lead to the following conclusions about transformation of the global structure of wind velocity field above the urbanized surface (Fig.1).

## 4.1 Momentum

Comparison of the vertical profile of local $u_*$ defined as $\left(\overline{uw}^2 + \overline{vw}^2\right)^{1/4}$ with the measurements data [6-8] is presented in Fig. 2. Above the roughness sublayer, urban simulations show a region where $u_*$ is nearly constant with height during day and night for both geostrophic wind speeds. In the roughness sublayer the behavior of vertical profile of $u_*$ exhibit a very similar shape as in the observations during night and daytime.

The extensive data set of measurements in the cities is presented in review [9] for the ratio of the local friction velocity $u_*$ to the mean velocity of horizontal wind (six groups of data; squares in Fig. 3). The calculated profile of $u_*/U$ (solid line in Fig. 3) has a maximum near the top of the building and then decreases with increasing height, reaching a value close to 0.1 at a height of about a fourfold average height of the building. The profiles calculated for two values of the geostrophic wind (3 and 5 m/s) are in good agreement with observational data.

The simulated results presented in these two figures show that the modified model of turbulence for the

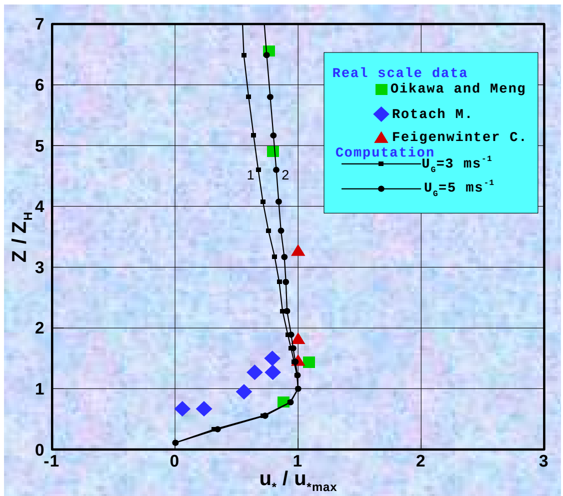



Fig. 2. Vertical profiles of the local velocity friction $u_* / U_{max}$.

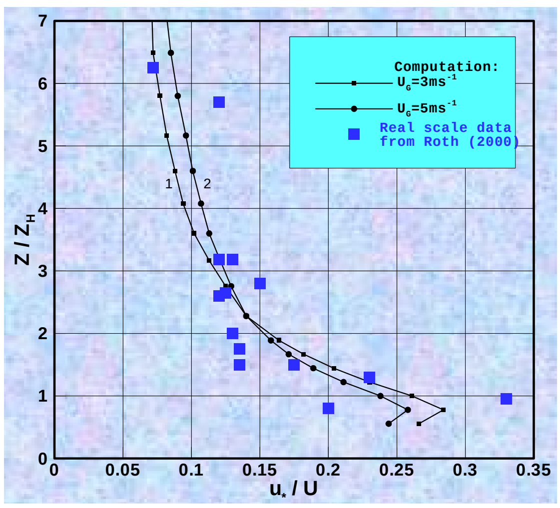



Fig. 3. Vertical profiles of the ratio between the local $u_*$ to the mean wind speed $U$. The squares refer to the large number of full-scale observations [9].

ABL and a more realistic model of urban roughness (Fig. 1) are able to reproduce the vertical profiles of both the turbulent momentum flux and the mean velocity of horizontal wind that are consistent with observational data.

### 4.2 Sensitivity to wind speed

For low synoptic speed of 1 m $s^{-1}$, the horizontal gradient between the temperature above the city and above the rural area generates a thermal circulation (Fig. 4). When the wind speed increases to 3 m $s^{-1}$, the column of hot, unstable air above the city is still present, but it is advected downwind and thermal circulation it is displaced on the leeside of the city (Fig. 5).

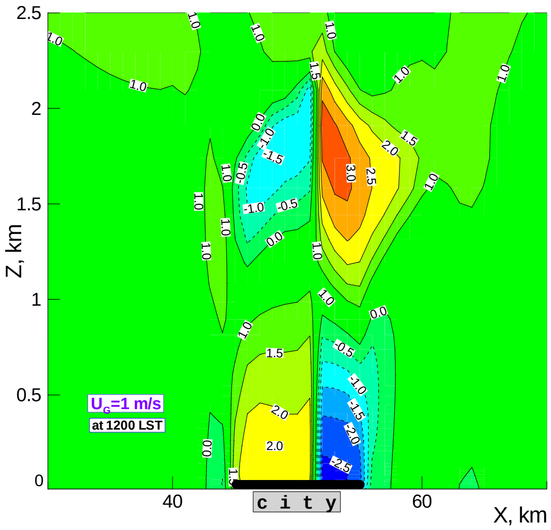



Fig. 4. Vertical section of horizontal wind speed for simulation with 1 m $s^{-1}$ at 12:00 LST.

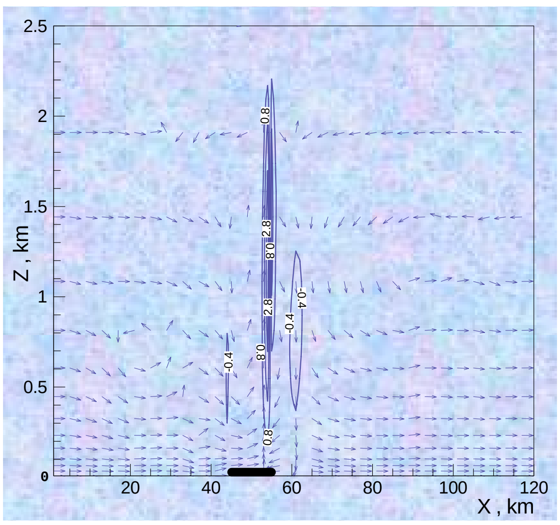



Fig. 5. A vector field of horizontal wind speed and isotachs of the mean vertical wind speed at 13 LST (second day of modeling).

### 4.3 Impact on the dispersion of a passive tracer

A passive tracer is emitted in the city at ground level with a time variation typical of traffic emissions characterized by high values in a morning and low values during night hours in order to reproduce realistic profiles. Concentrations computed by the model at the lowest level in the centre of the urban area are plotted in Fig. 6. They show the impact of the city on pollutant dispersion (cf. Fig. 6 and Fig. 5).

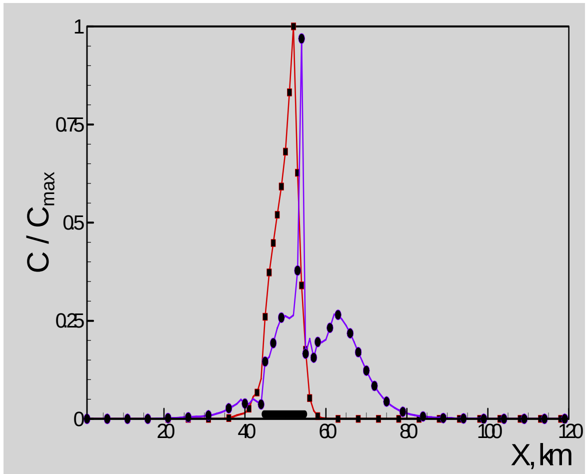



Fig. 6. Passive tracer concentration $C/C_{max}$ at the lowest level at 07 LST of the first day of modeling (■) and at 13 LST the second day of modeling (●), as function of horizontal distance.

### 4.4 Countergradient heat flux: comparison between $E-\varepsilon-\overline{\theta^2}$ and $K-\varepsilon$ turbulence models

The two turbulence models commonly used for simulating the urban boundary layer include standard $k-\varepsilon$ model modified for effects of buoyancy on vertical turbulent transport [10], and a traditional approach [11] based on the one-parameter turbulence model. In this model, the turbulence length scale is found as a function of the vertical coordinate based on some assumptions. Such an approach does not take into account either anisotropic transport in vertical and horizontal directions, or effects of buoyancy on vertical turbulent transport. Computations of vector field, temperature and turbulent quantities inside the urban boundary layer allow detecting differences in the turbulent transport modeled with the three-parameter $E-\varepsilon-\overline{\theta^2}$ model and standard K-theory [11]. For this purpose, values of turbulent exchange coefficients $K_M = -\overline{uw}/(\partial U/\partial z)$ and $K_H = -\overline{w\theta}/(\partial\Theta/\partial z)$ are computed diagnostically in the same way as for the horizontal homogeneous atmospheric boundary layer [12], and the results are shown in Fig. 7a,b.

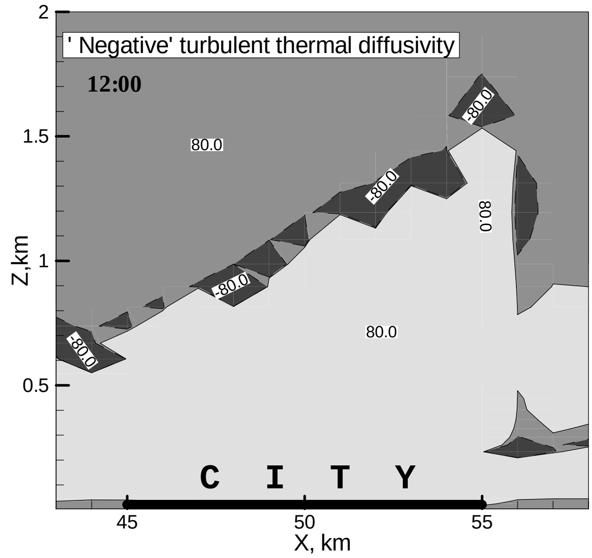
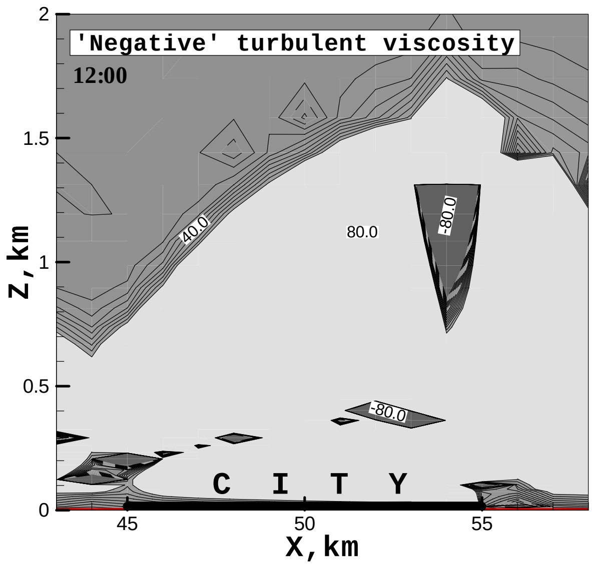



Fig. 7a. Heat turbulent exchange coefficient for *Urban* simulation at noon. Results are for the case with $3\,\mathrm{m\,s^{-1}}$ geostrophic wind.




aFig. 7b. Momentum turbulent exchange coefficient for *Urban* simulation at noon. Results are for the case with $3\,\mathrm{m\,s^{-1}}$ geostrophic wind.

As can be clearly seen in Fig. 7a, b, negative values of $K_M$ and $K_H$ are predicted in the region of turbulent thermal circulation on the leeward side of the urbanized area (Fig. 8). However, their negative values are also predicted in the lower urban boundary layer part for $K_M$ and upper urban boundary layer part for $K_H$. Regions of negative values of $K_M$ and $K_H$ explicitly indicate non-local character of the turbulent transport which can not be described using simple one- or two-parameter turbulence models. In these two models, it is difficult to correctly account for effects of buoyancy on the turbulent transport of momentum, mass and heat. For example, Fig. 9 shows that the 'standard' $k-\varepsilon$ model underpredicts values of the vertical turbulent heat flux when compared with the $E-\varepsilon-\overline{\theta^2}$ model and fully explicit anisotropic model for turbulent fluxes of momentum, heat and mass.

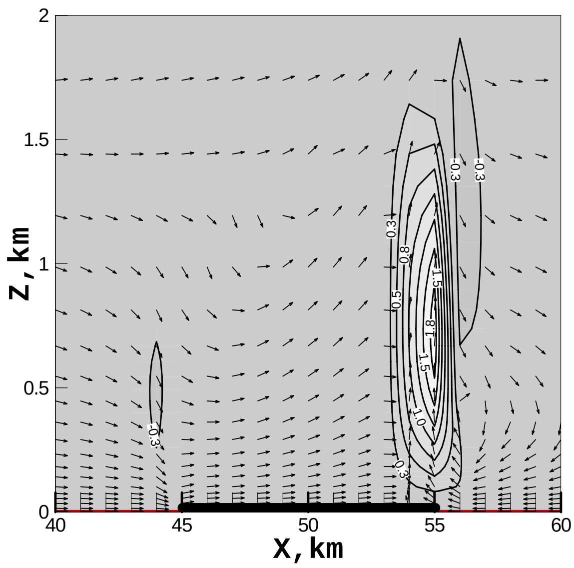



Fig. 8. Velocity vectors and isotachs ($\mathrm{ms^{-1}}$) for vertical velocity at 12:00 (*noon*) in the diurnal cycle of simulation for the geostrophic wind speed $U_G = 3\,m\,s^{-1}$.

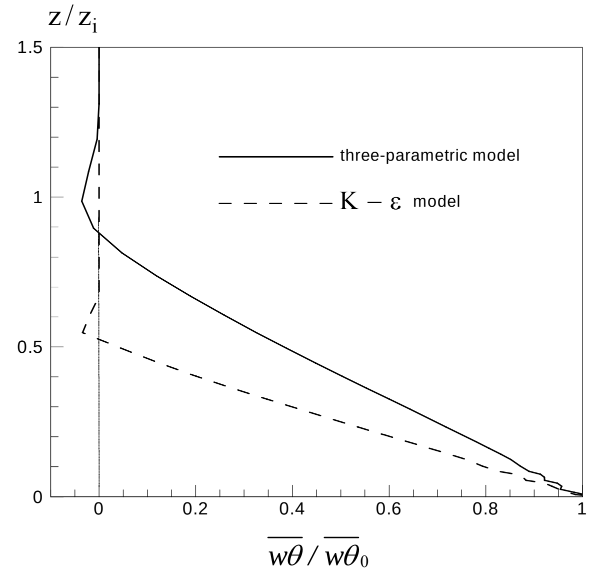



Fig. 9. Vertical turbulent heat flux in a point in the center of the city at 12:00 (*noon*) in the diurnal cycle of simulation for the geostrophic wind speed $U_G = 3\,m\,s^{-1}$ computed by means of 'standard' $k-\varepsilon$ model and the three-parametric $E-\varepsilon-\overline{\theta^2}$ turbulence model with the fully explicit anisotropic model for turbulent fluxes. The fluxes normalized on the maximum value of $\overline{w\theta}_0$.

## 5 Conclusion

A three-parameter meso'scale model of explicit anisotropic turbulent fluxes of momentum and heat has been developed in this paper for modeling atmospheric flows over an inhomogeneous underlying surface. An important property of the model lies in the improvement of estimating the processes of transfer in the vertical and horizontal directions under different stratification conditions, which are usually observed in an urban boundary layer. A simple two-dimensional numerical test on the influence of mechanical factors (urban roughness) and thermal factors (effect of an urban heat island) on a global structure of the atmospheric boundary layer has been implemented. This test has shown that the results of numerical simulation are in good qualitative and quantitative agreement with the data of field measurements. The model is able to reproduce turbulent processes within the urban canopy layer and above it with satisfactory accuracy. The formulated model of turbulent fluxes with closure level 3.0 can be potentially used to model the atmospheric boundary layer within the "urban" scale and meso'scale. It is necessary to note, that the description of a detailed pattern of urban climate requires measurement data on turbulent quantities within the urban canopy layer. Such data allow a more accurate specification of the desired functions of the three-parameter model at the lower boundary near the surface (at the first computation level), because the use of the approximations of constant fluxes in the surface layer that are based on the Monin–Obukhov theory does not allow an adequate (to the data of field measurements; see, for example, [13]) reproduction of the vertical structure of turbulent fields in the urban canopy layer (from the level of the urban street canyon to heights of 50–100 m). It is clear that a realistic modeling of the dispersion of urban pollutants requires an accurate knowledge of meteorological parameters for this region of the urban ABL, where the pollutants are emitted and where people live. An efficient use of this model for the turbulent ABL requires the specification (from measurement data) of "input" parameters such as the vertical distributions of the three base functions of the model, $E$, ε, and $\overline{\theta^2}$ (for example, in the morning hours for a stably stratified ABL). Testing the potentials of the RANS turbulence model for an urban ABL requires the measurement data on the distributions of a number of quantities, such as the variance of the vertical component of turbulent velocity and the boundaries of surface and raised inversions (including those under the conditions of weakened ABL turbulence in the night and early-morning hours, measurement data on vertical distributions of temperature, turbulent heat flux, TKE, and other parameters).

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