TURBULENCE CLOSURE IN ATMOSPHERIC CIRCULATION MODEL AND ITS INFLUENCE ON THE DISPERSION

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INTRODUCTION

The aim of this work is to improve the turbulence and, consequently, the dispersion simulation in the RMS (RAMS-MIRS-SPRAY, Ferrero et al., 2003, Alessandrini et al, 2005) modelling system. It is specially designed for dealing with atmospheric pollutant dispersion in complex terrain and strong convective situations. It is well-known that the performance of a dispersion model depends on the turbulent parameters. This is particularly evident when the model is applied to case of complex terrain, low wind speed, strong convection and so on. For this reason we modified the turbulence closure model to obtain better turbulent kinetic energy and wind velocity standard deviation fields. As a matter of fact the closure usually implemented in the circulation models are designed only with the aim of reproducing the mean wind and temperature fields. In order to assess the ability of RMS we have considered the BULL RUN tracer campaign (Hanna, et al., 1991). The experiment was simulated employing two different alternative turbulence closures and two dispersion models. The mesoscale atmospheric model RAMS (Pielke et al., 1992) was used to simulate the mean flow and turbulence, while the parameterisation code MIRS (Trini Castelli, 2000) estimates the turbulent and boundary layer parameters for the dispersion models. For sake of comparison, beside the Lagrangian Particle model SPRAY (Tinarelli et al. 2000) included in RMS, a Puff model CALPUF (Shire et al. 2000) was applied by prescribing the mean flow with the circulation model RAMS. The results of the comparison between the simulated turbulence fields are presented. Finally, the mean concentration fields are compared in terms of statistical indexes and scatter plots of cross wind integrated concentrations.

THE NUMERICAL MODELS

The first modelling system consists in a coupled model based on the regional atmospheric model RAMS and the Lagrangian particle model SPRAY. RAMS (Regional Atmospheric Modeling System) is a well-known prognostic model, developed at the Colorado State University (Pielke et al., 1992). The two models are interfaced by MIRS 2.0 code (Trini Castelli, 2000), which uses the RAMS outputs to calculate the boundary layer and turbulence parameters for the Lagrangian dispersion model SPRAY not directly provided by the circulation model. In this work we use the RAMS version 4.4 initialised with the ECMWF analysis with a nudging procedure applied every 6 hours. Two options for the turbulence closures are available. The first is the well known Mellor and Yamada (1982) closure model (here after MY), which is implemented as standard closure in RAMS. It provides the turbulence kinetic energy (E) to MIRS that in turn calculates the wind velocity standard deviations, and the Lagrangian Time Scales needed to the dispersion model as input. The vertical component of diffusivity is calculated on the basis of the E equation from MY while the horizontal components are assigned from a deformational Smagorinsky-type scheme, based on the deformation strain tensor and the horizontal grid spacing. It is worth to notice that an anisotropic diffusivity is introduced mainly for numerical reasons, even if, from a physical point of view this choice could be not consistent. As a matter of fact, assuming the diffusivity to be different along the different directions implies that the Reynolds stress tensor is not symmetric. Nevertheless, in the numerical simulation of the mesoscale flows the vertical resolution should be higher than the horizontal one and hence, the model resolves the turbulent eddy at scales smaller than the horizontal resolution producing instability. In order to damp this instability in the horizontal direction a larger diffusivity should be considered. A second turbulence model, the E-*l* closure, has been introduced by our group in order to overcame the tendency to underestimate the boundary layer turbulence of MY (Trini Castelli et al, 2001 and Ferrero et al., 2003). We developed an anisotropic version of the standard isotropic E-*l* model, in the sense that the horizontal diffusivity is modified in order to account for the difference in the model resolution. We recall that the E-*l* model (see for instance Duynkerke P.G., 1988) is based on the turbulent kinetic energy E-equation:

$$\frac{dE}{dt} = \frac{\partial}{\partial z} K_E \frac{\partial E}{\partial z} + P - \varepsilon$$

where $P = -\overline{u'_i u'_j}\frac{\partial \bar{u}_i}{\partial x_j} + \delta_{i,3} g \alpha \overline{u'_i \theta'}$ is the shear and buoyancy production term, $\varepsilon = c_\varepsilon \frac{E^{3/2}}{l}$ is the TKE dissipation and α is the thermal expansion coefficient. The turbulent fluxes are than calculated as a function of the TKE:

$$\overline{u'_i u'_j} = -K_m \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) + \frac{2}{3} E \delta_{ij} ; \qquad \overline{u'_i \theta'} = -K_\theta \frac{\partial \bar{\theta}}{\partial x_i}$$

where $K_m = c_\mu E^{1/2} l$. The diffusion coefficients of heat and TKE are: $K_h = \alpha_h K_m$ and $K_E = \alpha_e K_m$, being α_h and α_e constants. The value of c_μ has been set equal to 1.7.

The standard version of the E-*l* turbulence closure model is isotropic since it uses the same K_m for all the directions. The anisotropic version of it has been obtained defining instead different diffusivities in the vertical and horizontal directions:

$$K_{mh} = c_a K_m \text{ and } K_{mv} = K_m$$

The anisotropy coefficient c_a is taken as the ratio by the horizontal and vertical model grid resolution:

$$c_a \approx \frac{\Delta x}{\Delta z}$$

The dispersion model is a Lagrangian stochastic particle model (SPRAY, Tinarelli et al., 1994 and 2000) which is designed to study the pollutants dispersion in complex terrain. It is based on the Langevin equation for the turbulent velocities (Thomson, 1987), whose coefficients depend on a solution of the Fokker-Planck equation for a given Eulerian probability density function (PDF) of the turbulent velocity and on the inertial range turbulence theory respectively. In the two horizontal directions the PDF is assumed to be Gaussian. In the vertical direction the PDF is assumed to be non-Gaussian, so to deal with convective conditions.

The equations prescribing the evolution of the vertical velocity fluctuation *w* and the displacement *z* are the following:

$$dw = a(z,w)dt + \sqrt{C_0 \varepsilon dt}\, d\mu \qquad\qquad dz = wdt$$

where dμ has zero mean and unit variance, C_0 is a constant and ε is the dissipation rate of turbulent kinetic energy. a(z,w) must be determined by solving the Fokker-Planck equation for the velocity probability density function (PDF), that must be prescribed from the available measurements or parameterisations. In the present work, we have used the Gram-Charlier

PDF (Ferrero and Anfossi, 1998). The second modelling system used is the CALMET-CALPUFF chain. The wind field produced by RAMS 4.4 is processed by CALMET that also computes the turbulence variables necessary for CALPUFF. CALPUFF is a multi-layer, multi-species non-steady-state puff dispersion model, which can simulate the effects of time- and space-varying meteorological conditions on pollutant transport, transformation, and removal, developed and distributed by Earth Tech, Inc. The model has been adopted by the U.S. Environmental Protection Agency (U.S. EPA) in its Guideline on Air Quality Models as the preferred model for assessing long range transport of pollutants and their impacts on Federal Class I areas and on a case-by-case basis for certain near-field applications involving complex meteorological conditions. The modelling system consists mainly of CALMET (a diagnostic three-dimensional meteorological model) and CALPUFF (an air quality dispersion model). Advection is carried out by a three-dimensional wind field and the dispersion coefficients are computed from internally calculated wind standard deviations using CALMET micrometeorological variables (u_*, w_*, L, etc.)

BULL RUN DATA-SET

The models have been applied to the Bull Run experiment (Brown at al., 1985; Hanna and Pain, 1989). The Bull Run steam plant is located in the broad Tennessee River valley (about 60 km wide) surrounded by mountains rising over 1700 m of altitude. Close to the plant, the ridges are approximately 100 m and the region is cover by forests. The Melton Hill Lake cuts perpendicular across the ridges near the Bull Run steam plant (Figure 1). The meteorological measurements were collected from a 122 m TVA tower, located near the crest of a 70 m ridge about 2 km west of the stack, the central observing station, located at about the same elevation as the stack base in a field near the river about 5 km northwest of the stack, one acoustic sounder about 1 km east of the stack, the National Weather Service (NWS) stations at Knoxville and Nashville, Tennessee. The tracer (SF_6) was released from the 243 m high plant stack and measured on 203 monitors deployed on arcs from 0.5 to 50 km, during two 5-week long periods. The monitor locations were changed following the forecasted meteorological conditions in order to catch the wind direction and depending on the forecasted maximum ground level concentration. In particular during the day chosen for the simulations (21st of August 1982) 203 receptors were located on 5 circles of radius 7, 15, 20, 30, 50 Km around the source position (Figure 1). The tracer was released for 11 hours starting at 13 LST (Local Standard Time) and the hourly measurements have been performed for 9 hours since 16 LST. In Figure 1 the topography, the receptors and the source position are shown. 21st of August 1982 was a sunny day with Northeast winds with 4-5 m/s average speed.

RESULTS AND DISCUSSION

The dispersion models coupled with RAMS were applied to the case of the Bull Run experiment of the August 21; RAMS was run by using three nested grids with horizontal resolution equal to 32000 m, 8000 m and 2000 m respectively. The smallest grid has an extension of 84 x 84 km^2 and represents the domain for the dispersion simulations. We performed two simulations with SPRAY using respectively RAMS with the MY closure and the E-*l* closure. In the simulation carried out with CALPUFF, RAMS uses the MY closure. It is worth to notice that CALPUFF is driven by the mean flow produced by RAMS but not by the turbulence, which is parameterised by its pre-processor.

Figure 2 shows a comparison of the vertical standard deviation of wind velocity fluctuation as a function of time simulated by the model RAMS using different closures and the measured data at a height of 100 m by the meteorological tower.

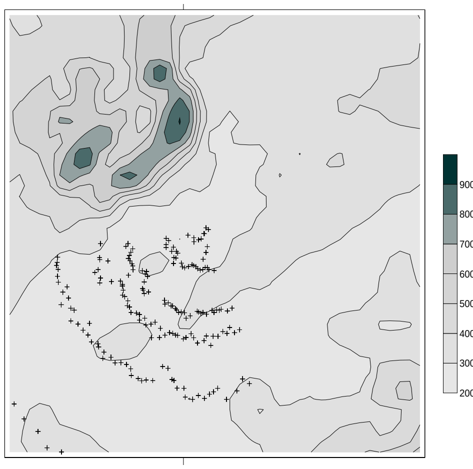


Fig. 1: Topography and receptors positions on 4 arcs around the source position (centre of the figure)

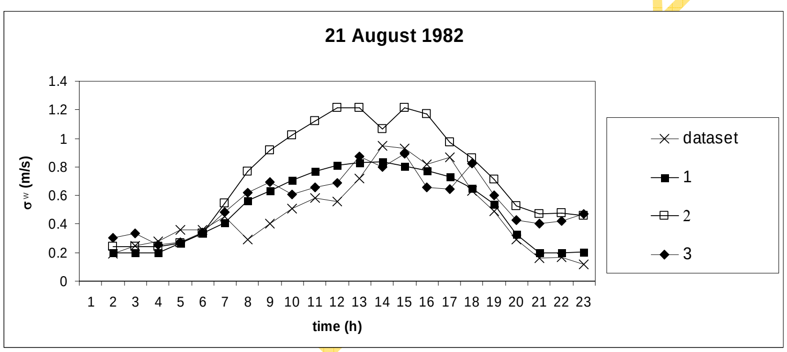
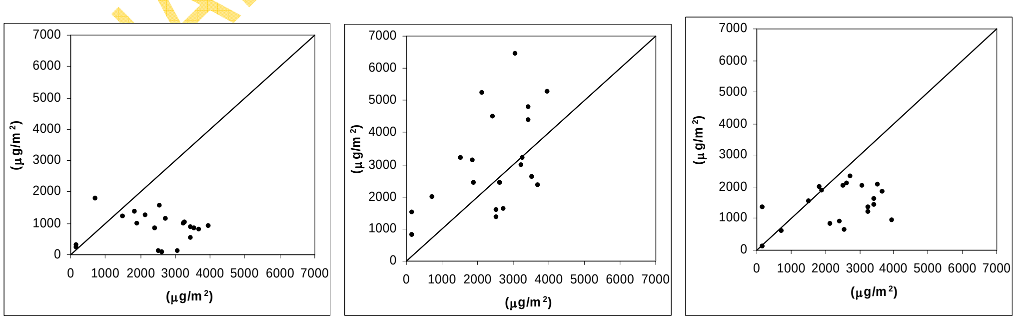


Fig. 2: Vertical wind standard deviation trend, dataset, 1 MY, 2 E-l- c_ε=0.17, 3 E-l- c_ε=0.4

Two different simulations were performed with the E-*l* closure setting the values of 0.17 and 0.4 for the constant c_ε. It results that E-l with c_ε=0.17 overestimated the measured data, MY exhibits a smooth trend while E-l with c_ε=0.4 follows the rapid variation of the measured data but fails at the end of the period considered.



a) b) c)

Fig. 3: Scatter plots (simulated vs. observed) of the three simulations: a) MY+SPRAY, b) E-l+SPRAY, c) MY+CALPUFF

The scatter plots obtained by the three dispersion simulations are shown in Figure 3. They represent the case of MY with SPRAY, E-*l* (c_ε=0.17) with SPRAY and MY with CALPUFF. The best performance is obtained using E-*l* with SPRAY, while the other two models underestimate the experimental data. This result is confirmed by the model evaluation performed by calculating the standard statistical indices (Table 1). It should be noted that this analysis is performed using 640 values obtained by all the receptors from 4 PM to 8 PM .
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Table 2. Models evaluation

Models	Mean	Sigma	Bias	NMSE	CORR.	FA2	FB	FS
OBS.	0.1	0.2	0	0	1	1	0	0
MY+SP	0.02	0.06	0.07	18	0.4	0.08	1.21	1.10
E-*l*+SP	0.11	0.25	-0.02	4	0.6	0.29	-0.20	-0.20
MY+CALP	0.05	0.15	0.04	3	0.8	0.19	0.55	0.27

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