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ON THE PROBLEM OF HEAVY POLLUTION EPISODES IN SHALLOW LONG-LIVED PBL

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Abstract: This article analyzes parameterization schemes for different stable/neutral regimes with some applications to diffusion of pollutants at these conditions.

Key words: bulk-Richardson methods, free-flow stability, stable and overcritical regimes, PBL diffusion, non local parameterization.

INTRODUCTION

According to Zilitinkevic et al. (2007) several types of turbulent regimes in stable / neutral PBL exist: the truly neutral (TN), observed more or less often; the conventional neutral (CN), typically observed over the ocean in the late summer and autumn; nocturnal stable (NS), typically observed during the night at low and mid latitudes; long-lived stable (LS) strongly affected by the free-flow Brunt-Vaisalla frequency \( N = \sqrt{\beta \theta' / |u'|} \) over the top \( H \) of PBL; very stable PBL characterized by different values of the non local parameter \( \mathcal{A} \). In this work is to parameterize the above regimes by bulk Richardson number method and on this base to explore some dependences of diffusion of pollutants at these conditions.

METHOD

Suppose that \( z_i \) is a fixed reference height in the surface layer (practically, the height of the lowest calculation level in numerical prognostic models, or the height of measurements). Then the bulk Richardson number becomes:

\[
R_s = \frac{\beta A \Delta \theta}{u_i^2} z_i
\]

(1)

Where \( \beta = g/T \) is the buoyancy parameter, \( \Delta \theta = \theta - \theta_b \) is the temperature increment in the layer \( (0 - z_i) \) and \( u_i = u(z_i) \). We will use the relations \( dz/du = u/|\xi| \), \( d\theta'/dz = \theta'/|\xi| \), as the universal functions \( \phi_\xi, \phi_\theta \) in the Monin, A. and A. Obukhov, (1954) similarity theory, have to be modified in accordance to the considered new stable/neutral regimes, taking into account the free-flow stability effect (Zilitinkevich, S., 2005):

\[
\phi_\xi(\xi) = 1 + B_i \xi, \quad B_i = B_i(1 + C_{\text{nm}}^i F_i^+)^
\]

(2)

Where \( \xi = z/L, L = -u_i/|\beta \xi| \) is the Monin-Obukhov length, \( F_i = \sqrt{\xi L}/u_i \equiv F_{\text{io}} / s \), \( s = z_i / \xi L, F_{\text{io}} = N z_i / u_i \), \( B_i = 5, B_p = 6.25 \) (see Syrakov et al. 2008), \( C_{\text{nm}}, C_{\text{sn}} \) are new empirical constants of order 0.1, \( R = \xi = 0.4 \). Taking into account (2), (1) becomes:

\[
R_s(\lambda_\xi, \lambda_\theta, s, F_{\text{io}}) = \frac{\lambda_\xi + R B_i(\xi^2 + C_{\text{nm}}^i F_i^+)^2 / C_{\text{sn}}^i}{\lambda_\xi + R B_i(\xi^2 + C_{\text{nm}}^i F_i^+)^2 / C_{\text{sn}}^i}
\]

(3)

where \( \lambda_\xi = \ln z_i / z_0 \), \( \lambda_\theta = \ln z_i / z_{\text{oz}} \), \( z_0 \) and \( z_{\text{oz}} \) are aerodynamic and temperature roughness, \( C_{\text{sn}}^{i} = u_i / u_i \) and \( C_{\text{nm}} = \theta' / \Delta \theta \) are the drag and heat transfer coefficients to be determined, \( \theta' = -q/u_i \). At \( s \to \infty \) from (3) we determined the critical bulk-Richardson number (see Syrakov, E 2005):

\[
R_s(F_{\text{io}}) = R_{\text{cvo}} = \frac{\left(1 + C_{\text{nm}}^i A F_{\text{io}}^2 A^2 \right)^2}{1 + C_{\text{nm}}^i A F_{\text{io}}^2 A^2}, \quad A = \frac{1}{R B_i}\left(-C_{\text{nm}} B_i F_{\text{io}}^2 \right)^2
\]

(4)

At \( F_{\text{io}} = 0 \) from (4) follows the classical result \( R_s(F_{\text{io}} = 0) = R_{\text{cvo}} = B_i / B_p^2 = 0.25 \) (using the above values of \( B_i ) \) and \( B_p \). On Figure 1a) it is shown the dependence of \( R_s \) on \( F_{\text{io}} \). It is seen, that in the case with nonlocal effects \( F_{\text{io}} > 0 \), \( R_s \) is significantly greater then the corresponding classical \( R_{\text{cvo}} = 0.25 \). Substituting (2) in \( C_{\text{sn}}^{i} \) and \( C_{\text{nm}} \), after solving the quadratic equation, we obtain analytical expressions for the dependence of these coefficient on \( \lambda_\xi, \lambda_\theta, F_{\text{io}} \) and \( s \). In this way the right part of (3) becomes function only of \( s \). After mathematical conversion of (3) we determined the dependence of \( s \), and from here the dependence of \( C_{\text{sn}}^{i} \) and \( C_{\text{nm}} \) on \( \lambda_\xi, \lambda_\theta, R_s, F_{\text{io}} \):

\[
C_{\text{sn}}^{i} = f_s(\lambda_\xi, \lambda_\theta, R_s F_{\text{io}}), \quad C_{\text{nm}} = f_s(\lambda_\xi, \lambda_\theta, R_s F_{\text{io}})
\]

(5)

These dependencies are presented for \( C_{\text{sn}}^{i} \) on Figure 1. At Figure 1b) \( R_s \geq 0 \) the curves have four branches respective to different values of the non local parameter \( F_{\text{io}} \). At \( R_s = 0 \) these branches correspond to (CN) regime. The branch with parameter \( F_{\text{io}} = 0 \) corresponds to (TN) regime. The rest of the cases at \( R_s \geq 0 \) correspond to long-lived (LS) PBL.

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Figure 1. Dependence on: a) critical bulk Richardson number $R_{br}$ on the free flow stability parameter $F_{io}$, b) drag coefficient $C_d^{1/2}$ on $R_b \geq 0$ at different values of $F_{io}$ and c) comparison of $C_d^{1/2}$ for conventional stable regime ( $R_p < R_{oc} = 0.25$ ) and for stable (OC) regime at overcritical Richardson numbers ( $R_b > R_{oc} = 0.25$ ).

Experimental and LES data show, that at (OC) regime at very strong stable stratification and weak and intermittent turbulence, capable of transportation of momentum but much less effective than transporting of heat at $R >> R_{oc}$ and turbulent Prandtl number $P_{tr}$ is significantly greater than one (Zilitinkevich, S., 2007). Phenomenically this means that the asymptotic $\xi$ -dependence of $\varphi_p$ should be stronger (e.g. quadratic) than linear:

$$\varphi_p = 1 + B_{a1} \xi + B_{a2} \xi^2$$  \hspace{1cm} (6)

where $B_{a1} = B_{a1}' \left(1 + C_{nh} \xi \right)^2$, $B_{a2} = B_{a2}' \left(1 + C_{nh} \xi \right)$, $B_{a1}' = 5.5$ and $B_{a2}' = 1.25$ are empirical constants verified with data for $P_{tr}$ (see Syrakov et al., 2008). Taking into account (6) the bulk Richardson method is extended and for parameterization (OC) stable turbulent regime. On Figure 1c it is given comparison of $C_d^{1/2}$ at NS and overcritical (OC) stable regimes at $F_{io} = 0$.

RESULT AND DISCUSSION

We will use multiple component modelling system (MCMs) (see Table 1 in Syrakov et al. 2010 in the current proceedings), more precisely its part: $R_b$ - ($R_b - R_{oc}$)-PBL-plume MM. Taking into account the commented different parameterization schemes for stable/neutral regimes, based on $R_b$ and ($R_b - R_{oc}$) methods, using appropriately chosen surface data and given free-flow parameter $\mu = N / f = 400$, the basic PBL (geostrophic drag coefficient $C_g$, the cross isobaric angle $\alpha$, the inner $\mu$ , integral stratification parameter $S$ and model of geostrophic wind $G_p$) are determined and shown in Table 1.

<table>
<thead>
<tr>
<th>case</th>
<th>regimes</th>
<th>$C_s$</th>
<th>$\alpha$</th>
<th>$\mu$</th>
<th>$\mu_p$</th>
<th>$G_p [ms^{-1}]$</th>
<th>$S$</th>
<th>$H [m]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TN</td>
<td>0.03</td>
<td>23</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>850</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>CN</td>
<td>0.008</td>
<td>40</td>
<td>0</td>
<td>400</td>
<td>8</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>NS</td>
<td>0.012</td>
<td>51</td>
<td>88</td>
<td>0</td>
<td>800</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>LS</td>
<td>0.01</td>
<td>46</td>
<td>120</td>
<td>400</td>
<td>3</td>
<td>1100</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>OC</td>
<td>0.005</td>
<td>54</td>
<td>210</td>
<td>400</td>
<td>1.5</td>
<td>1850</td>
<td>25</td>
</tr>
</tbody>
</table>

Applying these parameters in the PBL model provides the $u$, $v$, $K_z$, $K_{xz}$ and enables the realization of the Plume-MM model. We will discuss some of the obtained results.

The regimes TN and NS are conventional (analysis of similar regimes is given in Syrakov et al., 2010 in the current proceedings), while CN, LS and OC are shallow PBL stable/neutral non local regimes.

On Figure 2 it is given the comparison between vertical sections of the concentration $c(x,z)$ along the plume axis with source height $h_{source} = 5m$ and the different stable non local regimes (NS), (LS), (OC).
It can be seen, that in towards (NS)→(LS)→(OC) regimes, there are increasing anisotropies of the cloud in direction of the prevailing wind, which is particularly strongly expressed for the (OC) regime.

More detailed analysis can be done on the basis presented on Figure 3 of the surface concentration along the plume axis \( c(x, z = 0) \) and the respective horizontal concentration at source level \( c(x, z = h_{\text{source}} = 5m) \), as it is added and TN and NS regimes.

Although the source is at low height at (OC) regime the clouds do not reach the land surface as it is fully located in the area in thin layer at height \( z = h_{\text{source}} \) with horizontal scale around \( 1\text{--}2km \) directed along the wind direction. The concentration in the center of this cloud is extremely high. There is analogical effect, but slightly expressed, and at LS regime. In this case the concentration in the center of the cloud is much greater than the concentration for the other regimes, but at the same time is about an order smaller than that at (OC) regime.

The concentration in the center of the cloud at source height increases around three times, which it is seen from Figure 3. The above commented effects are confirmed and presented on Figure 4 vertical lagrangian coordinate \( Z(t) \) and the dispersion \( \sigma_z(t) \) for the (OC) regime, calculated by plume-MM model. It can be seen that \( Z(t) \) is almost constant (even slowly decreases with time), while \( \sigma_z(t) \) does not exceed 2m. The dependence of the

Since the admixture is scalar quantity in the Plume-MM model, it follows that \( K_e \) has to be used as vertical exchange coefficient. The numerical experiments show that, when using the coefficient \( K_e \), shown on figure 3) or \( K_a \), the concentration field is analogical, but when \( K_e \) is used, the concentration in the center of the cloud at source height increases around three times, which is shown in Figure 3. The above commented effects are confirmed and presented on Figure 4 vertical lagrangian coordinate \( Z(t) \) and the dispersion \( \sigma_z(t) \) for the (OC) regime, calculated by plume-MM model. It can be seen that \( Z(t) \) is almost constant (even slowly decreases with time), while \( \sigma_z(t) \) does not exceed 2m. The dependence of the

Figure 2 Cross-section of the dimensionless concentration along the plume axis for different stable non local regimes from Table 1: case 2-CN (a), 4-LS (b), 5-OC (c).
anisotropy of the dispersions \( \left( \sigma^2_z / \left( \sigma^2_x + \sigma^2_y \right) \right) \) on time gives quantities estimation for the “channel” effect around the source.

Figure 4 Dependence of the lagrangian vertical coordinate \( Z \), the dispersion \( \sigma_z \) and the dispersion asymmetry \( \left( \sigma^2_z / \left( \sigma^2_x + \sigma^2_y \right) \right) \) on the time, calculated by puff-MM model with \( h_{\text{source}} = 5m \) for overcritical (OC) stable regime.

CONCLUSION

The described approach can be used for differentiated parameterization, taking into account the specificities of different by their physical nature stable/neutral regimes, as in prognostic and climate models as well in pollution tasks.

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