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"A Simple Way of Computing Buoyant Plume Rise in Lagrangian Stochastic Dispersion Models"

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A SIMPLE WAY OF COMPUTING BUOYANT PLUME RISE IN LAGRANGIAN STOCHASTIC DISPERSION MODELS

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Abstract—A simple and easy to use method to include Eulerian plume rise in Lagrangian particle models is presented. This approach takes into account the vertical variation of wind and stability. Its ability to realistically simulate plume rise and spread, both through numerical experiments under typical atmospheric conditions and by comparison with actual plumes detected by a Differential Lidar in a case study, is shown. Despite its simplicity, our method proved to describe the main plume rise characteristics in a satisfactory way and to yield a fair agreement among observed and predicted plume centreline heights and standard deviations.

Key word index: Plume rise, Lagrangian particle models, plume spread, elevated releases, field experiment.

NOTATION

$\bar{F}$	buoyancy flux ($m^4 s^{-3}$)
F_i	buoyancy flux of each particle ($m^4 s^{-3}$)
F'	buoyancy flux fluctuation ($m^4 s^{-3}$)
g	acceleration of gravity ($m s^{-2}$)
$\bar{H}$	mean plume centreline height at a particular cross-section (m)
$H(t)$	plume rise as a function of t (m)
H_e	final plume rise (m)
H_s	stack height (m)
r	stack radius (m)
s	stability parameter (s^{-2})
t	time (s)
T_a	ambient temperature (K)
T_f	plume exit temperature (K)
T_{Li}	Lagrangian time scales (s)
u	longitudinal component of wind speed ($m s^{-1}$)
$\bar{U}$	mean horizontal wind speed at a particular cross-section ($m s^{-1}$)
U'	wind fluctuation ($m s^{-1}$)
v	crosswind component of wind speed ($m s^{-1}$)
$\bar{X}$	horizontal downwind distance of a cross-section (m)
$\bar{w}$	vertical component of wind speed ($m s^{-1}$)
w'	fluctuation of the vertical component of wind speed ($m s^{-1}$)
w_b	buoyancy velocity ($m s^{-1}$)
w_0	plume exit velocity ($m s^{-1}$)
Z	vertical coordinate (m)
Δt	time step (s)
ΔZ	plume rise increment (m)
$\partial_\theta/\partial_z$	ambient potential temperature gradient ($K m^{-1}$)
μ	random forcing ($m s^{-1}$)
$\bar{\rho}$	mean range (m)
σ_u	longitudinal component of wind speed standard deviation ($m s^{-1}$)
σ_v	crosswind component of wind speed standard deviation ($m s^{-1}$)
σ_w	vertical component of wind speed standard deviation ($m s^{-1}$)
σ_Z	vertical standard deviation (m)
σ_ρ	horizontal standard deviation (m).

1. INTRODUCTION

A correct estimation of buoyant plume rise is one of the basic requirements for the determination of ground level concentrations of airbone pollutant emitted by industrial stacks. In fact maximum ground level concentration is roughly inversely proportional to the square of the plume final height H_e.

In Eulerian models, H_e is generally computed by means of simple analytical expressions like the well-known Briggs' formulae (1975) and inserted in the model as an input parameter. In contrast, the inclusion of plume rise in Lagrangian particle models is not as straightforward as in the Eulerian ones, so that a complete and rigorous method is not yet available. This is mainly due to the intrinsic impossibility of Lagrangian particle models to simulate correctly the entrainment phenomenon. To do this, these models should take into account all the fluid simultaneously. In fact the buoyancy and, as a consequence, the vertical velocity of each portion of the plume depend on its position with respect to the other parts of the plume. Each trajectory in a particle model is one of the possible outcomes of the given stochastic process and is independent of the other trajectories. Therefore, only the ensemble average of many trajectories gives the expected results (such as: concentration or standard deviations or mean plume height).

To our knowledge, only four papers describe attempts to deal with plume rise in particle models, namely those of Zannetti and Al-Madani (1984), Cogan (1985), Shimanuki and Nomura (1991) and Van Dop (1991). However, none of them present a validation against experimental data.

The aim of this paper is to present and discuss a simple method to account for buoyant plume rise in Lagrangian particle models. This has been developed starting from the Zannetti and Al-Madani (1984) paper.

The above quoted papers will be discussed briefly in the next section, and our method will then be illustrated in Section 3. Some qualitative examples will be given in Section 4 and, finally, the application of our technique to a real situation (a case study based on Differential Lidar (DIAL) plume measurements during a field campaign) will be illustrated in Section 5.

2. PREVIOUS LAGRANGIAN PLUME RISE TECHNIQUES

Zannetti and Al-Madani (1984) did not try to simulate the entrainment process and simply introduced an additional velocity in the random walk equation for the vertical velocity. This extra-velocity was obtained by time differentiating the following TVA plume rise equation:

$$H(t) = (1.58 - 0.414\ \partial_\theta/\partial_z)\ \bar{F}^{1/3}\ \bar{u}^{-1/3}\ t^{2/3} \qquad (1)$$

where $\bar{F} = g\, w_0\, r^2\ (T_f - T_a)/T_f$. Both $\partial_\theta/\partial_Z$ and u are allowed to vary with height. Thus, the same plume rise contribution is given to all the particles provided that they are at the same height and have the same age. The plume spreads in the vertical as a consequence of the ambient turbulence only. This appears in the stochastic equation for vertical velocity. The ensemble averaged plume mean height is therefore simulated, but nothing is said about the vertical spread, when or if the plume rise stops contributing to the vertical particle motion. The authors presented some numerical examples showing how the method works and its ability to give qualitatively reasonable results. Zannetti and Al-Madani (1984) also suggested a possible alternative method, but without developing it: again all the particle extra-velocity due to buoyancy could be computed by equation (1), but a random buoyancy:

$$F_i = \bar{F} + F' \qquad (2)$$

of "suitable intensity" should be attributed to each particle.

Cogan (1985) tried to model the entrainment process although on an empirical basis. His procedure is the following. The plume is divided into layers of constant thickness and, within each layer, is separated into an inner region (containing the particles included within the center of mass $\pm$ one standard deviation) and an outer region. In the inner region the temperature of each particle is computed as a function of its distance from the center of mass, whereas in the outer region the particle temperature is reduced by a preset amount. The latter depends on the chosen value of the entrainment constant. This interesting attempt was limited to numerical experiments.

Shimanuki and Nomura (1991) tried to simulate numerically the instantaneous images of chimney plumes under convective conditions. Their technique is based on single Lagrangian particle trajectories, whose velocity fluctuations are spatially correlated. The way in which the field of spatially correlated random variables is generated is based on a subdivision of the plumes in 3D cells, whose dimensions are related to the local scales of turbulence. The spatial auto-correlation function is prescribed in a completely empiric way and all the trajectories within a single cell assume the same value of the spatial auto-correlation function. The buoyancy effect is roughly accounted for by assigning a given initial vertical velocity to each particle. The air stability does not affect directly the particle motion but is taken into consideration in the computation of turbulence scales and hence in the definition of the cell dimensions. These authors do not provide a comparison with real plumes, but merely show that their plume images look realistic.

The method proposed by Van Dop (1991) is the following. A first random walk equation (Langevin equation) for the motion of the vertical velocity, including the buoyancy acceleration, is associated to a second stochastic equation (formally equal to the first one) which describes the evolution of the particle buoyancy (this is done independently for each plume particle trajectory, neglecting all the mutual interactions among different parts of the plume). The buoyancy contribution to the vertical velocity w_b is thus computed at each time step and for each particle by a dynamic equation rather than being prescribed on the basis of an analytical formula. Van Dop demonstrates that his Lagrangian plume rise formulation is not only in good agreement with the classical Csanady (1973) formulation in a calm environment, but is also able to accommodate recent Eulerian formulations in a turbulent environment by Netterville (1990). To do this, however, he needs to consider a pure buoyant plume (that is, a plume having zero initial velocity), which also means starting the plume rise simulation after a certain initial time has elapsed. This is the time during which the effect of the initial vertical momentum is felt.

This model predicts, in particular, that the rate of change of the vertical plume width is faster than the mean plume rise. This fact is very interesting since it leads to ground level concentrations from buoyant point sources higher than usually expected.

Another important feature of Van Dop's formulation is the following. His derivation of the Lagrangian equations is based on Netterville's recent work on turbulent entrainment (1990) who, in particular, introduced an additional turbulent exchange mechanism, "extrainment", generated by ambient turbulence. Extrainment means negative *entrainment* or mass loss (Briggs, 1975). It refers to the process in which the plume loses some of its mass into the surrounding turbulent atmosphere in the same manner as an atmospheric eddy loses a part of its mass of the plume.

Van Dop's paper is a very interesting and original contribution to the solution of the Lagrangian simulation of plume rise. However, it is not immediately applicable in Lagrangian models to simulate the dispersion of real chimney plumes.

3. OUR TECHNIQUE

Our aim was to introduce the plume rise mechanism into a previously existing Lagrangian model for the dispersion of non-buoyant airborne pollutants, attempting to achieve the best compromise among computational requirements, physical consistency and reliability of the numerical results. This was carried out by modifying our previous model for non-buoyant emissions, LAMDA, based on the Langevin equation and designed to simulate the dispersion on flat terrain, which was validated under various atmospheric conditions (Anfossi *et al.*, 1990 and 1992; Brusasca *et al.*, 1989 and 1992). We named the new version of the code LAMBDA (LAgrangian Model for the Buoyant emission Dispersion in Atmosphere).

Let us recall that in LAMBDA the particle positions $X_i (i=x, y, z)$ are computed at each time step Δt as follows:

$$X_i(t+\Delta t)=X_i(t)+(\overline{U_i(t)}+U_i'(t))\Delta t \qquad (3)$$

where $\overline{U_i(t)}$ represents the transport which can be provided by either measured wind profiles or the output of a mass consistent model, and $U_i'(t)$ refers to the turbulent terms (random forcing) which are computed from the Langevin equations (De Bass *et al.*, 1986);

$$U'(t+\Delta t)=U'(t)\left(1-\frac{\Delta t}{2T_{Li}}\right)\left(1+\frac{\Delta t}{2T_{Li}}\right)^{-1} + \mu_i\left(1+\frac{\Delta t}{2T_{Li}}\right)^{-1} \qquad (4)$$

where μ_i are picked up at random from a probability distribution function (p.d.f) which is assumed gaussian in the horizontal plane and skewed in the vertical one (Anfossi *et al.*, 1992). The moments of the p.d.f. are computed from the Eulerian statistics of the 3D wind field, according to the Thomson scheme (Thomson, 1984; Brusasca *et al.*, 1992). The vertical profiles of wind and turbulence are defined at the source locations and kept constant in the whole of the computational domain.

The way in which our model accounts for the rise of buoyant plumes is the following. The buoyancy contribution to the vertical velocity w_b is added to equation (3), written for the vertical coordinate, i.e.

$$X_z(t+\Delta t)=X_z(t)+(\overline{U_z(t)}+w_b+w'(t))\Delta t. \qquad (5)$$

Then, it is assumed that the plume centreline grows according to the following plume rise formula (Anfossi, 1985):

$$H(t)=2.6\ (\bar{F}\ t^2/\bar{u})^{1/3}\ (t^2\ s+4.3)^{-1/3} \qquad (6)$$

where $s=g/\theta\ \partial_\theta/\partial_Z$. We did not choose equation (1) as Zannetti and Al-Madani (1984) did, but preferred to rely on equation (6) which is a generalization of the well-known and validated Briggs' formulae (1975). Furthermore, to each ith particle a normally distributed F_i is assigned (fixing the mean value equal to $\bar{F}$ and the standard deviation equal to $\bar{F}/3$; this was empirically obtained assuming that the plume radius increase is roughly equal to 0.6 $H(t)$ near the stack mouth under typical neutral conditions (Briggs, 1975)). Finally w_b is computed, for each particle at every Δt, as follows:

$$w_b=\Delta z/\Delta t=[H(u,\ s,\ t+\Delta t)-H(u,\ s,\ t)]/\Delta t \qquad (7)$$

in which $H(u, s, t+\Delta t)$ and $H(u, s, t)$ are computed by equation (6). As in general u and s vary with z, their average values in the layer included between z_1 and $z_1 + \Delta z$ (where z_1 is the height of the ith particle at time t and Δz is the plume rise increment at the previous step) are considered. In the real atmosphere the plume rise ends when the plume is levelled. As a consequence the contribution of the plume rise to the vertical particle motion stops being computed in our model when one of the following conditions is met (the choice is an option of the user): (i) the slope of the plume axis is less than a given value, such as 0.005; (ii) w_b is less than the local value of the standard deviation of the wind vertical velocity σ_w (Kranz and Hoult, 1973; Anfossi, 1982). As can be seen in equation (5) the ambient turbulence continually affects the plume rise and spread. This is an important point, as suggested by Lamb (1982). On the contrary the plume self-induced turbulence contribution (simulated through the random F_i and, hence, through w_b decreases progressively. From equations (3), (4) and (5) it follows that ambient turbulence influences both the vertical and the horizontal dispersion, whereas the self-induced turbulence directly affects the vertical spread only.

To conclude this section, we point out that our technique of computing buoyant plume rise consists of adding a previously obtained Eulerian plume rise equation (6) to the calculation of Lagrangian particle trajectories. In fact, equation (3) shows that the velocity of the ith particle of each time step is the sum

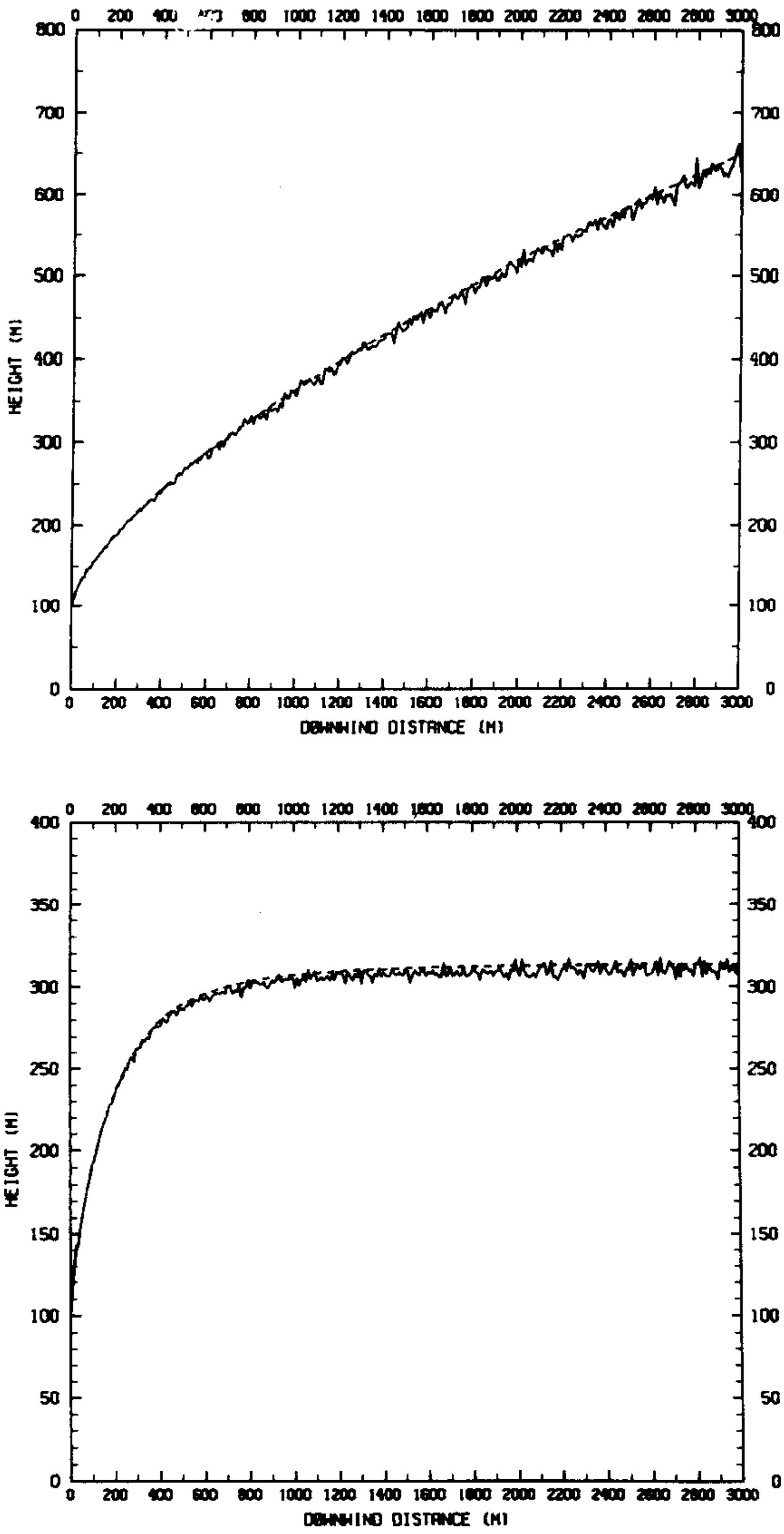

Fig. 1. Plume centreline height $H(t)$ vs downwind distance x under homogeneous conditions: the trend calculated by means of equation (6) is indicated by a dashed line and the one computed by LAMBDA code by a continuous line. (a) Neutral atmosphere; (b) stable atmosphere.

of two contributions: the first term $\overline{U_i(t)}$ represents the transport due to the average flow conditions (Eulerian wind), whereas the second term ($U'(t)$) represents the stochastic velocity fluctuation (Lagrangian). In equation (5) the contribution of the buoyancy to the vertical velocity w_b is introduced as another input parameter.

4. NUMERICAL EXPERIMENTS

In order to validate our plume rise approach, implemented in LAMBDA code, the following numerical experiments have been carried out.

First of all it was checked that the predicted trend of the plume centreline height $H(t)$ vs t is correct and consistent, i.e. that it is the same as the one given by equation (6) under the conditions in which equation (6) is likely to be correct (uniform temperature and wind speed). Figures 1a and 1b show this comparison: they refer, respectively, to neutral and stable atmosphere. In the neutral case, wind speed was fixed to 5 m s^{-1}. An isothermal temperature profile and a wind speed of 3 m s^{-1} were assumed in the stable case. In both cases, the emission parameters ($\bar{F}=592$ m^4 s^{-3}, $H_s=100$ m, $r=2.5$ m, $w_0=30$ m s^{-1} and $T_f=413$ K) were the same. The agreement between the analytical formula and the LAMBDA simulation is excellent under both stability conditions.

Next, a qualitative check of our approach under non-homogeneous conditions was carried out. Under such conditions no comparison with simple analytical formulas is possible. Three different simulations have been performed with reference to three different meteorological scenarios: a neutral one, a stable one (a power law wind profile was used in both cases) and a more complicated one characterized by a fog layer, associated with nearly wind calm conditions, from ground level up to 250 m capped by an inversion layer up to 400 m. The last scenario is quite typical of the Po Valley in Northern Italy (Bonino *et al.*, 1985). The emission conditions were as in the previous tests. Figures 2–4 illustrate the results of these simulations. The computed plumes look quite familiar and appear to be rather realistic, on the basis of our previous experience of plume tracking (Anfossi, 1982; Sandroni *et al.*, 1981). For instance, in the stable case (Fig. 2) the vertical spread is strongly reduced with respect to the neutral case (Fig. 3). We also recognize the kind of fumigation conditions within the fog represented in

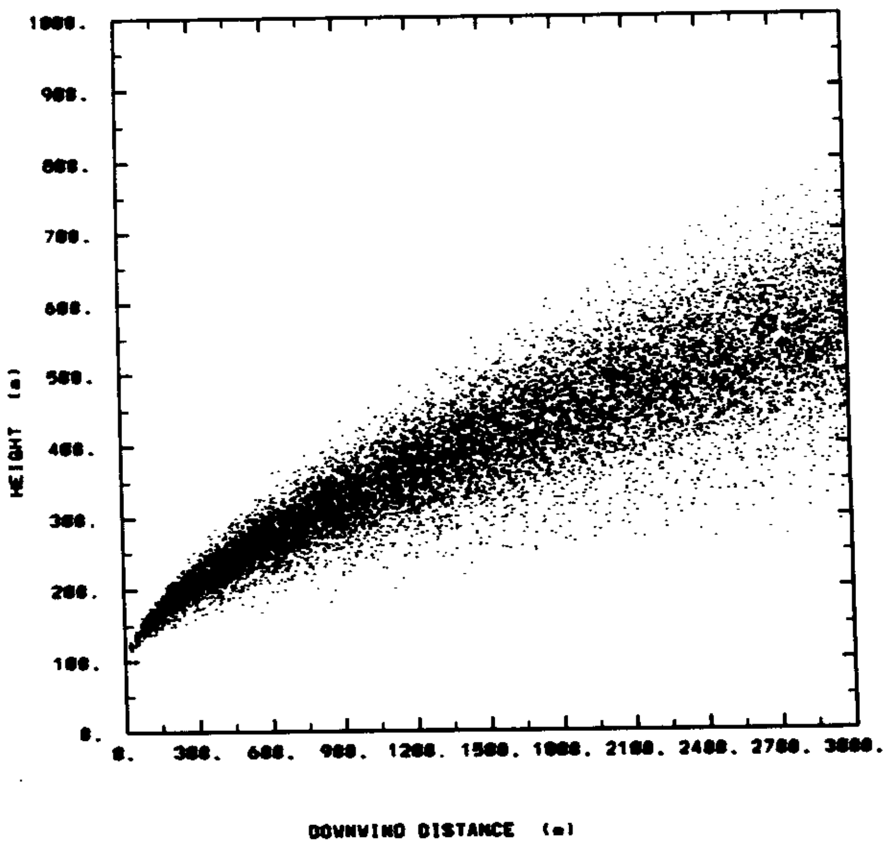

Fig. 2. Vertical cross-section of particle simulation of plume rise in neutral non-homogeneous conditions. Height above ground is indicated on Y-axis and the downwind distance x is reported on X-axis. Each point represents a single particle position.

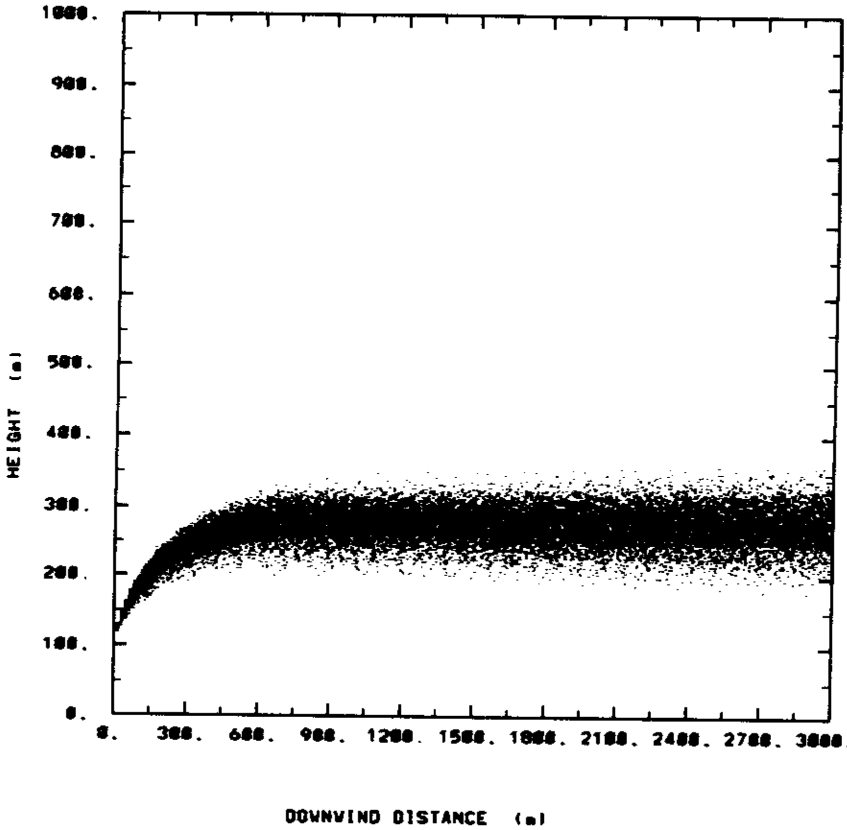

Fig. 3. As in Fig. 2 but for non-homogeneous stable conditions.

Fig. 4. In this last case, the rise of the plume is stopped by the inversion layer, and the pollutant then reaches the ground very near to the base of the stacks.

5. CASE STUDY

Besides the qualitative tests, we thought it useful to try and show a comparison between plume rise observations in the real atmosphere and the corresponding LAMBDA predictions. Data selected for the present case study were recorded on 2 April 1991 (from 18.38 to 19.28 l.t.) in the course of an international campaign held at the Sostanj Power Plant (Slovenia) during April 1991. ENEL/CRTN of Milan (Italy), CISE-Tecnologie Innovative of Milan (Italy) and Institut "Jozef Stefan" of Ljubljana (Slovenia) participated in the campaign. Its main objective was to perform a field test of an integrated system, based on: (i) conventional chemical–meteorological network and mobile laboratories; (ii) advanced remote sensing devices (Doppler Sodar and DIAL); (iii) complex terrain transport–diffusion and stochastic models; (iv) real time model validation and off-line data acquisition. The details of the campaign can be found elsewhere (ENEL/CISE/JSI Report, 1992); only a few facts especially related to the presented paper need to be recalled here.

Sostanj lies in the Saleska Valley, which is situated in the Northeastern part of Slovenia. The terrain configuration is rather complex: the power plant is located in the narrow plane of the river Plaka and all the area is surrounded by hills. The coal fired Sostanj Thermal Power Plant has five sections connected to three stacks. The three plume cross-sections examined were obtained by means of the ENEL UV-DIAL. This system (Marzorati et al., 1984) utilizes a doubled dye laser pumped by the second harmonic of a Nd-YAG laser with 20 Hz repetition rate.

The specifications of the plant relevant to the present study are resumed in Table 1 (not all the sections were operating on the afternoon of the examined day; plumes coming out from the two operative stacks (called stack 5 and stack 1, 2, 3) were examined. They merged at a distance of about 250 m from the smaller stack. DIAL was located at a distance of 1125 m from stack 5 and was about 20 m higher than the base of the stacks. Three vertical scans at three different azimuth angles were performed by stepping the elevation angle of 1.5° between 50° and 80° (every single measurement is obtained by averaging 200 laser shots with a spatial resolution of 15 m). Figure 5 shows a plan view of the DIAL, the stack positions and plume cross-sections. During the exercise the wind was blowing from 130–140° at the height of the stacks. As a consequence,

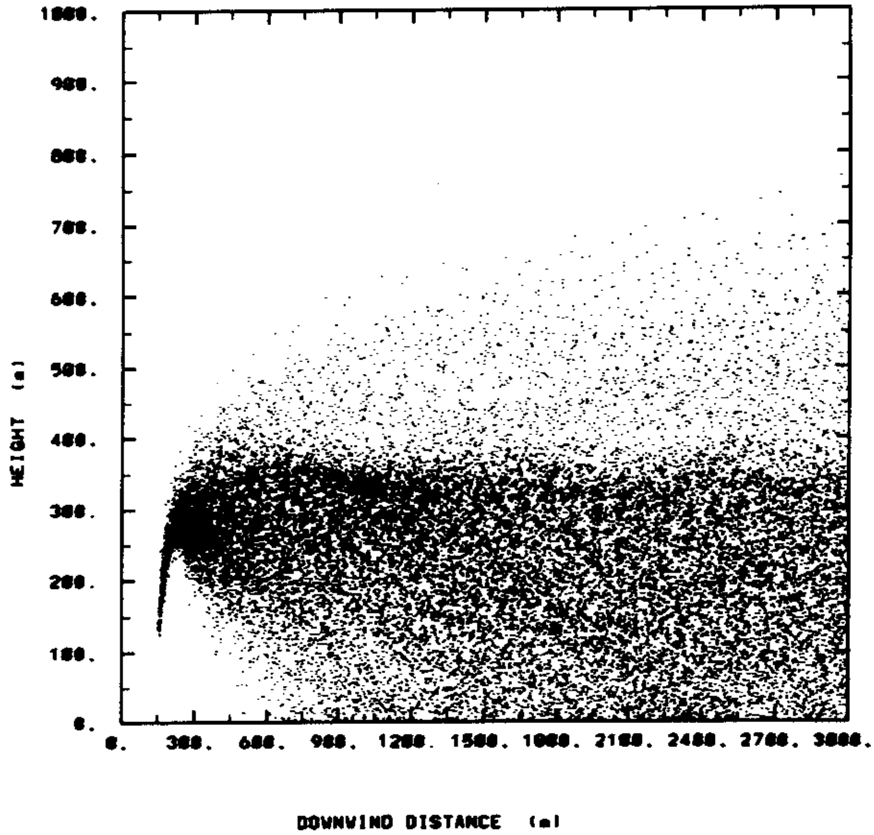

Fig. 4. As in Fig. 2 but for a non-homogeneous multi-layered atmosphere. A deep fog fills the first layer, from 0 to 250 m, where almost calm conditions prevail ($u = 1$ m s^{-1}); an inversion layer with a large temperature increase (8°) lies between 250 and 400 m; the superior layer is isothermal.

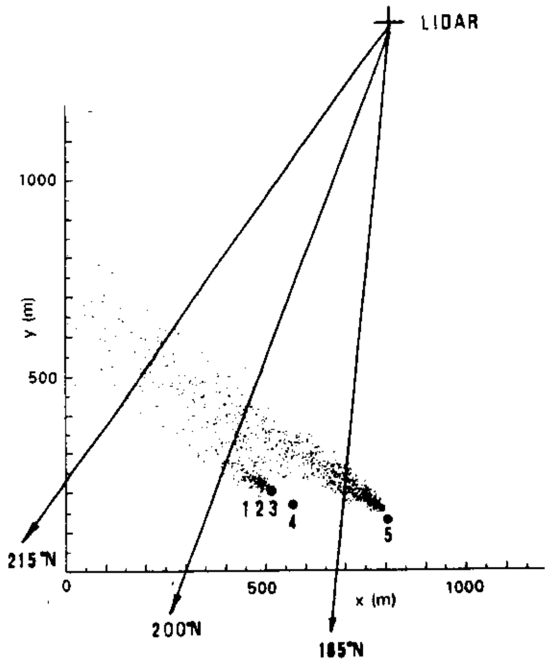

Fig. 5. Plain view of relative Lidar—stack positions, cross-sections and plume simulation.

Table 1. Sostanj Power Plant specifications on 2 April 1991

Stack operating	Stack height H_s (m)	Stack radius r (m)	Exit velocity w_0 (m s^{-1})	Exit temperature T_f (K)
5	230	3.1	9.2	450
1,2,3	100	3.25	6.2	450

in the first cross-section (185°) only the plume emitted by stack 5 was tracked; in the second cross-section (200°) both plumes (not yet combined) were detected and in the third one (215°) the merged plume was measured.

Wind (u, v, w) information was continuously collected by the ENEL Doppler Sodar (Elisei *et al.*, 1986), averaging every 30 min, from a minimum height of 50 m to a maximum height of about 1000 m (space resolution of about 50 m). However, as the Doppler Sodar (located near the DIAL) was more than 1000 m away from the stacks and the terrain was rather complex, the (u, v, w) data obtained by the mass consistent model MINERVE (Geai, 1987), initialized by the Sodar profile and by six low level wind records (given by the anemometers of the JSI network), were utilized in the simulation instead of the original Sodar data. The input data needed to run our model (such as the Lagrangian time scales and σ_u, σ_v, σ_w) were estimated through the expressions suggested by Hanna (1982).

The main plume parameters derived by DIAL measurements on the three cross-sections and the corresponding results of the simulation are illustrated in Tables 2–5. Starting from the left-hand side of the table we find: $\bar{\rho}$, σ_ρ, $\bar{H}$ and σ_z. $\bar{\rho}$ and $\bar{H}$, the mean distance along the DIAL line of sight (range) and height, and their standard deviations σ_ρ and σ_z are estimated as the centres of mass and standard deviations of the DIAL-derived SO_2 cross-section, respectively.

The comparison between observed and predicted values seems to be encouraging. The overall agreement for the plume centreline height $\bar{H}$ is reasonably good. In fact the relative errors of all $\bar{H}$ estimations are within a factor of 1.5, and this amount of error is to be expected when comparing model predictions with field observations. We notice that the agreement is worse in the third cross-section. In this last case, however, the plumes coming from the two stacks were combined. As a consequence (Anfossi *et al.*, 1978, Anfossi 1982, 1985), a certain extra rise due to the plume merging with respect to the plume rise of single plumes is to be expected. In fact, Anfossi (1985) found an enhancement due to the plume merging of between 13 and 29% while analysing plume rise data from five TVA Steam Plants' data.

Table 2. Comparison between plume rise parameters observed by DIAL and predicted by LAMBDA at the first cross-section

	Range $\bar{\rho}$ (m)	Horizontal SD σ_ρ (m)	centerline height $\bar{H}$ (m)	vertical SD σ_Z (m)
Observed	903	35	313	23
Predicted	1074	23	265	24

18.41–18.42 l.t.; only the plume from stack 5 was detected.

Table 3. As Table 2 but for 19.03–19.05 l.t.

	Range $\bar{\rho}$ (m)	Horizontal SD σ_ρ (m)	centerline height $\bar{H}$ (m)	vertical SD σ_Z (m)
Observed	858	81	424	34
Predicted	949	72	384	65

Table 4. As Table 3 but for the plume from stacks 1,2,3 and 19.00–19.01 l.t.

	Range $\bar{\rho}$ (m)	Horizontal SD σ_ρ (m)	centerline height $\bar{H}$ (m)	vertical SD σ_Z (m)
Observed	907	68	194	25
Predicted	1069	62	210	42

Table 5. As Table 2 but the two merged plumes from stack 5 and stacks 1,2,3 were detected and 19.21–19.24 l.t.

	Range $\bar{\rho}$ (m)	Vertical SD σ_ρ (m)	centerline height $\bar{H}$ (m)	vertical SD σ_Z (m)
Observed	778	69	453	86
Predicted	957	109	391	115

As far as the horizontal and vertical plume dimensions σ_ρ and σ_z are concerned, the results of the simulation can be considered satisfactory as, even in this case, the average error is within a factor of 1.5. We have also reported above that the site around the Sostanj Power Plant is rather complex. This fact makes the agreement between observed and predicted $\bar{H}$, σ_ρ and σ_z particularly interesting. In fact the vertical profiles of wind and turbulence were kept constant in the whole computational domain. As a consequence the horizontal and vertical inhomogeneities of the turbulence field induced by orography have not been accounted for in the p.d.f of random velocities. An error in the evaluation of the mean plume trajectories (which appears in the comparisons of predicted and observed $\bar{\rho}$) is likely to result from small errors in the mass-consistent reconstruction of the wind direction at the stack site. Therefore, our method can be considered to simulate both the plume centreline trend and the vertical plume dispersion around it in a satisfactory way.

6. CONCLUSIONS

A simple procedure for implementing the plume rise calculation in Lagrangian dispersion particle models is presented. Our computation of the rise of hot effluents in the atmosphere is empirical. It has the advantage of being very simple, easy to apply in a Lagrangian particle model and, in spite of this, describes the main features of the phenomenon with reasonable accuracy. In fact, some comparisons with: (i) analytical plume rise solutions, (ii) qualitative numerical tests and (iii) quantitative field experiments have shown that our procedure is realistic and reliable.

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