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ON THE DRY DEPOSITION OF ADMIXTURES WITH GRAVITY DEPOSITION

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ABSTRACT

It seems that the "big leaf" approach to the dry deposition assessment will be the one followed by the model developers in the near future. The resistance against turbulent transport of the component close to the surface - the aerodynamic resistance, is one of the major factors of dry deposition. The most popular parameterization schemes treat the aerodynamic resistance and the gravity deposition independently, most often by simply adding the gravity deposition velocity. As the gravity deposition modifies the admixture profiles and thus the turbulent fluxes in the Surface Layer (SL), this approach is obviously incorrect.

The present paper suggests a more general approach, based on the exact solution of the pollution transport (turbulent and gravity deposition) equation in the SL, which provides a correct expression for the aerodynamic resistance, accounting also for the gravity deposition effects. Some results from simple calculations, which demonstrate the importance of a joint treatment of turbulent transport and gravity deposition while calculating the aerodynamic resistance, are also shown in the paper.

Key Words: dry deposition, gravity sedimentation, aerodynamic resistance

1. INTRODUCTION

It seems that the "big leaf" approach (Erisman, van Pul and Wyers, 1994, Jakobsen, Jonson and Berge, 1996, Seland, van Pul, Sorteberg and Tuovinen, 1995, Wesley, 1989) to the dry deposition assessment will be the one followed by the model developers in the near future. These most popular parameterization schemes assume the following connection between the turbulent flux of gases or aerosol and their concentration at level z :

$$-F = k\frac{dc}{dz} = V_d(z)c(z)\,, \tag{1}$$

where $c(z)$ is the admixture concentration, V_d is the dry deposition velocity and $k(z)$ is the coefficient of vertical turbulent exchange.

By making analogy with the Ohms law in electrical circuits the dry deposition velocity V_d is most often presented in the form:

$$V_d = (r_a + r_b + r_s)^{-1}, \tag{2}$$

where r_a is the surface layer (SL) aerodynamic resistance, r_b is the quasi-laminar or viscous sub-layer resistance, and r_s is the surface resistance.

It seems that the most general expression for the aerodynamic resistance r_a is the following:

$$r_a(z) = \int_{z_0}^{z} \frac{dz}{k(z)}, \tag{3}$$

where z_0 is the roughness length. If it is assumed, as usual, that the SL turbulent transport of admixtures is similar to these of heat and momentum, it can be written:

$$k(z) = \frac{\kappa u_* z}{\varphi(\varsigma)}, \tag{4}$$

where κ is the von Karman constant, u_* is the friction velocity, $\varphi(\varsigma)$ is the universal function of the dimensionless height $\varsigma = z/L$, L - the Monin-Obukhov length. In such a case the expression for r_a resumes the form:

$$r_a(z) = \frac{1}{\kappa u_*}\left(f(z) - f(z_0)\right), \; f(z) = \int \frac{\varphi(\varsigma)}{z} dz. \tag{5}$$

From (3) it is obvious that $r_a(z_0) = 0$ and thus

$$V_{d0} = V_d(z_0) = \left(r_b + r_s\right)^{-1}, \tag{6}$$

i.e. the deposition velocity at roughness length height is subject only of the transport of the component trough the laminar layer adjacent to the surface by molecular diffusion and the various destruction or uptake processes of the component at the surface.

2. A MORE GENERAL APPROACH

The relation (1)-(2) between the turbulent flux and the component concentration in the SL is widely used, but is not the most general one. It does not account for factors, which may be important, like gravity deposition and pollution sources in the SL.

A more general approach based on the solution of the admixture transport equation in the SL is suggested by Ganev and Yordanov (1981, 2004, 2005), Venktaram and Pleim (1999). As generally accepted, the vertical transport is assumed dominant in the SL, so the concentration field is assumed to be locally horizontally homogeneous and stationary. In such a case the vertical profile $c(z)$ of the concentration of an admixture with gravity deposition $-w_g$, ($w_g > 0$) is described by the equation:

$$\frac{d}{dz} k \frac{dc}{dz} + w_g \frac{dc}{dz} = -q\delta(z - z_{source}), \tag{7}$$

where q is the capacity of a flat (locally) homogeneous admixture source, δ is the Dirac function. The boundary condition at $z = z_0$ is, according to (1), (2), (6), the following:

$$k \frac{dc}{dz} = V_{d0} c_0, \tag{8}$$

c_0 - the concentration at $z = z_0$. It is stratrforward to integrate (7), (8), which leads to the following expression forThe integration of (7), having in mind also (8) leads to:

$$kdc/dz + w_g c = (w_g + V_{d0})c_0 - qH_{source}(z), \tag{9}$$

where $H_{source}(z)$ is the Heavyside function ($H_{source}(z) = 0$ for $z < z_{source}$; $H_{source}(z) = 1$ for $z > z_{source}$). By the transformation

$$c = xe^{-w_g r_a}, \tag{10}$$

where r_a is the aerodynamic resistance (see (3)), equation (9) can be simplified to the form (from (10) it is obvious that $x(z_0) = c_0$):

$$kdx/dz = (w_g + V_{d0})c_0 e^{w_g r_a} - qH_{source}(z)e^{w_g r_a}, \tag{11}$$

and after some trivial manipulations an expression for $c(z)$ to be obtained:

$$c(z) = \left[1 + \frac{V_{d0}}{w_g}\left(1 - e^{-w_g r_a(z)}\right)\right] c_0 - H_{source}(z) \frac{q}{w_g}\left(1 - e^{w_g r_a(z_{source}) - w_g r_a(z)}\right). \tag{12}$$

By calculating c_0 from (12) and then inserting it in (9) the SL flux/concentration relation for the case of admixtures with gravity deposition and possible sources in the SL can be obtained:

$$k\frac{dc}{dz}=V_d(z)c(z)-H_{source}(z)\frac{V_d(z)}{V_d(z_{source})}q, \tag{13}$$

Where

$$V_d(z)=\left[\frac{1}{w_g}\left(e^{w_g r_a(z)}-1\right)+e^{w_g r_a(z)}\frac{1}{V_{d0}}\right]^{-1}. \tag{14}$$

It is easy to calculate that in case of admixture with no gravity deposition ($w_g\rightarrow 0$) the expression (14) takes the form (2). Further, if there are no sources in the SL the flux/concentration relation transforms into the form (1).

The particular cases when $V_{d0}\rightarrow\infty$ (total absorption at $z=z_0$) and $V_{d0}\rightarrow 0$ (total reflection at $z=z_0$) can also be considered. Obviously in the first case

$$V_d(z)\rightarrow\left[\frac{1}{w_g}\left(e^{w_g r_a(z)}-1\right)\right]^{-1}, \text{ when } V_{d0}\rightarrow\infty, \tag{15}$$

and, as it can be easily seen from (13), there will be zero concentration at $z=z_0$. In the second case $V_d\rightarrow 0$ when $V_{d0}\rightarrow 0$, but the ratio $V_d(z)/V_d(z_{source})$ remains limited, so the relation (13) obtains the form:

$$k\frac{dc}{dz}=-H_{source}(z)\frac{e^{w_g r_a(z_{source})}}{e^{w_g r_a(z)}}q, \tag{16}$$

or in the case with no gravity deposition ($w_g\rightarrow 0$):

$$k\frac{dc}{dz}=-H_{source}(z)q. \tag{17}$$

If the deposition velocity, calculated according to (1) is denoted by V_{d1}, then having in mind (6) the aerodynamic resistance r_a may be expressed in the form:

$$r_a=V_{d1}^{-1}-V_{d0}^{-1}. \tag{18}$$

Inserting (18) in (14), leads, after some simple transformations to the dimensionless relation:

$$\widetilde{V}_d=\left[\frac{1}{\widetilde{w}_g}\left(e^{\widetilde{w}_g\left(\widetilde{V}_{d1}^{-1}-1\right)}-1\right)+e^{\widetilde{w}_g\left(\widetilde{V}_{d1}^{-1}-1\right)}\right]^{-1}, \tag{19}$$

where $\widetilde{V}_d = V_d / V_{d0}$, $\widetilde{V}_{d1} = V_{d1} / V_{d0}$, $\widetilde{w}_g = w_g / V_{d0}$.

The difference between $\widetilde{V}_d$ and $\widetilde{V}_{d1}$ is well demonstrated by Figure 1. It is clear that even in the cases when w_g is of the order of magnitude of V_{d0} the effect of gravity deposition on the turbulent (aerodynamic) deposition is significant. The gravity deposition modifies the admixture profiles and thus the admixture turbulent fluxes in the SL, which results in a decrease of the dry deposition velocity.

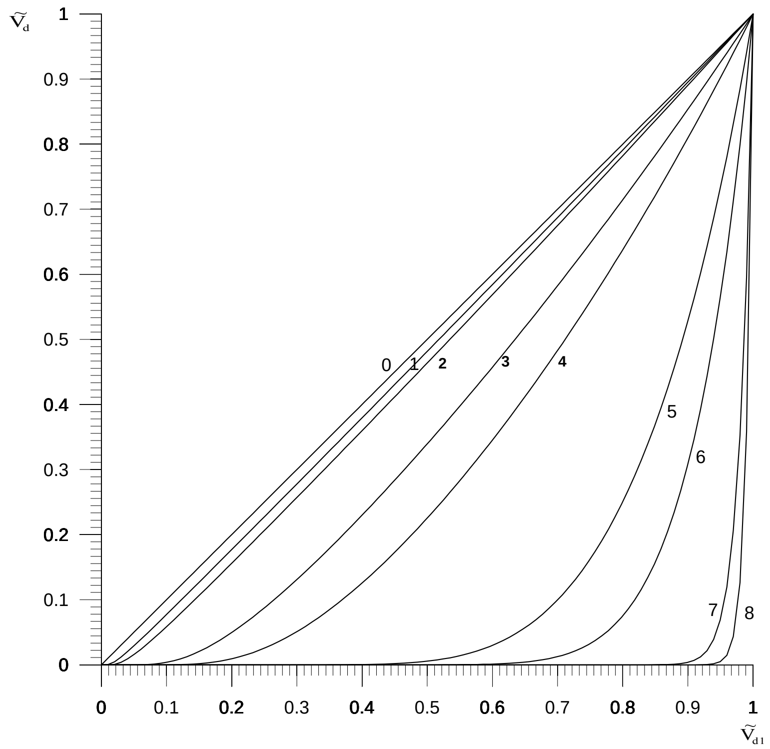

Figure 1. The difference between $\widetilde{V}_d$ and $\widetilde{V}_{d1}$ for different $\widetilde{w}_g$ values: $\widetilde{w}_g$ =0 (0). 0.05 (1), 0.1 (2), 0.5 (3), 1 (4), 3 (5), 10 (6), 50 (7) and 100 (8)

If the total (turbulent + sedimentation) flux/concentration relation is concerned from (13, 14) it can be obtained:

$$-F = k\frac{dc}{dz} + w_g c = W_d(z)c(z) - H_{source}(z)\frac{W_d(z) - w_g}{W_d(z_{source}) - w_g} q\,, \tag{20}$$

$$W_d(z) = w_g\left(1 + \frac{w_g}{V_{d0}}\right)\left[1 + \frac{w_g}{V_{d0}} - e^{-w_g r_a(z)}\right]^{-1}. \tag{21}$$

Expressions (14, 21) can not be derived by using any sort of electrical analog.

Some well known relations can be derived as particular cases of (21). For example, when $w_g << V_{d0}$ (16) obtains the form (Venckatram, A. and J. Pleim, 1999):

$$W_d(z) = w_g \left[1 - e^{-w_g r_a(z)}\right]^{-1}, \tag{22}$$

and when $w_g r_a << 1$ - the form (J.H. Sienfeld and S. Pandis, 1998):

$$\begin{aligned} W_d(z) &= w_g + \left[r_a(z) + \frac{1 + w_g r_a(z)}{V_{d0}} \right]^{-1} = \\ &= w_g + \left[r_a(z) + r_s + r_b + w_g\, r_a(z)(r_s + r_b) \right]^{-1} \end{aligned} \tag{23}$$

The application of the dry deposition parameterization suggested above can be demonstrated by the following example: Let a two-layer model for k is assumed - $k = k(z)$, calculated according to (4) in the SL ($z_0 \le z \le h_{SL}$), h_{SL} - the SL height; $k = k_h = k(h_{SL})$ for $h_{SL} \le z < \infty$. Then, in the horizontally homogeneous case, the vertical profile above SL of the concentration $c(z,t)$ from an instantaneous flat source with height $h > h_{SL}$ can be obtained from the equation:

$$\frac{\partial c}{\partial t} - w_g \frac{\partial c}{\partial z} - k_h \frac{\partial^2 c}{\partial z^2} = 0\,,\ h_{SL} \le z < \infty\,, \tag{24}$$

under the following initial and boundary conditions:

$$c(z,0) = \delta(z - h)\,;\ k_h \frac{\partial c}{\partial z} = \beta c(h_{SL}, t)\,. \tag{25}$$

Here β is the dry deposition velocity at $z = h_{SL}$. Depending on the chosen parameterization β is equal to $V_d(z = h_{SL})$ or to $V_{d1}(z = h_{SL})$ - respectively the cases when the gravity deposition effects on the aerodynamic resistance are accounted, or not accounted for. As it can be easily shown (Galperin, Yordanov and Ganev, 2000), the solution of (20-21) is:

$$c(z,t) = e^{-\frac{w_g(z'-h')}{2k_h} - \frac{w_g^2 t}{4k_h}} \left\{ \frac{1}{2\sqrt{\pi k_h t}} \left[e^{-\frac{(z'-h')^2}{4k_h t}} + e^{-\frac{(z+h)^2}{4k_h t}} \right] - \frac{\tilde{\beta}}{k_h} e^{\frac{\tilde{\beta}(z'+h'+\tilde{\beta} t)}{k_h}} erfc\left(\frac{z'+h'+2\tilde{\beta} t}{2\sqrt{k_h t}} \right) \right\} \tag{26}$$

where $\tilde{\beta} = \beta + w_g / 2$, $z' = z - h_{SL}$ and $h' = h - h_{SL}$.

This rather simplified model is applied because it allows obtaining an analytical solution in the explicit form (26) and on the other hand is realistic enough, at any rate much more realistic if a one-layer model for k ($k = const$ for $z_0 \le z < \infty$) is assumed.

The horizontally homogeneous concentration pattern is not often observed in the real world, but in factorized pollution transport models, like the trajectory "puff" model, the multiplier that accounts for the vertical concentration distribution is also defined as a solution of (24), (25). That is why the chosen simplification can be estimated as a relevant one for demonstrating the effects of the suggested dry deposition parameterization scheme.

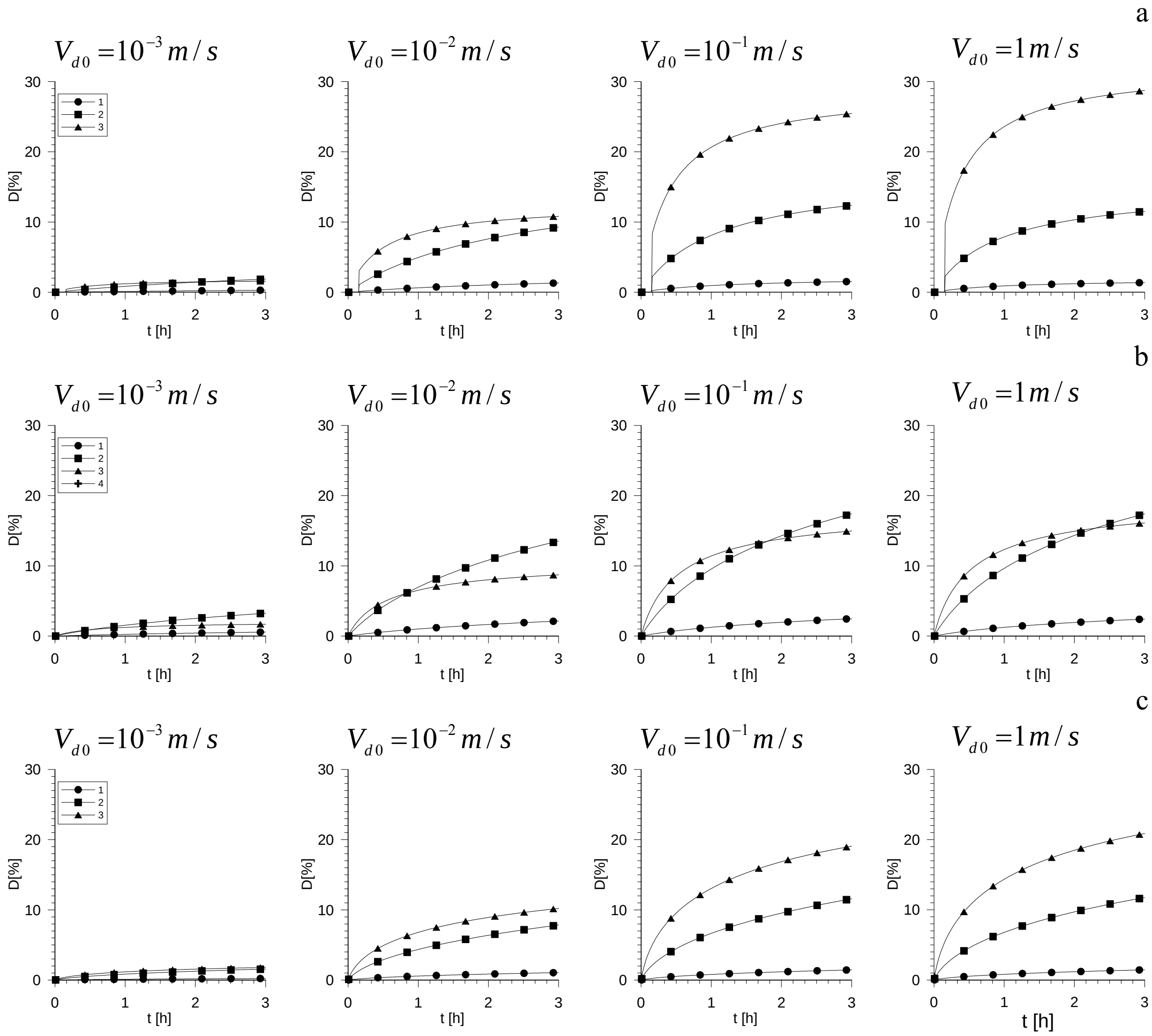

Figure 2. Time evolution of $D_h = (c'(h_{SL}, t) - c''(h_{SL}, t)) / c'(h_{SL}, t), [\%]$ for different V_{d0} values and for $w_g = 10^{-3}\, m/s$ (1), $w_g = 10^{-2}\, m/s$ (2) and $w_g = 10^{-1}\, m/s$ (3). Cases of Stable (a), Neutral (b) and Unstable(c) stratification

Formula (26) was applied for calculating the concentrations $c'(h_{SL}, t)$ and $c''(h_{SL}, t)$ at SL height for the cases when gravity deposition is accounted ($\beta = V_d(z = h_{SL})$) and not accounted ($\beta = V_{d1}(z = h_{SL})$) for. The calculations were made for a wide range of V_{d0} and w_g values for the cases of stable ($u_* = 0.5\, m/s$, $L = 10$), neutral ($u_* = 0.2\, m/s$) and unstable ($u_* = 0.2\, m/s$, $L = -10$) stratification for source height

$h = 200m$. When the concentrations $c'(h_{SL}, t)$ and $c''(h_{SL}, t)$ at SL height are calculated, it is easy also to obtain the respective concentrations concentration c_0' and c_0'' at roughness length level ($z = z_0$). c_0' is calculated from (12) for $z = h_{SL}$ and $c = c'(h_{SL}, t)$. c_0'' is calculated from the same formula for $z = h_{SL}$, $c = c''(h_{SL}, t)$ and $w_g \to 0$.

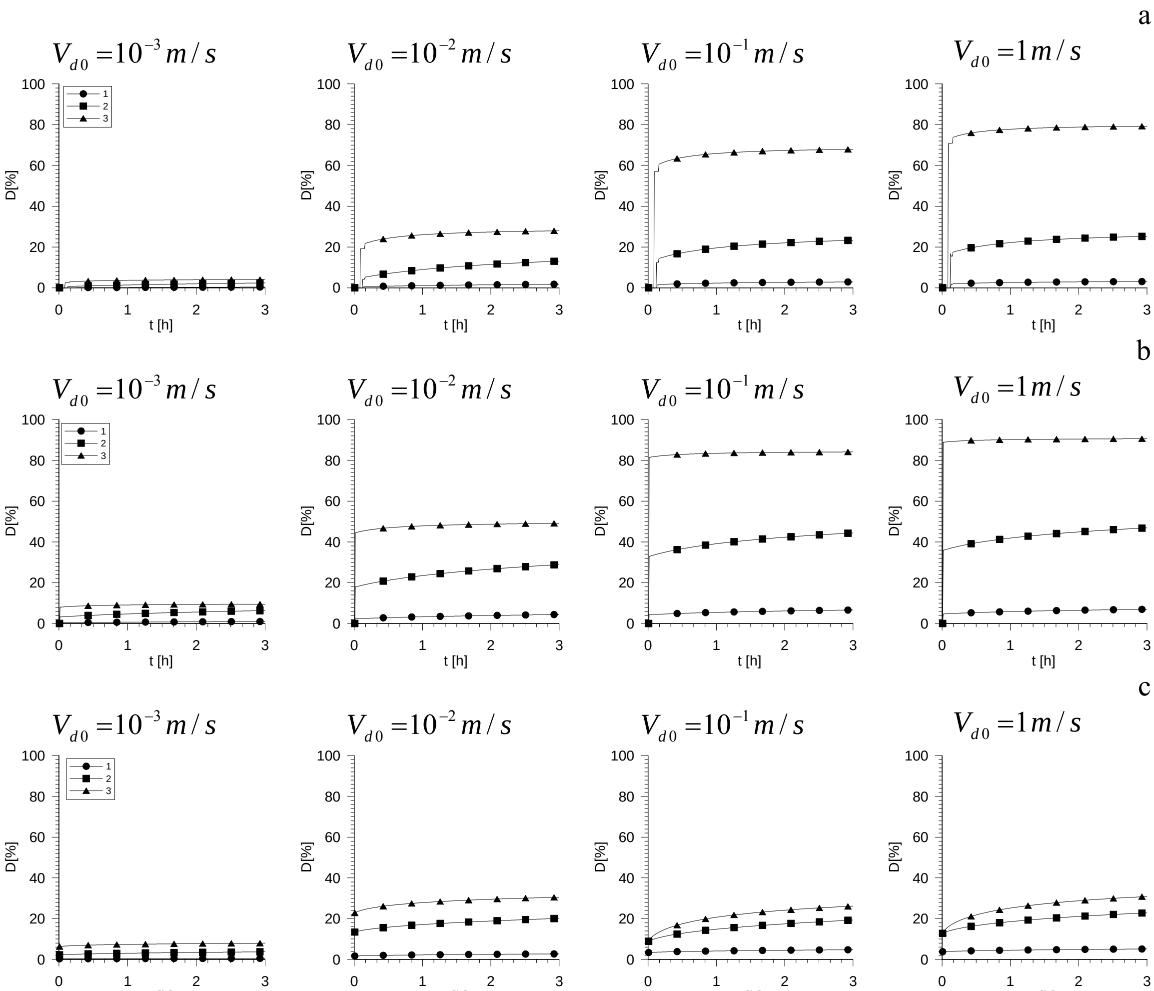

Figure 3. Time evolution of $D_0 = (c_0'(t) - c_0''(t))/c_0'(t), [\%]$ for different V_{d0} values and for $w_g = 10^{-3} m/s$ (1), $w_g = 10^{-2} m/s$ (2) and $w_g = 10^{-1} m/s$ (3). Cases of Stable (a), Neutral (b) and Unstable(c) stratification

Some of the results are demonstrated in Figures 2-3, where the time evolution of the relative differences $D_h(t) = (c'(h_{SL}, t) - c''(h_{SL}, t))/c'(h_{SL}, t), [\%]$ and $D_0(t) = (c_0'(t) - c_0''(t))/c_0'(t), [\%]$. The following conclusions can be maid by the comparison:

- taking into account the gravity deposition may have a significant effect on the calculated concentrations – in some cases up to almost 30% for the concentration at SL height and up to 80% at $z = z_0$;

- the effect generally increase with the increase of w_g and V_{d0};
- both $D_h(t)$ and $D_0(t)$ curves are pretty similar for $V_{d0} = 10^{-1} m/s$ and $V_{d0} = 1 m/s$, regardless of the stratification and w_g values. This means that the gravity sedimentation effects on dry deposition increase significantly with the increasing of V_{d0}, until it reaches some critical value. For V_{d0} above this critical value (and certainly for $V_{d0} > 10^{-1} m/s$) the turbulence/gravity deposition interaction and thus the gravity sedimentation effects on dry deposition become much less sensitive to V_{d0} variations;
- the gravity sedimentation influence on dry deposition an on the concentration profiles strongly depends on the stratification. This dependence is not monotonic or simple, however, and is manifested in rather different for different w_g and V_{d0} values.

3. CONCLUSION

The most popular parameterization schemes treat the aerodynamic resistance and the gravity deposition independently, most often by simply adding the gravity deposition velocity. As the gravity deposition modifies the admixture profiles and thus the admixture turbulent fluxes in the SL, this approach is obviously incorrect. The present paper suggests a more general approach, based on the exact solution of the pollution transport (turbulent and gravity deposition) equation in the SL, which provides a correct expression for the aerodynamic resistance, accounting also for the gravity deposition effects. The parameterization scheme is a generalization of the formula suggested by (Venckatram, A. and J. Pleim, 1999) and (J.H. Sienfeld and S. Pandis, 1998). The demonstrated examples show the importance of a joint treatment of turbulent transport and gravity deposition in calculating the aerodynamic resistance. They also demonstrate the sensitivity of the parameterization scheme to w_g, V_{d0} and stratification variations.

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