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LAGRANGIAN SIMULATIONS OF THE PLUME RISE IN STRONG CAPPING INVERSION

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Abstract: In this work we have performed new investigations applying our Lagrangian algorithm described by Alessandrini et al. (2013) to simulate the plume rise in a convective boundary layer, capped with a strong inversion layer. We tested our model with the results of a water tank experiment (Weil et al. 2002). For each case we compare the simulated and measured mean height, horizontal and vertical plume standard deviation and the entrapment, the fraction of the plume that remains captured above the inversion respect to the whole mass of the plume. The model is able to correctly reproduce the main characteristics of the plume.

Key words: *Lagrangian Model, Plume Rise, Entrapment.*

INTRODUCTION

The correct simulation of plume rise is of basic importance for a correct estimation of the transport and dispersion of airborne pollutants and for the evaluation of their ground level concentration. A buoyant plume rises because of its initial momentum and buoyancy. In the first stage one has also to account for the action of the buoyancy-generated turbulence. However, progressively the effect of ambient turbulence becomes predominant. The rising plume experiences a shear force at its perimeter, where momentum is transferred from the plume to the surrounding air, and ambient air is entrained into the plume. This phenomenon, called entrainment, is responsible for the plume diameter increase and for the decrease of both its mean velocity and the average air-plume temperature difference. In the Eulerian dispersion models, the calculation of the plume rise is based on the fluid dynamic equations, namely on the mass, momentum and energy conservation equations. Since a complete theory is not yet available, these equations generally assume that the rate at which ambient air is entrained into the plume is proportional to the mean local rise velocity. This assumption was generally used in semi-empirical formulations (Briggs, 1975) but more complex three-dimensional expressions are inserted in the integral models. In Lagrangian Particle Models (LPM) plume rise can be dynamically computed, i.e. each particle, at each time step, can respond to local conditions: wind speed and direction, ambient stability and turbulence (both the self-generated and ambient ones). This allows obtaining a high degree of resolution. In particular, with a reference to the present work, it allows simulating the interaction of a plume with a capping inversion layer in a "natural" way. In this paper the method proposed by Alessandrini et al. (2013) is considered. It makes use of two scalars transported by the particles. They represent the temperature and vertical velocity difference between the plume and the environment. The entrainment is properly simulated and the plume rise is calculated from the local property of the flow. In that paper, concerning controlled conditions, the algorithm was tested only in neutral and stable boundary layers both in water tank and ideal experiment showing good results. In the present work we have performed new investigations applying the algorithm in a convective boundary layer (CBL) capped with a strong inversion layer. We considered the laboratory water tank experiment carried out by Weil et al. (2002). The focus of the experiment is on highly buoyant plumes that loft near or become trapped in the CBL capping inversion and resist downward mixing. Such plumes can be defined by a dimensionless buoyancy flux, F_{b*} (which depends on the stack buoyancy flux, the mean wind speed, the convective velocity scale and the CBL depth) and the dimensionless down-wind distance X (which depends on the distance, the mean wind speed, the convective velocity scale and the CBL depth). By comparing the simulated and measured plume rise characteristics as a function of F_{b*} and the dimensionless down-wind distance X, we verified that the plume rise model is able to fulfil the experiment results.

THE PLUME RISE MODEL

The Lagrangian plume rise module was introduced in the Lagrangian stochastic particle model SPRAY (Tinarelli et al., 2000, Alessandrini and Ferrero, 2009). Each particle carries two quantities that specify the difference between the temperature and the momentum of the plume air and the environment. To this aim we assign to any i-th emitted particle in the time interval the "temperature mass" m_T, defined as follows:

$$m_{T_i} = \frac{\left[T_{pinit} - T_a(H_s)\right] w_u A \Delta t}{N_p} \tag{1}$$

where T_{pinit} is the initial plume temperature, $T_a(H_s)$ is the environment air temperature at the stack height, A is the stack exit section and N_p is the total number of particles released in the time interval Δt and w_u the plume exit velocity. Note that m_T does not have the dimension of a mass but can be considered a "mass" when the temperature difference is considered a density. Considering the domain divided in fixed regular cubic cells, the air-plume temperature difference for the generic cell, ΔT_c , is:

$$\Delta T_c(t_0) = \frac{\sum_M m_{Ti}(t_0)}{V_c} \tag{2}$$

where M is the number of particles in the cell c and V_c is the cell volume. In order to take into account the momentum flux we define the momentum mass m_{w_i}, which is assigned to each particle. At the beginning of the simulation we have:

$$m_{w_i} = \frac{\left[W_{pinit} - w_u\right] A \Delta t}{N_p} \tag{3}$$

where W_{pinit} is the stack exit vertical velocity of the plume. Also in this case, m_{w_i} has not the dimension of a mass but it can be considered so when W_{pinit} is considered a density. Then the cell vertical velocity $w_c(t_0)$ at the time t_0 is computed as

$$w_c(t_0) = \frac{\sum_i^M m_{w_i}(t_0)}{V_c} \tag{4}$$

The new temperature difference $\Delta T_c(t_1)$ at the time t_1 (where $t_1 = t_0 + \Delta t$) is calculated by the equation:

$$\Delta T_c(t_1) = \Delta T_c(t_0) + \Gamma(z_c) \cdot w_c(t_0) \cdot \Delta t - 0.0098 w_c(t_0) \cdot \Delta t \tag{5}$$

where z_c is the cell height and $\Gamma(z_c)$ is the lapse rate of the ambient air at cell height z_c. The second term on the right side updates the temperature difference between the cell and the ambient considering the vertical inhomogeneity of the atmosphere temperature. The third term on the right takes into account the adiabatic expansion due to the plume ascending motion. Clearly, in case of neutral temperature profile, these two terms delete each other. Equation 5 aims to simulate the variation in time of plume-ambient air temperature difference due to the ascending motion.

Afterwards, the value of w_c at the time t_1 is computed for every cell using the following equation:

$$w_c(t_1) = w_c(t_0) + \frac{\Delta T_c(t_0)}{T_a(z_c) + \Delta T_c(t_0)} g \Delta t - \frac{0.5 \cdot c_D \cdot S \cdot w^2(t_0) \cdot r_a}{r_p \cdot V_c} \cdot \Delta t \tag{6}$$

where $T_a(z_c)$ is the ambient air temperature at the same cell height z_c, S the cell horizontal surface area, c_D the drag coefficient, r_a and r_p are the ambient air and plume density, respectively. The second term on the right represents the buoyancy vertical acceleration while the last term on the right represents the aerodynamic drag. Equation 6 simulates the plume vertical ascending velocity variation in time due to the buoyancy acceleration and the aerodynamic drag. Then, the "temperature difference and velocity masses" at the time t_1, $m_{T_i(t_1)}$ and $m_{w_i(t_1)}$ are computed for each particle following the two equations:

$$m_{T_i}(t_1) = \frac{m_{Ti}(t_0)\Delta T_c(t_1)}{\Delta T_c(t_0)}; \qquad m_{w_i}(t_1) = \frac{m_{wi}(t_0)\Delta T_c(t_1)}{\Delta T_c(t_0)} \tag{7}$$

This method was proposed by Chock and Winkler (1994 a,b) and applied for a different purpose. In fact, in their papers, the masses were representing the actual masses of different substances carried by the particles in a chemically reactive plume. In our algorithm they carry the information, for each particle, relative to the two scalars introduced, the difference between the plume and environment temperatures and the vertical momentum.

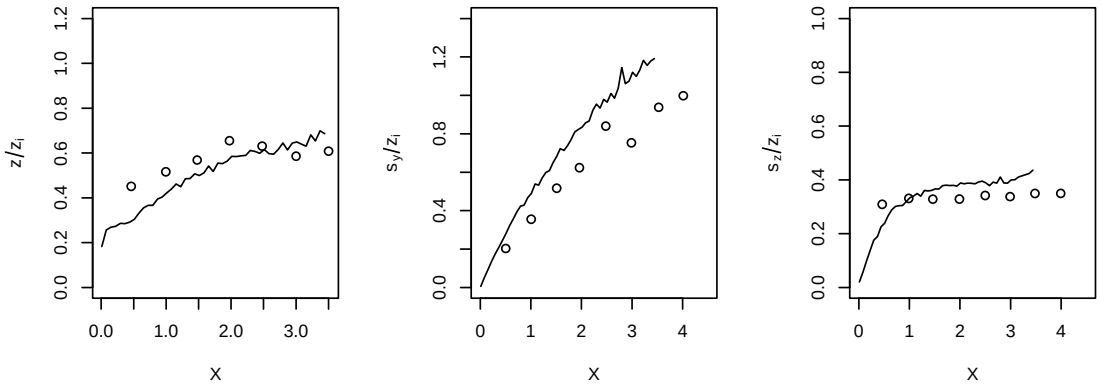

Figure 1. Comparison between model results (lines) and measured data (circles) for F_{b*}=0.0 as a function of the dimensionless downwind distance. From left to right the plots refer to the dimensionless mean plume height and to the dimensionless crosswind and vertical concentration standard deviations, respectively

THE CASE STUDY

We considered the Weil et al. (2002) experiment, which reproduced, in a water tank, the dispersion of a plume emitted from an elevated source in a convective boundary layer with a strong inversion at the top. It is important to mention that in the experiment there was no mean flow (and, hence, no environment turbulence) and the mean wind, constant with the height, was simulated by towing a model stack along the tank centreplane. The experiments are characterized by four different values of the normalized stack buoyancy flux

$$F_{b^*} = \frac{F_b}{w_*^3 z_i} \quad \text{with} \quad F_b = w_s r_s^2 g \frac{r_a - r_s}{r_a} = w_s r_s^2 g \frac{T_s - T_a}{T_s} \tag{8}$$

where F_b is stack buoyancy flux, z_i the mixing height, w_* the convective velocity scale, ρ the density, T the temperature, r is the source radius, W_s the plume velocity at the source, and g the gravitational acceleration. 's' stands for stack values and 'a' for ambient air values. In order to perform the simulation we reported the experiments to typical atmospheric conditions. The scaling factor for the lengths, velocity and buoyancy were based on the Froude number similarity: $L_m = 5000 L_v, V_m = 200 V_v,\ \Delta_m = 8\Delta_v$; where 'm' indicates the numerical model and 'v' the experiment. Furthermore, $\Delta_v = \frac{r_a - r_s}{r_a}$ and $\Delta_m = \frac{T_s - T_a}{T_s}$.

Using these scaling factors we calculated the values for the simulation parameters. In the simulations u was kept constant with height as was in the experiment. The potential temperature profiles were set constant from 0 to z_i and increasing above z_i up to the top of the domain with the value of the vertical gradient corresponding to that of the experiment.

RESULTS

We present the results of the simulation performed with c_D=0.3, which we considered the best choice for this parameter. We compare the simulated and measured mean height, horizontal and vertical plume standard deviations and the entrapment, the fraction of the plume that remains captured above the inversion with respect to the whole mass of the plume. The Figures 1 – 4 indicate that the overall simulation results are good, even if there are some deviations between predictions and observations. The model is able to correctly reproduce the basic characteristics of the plume rise phenomenon in convective conditions. This is interesting because the emission conditions cover a large scale of buoyancies: from a neutral emission (no buoyancy, F_{b*}=0.0) to very high buoyancy (F_{b*}=0.4). We have also to mention that

the absence of environmental turbulence in the experiment limits somehow the accuracy of our simulations. For instance, the plots of dimensionless crosswind standard deviation versus X show a slight overestimation at the furthest distances for the first three F_{b*} values and a perfect agreement for the highest buoyancy.

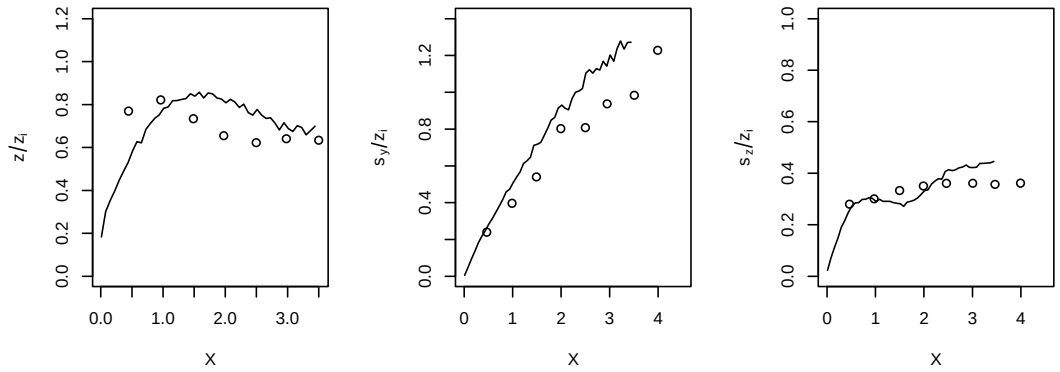

Figure 2. As in Figure 1 but for for F_{b*}=0.1

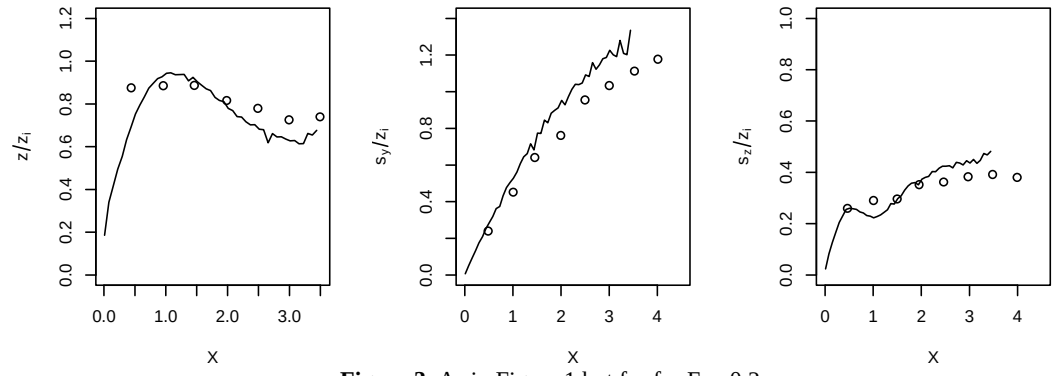

Figure 3. As in Figure 1 but for for F_{b*}=0.2

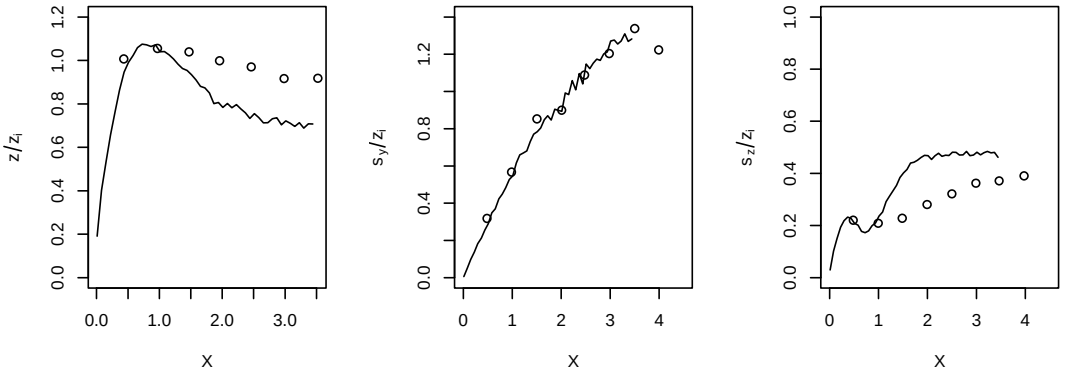

Figure 4. As in Figure 1 but for for F_{b*}=0.4

Figure 5 shows the mean plume entrapment as a function of the dimensionless distance for the four buoyancy cases. The model predictions are better close to the source while the model slightly overestimates for X>3. Furthermore, for X>1 simulations results underestimates the measured data in the cases with Fb*=0.2 and Fb*=0.4. We add that the simulation with different c_d perform almost in the same way in the case of Fb*=0 and that in the other cases the lower is the value of c_d and the higher is the entrapment, as it can be expected.

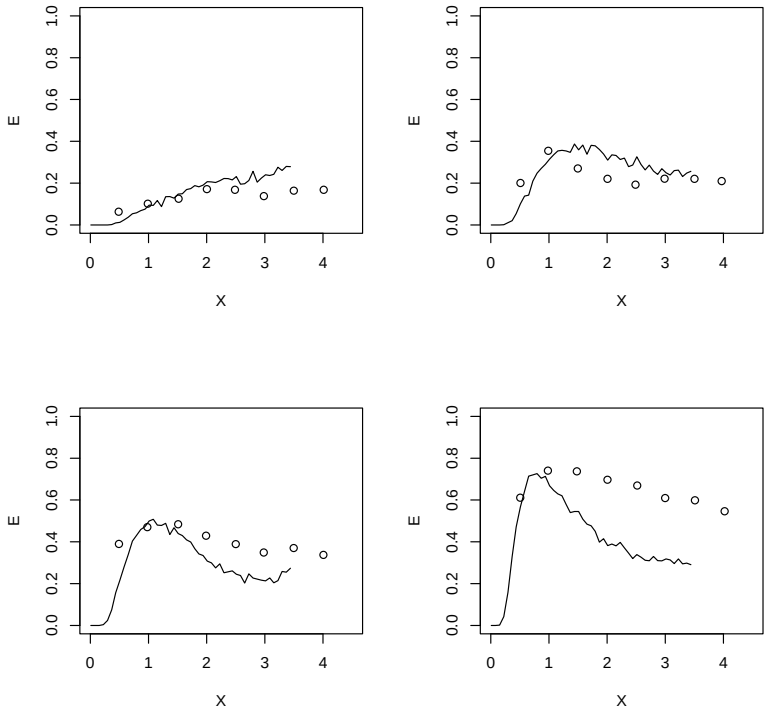

Figure 5. Comparison of the simulated (lines) and measured (circles) entrapment. From left to right and from top to bottom: for F_{b*}=0.0, for F_{b*}=0.1, for F_{b*}=0.2, for F_{b*}=0.4

REFERENCES

Alessandrini S. and Ferrero E. (2009). A hybrid Lagrangian-Eulerian particle model for reacting pollutant dispersion in non-homogeneous non-isotropic turbulence. *PHYSICA A*, ISSN: 0378-4371, 388, **8**, 1375-1387

Alessandrini S., Ferrero F., Anfossi D., (2013), A new Lagrangian method for modelling the buoyant plume rise, *Atmos. Environ*., **77**, 239-249

Anfossi, D., Ferrero E., Brusasca G., Marzorati A., Tinarelli G. (1993) A simple way of computing buoyant plume rise in a Lagrangian stochastic model for airborne dispersion, *Atmospheric Environment*, **27A**, 1443-1451

Anfossi D., G. Tinarelli, S. Trini Castelli, M. Nibart, C. Olry and J. Commanay (2010): A new Lagrangian particle model for the simulation of dense gas dispersion, *Atmospheric Environment*, **44**, 753-762

Briggs, G.A. (1975): Plume rise predictions. In: Lectures on air pollution and environmental impact analyses, D. Haugen (editor). Workshop proceedings, Boston, Massachusetts, September 29 – October 3, pp. 59-111, American Meteorological Society, Boston, Massachusetts, USA.

Chock, D.P. and Winkler, S.L. (1994a) 'A particle grid air quality modeling approach, 1. Dispersion aspect', *Journal of Geophysical Research*, **99**, D1, pp.1019–1031.

Chock, D.P. and Winkler, S.L. (1994b) 'A particle grid air quality modeling approach, 2. Coupling with Chemistry', *Journal of Geophysical Research*, **99**, D1, pp.1033–1041.

Hoult, D.P., and J.C. Weil (1972): A turbulent plume in a laminar crossflow. *Atmos. Environ*., **6**:513-531

Morton, B.R., G.I. Taylor, and J.S. Turner (1956): Turbulent gravitational convection from maintained and instantaneous sources. *Proc. Roy. Soc. London*, **A234**, 1-23.

Tinarelli, G., Anfossi, D., Bider, M., Ferrero, E., & Trini Castelli, S. (2000). A new high performance version of the Lagrangian particle dispersion model SPRAY, some case studies. In S. E. Gryning & E. Batchvarova (Eds.), Air pollution modelling and its applications XIII (pp. 499– 507). New York: Plenum Press.

Weil C. J., Snyder W. H., Lawson R. E. JR. and Shipman M. S. (2002) Experiments on buoyant plume dispersion in a laboratory convection tank, *Bound.-Layer Meteor*., *102*, 367–414.