

## Simulation of a Diffusion Experiment in Neutral Conditions Over Gentle Topography

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### 1 Introduction

The integrated modeling system RMS (RAMS-MIRS-SPRAY) is used to reproduce a tracer dispersion experiment that was performed in a wind tunnel simulating a neutral boundary layer, over gentle topography. RMS is based on a combination of the meteorological model RAMS (Regional Atmospheric Modeling System) (Pielke et al., 1992), the interface code MIRS (Method for Interfacing RAMS and SPRAY, Trini Castelli and Anfossi, 1997, Trini Castelli, 2000) and the Lagrangian particle model SPRAY (Tinarelli et al., 1994, Tinarelli et al., 2000, Ferrero et al. 2001a). RAMS is a mesoscale prognostic model developed at the Colorado State University. The interface code MIRS, developed by our group, uses the RAMS outputs (typically, wind speed, turbulent kinetic energy (t.k.e.), diffusion coefficients, potential temperature, surface fluxes and topography) and calculates the surface layer parameters as well as the turbulent parameters needed by the Lagrangian model SPRAY and not directly provided by RAMS, i.e. the moments of the wind velocity fluctuation probability density function, the Lagrangian timescales  $T_{L_i}$  and the PBL height  $z_i$ . SPRAY is a Lagrangian stochastic particle model designed by our group, to study the pollutants dispersion in complex terrain. It is based on a three-dimensional form of the Langevin equation for the random velocity.

In this work RAMS is run by adopting different turbulence closures implemented by us (Trini Castelli et al. 1999; Ferrero et al. 2001 b): the one-equation E-1 and two-equations E- $\epsilon$  models. The turbulent model provides the t.k.e. and hence, through MIRS,  $\sigma_i$  and  $T_{L_i}$ . These last are obtained alternatively from the diffusion coefficient of momentum, in the case of E-1 closure or from the t.k.e. dissipation rate  $\epsilon$ , in the case of the E- $\epsilon$  closure. The observed concentration profiles at different distances from the source and levels are compared to the corresponding predictions of the simulations performed with the Lagrangian dispersion model SPRAY. The differences due to the turbulent parameters introduced in the models are discussed with a particular care paid to the problem of dispersion in complex terrain.

### 2 The wind tunnel experiment

The data set used in this work was collected in the EPA-RUSVAL wind tunnel experiment (Khurshudyan et al., 1990, Busuoli et al., 1993), carried out in the Environment Protection Agency Laboratory (USA). In this experiment a neutral flow over a two dimensional valley was reproduced. The wind tunnel was characterised by a roughness length  $z_0=0.16 \cdot 10^{-3}$  m, a friction velocity  $u_*=0.19$   $\text{ms}^{-1}$  and free stream velocity  $u_\infty=4$   $\text{ms}^{-1}$ . The maximum valley depth was  $H=0.117$  m and the valley width was  $2a$ , where  $a = 0.936$  m, so that. the aspect ratio  $a/H$  was 8. Vertical profiles of mean wind velocity ( $\bar{u}, \bar{w}$ ) and Reynolds stress components  $\overline{u^2}$ ,  $\overline{v^2}$ ,  $\overline{w^2}$  and  $\overline{u'w'}$  were measured at 15 different positions along the x axis upwind, inside and downwind the valley.

It can be noticed that the flow was essentially two-dimensional because of the symmetry with respect to the x-z plane. The velocity component along the y direction (crosswind direction) is assumed to be zero.

### 3 Numerical simulations

In this work we performed numerical simulations reproducing the flow and dispersion over the two-dimensional valley with our modelling system RMS. As RAMS is a model designed for simulating real atmosphere, a scaling factor of 600 for lengths is chosen, according to the authors of the EPA experiments (Khurshudyan et al., 1981), to report the wind tunnel experiments to the dimension of an actual boundary layer. Consequently the maximum depth of the valley becomes  $H=70.2$  m and the roughness length  $z_0=0.096$  m. Due to the non-dimensional form of the logarithmic wind profile prevailing in neutral conditions, that must be equal both in the tunnel and in the actual prototype, no scaling on the velocities has to be done. As a consequence the scaling factor for time and for length is the same.

RAMS is used as an ensemble averaged model in its non-hydrostatic version. Since SPRAY needs 3D meteorological fields, despite the two-dimensionality of the case, the horizontal domain is set  $8000 \times 1000$  m<sup>2</sup>, with grid size  $\Delta x = \Delta y = 50$  m. Such a small horizontal resolution is needed to detail the valley with a satisfactory number of grid points. In the vertical direction a stretched grid is used in order to improve the resolution in the lower layer. The minimum vertical grid size is 10 m and the maximum 60 m. The total depth of the numerical domain is 2h. The simulation time step is 0.3 s. In MIRS the surface layer parameters are calculated from the RAMS surface fluxes and the constant value of 600 m is set for the height of the neutral boundary layer. The variances of velocity fluctuations and the velocity decorrelation Lagrangian time scales are calculated in MIRS from the t.k.e field supplied by RAMS output.

From the t.k.e. and  $\varepsilon$  fields of E-1 and E- $\varepsilon$  closures, the variances are calculated as

$$\sigma_u^2 = -2 K_{mx} \frac{\partial \bar{u}}{\partial x} + \frac{2}{3} E, \quad \sigma_v^2 = -2 K_{my} \frac{\partial \bar{v}}{\partial y} + \frac{2}{3} E, \quad \sigma_z^2 = -2 K_{mz} \frac{\partial \bar{w}}{\partial z} + \frac{2}{3} E \quad (1).$$

The Lagrangian time scales can be alternatively obtained from the diffusion coefficients,  $K_{ij}$ , calculated by RAMS, and from the variances as follows (DC1):

$$T_{Lu} = \frac{K_{mx}}{\sigma_u^2}, \quad T_{Lv} = \frac{K_{my}}{\sigma_v^2}, \quad T_{Lw} = \frac{K_{mz}}{\sigma_w^2} \quad (2)$$

or using the following formulation (DC2):

$$T_{Lu} = \frac{2\sigma_u^2}{C_{0u}\varepsilon}, \quad T_{Lv} = \frac{2\sigma_v^2}{C_{0v}\varepsilon}, \quad T_{Lw} = \frac{2\sigma_w^2}{C_{0w}\varepsilon}, \quad (3)$$

where  $\varepsilon$  is the t.k.e. dissipation rate and  $C_0$  is the Kolmogorov constant (Tennekes et al. 1982, Hinze, 1975). In this work we used for  $C_0$  the values suggested by Anfossi et al. 2000.

SPRAY is a Lagrangian stochastic model for the simulation of the dispersion of passive pollutants in complex terrain. It is based on a three-dimensional form of the Langevin equation for the random velocity (Thomson, 1987). The velocity and the displacement of each particle are given by the following equations:

$$du_i = a_i(\mathbf{x}, \mathbf{u}, t)dt + b_{ij}(\mathbf{x}, \mathbf{u}, t)dW_j(t) \quad (4)$$

and

$$d\mathbf{x} = (\mathbf{U} + \mathbf{u})dt, \quad (5)$$

where  $i, j = 1, 2, 3$ ,  $\mathbf{x}$  is the displacement vector,  $\mathbf{U}$  is the mean wind velocity vector,  $\mathbf{u}$  is the Lagrangian velocity vector,  $a_j(\mathbf{x}, \mathbf{u}, t)dt$  is a deterministic term,  $b_{ij}(\mathbf{x}, \mathbf{u}, t)dW_j(t)$  is a stochastic term and the quantity  $dW_j(t)$  is the incremental Wiener process. The deterministic coefficient depends on Eulerian probability density function (PDF)EMBED of the turbulent velocity and is determined from the Fokker-Planck equation. Since these simulations deal with neutral conditions, the PDF is assumed to be Gaussian in the three directions. The diffusion coefficient  $b_{ij}(\mathbf{x}, \mathbf{u}, t)$  is obtained from the Lagrangian structure function and is related to the above introduced constant,  $C_0$ , and to the

dissipation rate of turbulent kinetic energy  $\varepsilon$ , as  $b_{ij} = \sqrt{C_0 \varepsilon}$ .  $b_{ij}(\mathbf{x}, \mathbf{u}, t)$  can be also determined from the variances of the velocity fluctuation and the Lagrangian decorrelation time scale, namely  $b_{ij} = \sqrt{2\sigma_{ij}^2 / T_{L_{ij}}}$ .

#### 4 Results

We performed several simulations using the E-1 and E- $\varepsilon$  turbulence closure models coupled to different parameterisations. In the case of E-1 closure, the turbulent parameters were calculated using equations (1) and (2) (DC1), while in the case of E- $\varepsilon$  model the combination of equations (1) and (3) was also adopted (DC2). For sake of comparison, we carried out other simulations using, for the turbulent quantities, classical parameterisations developed for flat terrain. In this paper we show the results obtained by Hanna (1982) scheme (HAN).

Among the various simulations performed, the present comparison refers to the case of a source 17.4 m high placed in the centre of the valley. Since the valley depth is 70.2 m, the tracer was emitted at a height deeply inside the valley. This kind of complex configuration represents a valid benchmark to evaluate the capability of our modelling system to describe the transport and dispersion in complex terrain. Moreover, this particular experiment was characterised by a rich and complete concentration data set allowing the comparison to be exhaustive and significant.

The E-1 closure was tested by comparing DC1 and HAN parameterisations. In Table 1 the results of the model evaluation are reported. It can be seen that DC1 predicts correctly both mean and sigma, the correlation coefficient is good and the other statistical indexes are acceptable. Only the factor two is not satisfactory. Fractional bias indicates a tendency to overestimate. Concerning HAN parameterisation, the results are less satisfactory, showing a large overestimation. However this result can be expected since the Hanna scheme was designed for flat terrain.

**Table 1** E-1 model evaluation.

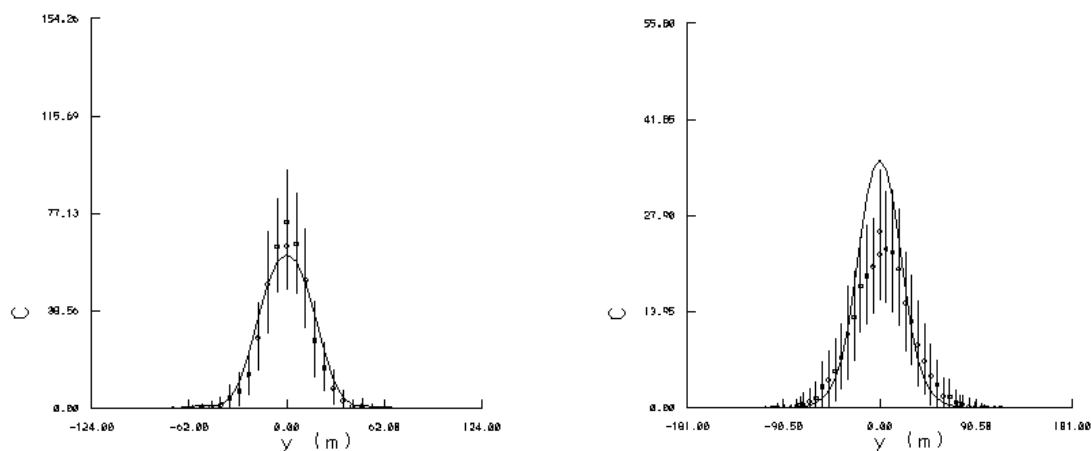
	mean	sigma	bias	nmse	cor	fa2	fb	fs
OBS	4.19	10.33	0.00	0.00	1.000	1.000	0.000	0.000
DC1	4.85	10.10	-0.66	0.97	0.908	0.323	-0.146	0.022
HAN	6.95	17.20	-2.75	3.85	0.839	0.151	-0.494	-0.499

The result of the model evaluation, concerning the simulations performed with the E- $\varepsilon$  closure model, is reported in Table 2. Comparing these results with those of Table 1, it can be concluded that the performance of the modelling system does not improve using the E- $\varepsilon$  closure instead of E-1 closure when the turbulence parameters are calculated from DC1. Different results are obtained using the DC2 formulation. The correlation coefficient and the factor two are better than those obtained with DC1, whilst the other indexes are less satisfactory. Even in this case HAN parameterisation gives much less accurate results. It is worth noticing that the different values of the statistical indexes referring to HAN parameterisation depend on the different flow fields produced by RAMS using the two alternative turbulence closures.

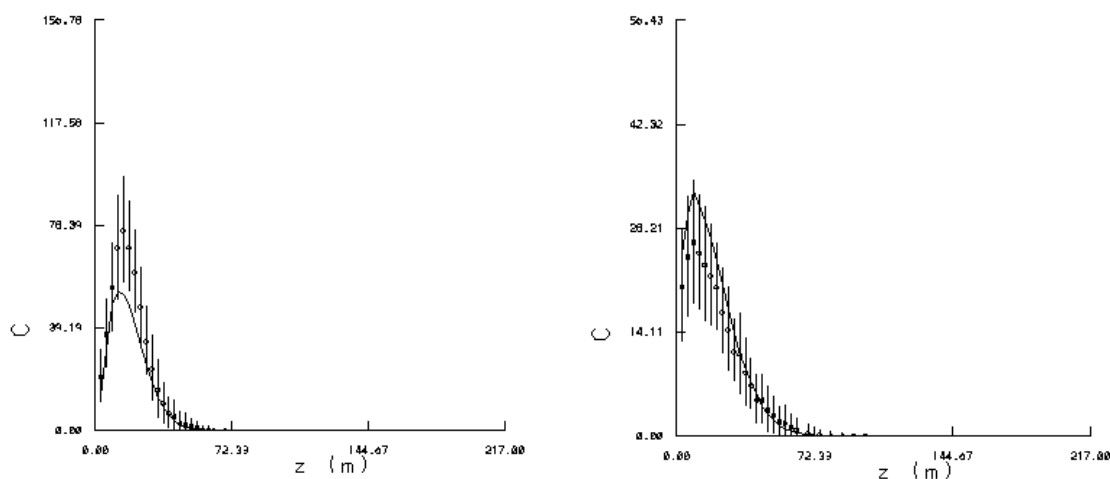
**Table 2** E- $\varepsilon$  model evaluation.

	mean	sigma	bias	nmse	cor	fa2	fb	fs
OBS	4.19	10.33	0.00	0.00	1.000	1.000	0.000	0.000
DC1	4.94	10.01	-0.75	0.88	0.915	0.325	-0.164	0.032
DC2	3.03	6.69	1.17	1.68	0.952	0.476	0.324	0.429
HAN	7.96	19.96	-3.77	5.15	0.842	0.145	-0.620	-0.630

The cross wind (Figure 1) and vertical (Figure 2) profiles of the concentrations calculated using E-ε model and DC1 formulation (continuous line) are compared with those observed (dots and error bars) for two locations close to the position of the ground level concentrations maximum.



**Figure 1** E-ε closure DC1 parameterisation ( $x=53$  m ,  $z=15$  m and  $x=106$  m,  $z=9$  m).



**Figure 2** E-ε closure DC1 parameterisation ( $x=53$  m and  $x=106$  m).

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