Influence of dry deposition velocity to the ground in the dispersion of the air pollutants

T Tirabassi\textsuperscript{1}, C P Costa\textsuperscript{2} and K Rui\textsuperscript{3}
\textsuperscript{1}Fedreal University of Santa Maria, Santa Maria, Brazil
\textsuperscript{2}Federal University of Pelotas, Pelotas, Brazil
\textsuperscript{3}Federal University of Rio Grande do Sul, Porto Alegre, Brazil

Corresponding author e-mail: t.tirabassi@isac.cnr.it

Abstract. Through numerical simulations it is studied the influence of dry deposition to the ground on air pollution concentrations. The simulations utilize the steady-state analytical solution of the advection-diffusion equation considering a vertically inhomogeneous PBL. The simulations showed that the phenomenon of local dry deposition can strongly influence the distribution of the air pollution concentrations and maximum concentrations near the ground. The work is an example of the usefulness of analytical solutions as a technical tool to study and understand the transport and diffusion in the atmosphere.

Keyword Dry deposition, atmospheric dispersion, ADMM solution, air pollution modelling

1. Introduction
The uptake of the pollutants at the Earth’s surface, either by soil, water, or vegetation, reduces airborne concentration levels at locations far downwind, while potentially it increases the level of surface contamination due to the deposited material. The Earth's surface is the ultimate sink for trace gases and particles emitted in the atmosphere. The gases and particles transfer to the surface occurs through two pathways: wet and dry deposition. Moreover, heavy particles fall to the surface by gravity effect.

Wet deposition involves precipitation. Dry deposition refers to the transfer of air pollution (gas and particles) to the ground, where it is removed. Dry deposition occurs as trace gases and particles are adsorbed or react on objects (plants, soil, water, buildings, etc.) at the Earth's surface. The various transfer mechanisms leading to dry deposition are complex and involve micrometeorological characteristics of the atmospheric surface layer [1], including the atmospheric turbulence intensity, the nature of the gas and particles and of the surface itself. The deposition flux is usually parameterized in terms of deposition velocity, which is either specified empirically or estimated from appropriate theoretical relations. Unlike molecular diffusion, turbulent diffusion is not a property of fluids, but of the turbulence itself of flows, and it may vary greatly from one flow to another and from one region to another one. Likewise, without turbulence even a perfectly adsorbing surface would be ineffective at removing suspended material from the atmosphere because dry deposition would be limited by molecular diffusion.

In this work, in order to study influence of the dry deposition on air pollution concentrations by analytical formulae, we solve the two-dimensional, steady-state advection-diffusion-deposition equation by the ADMM (Advection-Diffusion Multi-layer Method) method [2], [3]. The method is based on a discretization of the ABL in N sub-layers, where in each sub-layers the advection-diffusion equation is
solved by the Laplace transform technique, considering an average value for eddy diffusivity and the wind speed. Main feature of the ADMM approach consists on the following steps: stepwise approximation of the eddy diffusivity and wind speed, the Laplace transform application to the advection-diffusion equation in the x variable, analytical solution of the set of linear ordinary equation resulting for the Laplace transform application and construction of the pollutant concentration by the Laplace transform inversion using the Fixed-Talbot method [4].

Concerning the method, it is relevant to underline that in the approach no approximation is made in the solution derivation, except for the stepwise approximation of wind and eddy diffusivity profiles.

Concerning the issue of stepwise approximation, it is important to consider that the stepwise approximation of a continuous function converges to the continuous function when the stepwise of the approximation goes to zero.

More information on the ADMM method can be found in [5].

2. Boundary layer parameterization

The literature reports many varied formulae, for the calculation of the vertical turbulent diffusion coefficient [1]. As examples of applications of our ADMM solution we tested the following vertical and lateral diffusion parameterization suggested by [6] for convective conditions

\[
\frac{K_z}{w_*h} = 0.22 \left( \frac{z}{h} \right)^{1/3} \left( 1 - \frac{z}{h} \right)^{1/3} \left[ 1 - \exp \left( -\frac{4z}{h} \right) - 0.0003 \exp \left( \frac{8z}{h} \right) \right],
\]

where \( w_* \) is the convective velocity scale evaluated by \( w_* \approx \frac{-u_h}{k\sqrt{u^*L}} \), where \( z \) is height, \( k \) is the Von Karman constant, \( u^* \) the friction velocity, \( L \) is the Monin-Obukhov length and \( h \) is the thickness of the ABL.

In stable conditions we employed the formula in [7]:

\[
K_z = \frac{0.3(1-z/h)u_z z}{1 + 3.7 z/\Lambda}
\]

where \( \Lambda = L(1-h)^{3/4} \)

The wind speed profile was described by a power law expressed as follows [8]:

\[
\frac{\bar{u}_z}{\bar{u}_1} = \left( \frac{z}{z_1} \right)^p
\]

where \( \bar{u}_z \) and \( \bar{u}_1 \) are the mean wind velocity at the heights \( z \) and \( z_1 \), while \( p \) is an exponent that is related to the intensity of turbulence [9].

3. Influence of the dry deposition on the air pollution concentrations

The dry deposition is a local phenomenon that occurs near the ground. However, the depletion of the concentration at the ground generates flows of concentration from top to bottom. These flows are governed by the intensity of turbulence and may change considerably the pollution concentration profiles with altitude as well as the maximum concentration at the ground. We will illustrate and evaluate numerically this phenomenon through numerical simulations using the solution presented in [5].

For the simulations are identified different scenarios of turbulence corresponding to a very strong turbulence, light turbulence and a stable atmosphere. To do this we are referring to 3 typical diffusive
scenarios situations that can be identified with the 3 old stability turbulent Pasquill classes A, C and E [10], [11].

In table 1 are reported the meteorological data related to the three identified situations diffusive scenarios.

Table 1. Meteorological data related to the simulated scenarios

| Scenario | L (m) | u* (m/s) | u_1 (m/s) | p   |
|----------|-------|----------|-----------|-----|
| 1        | -7.2  | 0.1      | 1.5       | 0.07|
| 2        | -30   | 0.25     | 4         | 0.1 |
| 3        | 30    | 0.16     | 3.5       | 0.35|

Figure 1 shows the concentration at the ground as a function of distance from the source for different deposition rate ($V_d$ is the deposition velocity (m/s)) in a strong convective condition and for a height of the source $H_s = 0.1$ h. Figure 2 shows the same thing for a stable atmosphere.

As expected, the profiles are similar, but with lower concentrations values for the scenario less convective. The maximum concentration decreases with increasing deposition rate and, at the same time, it approaches the source.

On the contrary, in the case of stable atmosphere the dry deposition velocity has a great effect on the value of the maximum concentration and significantly change the concentrations on the ground at distances greater than the maximum ground level position. This is mainly due to the fact that, in stable conditions and tall sources, the distance of the maximum concentration considerably increases and therefore, the time of flight also increases, allowing a greater deposition of the pollutant in the ground.

An opposite behavior is present in scenarios characterized by convective and small sources ($H_s=0.01h$), as can be seen in Figure 3 where the value and position of maximum concentration does not change. This behavior is explained by the fact that in convective situations, the pollutant that comes from sources near the ground reaches maximum concentrations in the soil very close to the source and so, the phenomena of dry deposition do not have enough time to deplete the material emitted into the air.

In Figure 4 are presented the vertical profiles of concentrations in a convective case (scenario 1), at a distance (x) equal to twenty times the height of the source (x = 20$H_s$), for different deposition velocity. Of course, the phenomenon also depends on the height of the source, but you can see that the depletion affects portions of ABL higher than the height of the source.

Moreover, in the stable case (Figure 5), the profile is changed substantially only below the source. The explanation is that the deposition is a phenomenon that operates near to the ground and, given the weak turbulent diffusion, its effects do not reach (if not at large distances from the source) the upper part of the ABL.

4. Conclusions

Through numerical simulations, using the ADMM approach, the influence of dry deposition to the ground on air pollution concentrations is studied. It showed that the deposition is a local phenomenon but may affect the air pollution distribution in the ABL.

Three meteorological scenarios have been identified, corresponding, respectively, to a strongly and moderately convective ABL and a stable situation.

The simulations showed that the phenomenon of local dry deposition depend on the height of the source and on the intensity of the turbulence and, moreover, it can strongly influence the distribution of the air pollution concentrations and maximum concentrations near the ground.
Figure 1. The concentration at the ground as a function of distance from the source for different deposition rate in convective condition. $V_d$ is the deposition velocity (m/s) and $Q$ is the source emission.

Figure 2. The same of Fig.1 for stable condition.
Figure 3 The same of Fig.1 but for the scenario 2 and a source height $H_s=0.01h$

Figure 4. The concentration vertical profiles in convective conditions, at a distance equal to twenty times the height of the source ($x = 20H_s$), for different deposition velocity ($V_d$ is the deposition velocity (m/s))
This work has also highlighted the usefulness of analytical solutions as a technical tool to study and understand the transport and diffusion in the atmosphere.

**Acknowledgement** The authors thank the FAPERGS for the partial financial support of this work.

**References**

[1] Seinfeld, J.H. and Pandis, S.N. 1998. *Atmospheric chemistry and physics: from air pollution to climate change* (John Wiley & Sons, New York) p1326

[2] Costa CP, Vilhena MT, Moreira DM, Tirabassi T. *Atmospheric Environment* **40** 5659

[3] Moreira DM, Vilheha MT, Tirabassi T, Costa CP, Bodmann B 2006. *Water Air & Soil Pollution* **177** 411.

[4] Abate J and Valkò PP. 2004. *Int. Numer. Methods Eng.* **60** 979

[5] Moreira DM, Tirabassi T, Vilhena MT, Goulart AG 2010 *Atmospheric Environment* **44** 1859

[6] Degrazia, GA, Rizza., Mangia, C, Tirabassi, T. 1997. *Boundary-Layer Meteorol.*, **85** 243

[7] Mangia C, Moreira DM, Schipa I, Degrazia GA, Tirabassi T, Rizza U 2002 *Atmospheric Environment* **36** 7

[8] Panofsky HA. and Dutton JA. 1984 *Atmospheric turbulence*. (John Wiley & Sons, New York) p396

[9] Irwin, JS 1979 *Atmospheric Environment* **13** 191

[10] Zannetti P 1990 *Air Pollution Modelling* (Computational Mechanics Publications, Southampton) p444

[11] Tirabassi T, Tiesi A, Buske D, Vilhena MT, Moreira DM 2009 *Atmospheric Environment* **43** 22