H14-280

A COMPARATIVE ANALYSIS OF DIFERENT CONVENTIONAL AND NONE-LOCAL STABLE/NEUTRAL PBL REGIMES AND THEIR PARAMETERIZATION IN AIR POLLUTION PROBLEMS

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Abstract: The basic characteristics in several types stable/neutral PBL turbulent regimes are determined on the basis of applied oriented complex method. The significant influence of free-flow stability effects is demonstrated. In particular the results can be used for parameterization of dynamic and diffusion processes in PBL under such conditions.

***Key words:** PBL none-local parameterization, free-flow stability, neutral/stable regimes, transfer coefficients.*

INTRODUCTION

Recently it became clear that several types of turbulent regimes in stable/neutral PBL can be distinguished (see Zilitinkevitch et al, 2007):

- The truly neutral (TN), observed more or less often;
- The nocturnal stable (NS), typically observed during the night at low and mid latitudes;
- The long-lived stable (LS) strongly affected by the free-flow Brunt-Väisälla frequency $N{=}\beta(d\theta/dz)^{1/2}_{z>H}$, over the top H of PBL;
- The conventional neutral (CN), like LS affected by N, typically observed over the ocean in late summer and autumn;
- The very stable PBL characterized by the weak intermittent turbulence with large, but not critical Richardson number (WCR) in deep ocean, free atmosphere, over smooth land or very cold sea surface.

The purpose of this work is to parameterize and compare the above regimes and on this basis to explore some dependencies of diffusion of pollutants on the considered neutral/stable PBL conditions.

MODEL DESCRIPTION

Practically oriented parameterization scheme (R_b-method) based on the bulk Richardson number is applied:

$$R_b = \frac{\beta\Delta\theta}{u_1^2} z_1 \tag{1}$$

where $\beta = g/T$ is buoyancy parameter, z_1 is reference height (practically the height of the lowest calculation level in prognostic models, or, like in our case – the height of measurements $z_1 = 10m$, $u_1 = u(z = z_1)$, $\Delta\theta = \theta_1 - \theta_0$ is the temperature increment in the layer $(0 - z_1)$. Parameters $\Delta\theta$ and u_1 could be expressed by the universal functions φ_u and φ_θ from the Monin-Obuchov similarity theory, modified in accordance to the considered new none-local stable/neutral regimes, taking into account the free-flow stability effect (Zilitinkevich and Esau, 2005):

$$\phi_u(\xi) = 1 + \tilde{B}_u\xi\,,\ \tilde{B}_u = B_u(1 + C_{NM}^2 F_i^2)\ ,\ \phi_\theta(\xi) = 1 + \tilde{B}_\theta\xi\,,\ \tilde{B}_\theta = B_\theta(1 + C_{NH}^2 F_i^2)\,, \tag{2}$$

where $\xi = z/L$, $L = -u_*^3 / \aleph\beta q$ is the Monin-Obukhov length, $F_i = \aleph LN/u_* \equiv F_{i0}/(s_1 C_d^{1/2})$, $s_1 = z_1/\aleph L$, $F_{i0} = Nz_1/u_*$, $B_u = 5$, $B_\theta = 6{,}25$ (see Syrakov, 2011), C_{NM}, C_{NH} are new empirical constants of order of 0.1, $\aleph = 0{,}4$. It should be noted that experimental and LES data show, that at WCR regime at very strong and intermittent turbulence, i.e. at very large ξ, $\varphi_\theta > \varphi_u$ and the turbulent Prandtle number $\mathrm{Pr}_T = \varphi_\theta/\varphi_u$ is not constant, but is significantly greater than one (Monin and Yaglom, 1965).

Phenomenically this means that at WCR regime ξ dependence on φ_θ should be stronger, for example quadratic rather than linear (see Zilitinkevich and Esau, 2007):

$$\phi_\theta(\xi) = 1 + \tilde{B}_{\theta 1}\xi + \tilde{B}_{\theta 2}\xi^2\,, \tag{3}$$

where $\tilde{B}_{\theta 1} = B_\theta^{'}(1 + C_{NH}^2 F_i^2)^{1/2}$, $\tilde{B}_{\theta 2} = B_\theta^{''}(1 + C_{NH}^2 F_i^2)$, $B_\theta^{'} = 5.5$, $B_\theta^{''} = 1.25$, verified with data for Pr_T (see Syrakov, 2011). Taking into account (2), (3) the bulk Richardson number (1) can be presented in the form:

$$R_b(\lambda_u, \lambda_\theta, s_1, F_{i0}) = \aleph s_1 \frac{\lambda_\theta + \aleph B_\theta^{'}(s_1^2 + C_{NH}^2 F_{i0}^2/C_d)^{1/2} + (\aleph^2 B_\theta^{''}/2)(s_1^2 + C_{NH}^2 F_{i0}^2/C_d)}{[\lambda_u + \aleph B_u(s^2 + C_{NM}^2 F_{i0}^2/C_d)^{1/2}]^2} \tag{4}$$

where $\lambda_u = \ln z_1/z_0$, $\lambda_\theta = \ln z_1/z_{0T}$, z_0 and z_{0T} are aerodynamic and temperature roughness, $C_d^{1/2} = u_*/u_1$ and $C_t = \theta_*/\Delta\theta$ are the drag and heat transfer coefficients to be determined, $\theta_* = -q/u_*$. By applying a specific mathematical procedure (Syrakov, 2011) the dependences of $C_d^{1/2}$, C_t and s_1 on λ_u, λ_θ, R_b, F_{io} can be determined:

$$C_d^{1/2} = f_d(\lambda_u, \lambda_\theta, R_b, F_{i0}),\; C_t = f_t(\lambda_u, \lambda_\theta, R_b, F_{i0}),\; s_1 = f_s(\lambda_u, \lambda_\theta, R_b, F_{i0}) \tag{5}$$

Respective particular cases follow from the general expressions (5): TN (at $R_b = 0,\ F_{i0} = 0$), NS (at $R_b > 0,\ F_{i0} = 0$), CN (at $R_b = 0,\ F_{i0} > 0$), LS (at $R_b > 0,\ F_{i0} > 0, B_\theta^{'} = 0, B_\theta^{''} = 0$), WCR₁ (at $R_b > 0,\ F_{i0} = 0, B_\theta^{'} = 5.5, B_\theta^{''} = 1.25$), WCR₂ (at $R_b > 0,\ F_{i0} > 0, B_\theta^{'} = 5.5, B_\theta^{''} = 1.25$). It can be seen that WCR₁ and WCR₂ regimes can be distinguished in the framework of the WCR regimes (at $F_{i0} = 0$ and $F_{i0} > 0$ respectively).

The combination of the R_b method results (5) with the PBL resistance laws, after a chain of transformations leads to the following basic relations of the combined (R_b-R_L) method (Syrakov, 2011):

$$\frac{u_{g0}}{u_1} = f_{ug},\qquad \frac{v_{g0}}{u_1} = f_{vg},\qquad \frac{G_0}{u_1} = f_g,\qquad \frac{\delta\theta}{\Delta\theta} = f_\theta,\qquad \alpha = arctg\{-B/[\ln(\tilde{R}_o C_d^{1/2})] - A\},$$

$$f_{ug} = \frac{C_d^{1/2}}{\aleph}[\ln(\tilde{R}_o C_d^{1/2}) - A],\quad f_{vg} = -\frac{B}{\aleph} C_d^{1/2},\quad f_\theta = \frac{C_t}{\aleph}[\ln(\tilde{R}_o C_d^{1/2}) - C], \tag{6}$$

where $f_g = (f_{ug}^2 + f_{vg}^2)^{1/2}$, $\delta\theta = \theta_H - \theta_0$ is the temperature increment in PBL, u_{g0}, v_{g0} and G_0 are the components and the module of the geostrophic wind, α is the angle of full rotation of the wind in PBL, $\tilde{R}_o = u_1 / f z_0$ is the local Rosby number in the layer $(0 - z_1)$, A, B, C are the resistance laws universal functions, which depend on internal $\mu = (\aleph u_* / f)L$ and free-flow $\mu_N = N / f$ stratification parameters, i.e.:

$$A = A(\mu, \mu_N),\; B = B(\mu, \mu_N),\; C = C(\mu, \mu_N). \tag{7}$$

The explicit form of the universal functions (7) is given in Syrakov (2011). Using the relations $\mu \equiv \aleph^2 \tilde{R}_o C_d^{1/2} s_1 \exp(-\lambda_u)$, $\mu_N \equiv \tilde{R}_o F_{i0} \exp(-\lambda_u)$ and taking into account the parameters (5) (determined by the R_b method), it can be seen that the right-hand parts of (6) are known functions only of the input parameters $\lambda_u, \lambda_\theta, R_b, F_{i0}, \tilde{R}_o$. By this the parameters f_{ug}, f_{vg}, f_g (u_{g0}, v_{g0}, G_0 respectively), f_θ, α are determined as well, and from there the PBL drag coefficient $C_g = u_* / G_0 \equiv (u_* / u_1)(u_1 / G_0) = C_d^{1/2} f_g^{-1}$. Finally, by consecutive realization of the R_b method and the R_b-R_L method, the parameters C_d, α, μ, G_0 are determined. They are used as an input to a PBL model (Syrakov and Ganev, 2003, Syrakov et al, 2007), which calculates the dynamic characteristics u, v, k_z and k_θ. On this basis the diffusion plume-MM and puff-MM models, coordinated with the method of moments, are implemented (Syrakov and Ganev, 2004, Syrakov et al, 2007) and the basic pollution characteristics in PBL are obtained.

RESULTS AND ANALYSIS

The above described procedure of consecutive application of the R_b method and the R_b-R_L method is followed further in the study. Similar is the treatment of the other PBL regimes, determined by an appropriate choice of the input data and characterized by some basic parameters as follows: case 1 - TN ($\mu = 0$, $\mu_N = 0$, $H = 850m$, $G_0 = 7m/s$), case 5 - NS ($\mu = 90$, $\mu_N = 0$, $H = 260m$, $G_0 = 7m/s$), case 6 - LS ($\mu = 110$, $\mu_N = 600$, $H = 55m$, $G_0 = 3m/s$), case 7 – WCR₁ ($\mu = 130$, $\mu_N = 0$, $H = 30m$, $G_0 = 1.8m/s$), case 8 – WCR₂ ($\mu = 110$, $\mu_N = 600$, $H = 25m$, $G_0 = 1.5m/s$).

The dependence of the basic dynamic parameters of the CN – regime ($R_b = 0$) on the none-local free-flow parameter F_{i0} is demonstrated on Figure 1. Further in the paper the parameter μ_N will be used indeed of F_{i0} as an indicator for the respective regime, because of the synonymous connection between them. Three particular cases are selected as representatives of the CN regime: case 2 – CN₁ ($\mu = 0$, $\mu_N = 600$, $H = 180m$, $G_0 = 7m/s$), case 3 – CN₂ (

$\mu = 0$, $\mu_N = 1200$, $H = 130m$, $G_0 = 7m/s$) and case 4 – CN_3 ($\mu = 0$, $\mu_N = 1800$, $H = 90m$, $G_0 = 7m/s$).

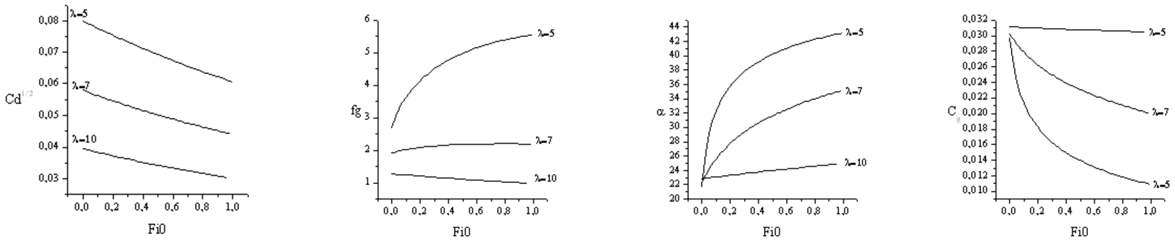

Figure 1. Dependence of surface layer drag transfer coefficient $Cd^{1/2}$, fg, full cross isobaric angle α .and PBL geostrophyc drag coefficient Cg on none-local free flow stability parameter $Fi0$ for different parameter λ values.

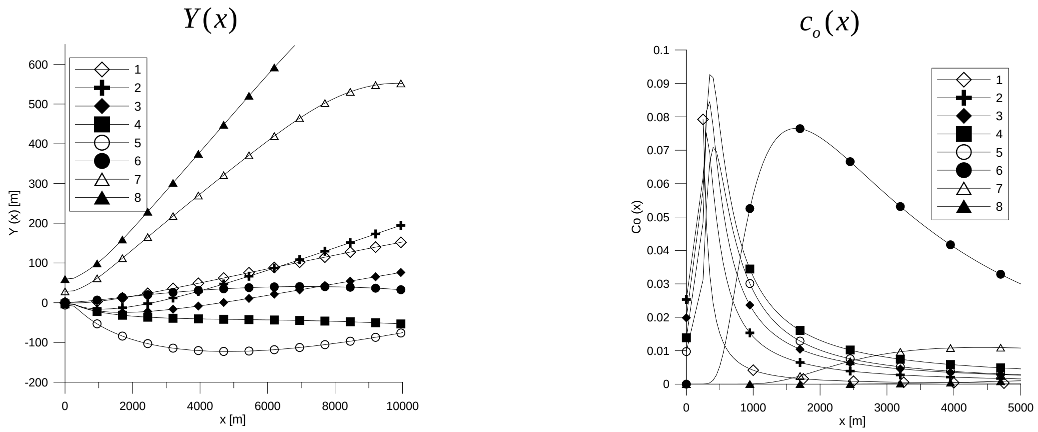

Figure 2. Surface horizontal displacement $Y(x)$ and surface concentrations along the plume axis $c_o(x)$ for stable/neutral cases 1 – 8.

From the different typical turbulent regimes in PBL, chosen for analysis, the regimes TN (case 1) and NS (case 5) are conventional, described by the Monin-Obuchov similarity theory, while CN (cases 2-4), LS (case 6) and WCR (WCR_1 – case 7 and WCR_2 – case 8) are shallow PBL none-local stable/neutral turbulent regimes, affected by free flow stability.

A brief comparative analysis of some dynamic and pollution characteristics, obtained by the plume-MM model, for the chosen regimes, will follow in the paper. Surface horizontal displacement $Y(x)$ and surface concentrations along the plume axis $c_o(x)$ for a source with height $h_{source} = 5m$ for the different stable/neutral regimes - cases 1 – 8 are give on Figure 2. For all the considered cases the $0x$ axis is oriented along the wind at source height. The biggest displacements $Y(x)$ can be observed for the WCR regimes (cases 7, 8). The $c_o(x)$ maximums are relatively close to the source for cases 1-5, significantly further for LS (case 6) and very far (out of the Figure2 horizontal margins, set at $x = 5000m$) for WCR_1 (case 7) and WCR_2 (case 8). A more comprehensive idea of the concentration field patterns can be obtained from Figure 3, where the vertical concentration cross-sections $c(x,z)$ for cases 1, 2, 5-8 are compared. Quantitative evaluation of the vertical concentration distribution give also the parameters skewness $Sk(x)$ and kurtosis $Ku(x)$, demonstrated on Figure 4. The deviations of Sk from the zero value and of Ku from the value of 3 are sound evidence that the obtained concentration fields differ from the Gaussian distribution ($Sk = 0$, $Ku = 3$).The deviations of Sk from the zero value are most significant for cases 2-7 and those of Ku from the value of 3 – for case 1.

From Figure 3 it can be seen, that following the turbulent regime sequence $TN \rightarrow CN \rightarrow NS \rightarrow LS \rightarrow WCR_1 \rightarrow WCR_2$ the concentration fields become more and more narrow and for regimes case 7, 8 the pollution transport is mostly horizontal, close to the source height level. Besides, for the mentioned cases the core of highest concentrations (for example $c(x,z) \geq 0.5$), becomes longer and more dense. For cases 7 and 8 the thickness of this layer is about 2 *m* and the horizontal propagation along the plume axis is about 1 – 2 *km*.

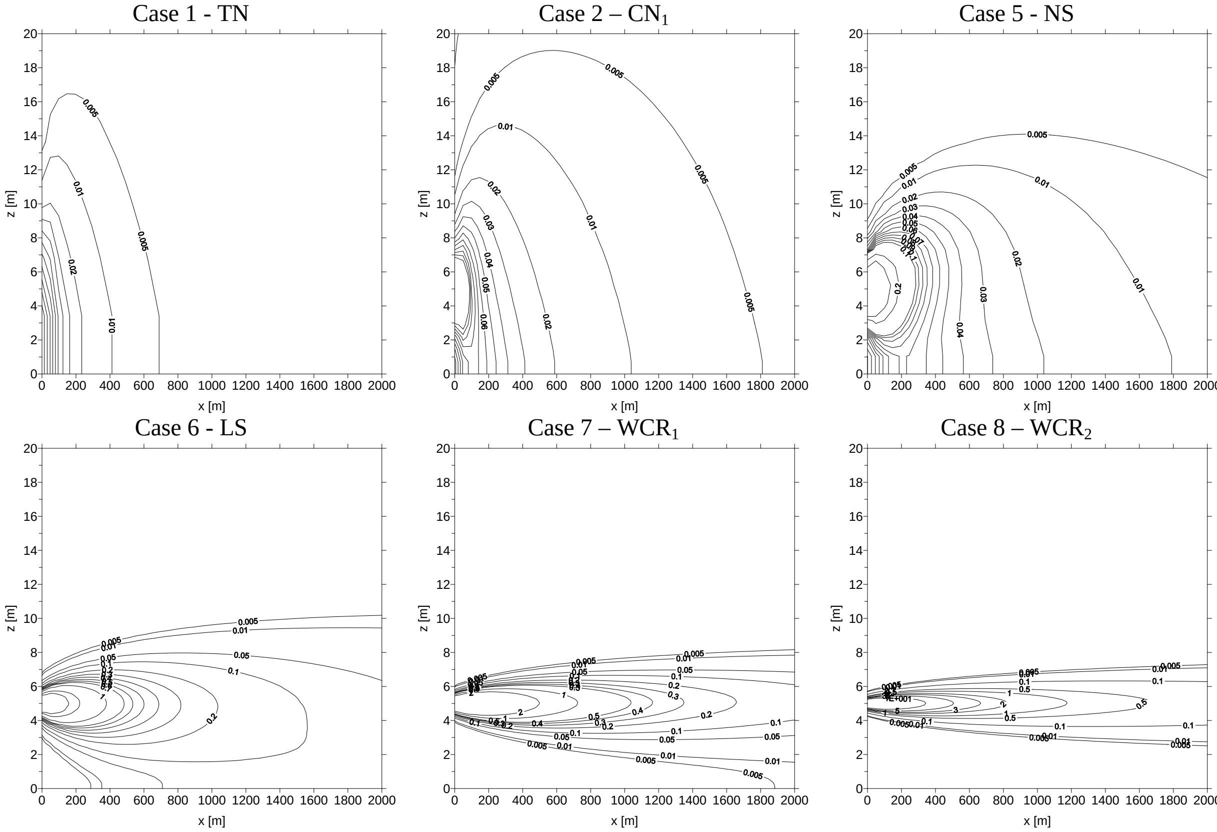

Figure 3. Vertical concentration cross-sections $c(x,z)$ for traditional cases 1 and 5 and none-conventional free flow stability affected cases 2, 4, 6, 8.

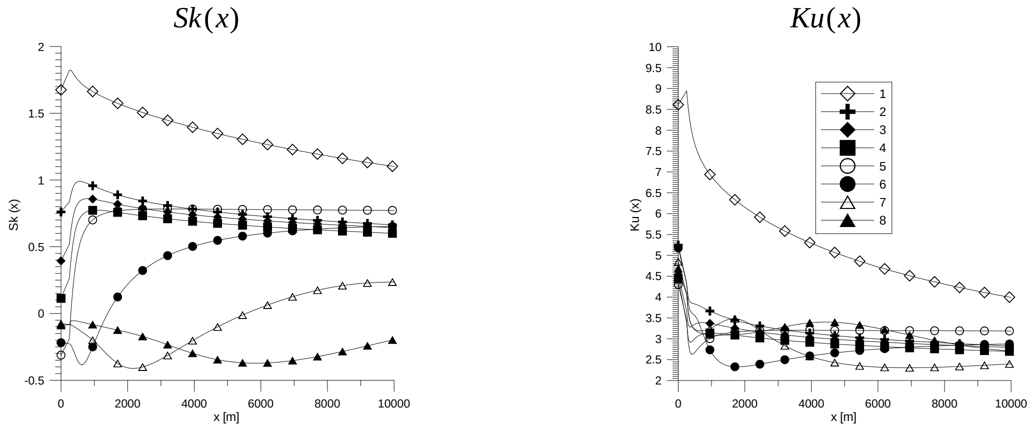

Figure 4. Skewness $Sk(x)$ and kurtosis $Ku(x)$ for stable/neutral cases 1 – 8 .

From the other hand, as it can be seen from Figure 2, the pollution for regimes WCR$_1$, WCR$_2$ practically does not reach earth surface - the concentrations are very small and reach small maximum very far from the source. The evaluations made, show the following maximal concentrations at source level ($z = h_{source} = 5m$): 0.4 – case 3, 0.55 – case 3, 0.96 – case 4, 1.5 – case 5, 19 – case 6, 83 – case 7, 270 – case 8. This conclusions agree very well with the horizontal $\sigma_y(x)$ and vertical $\sigma_z(x)$ dispersions and the ratio $\sigma_z^2(x)/\sigma_x^2(x)$, which is a characteristic of the rate of anisotropy of diffusion processes, demonstrated on Figure 5.

Let the WCR$_1$, WCR$_2$ regimes be considered once more. Some dynamic characteristics, calculated by the PBL model are demonstrated on Figure 6. The turbulent Prandtle number $\Pr_T$ values, much bigger than 1 for cases 7 and 8 (for the other cases it is close to 1), the small vertical turbulent exchange coefficients, as well as the k_z and wind components profiles shape, are evidence of largely reduced vertical exchange. This explains the blocking and accumulation of the pollution in a narrow layer around the source level (5 *m*). Virtually this is a pollution reservoir, which, if the meteorological conditions change towards intensification of the vertical exchange, could become a powerful quazy-2D area source with height 4.5-6 *km.* This may cause an explosive increase of the surface pollution concentrations.

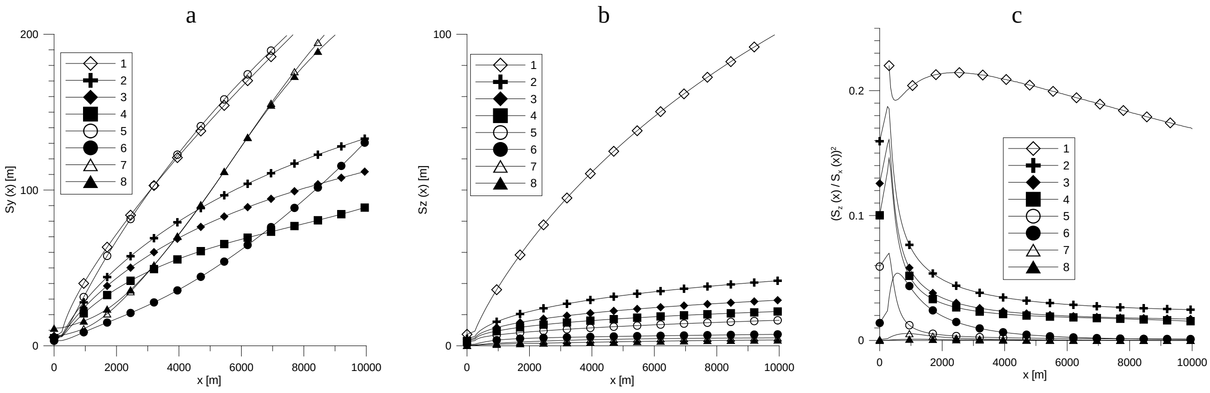

Figure 5. Dependence on x of horizontal $\sigma_y(x)$ (a), and vertical $\sigma_z(x)$ (b) dispersions and anisotropic dispersion coefficient $\sigma_z^2(x)/\sigma_x^2(x)$ for stable/neutral cases 1 – 8 .

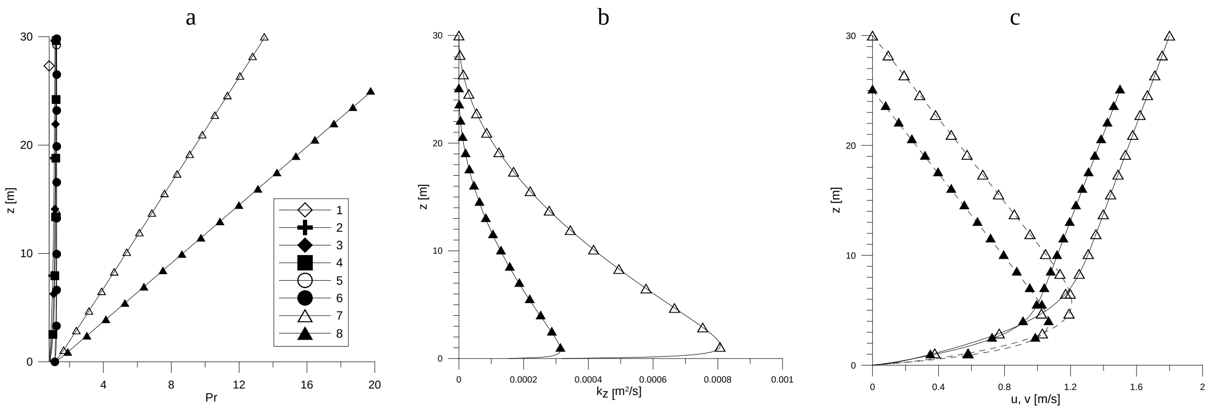

Figure 6. Dependence of turbulent Prandtle number Pr_T on z for stable/neutral cases 1 – 8 (a), profiles of u , v (b) and k_z (c) for cases 7, 8.

CONCLUSIONS

The above described methodology can be applied for differentiated PBL parameterization, taking into account the specifics in the physical nature of different stable/neutral PBL regimes in weather forecast and climate models, as well as in air pollution problems.

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