An intercomparison of two turbulence closure schemes and four parameterizations for stochastic dispersion models (*)

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Summary. — Two Lagrangian particle models, developed by Luhar and Britter (*Atmos. Environ.*, **23** (1989) 1191) and Weil (*J. Atmos. Sci.*, **47** (1990) 501), satisfying the "well-mixed" condition as prescribed by Thomson (*J. Fluid. Mech.*, **180** (1987) 529), are compared. They differ in the closure scheme used in calculating the probability density function of the random forcing in a convective boundary layer. Four different turbulent parameterizations were used as input to both models. Their performances are evaluated against one of the well-known Willis and Deardorff water tank experiments (*Atmos. Environ.*, **12** (1978) 1305). Predicted and measured ground-level concentrations (g.l.c.), maximum g.l.c. distance, mean plume height and plume vertical spread are presented and discussed.

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1. – Introduction

During the last ten years, many Lagrangian particle models, based on the fundamental Thomson 1987 paper [1], have been developed. In his paper Thomson stated that a Lagrangian stochastic model must satisfy the so-called "well-mixed" condition (if the marked particles of a tracer are well mixed, they will stay that way) to be physically consistent. In other words this means that the probability density

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function (PDF) of the particle velocities has to be a solution of the Fokker-Planck equation.

It is well known that, in a typical atmospheric convective boundary layer (CBL), the vertical velocity PDF is skewed. Baerentsen and Berkowicz [2] originally developed the scheme to generate the bi-Gaussian PDF, given by a convex combination of two Gaussian distributions, able to take into account up to the third-order moment.

In this work we consider two of these stochastic models: the first developed by Luhar and Britter [3] in which the PDF is defined according to Baerentsen and Berkowicz [2] and the second due to Weil [4]. The only difference between these two models is in the closure used for determining the moments of the PDF.

Besides testing the influence of different closure schemes in predicting the concentration field, it was the aim of this work to evaluate the models' sensitivity to different turbulent parameterizations. Four alternative parameterizations available in the literature, proposed by Luhar and Britter [3], Rodean [5], De Baas *et al.* [6] and Weil [4] respectively, were taken into account. They refer to the following quantities: standard deviation, skewness and Lagrangian time scale of velocity fluctuations.

Models have been tested against data measured in the water tank experiment performed by Willis and Deardorff [7], simulating atmospheric dispersion from a point source in convective conditions. The choice of this experiment is due to the richness and accuracy of its data set. In fact, besides g.l.c.'s, mean plume height and vertical plume spread at different distances from the source, are available. Moreover, this data set has been used by many authors to test new models.

Recently it has been demonstrated [8] that particular attention must be paid to the boundary conditions to satisfy the "well-mixed" condition. In the present simulations, a new method for the boundary conditions, proposed by our group [9] starting from the one suggested by Thomson and Montgomery [8], has been applied.

2. – Models

According to the conditions simulated in the Willis and Deardorff [7] experiment, in the present paper we considered the one-dimensional (vertical) dispersion of particles in stationary horizontally homogeneous and vertically inhomogeneous turbulence with no mean flow. In these conditions, the equations for the vertical velocity, w, and displacement, z, of a particle, have the following expression [1]:

$$\mathrm{d}w = a(z, w)\,\mathrm{d}t + \sqrt{2B_0(z)\,\mathrm{d}t}\,\mathrm{d}\mu\,, \tag{1a}$$

$$\mathrm{d}z = w\,\mathrm{d}t\,, \tag{1b}$$

where the random forcing $\mathrm{d}\mu$ has zero mean and unit variance and $a(z, w)$ is derived from the Fokker-Planck equation for stationary conditions

$$w\frac{\partial P}{\partial z} = -\frac{\partial (aP)}{\partial w} + B_0\frac{\partial^2 P}{\partial w^2} \tag{2}$$

as a function of the chosen PDF, $P(w, z)$. Equation (2) can be split [1] in two equations:

$$aP = B_0 \frac{\partial P}{\partial w} + \Phi , \tag{3a}$$

and

$$\Phi = -\frac{\partial}{\partial z} \int_{-\infty}^{w} wP \, dw; \tag{3b}$$

therefore

$$a(z, w) = \frac{1}{P}\left(B_0 \frac{\partial P}{\partial w} + \Phi\right). \tag{4}$$

Assuming the following expression for P [2-4]:

$$P(w, z) = A \cdot N_A(w_A, \sigma_A) + B \cdot N_B(w_B, \sigma_B) \tag{5}$$

(where $A + B = 1$, $A > 0$, $B > 0$ and N_A, N_B are Gaussian PDFs with means w_A, w_B, and standard deviations σ_A, σ_B) and solving eq. (3b), the following general expressions for Φ and a are found:

$$\begin{aligned}\Phi = {} & AN_A\left[\frac{\sigma_A^2}{A}\frac{\partial A}{\partial z} + \frac{\partial \sigma_A}{\partial z}\left(\sigma_A + \frac{w(w-w_A)}{\sigma_A}\right) + w\frac{\partial w_A}{\partial z}\right] + \\ & + \frac{1}{2}\frac{\partial (Aw_A)}{\partial z}\left[1 - \operatorname{erf}\left(\frac{w-w_A}{\sqrt{2}\,\sigma_A}\right)\right] + \\ & + BN_B\left[\frac{\sigma_B^2}{B}\frac{\partial B}{\partial z} + \frac{\partial \sigma_B}{\partial z}\left(\sigma_B + \frac{w(w-w_B)}{\sigma_B}\right) + w\frac{\partial w_B}{\partial z}\right] + \frac{1}{2}\frac{\partial (Bw_B)}{\partial z}\left[1 - \operatorname{erf}\left(\frac{w-w_B}{\sqrt{2}\,\sigma_B}\right)\right]\end{aligned} \tag{6}$$

and

$$a = \frac{1}{P}\left[B_0\left(AN_A \frac{(w-w_A}{\sigma_A^2} + BN_B \frac{(w-w_B)}{\sigma_B^2}\right) + \Phi\right]. \tag{7}$$

The usual assumption for B_0 is [1, 5]:

$$B_0 = \frac{C_0\,\varepsilon}{2} = \frac{\overline{w^2}}{\tau} , \tag{8}$$

where C_0 is a universal constant whose value was not yet established (it ranges from 2 to 7 [5]), ε is the ensemble-average rate of dissipation of turbulent kinetic energy, τ is the Lagrangian time scale and $\overline{w^2}$ is the second moment of the vertical velocity distribution.

Introducing eqs. (6), (7) and (8) into eqs. (1), defining the characteristics of the considered turbulent flow (*i.e.* prescribing the vertical profiles of $\overline{w^2}$ and $\overline{w^3}$), and determining the values of the PDF parameters (eq. (5)), permit to compute the trajectories of marked particles and, from their ensemble-average, to compute concentration fields.

3. – Closure schemes of the bi-Gaussian PDF

The general method for deriving bi-Gaussian model parameters, A, B, w_A, w_B, σ_A and σ_B, consists in equating the zeroth through third moments of P, $\overline{w^n} = \int w^n P(w, z)\,\mathrm{d}w$ (with $n = 0, 1, 2, 3$) to the corresponding Eulerian moments, obtaining the following system:

$$A + B = 1\,, \tag{9a}$$

$$Aw_A + Bw_B = 0\,, \tag{9b}$$

$$A(w_A^2 + \sigma_A^2) + B(w_B^2 + \sigma_B^2) = \overline{w^2}\,, \tag{9c}$$

$$A(w_A^3 + 3w_A\sigma_A^2) + B(w_B^3 + 3w_B\sigma_B^2) = \overline{w^3}\,, \tag{9d}$$

where the moments $\overline{w} = 0$, $\overline{w^2}$ and $\overline{w^3}$ are known.

The system of eqs. (9) has more unknowns than equations, with many different possible closures, which will be now considered. Baerentsen and Berkowicz [2] assumed that

$$\sigma_A = |w_A| \qquad \text{and} \qquad \sigma_B = |w_B| \tag{10}$$

and they found:

$$w_B = \frac{\left(\overline{w^3} - \sqrt{(\overline{w^3})^2 + 8(\overline{w^2})^3}\right)}{4\,\overline{w^2}}\,, \tag{11a}$$

$$w_A = -\frac{\overline{w^2}}{2w_B}\,, \tag{11b}$$

$$A = -\frac{w_A}{w_A - w_B}\,, \tag{11c}$$

$$B = 1 - A\,. \tag{11d}$$

Accounting for the closure (10) and eq. (9b), eqs. (6) and (7) become

$$\Phi = AN_A\left[\frac{\sigma_A^2}{A}\frac{\partial A}{\partial z} + \frac{\partial\sigma_A}{\partial z}\left(\sigma_A + \frac{w(w-w_A)}{\sigma_A}\right) + w\frac{\partial w_A}{\partial z}\right] - \tag{12a}$$
$$-\frac{1}{2}\,\mathrm{erf}\left(\frac{w-w_A}{\sqrt{2}\,\sigma_A}\right)\frac{\partial(Aw_A)}{\partial z} + BN_B\left[\frac{\sigma_B^2}{B}\frac{\partial B}{\partial z} + \frac{\partial\sigma_B}{\partial z}\left(\sigma_B + \frac{w(w-w_B)}{\sigma_B}\right) + w\frac{\partial w_B}{\partial z}\right] -$$
$$-\frac{1}{2}\,\mathrm{erf}\left(\frac{w-w_B}{\sqrt{2}\,\sigma_B}\right)\frac{\partial(Bw_B)}{\partial z}$$

and

$$a = \frac{1}{P}\left[B_0\left(AN_A\,\frac{w-w_A}{w_A^2} + BN_B\,\frac{w-w_B}{w_B^2}\right) + \Phi\right]. \tag{12b}$$

Equations (12) were originally derived by Luhar and Britter [3]. In the present study the system of eqs. (1), (10), (11), and (12) are named LB model.

Weil [4] modified the Baerentsen and Berkowicz closure assumption [2] as follows:

$$\sigma_A = Rw_A \quad \text{and} \quad \sigma_B = -Rw_B, \tag{13}$$

thus obtaining

$$w_A = \frac{1}{2}\sqrt{\overline{w^2}}\left[\alpha S + \left(\alpha^2 S^2 + \frac{4}{\beta}\right)^{1/2}\right], \tag{14a}$$

$$w_B = \frac{1}{2}\sqrt{\overline{w^2}}\left[\alpha S - \left(\alpha^2 S^2 + \frac{4}{\beta}\right)^{1/2}\right], \tag{14b}$$

where

$$S = \frac{\overline{w^3}}{(\overline{w^2})^{3/2}}\,, \qquad \alpha = \frac{1+R^2}{1+3R^2} \qquad \text{and} \qquad \beta = 1 + R^2\,.$$

It can be noted that if $R = 1$ this model reduces to the LB one. Substituting closure (13) into the squared brackets of eq. (6) and accounting for eq. (9*b*), Weil obtained

$$\Phi = N_A\left[\sigma_A^2\,\frac{\partial A}{\partial z} + \frac{A}{2}\left(1 + \frac{w^2}{\sigma_A^2}\right)\right]\frac{\partial \sigma_A^2}{\partial z} - \frac{1}{2}\,\mathrm{erf}\left(\frac{w-w_A}{\sqrt{2}\,\sigma_A}\right)\frac{\partial (Aw_A)}{\partial z} + \tag{15}$$
$$+ N_B\left[\sigma_B^2\,\frac{\partial B}{\partial z} + \frac{B}{2}\left(1 + \frac{w^2}{\sigma_B^2}\right)\right]\frac{\partial \sigma_B^2}{\partial z} - \frac{1}{2}\,\mathrm{erf}\left(\frac{w-w_B}{\sqrt{2}\,\sigma_B}\right)\frac{\partial (Aw_B)}{\partial z}\,.$$

The system of eqs. (1), (13), (14) and (15), in which $R = 1.5$ according to Weil [4], are named WE model.

4. – Turbulence parameterization

In the present analysis we considered four turbulence parameterization schemes for the convective boundary layer, LB-TU, R-TU, DVN-TU and W-TU, suggested by Luhar and Britter [3], Rodean [5], De Baas *et al.* [6] and Weil [4], respectively. The expressions for the moments of vertical wind velocity fluctuations $\overline{w^2}$, $\overline{w^3}$ and for the Lagrangian time scale τ are the following:

i) LB-TU

$$\overline{w^2} = 1.1 w_*^2\left(\frac{z}{z_i}\right)^{2/3}\left(1 - \frac{z}{z_i}\right)^{2/3}\left[1 - \frac{4\,(z/z_i - 0.3)}{(2 + |z/z_i - 0.3|)^2}\right], \tag{16}$$

$$\overline{w^3} = 0.8\,w_*^3\left(\frac{\overline{w^2}}{\overline{w_*^2}}\right)^{3/2}, \tag{17}$$

$$\tau = \left[1.5 - 1.2 \left(\frac{z}{z_i} \right)^{1/3} \right]^{-1} \frac{\overline{w^2} z_i}{w_*^3} \,. \tag{18}$$

ii) R-TU

$$\overline{w^2} = 1.6 u_*^2 \left(1 - \frac{z}{z_i} \right)^{3/2} + 2.4 u_*^2 \left[\left(\frac{z}{-L} \right) \right]^{2/3} \left(1 - 0.8 \frac{z}{z_i} \right)^2 , \tag{19}$$

$$\overline{w^3} = 0.84 \frac{u_*^3}{k} \left(\frac{z}{-L} \right) \left(1 - \frac{z}{z_i} \right) , \tag{20}$$

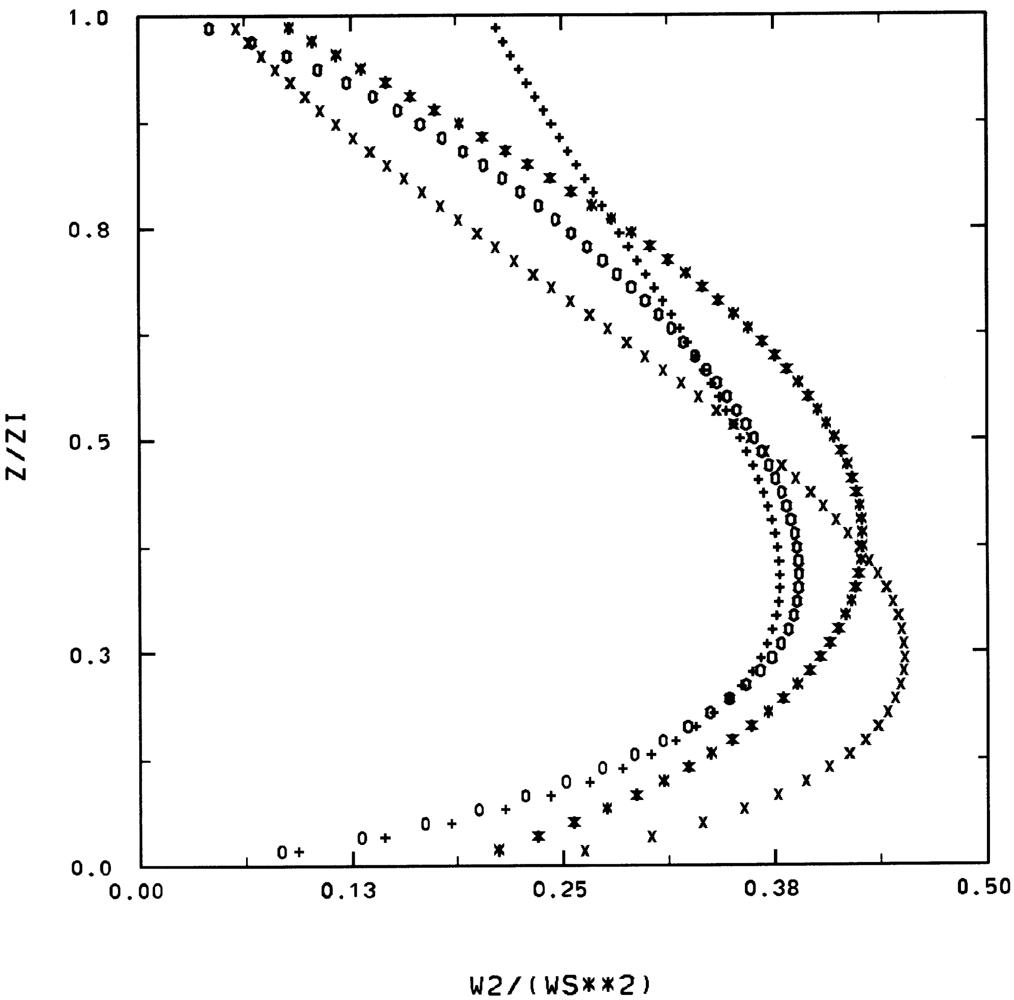

Fig. 1. – Second moment of turbulence vertical velocities as prescribed by LB-TU ($*$), R-TU ($\times$), DVN-TU ($+$) and W-TU ($\bigcirc$).

$$\tau = \frac{2\,\overline{w^2}}{C_0\,\varepsilon}\,, \tag{21}$$

where $k = 0.4$ is the Von Karman constant, $C_0 = 5.7$, u_* is the friction velocity, L the Monin-Obukhov length and

$$\varepsilon = \frac{u_*^3}{k}\left\{\frac{1}{z}\left[1+0.75\left(\frac{z}{-L}\right)\right]\left(1-0.85\,\frac{z}{z_i}\right)^{3/2}+\frac{0.3}{-L}\right\}.$$

u_* appears in eqs. (19), instead of w_* because Rodean [5] proposed a parameterization for $\overline{w^2}$, $\overline{w^3}$ and τ that is continuous for all elevations within the turbulent boundary layer and the full range of atmospheric conditions from unstable to stable ($-\infty < 1/L < \infty$).

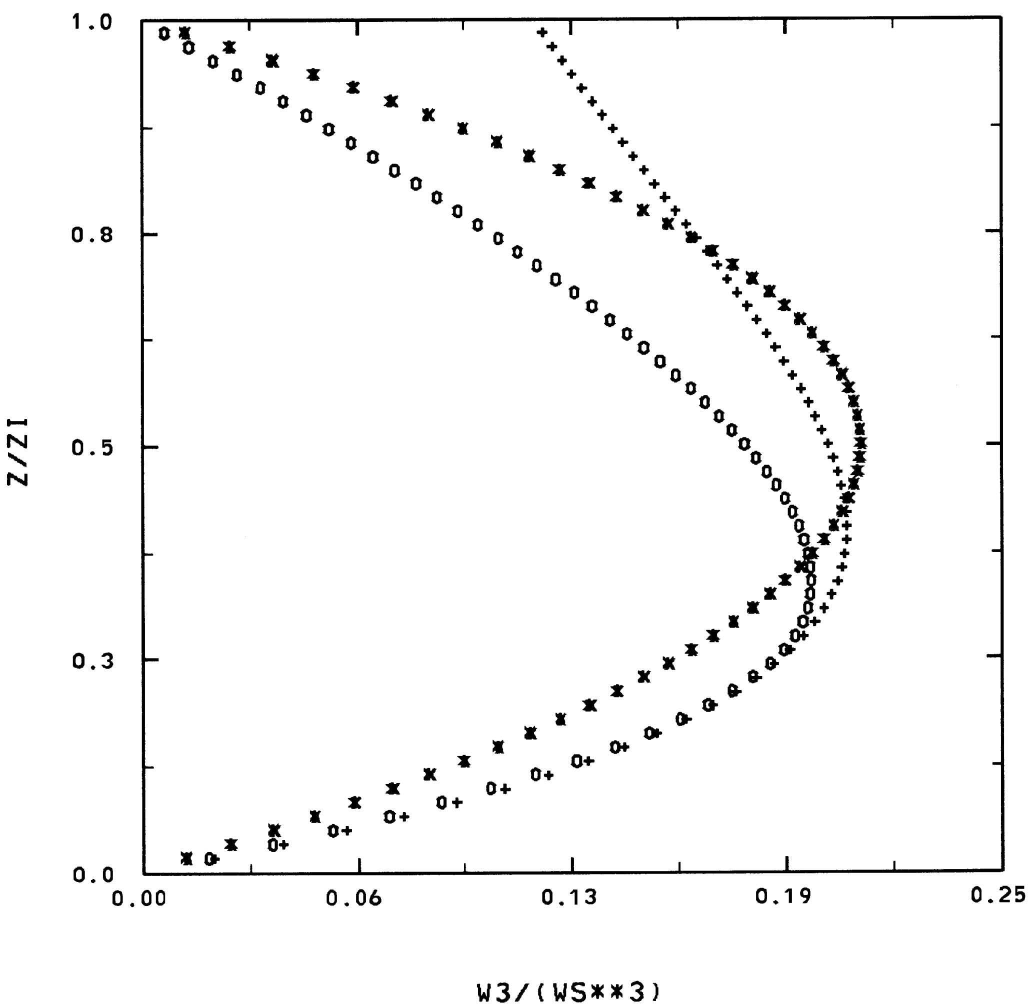

Fig. 2. – As in fig. 1 but for the third moment of turbulence vertical velocities.

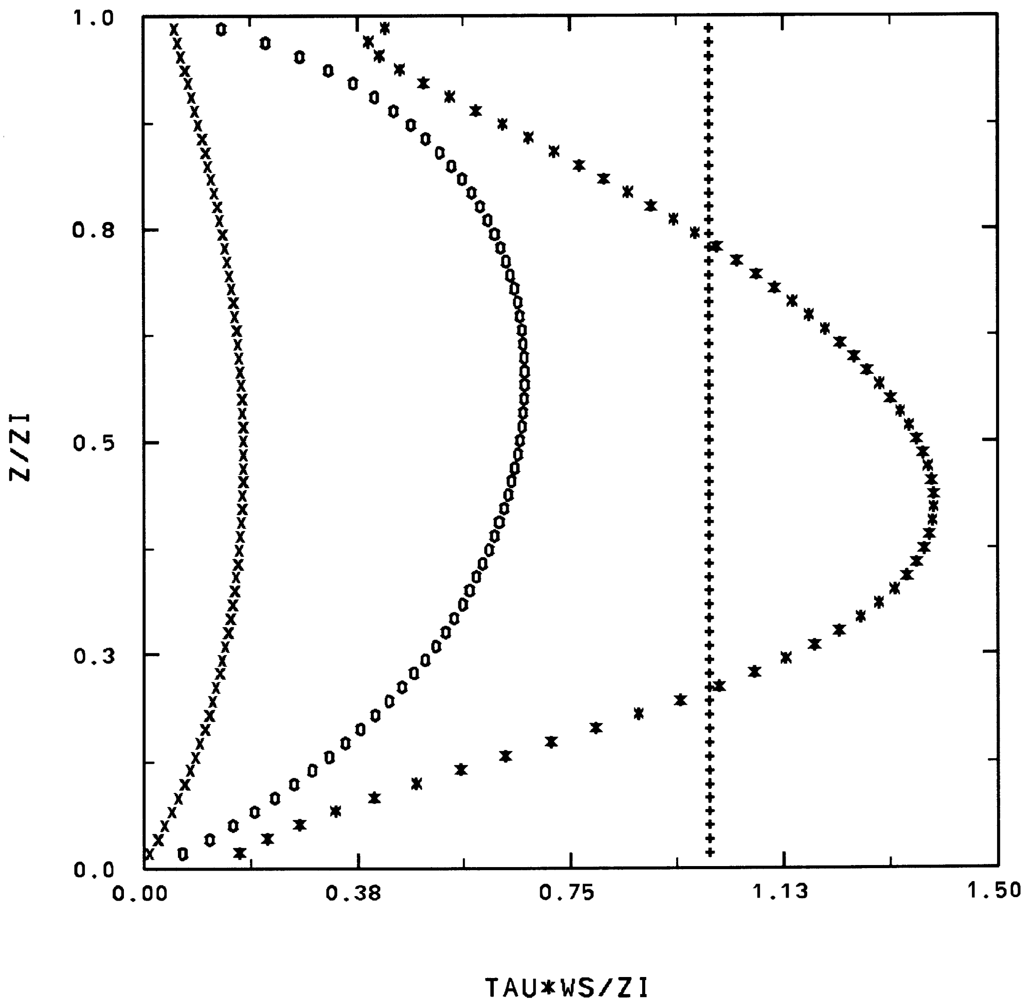

Fig. 3. – As in fig. 1 but for Lagrangian time scale of turbulence vertical velocities.

iii) DVN-TU

$$\overline{w^2} = 1.54 w_*^2 \left(\frac{z}{z_i} \right)^{2/3} \exp\left[-\frac{2z}{z_i} \right], \tag{22}$$

$$\overline{w^3} = 1.4 w_*^3 \left(\frac{z}{z_i} \right) \exp\left[-\frac{2.5z}{z_i} \right], \tag{23}$$

$$\tau = \frac{z_i}{w_*} \, . \tag{24}$$

iv) W-TU

$$\overline{w^2} = w_*^2 \left[\left(\frac{u_*}{w_*} \right)^3 \left(1.6 - \frac{z}{z_i} \right)^{3/2} + 1.2\, \frac{z}{z_i} \left(1 - 0.98\, \frac{z}{z_i} \right)^{3/2} \right]^{2/3}, \tag{25}$$

$$\overline{w^3} = 0.84\, w_*^3 \left(\frac{z}{z_i} \right) \left(1 - \frac{z}{z_i} \right), \tag{26}$$

$$\tau = \frac{2\, \overline{w^2}}{C_0\, \varepsilon}, \tag{27}$$

where $C_0 = 2.0$, and

$$\varepsilon = \frac{w_*^3}{z_i} \left\{ 1.15 \exp\left[-12.5\, \frac{z}{z_i} \right] - 0.2 \exp\left[-50 \left(1 - \frac{z}{z_i} \right) \right] + 0.3 \right\}.$$

The vertical profiles of $\overline{w^2}$, $\overline{w^3}$ and τ, for the four parameterizations above presented, are shown in figs. 1-3, respectively. Even if all the $\overline{w^2}$ and $\overline{w^3}$ parameterizations were obtained fitting the same experimental data, due to the large scatter among these data, they look rather different. In fact DVN-TU shows a different slope above the maximum in both graphs and R-TU has its maximum $\overline{w^2}$ value at a height lower than $z_i/3$ as indicated by the other parameterizations. Then in fig. 2 it appears that each parameterization locates the $\overline{w^3}$ maximum at different heights (notice that eqs. (26) and (20) become equal because of the subsequent eq. (30)). As far as τ profiles are concerned, the differences are still larger: DVN-TU prescribes a constant value throughout the PBL, W-TU maximum is about 2 times greater than the LB-TU one and about 7 times greater than that of R-TU.

5. – Boundary conditions

Concerning the reflection of particle velocities at the top and bottom of the computation domain, we used the treatment of Thomson and Montgomery [8]. They assumed that the distribution of particle velocities crossing any level in a fixed time interval must be preserved. This means that the following equality must hold:

$$\int_{w_{\mathrm{r}}}^{\infty} w P_a \, \mathrm{d}w = - \int_{-\infty}^{w_{\mathrm{i}}} w P_a \, \mathrm{d}w, \tag{28}$$

where w_{r} is the reflected velocity and w_{i} the incident velocity. Equation (28) assures that the average vertical velocity through any arbitrary level of the domain is zero. Unfortunately eq. (28) does not have an analytical solution, therefore we used an approximate analytical method developed by Anfossi *et al.* [9]. For top reflection these authors found

$$\gamma_1 = 1 + (-0.6869\, S + 0.3868\, S^2 - 0.2104\, S^3 + 0.0603\, S^4) \cdot (0.1008 + 1.6280\, V - 1.0160\, V^2 + 0.2795\, V^3 - 0.028\, V^4) \tag{29a}$$

and for bottom reflection:

$$\frac{1}{\gamma_2} = 1 + (-1.2451 S + 0.1842 S^2 + 0.1168 S^3 - 0.0501 S^4) \cdot \cdot (-0.1251 - 1.8674 V - 2.0772 V^2 - 1.0072 V^3 - 0.1797 V^4), \tag{29b}$$

where $V = w_i / (\overline{w^2})^{1/2}$ and $w_r = -\gamma_1 w_i$ for top reflection and $w_r = -1/\gamma_2 w_i$ for bottom reflection.

6. – Results

The performances of the two models (LB and WE) have been compared to a water tank diffusion experiment [7] in which stationary inhomogeneous convective turbulence prevailed. A line source, located at a height $h_s / z_i = 0.24$, where z_i is the PBL depth, released a non-buoyant emission. No mean flow was present and the particles' diffusion was measured with respect to a dimensionless time $T = (w_* / z_i)\, t$, where w_* is the convective velocity scale and t is the actual time elapsed from the particle release. Dimensionless crosswind concentration C_y as a function of time T was then expressed by Willis and Deardorff [7] as a function of dimensionless distance $X = (w_* x)/(z_i u)$, where $u = x/t$. To compare laboratory measurements and model simulations, models' output C_y and X have been computed [3] as follows: $C_y = (n_p z_i)/(N_p \Delta z)$ and $X = (w_* / z_i)\, k_i \Delta t$, in which N_p is the total number of emitted particles, n_p the number of particles counted in the vertical layer $\Delta z = 0.05 z_i$ adjacent to the ground, Δt the simulation time step and k the number of time steps elapsed from the particle emission. 25 000 particles were released in each model simulation. Many tests showed that the choice of this number of particles, coupled to the above dimension of the cell in which g.l.c.'s are computed, reduces the statistical variability of the simulation results to a few percent. Particle initial velocity distribution was prescribed with the same moments as the Eulerian turbulent velocity distribution at the corresponding height.

Since no mean flow was present in the laboratory experiment, the u_* value needed in R-TU and W-TU parameterizations was computed from

$$u_* = w_* \left(- \frac{0.4 L}{z_i} \right)^{1/3}, \tag{30}$$

where L was prescribed from the relation $z_i / L = -10$, since that L value allows to transpose the water tank CBL to the real atmospheric CBL [10].

TABLE I.

Model	LB				WE				Experimental
TURB	LB	R	DVN	W	LB	R	DVN	W	
χ_{max}	2.9	2.1	3.4	2.8	2.4	2.6	3.1	2.5	2.98
X_{max}	0.75	0.75	0.55	0.48	0.75	0.62	0.55	0.48	0.48

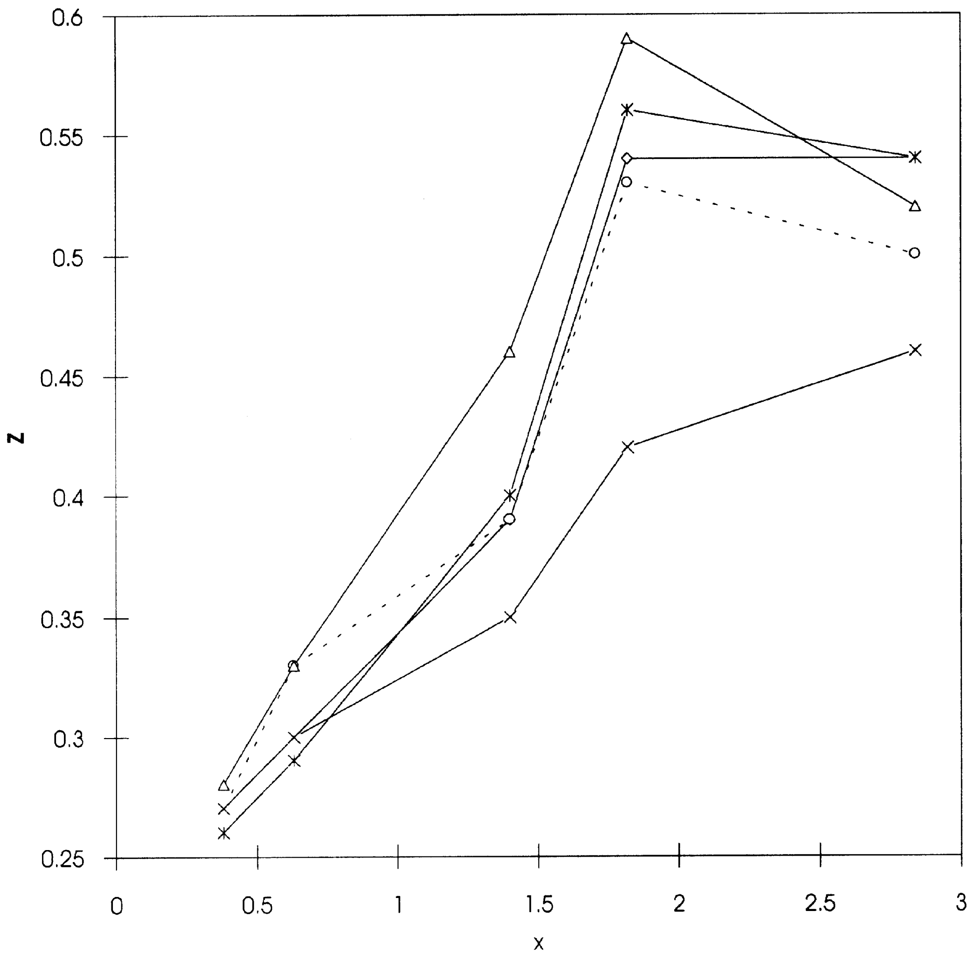

Fig. 4. – $Z = \bar{z}/z_i$ *vs.* X for LB model; ○ and dashed line, measured, × R-TU, ∗ DVN-TU, △ W-TU, ◊ LB-TU.

The results obtained by using the two models are presented in table I and figs. 4-7. For the sake of clearness, we shall call the eight different combinations of the two models and four parameterization as follows: LB-LB (LB model using LB-TU parameterization), LB-R (LB model using R parameterization), WE-DVN (WE model using the DVN-TU parameterization) and so on.

For each model table I lists the g.l.c. maximum (χ_{max}) and its distance from the source (X_{max}) corresponding to the four used parameterizations. In the last column the corresponding observed values are indicated. These last values and those plotted in figs. 4-7 were estimated from figs. 4-6 of de Baas *et al.* paper [6].

Looking at table I, it may be observed that g.l.c. maximum is better captured by LB-LB and WE-DVN, whereas LB-R largely underestimates the observed value. (X_{max}) prediction is almost independent on the models but depends on the turbulent parameterization. The best results are given by W-TU parameterization; using the

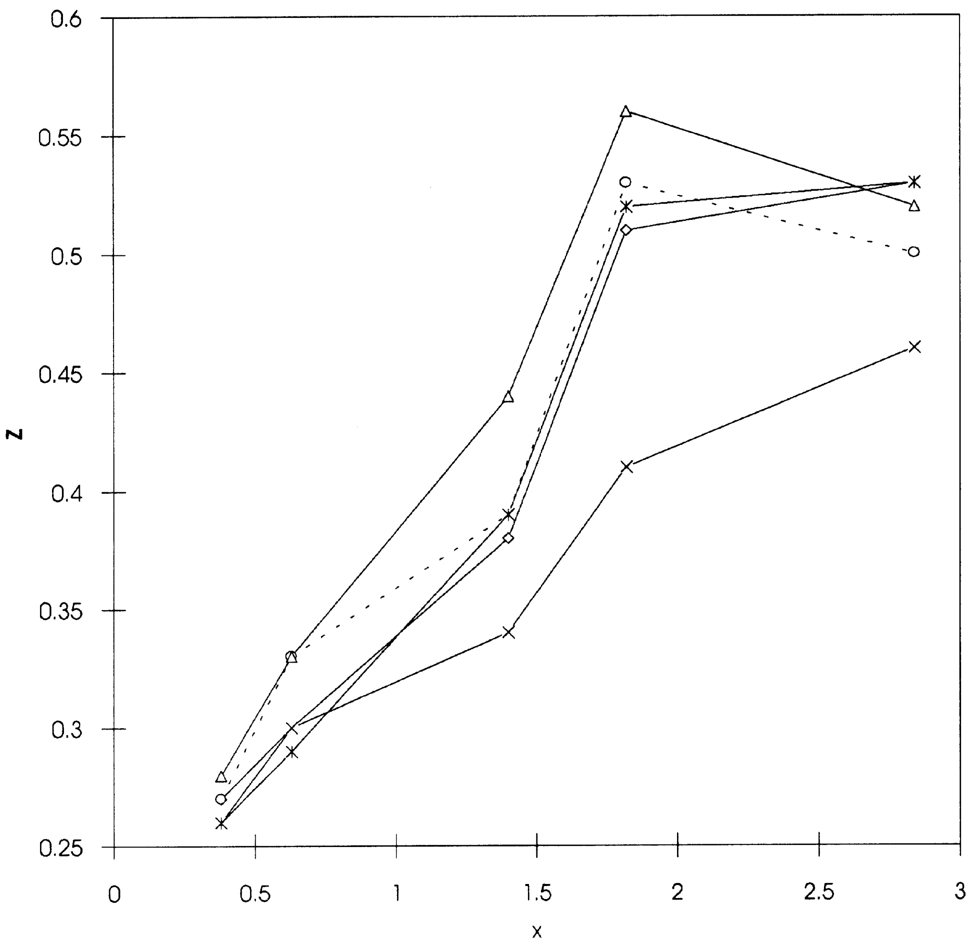

Fig. 5. – As in fig. 4 but for WE model.

other parameterizations, the predicted values overestimate the experimental data.

Figure 4 reports the comparison among mean particle height $Z = \bar{z}/z_i$ obtained in the simulations with LB model at five downwind distances ($X = 0.38$, 0.63, 1.04, 1.82 and 2.84), using the four different parameterizations, and the corresponding experimental values. Figure 5 is similar to fig. 4 but refers to the simulations with WE model. Figures 6 and 7 are similar to figs. 4 and 5 but refer to the particle spread $\sigma_z = \sqrt{\overline{(z - z_s)^2}}/z_i$. It may be worth noting that the results shown in figs. 1-4 do not experience a significant statistical variability related to the variation of the number of used particles. Actually the relative errors of the various Z and σ_z values passing from $N = 25\,000$ to $N = 20\,000$ or $N = 30\,000$ are in the order of 10^{-4}.

An inspection of figs. 4-7 confirms that differences between LB and WE models are unimportant, whereas the differences among the four parameterizations are more significant. For X greater than 0.63, R-TU underestimates both Z and σ_z. This fact may be due to the small values of τ profile (see fig. 3). Figures 4 and 5 show that, while

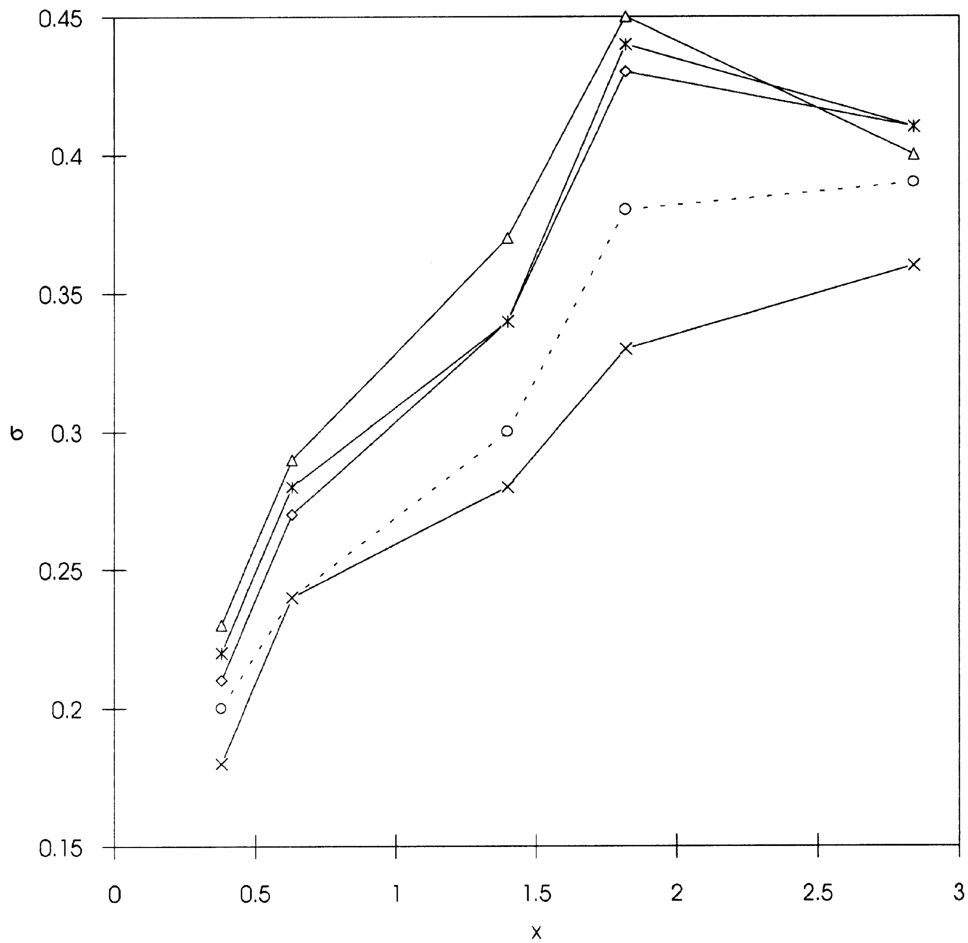

Fig. 6. – As in fig. 4 but for particle spread $\sigma_z = \sqrt{\overline{(z - z_s)^2}}/z_i$.

measured Z's are well mixed ($Z = 0.5$) at $X = 2.84$, none of the eight models is completely well mixed at that distance. Moreover, in this case W-TU shows the best agreement at $X = 2.84$ and at $X = 0.38$ and $X = 0.63$, but has the worst performance at the intermediate distances. Generally speaking DVN-TU shows the best agreement between observed and predicted Z's.

As regards σ_z trend (figs. 6 and 7), while R-TU systematically underestimates (except at $X = 0.63$), the other parameterizations overestimate in the whole X range. Again, at the furthest distance, W-TU shows the best agreement.

7. – Conclusions

In this work two Lagrangian 1-D Ito's type particle models, developed by Luhar and Britter [3] and Weil [4], have been tested against an experimental data set [7] in convective conditions. Both models are based on the same solution of the Fokker-

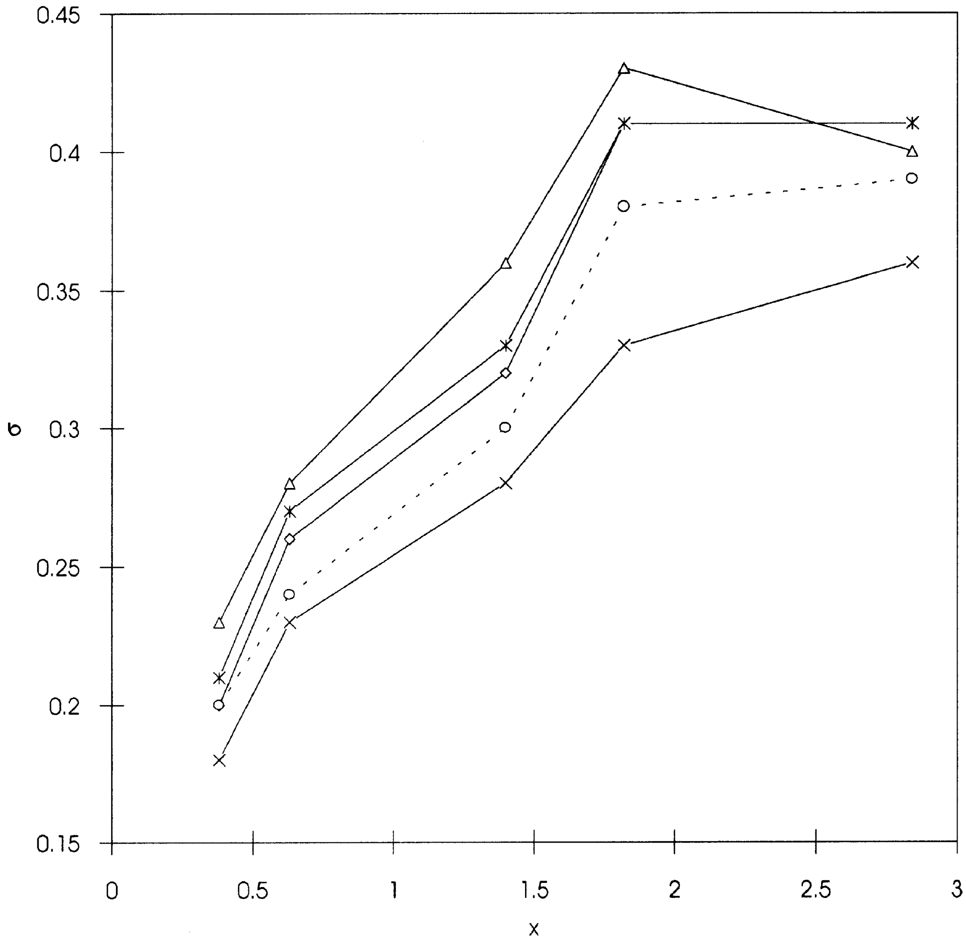

Fig. 7. – As in fig. 6 but for WE model.

Planck equation, but they have different closure schemes for calculating the random forcing PDF parameters. The tests have been performed using four parameterizations for the vertical turbulence. As a consequence, eight different models have been considered.

The predicted values of maximum of g.l.c., distance from the source of the maximum, mean plume height and the vertical spread of the plume are presented and compared with the corresponding measured values.

The aim of such an analysis was to select the model and the turbulence parameterization able to give better results. It was found that it is not possible to select the best model and the best parameterization because models behave in different manners according to the different considered parameters. The two models coupled to the four parameterizations yield different maximum g.l.c. estimates (LB-LB and WE-DVN showing the best agreement).

With reference to the other considered parameters ($X_{\max}$, Z and σ_z trends), no meaningful differences between the two models were found, whereas considerable differences were due to the used turbulence parameterizations. As far as $X_{\max}$ is concerned, W-TU parameterization gave the best agreement with observation. While DVN-TU shows the best agreement between observed and predicted Z's, all the parameterizations have almost the same scatter in the simulation of σ_z's and almost all exhibit the tendency to shift forward g.l.c. maximum position.

These conclusions may have two interesting consequences:

i) Different authors (see figs. 1-3) prescribed rather different $\overline{w^2}$ and $\overline{w^3}$ parameterizations, even if these last are based on the same experimental data (measured both in water tanks and in the real CBL). This is because $\overline{w^2}$ and $\overline{w^3}$ observations experience a large amount of scatter. As it could be expected these differences in the turbulence parameterization cause differences in the simulation results. As a consequence it appears that there is a need of further experimental investigation on the form of $\overline{w^2}$ and $\overline{w^3}$ profiles.

ii) The two considered models, coupled to the four parameterizations, were not able to fit correctly all the dispersion characteristics considered in this paper. This seems to suggest that either the PDF accounted for by LB and WE models (*i.e.* bi-Gaussian PDF) or the closure scheme adopted (up to the third moment of vertical velocity fluctuations) may not be sufficiently accurate. It could probably be worth to consider different PDFs and/or closure schemes.

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