EXTENSION AND MODIFICATION OF THE BULK RICHARDSON NUMBER METHOD FOR PARAMETERIZATION OF EXCHANGE AND INTERACTION PROCESSES OVER URBAN AREAS

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Abstract: The bulk Richardson number method (Rb-method) is modified and applied to areas with large urban roughness, accounting for a wide range of turbulent urban regimes. Comparison of the developed method with tracer data from BUBBLE 2002 experiment is made. Special attention was paid to the evaluation of the effects caused by the different roughness parameter for impulse and temperature over urban areas.

***Key words:** Richrdson-bulk method, modification for urban conditions, urban roughness sub-layer, drag and heat transfer coefficients, effects caused by the difference between roughness lengths for impulse and temperature.*

INTRODUCTION

In the traditional case at relatively homogeneous (rural) surface the bulk Richardson number $Rb=\beta\Delta\theta z_1/u_1^2$ (see van den Hurk B. and M. Holstag,1999) is used, where $\Delta\theta=\theta_1-\theta_0$, $u_1 = u(z = z_1)$, z_1- reference height (a low level in numerical models, or z_1=10m, etc.), θ, u – potential temperature and velocity, described in the Monin-Obukhov theory framework. A practically oriented Rb-method when effects, connected with free-flow stability (Zilitinkevich S. and I. Esau,2005), as well as very stable stratification and intermittent turbulence-regime without critical Richardson number (WCR) (Syrakov E., 2011, Zilitinkevich S. et al.,2009) are considered, was developed in (Syrakov E., 2011, Syrakov E. et al., 2012a, b), which embraces unstable, as well as a wide range of neutral/stable regimes: TN (truly neutral), NS (nocturnal stable), CN (conventional neutral), LS (long-lived stable) and WCR. The dependence of surface fluxes and other parameters for the above listed regimes on the input parameters:

$$Rb,\ \lambda_u,\ \lambda_\theta,\ F_{i0} \qquad (1)$$

is determined in (Syrakov E., 2011, Syrakov E. et al., 2012a, b), where $\lambda_u= \ln(z_1/z_0)$, $\lambda_\theta = \ln(z_1/z_{0T})$, z_0 and z_{0T} are the aerodynamic and temperature roughness lengths, $F_{i0}=Nz_1/u_1$, N-free-flow Brunt-Väisälla frequency.

The aim of the present paper is the extension and modification of the bulk Richardson number method for urban conditions

MODIFIED BULK RICHARDSON METHOD FOR URBAN AREAS

The urban roughness sub layer with a height of z_*=(2-5)h (for example the lower limit z_*=2h is used for typical European cities(Clark P. et al., 2009)) includes the urban canopy layer (street canyons, buildings and other roughness elements) and the layer above, where the influence of the listed urban heterogeneities with a typical height h can still be felt. When the reference height is chosen to be $z_1 \equiv z_*$, this influence is negligible and so the Monin-Obukhov similarity theory is valid when respective effective parameters are used (see [1]). These parameters are u_*^{eff} (the maximum of Reynolds stress around level z_*), the respective typical value of the heat flux q^{eff} (relatively slowly changing with height over roofs in layer $z<z_*$). Parameters u_*^{eff} and q^{eff} are unknown quantities, which will be determined below by implementation of the modified Rb-method) and the typical roughness parameters z_0^{eff} and $z_{0T}^{\ eff}$. The blending height method (see Gryning S-E and E. Batchvarova, 2002), or simple weighted averaging of the kind $z_0^{eff}=\sum P_i z_{0i}$, P_i – weighting function, can be used for determining the last for chosen suburban regions with different land use types, while for suburban regions with relatively compact massifs of forest (park) ore building groups with typical height h. Simple relations of the kind z_0^{eff}=ph and for displacement height $d=p_1h$ can be applied (the parameters p and p_1 will be specified bellow). Taking this into account, respective effective Richardson number Rb^{eff} can be introduced (instead of Rb-rural), which characterize in an integral way the urban roughness sub layer (at $z \le z_*$):

$$Rb^{eff}=\beta\Delta\theta^{eff}z_*'/(u^{eff})^2 \quad (2)$$

$$\Delta\theta^{eff} = \theta(z'_*) - \theta(z_{0T}^{eff}) = (\theta_*^{eff}/\kappa)[\lambda_\theta^{eff}-\Psi_\theta(\xi^{eff})],\ \lambda_\theta^{eff}=\ln((z_*-d)/z_{0T}^{eff}) \quad (3)$$

$$u^{eff} = u(z'_*) = (u_*^{eff}/\kappa)[\lambda_u^{eff}-\Psi_u(\xi^{eff})],\ \lambda_u^{eff}=\ln((z_*-d)/z_0^{eff}), \quad (4)$$

where $\theta_*^{eff}= -q^{eff}/u_*^{eff}$, $\xi^{eff}= z_*'/L^{eff}$, $z_*'= z_* - d$, $L^{eff}= -(u_*^{eff})^3/(\kappa\beta q^{eff})$, $\Psi_u(\xi^{eff})$ and $\Psi_\theta(\xi^{eff})$ are similarity functions for level z'_*. They are expressed in a standard way by the universal functions of the Monin-Obukhov similarity theory φ_u and φ_θ, which are calculated by formulas, which contain the "-1/3" asymptote at free convection regime (see Syrakov, 2011).

The urban roughness layer drag and heat transfer coefficients $(C_d^{eff})^{1/2}=u_*^{eff}/u^{eff}$ and $C_t^{eff}=\theta_*^{eff}/\Delta\theta^{eff}$, in dependence on the modified input parameters (1) Rb^{eff}, λ_u^{eff}, λ_θ^{eff}, $F_{i0}^{eff}=Nz'_*/u^{eff}$, can be obtained on the basis of (2), taking into account (3) and (4), applying respective mathematical procedure (analogous to the conventional case). Results for N=0, $\lambda_u^{eff}=\lambda_\theta^{eff}=\lambda$ are given in Fig.1 for z_*=30m and different values of h, d=0.7h, z_0^{eff}=0.1h (e.g. p=0.1 (Grimond C. and T. Oke, 1999) and p_1=0.7 (Fischer B. et al., 1999). The method can be easily generalized for cases when coefficients p and p_1 depend on none-dimensional plane λ_p and area λ_F parameters. The curve at h=0.1 from Fig.1 corresponds to rural conditions. Significant increase of $(C_d^{eff})^{1/2}$ and C_t^{eff} with increasing of h (urban conditions) can be seen.

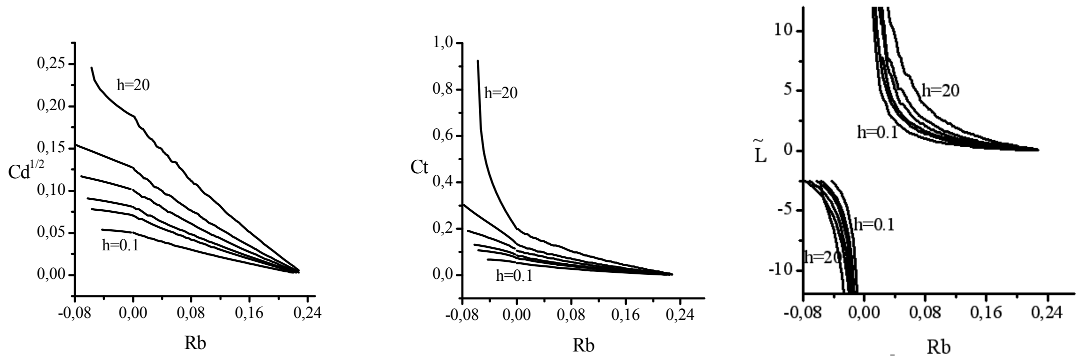

Figure 1. Dependence of parameters $C_d^{1/2}=(C_d^{eff})^{1/2}$, $C_t= C_t^{eff}$ and dimensionless Monin-Obukhov length $\widetilde{L} = L^{eff} / z_*$, integrally characterizing roughness sub-layer in urban PBL on stratification ($Rb=Rb^{eff}$) and a set of typical urban heterogeneities heights h= 0.1, 2.5, 5, 10, 15, 20 m, corresponding for a set of none-dimensional values of $\lambda_u^{eff}=\lambda_\theta^{eff}=\lambda$=8, 4.8, 4, 3.15, 2.6, 2.1. (at this λ values the curve families from Fig.1 can be presented in the equivalent form $f=f_\lambda(Rb)$, $f= C_d^{1/2}$, C_t, or $\widetilde{L}$).

AN APPLICATION

An example of the application of the modified for urban conditions Rb-method will be shown. The data applied was generated by BUBBLE tracer experiment, carried out for Sperrstrasse, Basel (BUBBLE 2002 tracer experiment, Meteorological surface network database, University of Basel). Table 1 shows the comparison of the observed meteorological data with model results of the modified Rb-method.

Table 1. Comparison of measured (BUBBLE 2002 tracer experiment 1: 4 July, time 15:00-15:30 and experiment 2: 4 July, time 17:30-18:00, CET) and corresponding modelled 1 and 2 (using modified Rb-method) parameters.

	Input parameters						Current parameters				
parameters	z_*[m]	h[m]	z_*/h	λ	$u(z_*)$ [ms^{-1}]	$u_*(z_*)$ [ms^{-1}]	Q [$Km\ s^{-1}$]	L [m]	$C_d^{1/2}$	$\widetilde{L}$	C_t
measured1	25.4	15.1	1.68	2.28	2.2	0.422	0.077	-72.7	0.19	-2.86	0.5
modelled1	30	17.8	1.68	2.28	2.2	0.44	0.064	-75.6	0.2	-2.98	0.42
measured2	31.6	15.1	2.09	2.63	4.16	0.53	0.197	-56.7	0.13	-1.8	0.286
modelled2	30	14.3	2.09	2.63	4.16	0.59	0.225	-69	0.15	-2.21	0.3

The modelled results in Table1 are obtained by applying the modified Rb-method (see Fig.1) for z_*=30 m, by varying the height h (and z_0=0.1h, d=0.7h) and the corresponding to h values of λ and z_*/h. Following the similarity criteria, values for λ and z_*/h, coinciding with experiments 1 and 2 are used as input for the modelling. At this conditions for values Rb=-0.06 and Rb=-0.08, the respective modelled1 and modelled2 results are obtained (the dimensionless parameters $C_d^{1/2}$ and $\widetilde{L}$ are obtained at first and then the temperature increments $\Delta\theta = Rbu^2(z_*)/\beta\, z_*$: $\Delta\theta_1=0.343$ [^oC], $\Delta\theta_2=1.3$ [^oC], trough which the variables C_t are determined and finally by a de-normalisation procedure the rest of the modelled dimension parameters are obtained. It can be seen that the measured and modelled parameter values are close to each other.

EFFECTS CAUSED BY THE DIFFERENCE BETWEEN ROUGHNESS LENGTHS FOR IMPULSE AND TEMPERATURE

In most of the meso-meteorological urban models it is accepted that thermal roughness z_{0T}^{eff} is equal to the aerodynamic roughness length z_0^{eff} (for momentum). However numerous experimental data and theoretical calculations show that, especially for very rough surface, such as urban canopies and forests, this assumption can lead to erroneous results for the heat and moisture fluxes. Measurements indicate that the ratio z_0^{eff}/z_{0T}^{eff} is about 10 for natural vegetation and above 10^2 for urban surfaces. This is caused by the large contribution of bluff body pressure forces to the momentum flux. Fig. 2 shows the sensitivity of $(C_d^{eff})^{1/2}$, C_t^{eff} and $\widetilde{L}$ to changes in z_0^{eff}/z_{0T}^{eff} for case 1-5, given in Table 2 (see Clark P. et al., 2009).

Table 2. Typical z_0^{eff}/z_{0T}^{eff} ratios for urban area

case	1	2	3	4	5
z_0^{eff}/z_{0T}^{eff}	1	10^{-1}	10^{-3}	10^{-5}	10^{-7}

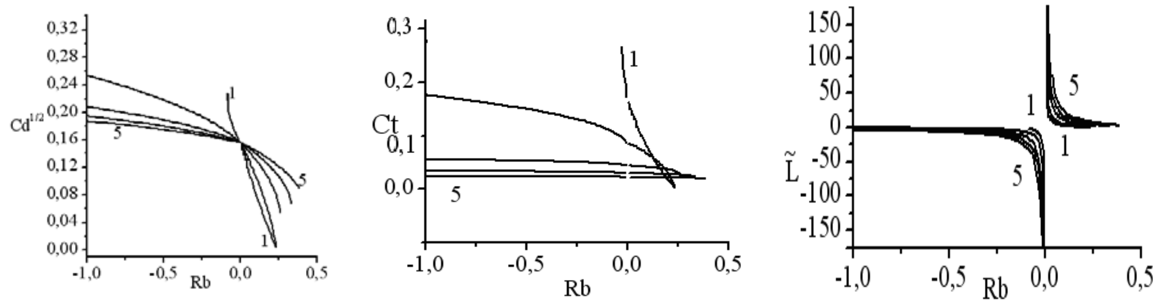

Figure 2. Influence of the z_0^{eff}/z_{0T}^{eff} parameter (case 1-5 from Table 2) on parameters $C_d^{1/2}=(C_d^{eff})^{1/2}$, $C_t= C_t^{eff}$ and $\widetilde{L} = L^{eff}$, demonstrated for the case h=15 (λ = 2.6) from Fig. 1.

A drastic decrease in C_t^{eff} in cases 2-5 can be observed in comparison to case 1 ($z_0^{eff}=z_{0T}^{eff}$) for unstable/neutral conditions and rather small increase for stable conditions. For $(C_d^{eff})^{1/2}$ the decrease for unstable conditions is significantly smaller, while the increase for stable conditions is much more significant. The ratio C_t^{eff}/C_d^{eff} decreases drastically as a result, which means that the momentum of flux is a strongly dominating factor.

CONCLUSIONS

The modified Rb-method, presented in this paper allows a set of representative effective parameters z_0^{eff}, z_{0T}^{eff}, $(C_d^{eff})^{1/2}$, C_t^{eff}, L^{eff} and other, which parameterize the urban roughness sub-layer for given urban sub-region to be determined.

In general plan the whole urban area is divided into a number of local areas, such as central inner, residential, recreation and industrial parts. In this aspect, after an expert evaluation, the whole urban area should be divided into a given number of generalized typical (with relatively homogeneous properties) sub-areas – different surface patches, each characterised by its effective parameters, determined by the modified Rb-method. These parameters change at the transition from one sub-region to another, thus for the city as a whole the dependence on horizontal coordinates (x, y) can be parametrically accounted for. With this respect, depending on the specific synoptic situation and intruding air flows, the dynamicthermal reaction of the city region will be different and will depend on the important background factor the flow azimuth angle.

In conclusion it will be noted that the procedure presented here, could facilitate further improvement of the parameterization of the lower boundary conditions of the 3D urban meso-meteorological models, as well as solving different specific tasks for a given urban sub-region.

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REFERENCES

Clark P., M. Best and A. Porson, 2009: Evolution of urban surface exchange in the UK Met Office's unified model. In Chapter 9, Meteorological and air quality models for urban areas (A. Baklanov, S. Grimmond, A. Mahura, M. Athanassiadou, Eds.) Spr.-Verlag, Berlin, Heidelberg.

Fischer B., S. Joffre, J. Kukkonen, M. Pringe, M. Rotach and M. Schatzmann, 1999: Meteorology applied to urban air pollution problems, Final report COST Action 715, Luxembourg, OPEC

Grimond C. and T. Oke, 1999: Aerodynamic properties of urban areas derived from analysis of surface form. *J Appl Meteor*, **38**, 1261-1292

Gryning S-E and E. Batchvarova, 2002: Pre-processor for regional-scale fluxes and mixed layer height over inhomogeneous terrain. In: Borego, Schayers, Eds. Air pollution modeling and its application XV, Kluwer Acad/Plenum Publ, New York

Syrakov E. and K. Ganev, 2003: Accounting for effects of wind rotation in the PBL on the plume characteristics. *Int J Environment & Pollution*, **vol. 20**, No.1-6, 154-164.

Syrakov E., 2011: Atmospheric boundary layer: Structure, Parameterization, Interactions, Heron Press, Sofia, p. 394

Syrakov E, Ganev K, Tsankov M, Cholakov E, 2012a: A comparative analysis of diferent conventional and none-local stable/neutral pbl regimes and their parameterization in air pollution problems. *Int. J. Environment and Pollution,* **vol. 50**, Nos. 1/2/3/4, 351-362

Syrakov E., K. Ganev, M. Tsankov and E., Cholakov, 2012b: Estimation and parameterization of the influence of synoptic conditions on pollution characteristics in the PBL, *Int. J. Environment and Pollution,* **vol. 50**, Nos. 1/2/3/4, 327-341

Zilitinkevich S. and I. Esau, 2005: Resistance and heat/mass transfer laws for neutral and stable planetary boundary layers: old theory advanced and re-evaluated. *Quart J Roy Met Soc* **131**, 1863-1892

Zilitinkevich S., S. Elperin, N. Kleeorin and I. Rogachevski, 2007: Energy and flux budghet turbulence closure model for the stably stratified flows. Part I: Steady-state homogeneous regimes, *Boundary Layer meteorology*, **125**, 167-192

Van den Hurk B. and M. Holstag, 1999: On the bulk parameterization of surface fluxes for various conditions and parameter ranges, *Boundary Layer meteorology*, **92**, 119-134.