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ON THE EXTENSION AND MODIFICATION OF THE SIMILARITY FORMAT PARAMETERIZATION SCHEMES OVER URBAN AREA

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Abstract: A number of flux and diffusion characteristics in urban boundary layer with height *H* are analyzed on the basis of parameterization schemes, modified and applied over canopy layer in the framework of a two-layer model – roughness sub-layer and overlying layer, extended height *H*.

Key words: *Richardson bulk method, PBL resistance laws, roughness sub-layer, drag and heat transfer coefficients, dispersions, free-flow stability.*

INTRODUCTION

The traditional parameterization schemes for homogeneous/rural conditions – surface bulk Richardson number (Rb-method) and PBL resistance laws (RL-method) allow parameterization of dynamic and diffusion processes for a set of turbulent regimes. An important practical task appears this reach parameterization status, by making respective modification, to be adapted to urban conditions. The present work is dedicated to this problem

METHOD AND BASIC RESULTS

In traditional (rural) case the bulk Richardson number $R_b = \beta \Delta\theta\, z_1 / \Delta u^2$, where $\Delta\theta = \theta(z_1) - \theta_0$, $\Delta u = u(z_1) - u(z = z_0) \equiv u_1$, β - buoyancy flux parameter, z_1 - reference height over the surface (for example $z_1 = 10m$) is often used.

Complex exchange processes and interaction between the atmosphere and the urban canopy sub-layer (UCL) ($z \le h, h$ - averaged buildings height) appear in urban conditions, which take place not only within the UCL, but also significantly in the overlaying urban roughness sub-layer (URL) at $h \le z \le z_*$. Here z_* is the height of URL at which the influence of urban heterogeneities disappears and the Monin-Obukhov similarity theory (MOST) is valid. It is reasonable a bulk Richardson number for URL in terms of displacement height d to be introduced in order these important processes to be integrally characterised (the subscript "eff" marks correspondence to urban case):

$$R_b = \frac{\beta \Delta\theta^{eff}}{(\Delta u^{eff})^2} \Delta z^{eff} , \qquad (1)$$

where $\Delta\theta^{eff} \equiv \Delta\theta(z_*) = \theta(z_*) - \theta(z_{0T} + d)$, $\Delta u^{eff} \equiv \Delta u(z_*) = u(z_*) - u(z_{0u} + d)$, $\Delta z^{eff} = [z_* - (z_{0u} + d)]^2 / [z_* - (z_{0T} + d)]$, z_{0u} and z_{0T} are the urban effective aerodynamic and temperature roughness lengths (determined for example by blending height method, simple weighted average or similar procedures). Having in mind that $u(z_{0u} + d) = 0$, $\Delta z^{eff} = z_* - d$ (because $z_{0u}, z_{0T} << d$), denoting $\theta(z_{0T} + d) = \theta_0$ and comprehending that at $z \to z_*$ MOST is valid, (1) can be presented in the form:

$$R_b = \frac{\beta \Delta\theta(z_*)}{u^2(z_*)} (z_* - d) , \qquad (2)$$

where

$$u(z_*) = \frac{u_*(z_*)}{\kappa}[\lambda_u - \psi_u(\xi_*^{'})], \ \lambda_u = \ln\frac{z_* - d}{z_{0u}}, \tag{3}$$

$$\Delta\theta(z_*) = \frac{T_*(z_*)}{\kappa}[\lambda_\theta - \psi_\theta(\xi_*^{'})], \ \lambda_\theta = \ln\frac{z_* - d}{z_{0T}} \equiv \lambda_u - \ln m, \ m = z_{0T} / z_{0u}. \tag{4}$$

Here $\xi_*^{'} = (z_* - d)/L_*$, $L_* = -u_*^3(z_*)/[\kappa\beta q(z_*)]$ is MO length for $z = z_*$, $T_*(z_*) = -q(z_*)/u_*(z_*)$, $u_*(z_*)$ and $q(z_*)$ are the values of the local parameters in URL – dynamic velocity $u_*(z)$ and cinematic heat flux $q(z)$ at $z = z_*$, $\psi_u(\xi_*^{'})$ and $\psi_\theta(\xi_*^{'})$ are similarity functions for level z_*. They are expressed by MOST functions $\varphi_u(\xi_*^{'})$ and $\varphi_\theta(\xi_*^{'})$, for stable/neutral case which take into account additionally free-flow stability effect, connected with a new additional parameter $F_{i0} = Nz_*/u_*(z_*)$ (see Zilitinkevich and Esau, 2005), where N is the height-constant free-flow Brunt-Väisällä frequency.

It should be noted that while $u_*(z)$ normally increases with height in URL, reaching for example at $z = z_*$ its maximum $u_*(z_*)$. This parameter, as well as the typical value of $q(z_*)$ (it should be noted that $q(z)$ changes relatively slowly), which appears to be a suitable velocity and heat flux scales for parameterization of URL (Fischer et al., 2005, Kono and Yas, 2011).

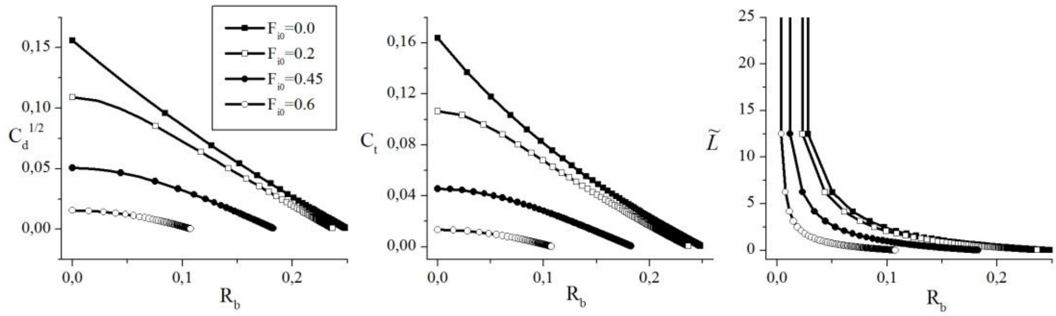

Figure 1. Dependence of $C_d^{1/2}$, C_t and $\widetilde{L}_*$ on R_b for different values of the free-flow stability parameter F_{0i}.

By applying the above described methodology the URL drag and heat transfer coefficients $C_d^{1/2} = u_*(z_*)/u(z_*)$ and $C_t = T_*(z_*)/\Delta\theta(z_*)$, as well as the dimensionless MO-length $\widetilde{L}_* = L_*/(z_* - d)$ in dependence of the modified input parameters:

$$R_b, \ \lambda_u, \ \lambda_\theta, \ F_{0i}, \tag{5}$$

can be obtained on the basis of (2), (3), (4), applying mathematical procedure, which is in principle analogous to the conventional rural case (see Syrakov, 2011, Syrakov et al., 2012a).

According to (4) λ_θ is expressed trough the parameter λ_u, which have to be parameterized accounting for the urban conditions. The relations $z_* = nh$, $\alpha = p_1 h$ and $z_{0u} = ph$ are used and so λ_u obtains the form:

$$\lambda_u = \ln\frac{n - p_1}{p}, \tag{6}$$

where $n = (2 \div 5)$ and in the general case p and p_1 are functions of the plan area density λ_p, frontal area density λ_f and frontal solidity λ_{fs} (see Macdonalds, 2000, Fernando et al., 2010, Kanda et al., 2013). It should be noted that for each particular case of arbitrary building groups accounting for their specific characteristics and specifics, p and p_1 are reduced to typical constant parameters, by which (6) can be determined. The present considerations will be restricted to the relatively simple, but often used case: $n = 2$ (used for typical European cities (Fischer et al., 2005)), and $p_1 = 0.7$, $p = 0.1$ (Grimmond and Oke, 1999). It will be noted that the developed R_b urban-modified model was verified with data from BUBBLE 2002 tracer experiment, carried out for Sperrstrasse, Basel (Syrakov and Ganev, 2013).

Some results for $C_d^{1/2}$, C_t and $\widetilde{L}_*$ dependence on R_b for different values of the free-flow stability parameter F_{0i} and $m=1$ are presented in Figure 1. Significant increase of $C_d^{1/2}$, C_t and $\widetilde{L}_*$ with increasing of R_b and in particular of F_{0i} can be seen, which is an evidence of strongly limited exchange processes over urban areas at this conditions.

Let the resistance laws (RL-method) be considered. Above RSL in urban boundary layer (UBL) the Rossby number similarity is approximately valid (see Fischer et al., 2005). Combining that with the displacement height concept in RSL makes it possible the RL-method for rural conditions (see Syrakov et al., 202b) to be modified for urban conditions (Syrakov and Ganev, 2014a,b). Combining with a respective procedure (Syrakov, 2011, Syrakov et al., 2012,a) these Rb and RL-methods leads to the urban-modified combined (Rb-RL)-method. Trough this method the parameters $f_g = G_0 / u_*(z_*)$ (G_0 is the module of the geostrophyc wind at the top H of UBL), $f_t = \delta\theta / \Delta\theta(z_*)$ ($\delta\theta = \theta_H - \theta(z_{0T} + d)$, the full wind rotation angle in the UBL α, as well as the drag coefficient $C_g = u_*(z_*)/G_0 \equiv C_d^{1/2} f_g^{-1}$ and the internal stratification parameter $\mu = \kappa u_*(z_*)/ fL_* \equiv \kappa^2 R_b C_t C_d^{-1/2} \widetilde{R}_o \exp(-\lambda_u)$, which integrally characterize the UBL can be obtained, in dependence on the parameters (5) and the additional parameter $\widetilde{R}_o = u(z_*)/ fz_{0u}$ (Rossby number in RSL).

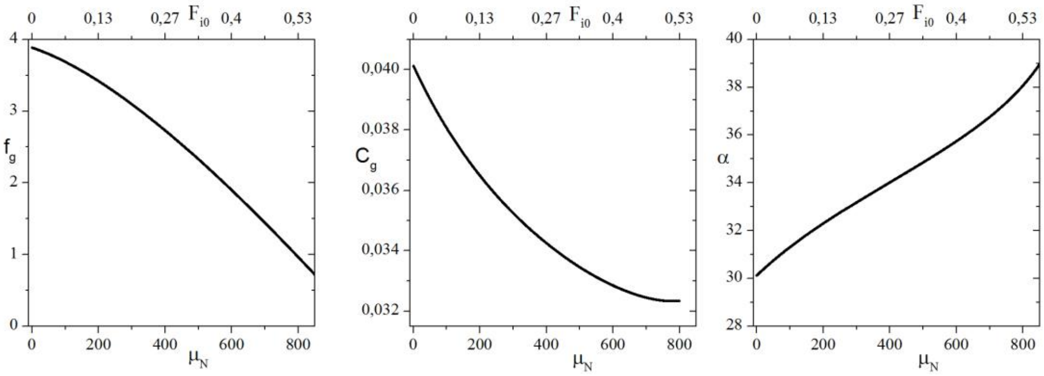

Figure 2. Dependence of parameters f_g, C_g and α on free-flow stability parameter μ_N and its corresponding parameter F_{0i}.

Let focus on the neutral conditions ($R_b = 0$, $\mu = 0$) in order to study basically the effects connected with the free-flow stability in a conventional neutral UBL, for example at high latitudes. The dependence of parameters f_g, C_g and α on free-flow stability parameter $\mu_N = N / f$ and its corresponding parameter $F_{i0} = \mu_N \widetilde{R}_0 \exp(-\lambda_u)$ is shown in Figure 2 for the already used parameters $m=1$, $n=2$, $p_1 = 0.7$, $p = 0.1$ and $h = 15m$ (i.e. $z_* = 30m$, $z_{0u} = 1.5m$) and $u_*(z_*) = 4.5m/s$, i.e. $\widetilde{R}_0 = 3.10^4$. It can be seen that with increasing of μ_N the exchange processes strongly decrease (C_g decreases) and the wind rotation angle in UBL α significantly increases.

UBL DIFFUSION CHARACTERISTICS

The so obtained parameters C_g, $G_0 = u(z_*) f_g$ and α are used as input to a urban-modified (by accounting of the displacement height) PBL model (Syrakov and Ganev 2014,b), which calculates the basic dynamic characteristics (wind velocity components and coefficient of vertical turbulent exchange) in PBL. They are used as an input to the none-Gausssian Plume-MM model, coordinated with the method of statistical moments (Syrakov and Ganev, 2003) is implemented.

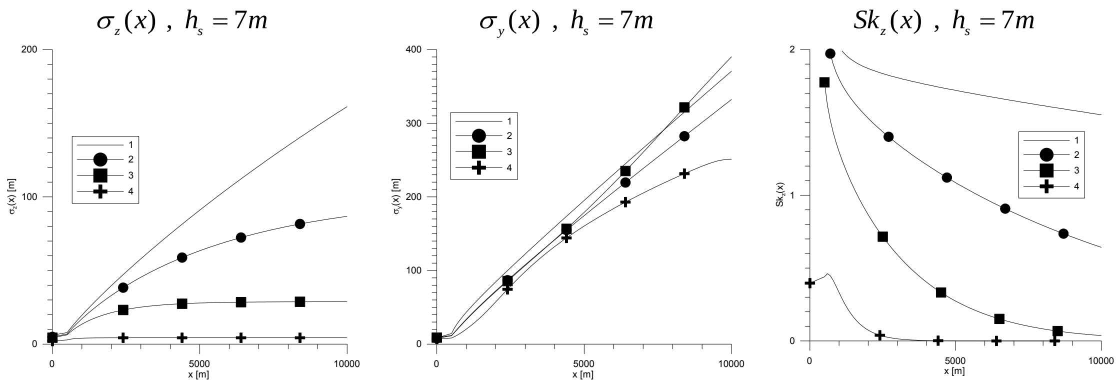

Figure 3. Plots of $\sigma_z(x)$, $\sigma_y(x)$ and $Sk_z(x)$ for $h_s = 7m$ in conventional neutral UBL for different μ_N values: case 1 - $\mu_N = 0$, case 2 - $\mu_N = 300$, case 3 - $\mu_N = 650$, case 4 - $\mu_N = 800$.

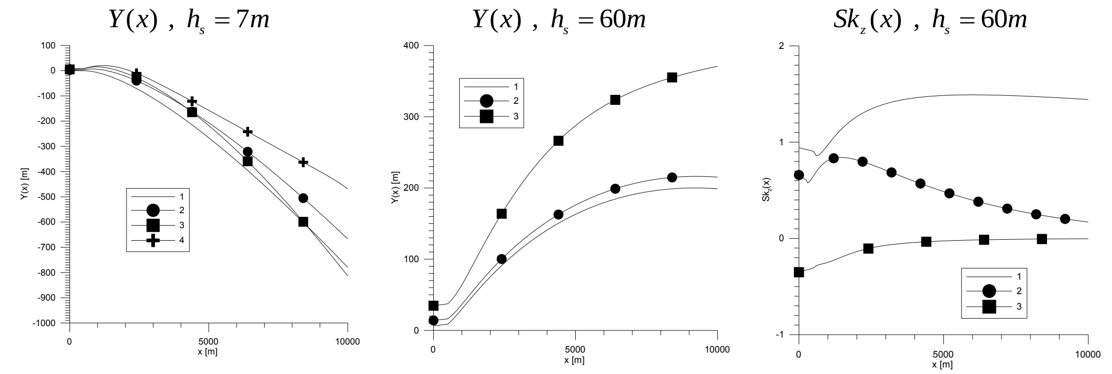

Figure 4. Plots of $Y(x)$ for $h_s = 7m$ and $h_s = 60m$ and of $Sk_z(x)$ for $h_s = 60m$ for μ_N values as in Figure 3.

Some plume-MM characteristics: dispersions $\sigma_y(x)$, $\sigma_z(x)$ and skewness $Sk_z(x)$ in UBL from sources with height $h_s = 7m$ and $h_s = 60m$ above roofs are shown in Figures 3 and 4, for different values of the free-flow stability parameter μ_N . $\sigma_z(x)$ decreases particularly strongly with increasing of μ_N . For $\mu_N = 800$ the vertical exchange is practically absent and $\sigma_z(x)$ does not exceed several meters. Besides for $\mu_N = 800$ and $\mu_N = 675$ for distances x exceeding 2-3000 m $\sigma_z(x)$ practically does not change. The influence of μ_N on $\sigma_y(x)$ is relatively smaller and the increase with distance x is smallest for $\mu_N = 800$. The comparison of the differences in Figures 3 and 4 outlines the differences of the parameters $Y(x)$ and $Sk_z(x)$ for the two sources. The parameter $Y(x)$ characterises the rotation of the plume trajectory in a coordinate system with axis OX oriented along the wind at the source height. The opposite rotation in the two cases (lower and higher source) is in accordance with the Corriolis effect in the boundary layer.

From the comparison of $Sk_z(x)$ for $h_s = 7m$ and $h_s = 60m$ it can be seen that for $h_s = 7m$ it is always positive and decreases with x, while for $h_s = 60m$ in cases 1 and 3 it increases and for case 3 the skewness is negative.

Case 4 for $h_s = 60m$ is not shown in Figures 3, 4, because the height $H = 20m$ and so is below the source height.

CONCLUSIONS

Application oriented parameterization schemes, based on combined and modified for urban areas Rb, RL and (Rb-RL) methods are developed. The drag and heat transfer coefficients and some diffusion characteristics in urban boundary layer are determined at $m = 1$. The developed approach allows solving the more general problem $m \neq 1$ (for urban conditions usually $z_{0u} > z_{0T}$) as well as accounting for the influence of stratification on z_{0u}. That makes the approach applicable for solving a wide class dynamic and diffusion processes in UBL.

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