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MODEL CHAIN FOR BUOYANT PLUME DISPERSION

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Abstract: The model chain is aimed to simulate high buoyant plume and can be applied in case of risk assessment and emergency response. It consists of the WRF mesoscale meteorological model and the SPRAYWEB dispersion model. The novelty lies in the new interface linking the two models. We use the Bull-Run data-set from the model evaluation kit in order to compare our results.

Key words: *Lagrangian model, pollution dispersion, plume rise*

INTRODUCTION

Emissions from many natural and anthropogenic hot sources are compared with the surrounding ambient air. Buoyancy effects cause the emitted plume to rise, increasing the effective source height and significantly decreasing the maximum ground level concentrations. A major aspect that distinguishes buoyant and passive dispersion is that buoyant fluid particles create their own turbulence and hence exchange processes between the plume and its environment need to be accounted for. The inclusion of plume rise in Lagrangian stochastic models of turbulent dispersion has been considered by many authors (i.e. Anfossi et al. 1993, Bisignano and Devenish 2015) but the interaction of the buoyant plume with the environment through the entrainment phenomenon is difficult to be modelled in a Lagrangian framework. In this work we develop a model chain for the dispersion of buoyant plumes. The meteorological input to the dispersion model is provided by the WRF (Weather Research and Forecasting) model in term of mean flow, temperature and wind profiles. Then a Lagragian stochastic model that satisfies the well-mixed condition calculates the pollutant concentrations. In order to verify our model chain we simulate the EPRI Bull Run experiments, which were conducted in moderately complex terrain. The plume was very buoyant, and the wind was often light and variable (Model Evaluation Kit, Olesen and Chang 2010). The results in term of statical analysis as indexes are presented.

THE DISPERSION MODEL

SPRAYWEB (Tinarelli et al, 1994; Alessandrini and Ferrero, 2009; Alessandrini et al. 2013) is a Lagrangian stochastic particle model 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:

$$\begin{aligned} dw &= a(z,w)\,dt + \sqrt{C_0}\,dW \\ dz &= w\,dt \end{aligned} \tag{1}$$

where dW is a Wiener process with 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, obtaining:

$$a(z,w)=\frac{1}{P}\left(B_0\frac{\partial P}{\partial w}+\Phi\right) \tag{2}$$

with $B_0=\frac{1}{2}C_0$ and, as suggested by Thomson (1987):

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

where $P(z,w)$ is the PDF that must be prescribed from the available measurements or parameterizations. In the present work, we used the Gram-Charlier PDF (Ferrero and Anfossi, 1998).
Furthermore SPRAYWEB includes the method for the buoyant plume rise simulation proposed by Anfossi et al. (1993). The dispersion model is coupled to the circulation model WRF, which provides the mean flow and from which the turbulence parameters are evaluated.

THE NUMERICAL WEATHER PREDICTION MODEL

WRF (Weather Research and Forecasting, http://www.wrf-model.org) modeling system is used for various forecast and analysis applications, from the microscale to the synoptic and even global scales. WRF includes dozens of parameterizations for boundary layer processes, convection, microphysics, radiation, and land surface processes, and several options for numerical schemes (Skamarock et al., 2008). In the following we list the choice for some physics parameter. The WRF pre-processing module, WRF Preprocessing System (WPS), sets the computational domain, the geographical projection, and the resolutions both in the horizontal and in the vertical, and interpolates the meteorological fields used as initial and boundary conditions. In order to simulate the EPRI Bull Run experiments we used the NNRP data, that is the NCEP/NCAR reanalysis with a resolution of 2.5 deg, a six hours output frequency , 17 pressure levels. In the WRF simulation we used WSM 5-class scheme as microphysics option, the RRTM scheme for the longwave radiation, the MM5 (Dudhia) scheme for the shortwave radiation, the Monin-Obukhov similarity theory as surface scheme, the Noah Land Surface Model (Unified ARW/NMM version in Version 3) for the surface physics, the YSU PBL scheme (Hong, Noh and Dudhia 2006) for the PBL parameterization, the Kain-Fritsch as cumuls scheme, and a 2nd order diffusion on model levels with constant k.

WRF-SPRAYWEB INTERFACE

The most inherent difficulty in interfacing WRF and SPRAYWEB lies in the different coordinates used to formulate the equations. SPRAYWEB uses terrain-following coordinates (x,y,s) to express the orography that are related to the cartesian coordinates (x,y,z) as:

$$x=x \quad y=y \quad s=\frac{z-z_g(x,y)}{z_t-z_g(x,y)} \tag{4}$$

where z_t is the top of the domain and $z_g(x,y,z)$ is the orography. Hence $s=1$ for $z=z_t$ and $s=0$ for $z=z_g(x,y)$ so that $s=0$ is not a horizontal plane but the orographic surface.

In WRF the vertical coordinates are terrain-following as well, but they are expressed as terrain-following hydrostatic-pressure (Laprise 1992) coordinates defined as:

$$\eta = \frac{p_h - p_{ht}}{p_{hs} - p_{ht}} \tag{5}$$

where p_h is the hydrostatic component of the pressure, p_{hs} and p_{ht} refer to the values along the surface and top boundaries respectively. This coordinate definition is analogous to the traditional σ coordinate use in many hydrostatic models but η varies from a value of 1 at the surface to a value of 0 at the upper boundary. η are also called vertical mass coordinate and they are time-dependent. Hence we need a time independent mapping from η to s in order to match the WRF output with the SPRAYWEB input. In particular we choose s to be equivalent to a certain η at fixed time and then we interpolate all the time-dependent WRF output variables on this given η. Then we use the Hanna (1982) parameterisation in order to evaluate the turbulence parameters.

BULL RUN DATA SET

The models have been applied to the Bull Run experiment (Hanna and Paine 1989) . Hourly ground level concentrations due to SF6 emissions from a 244 m stack at Bull Run, a moderately hilly site near Oak Ridge, Tennessee, were observed by a network of about 200 monitors, spaced on arcs at downwind distances ranging from 0.5 to 50 km during convective conditions. In Figure 1 the topography from WRF simulation, the receptors and the source position are shown. Generally, about 5 arcs of monitors were operating. The monitoring arcs extended completely around the stack, since the winds were often light and variable at that site during the field study period of August-October 1982. In particular we choose for the simulations the day 5 October 1982 when the tracer was released for 12 hours starting at 9 LST (Local Standard Time) and the hourly measurements have been performed for 9 hours since 11 LST. In Figure 2 we plot the wind speed and the temperature of air evaluated from WRF showing that October 5th 1982 was a sunny day with low winds.

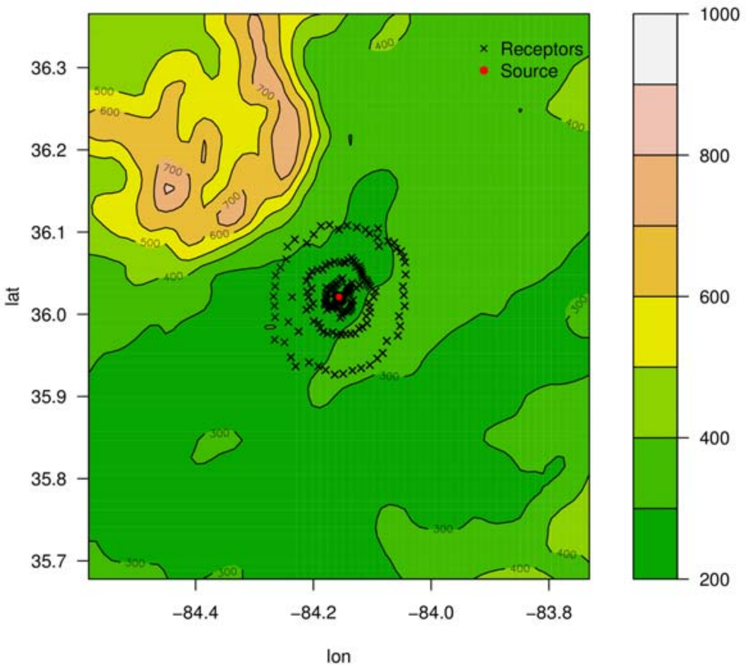

Figure 1. Topography, receptors positions on 4 arcs and source position (centre of the figure).

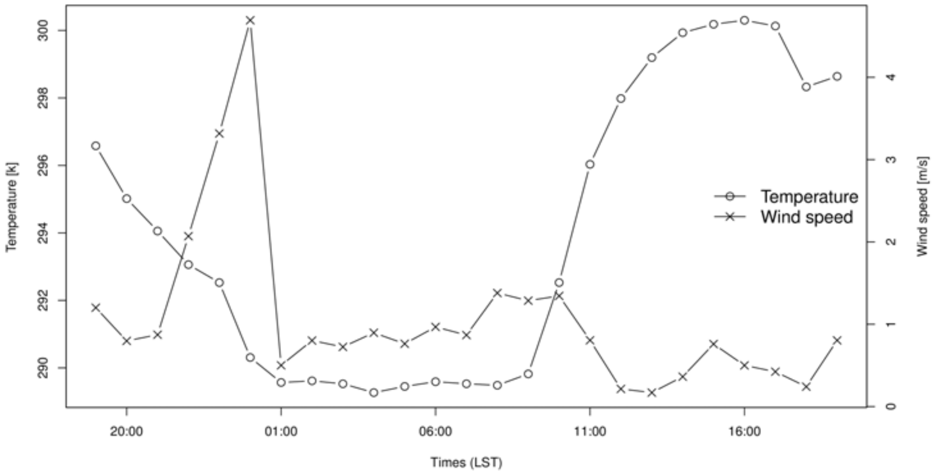

Figure 2. Wind speed and temperature measured near the surface by the WRF simulation during 5 October 1982.

SIMULATION AND RESULTS.

WRF was run using for horizontal nested grids corresponding to domains of extension 3960 km, 1320 km, 440 km and 73 km with horizontal resolution equal to 30000 m, 10000 m, 3333 m and 1111 m respectively. In the vertical direction a stretched grid of 38 levels from η=1 to η=0. The integration time steps for the three grids were 90 s, 30 s, 10 s and 3 s, respectively. The WRF simulation was carried out for a period of 24 hours from 5 October 00 UTC until 6 October 00 UTC. The initial and boundary conditions were provided by the NNRP data from NCEP/NCAR analysis. The results of the SPRAYWEB simulation evaluation are presented in Table 1 for the maximum of concentration at ground, and in Table 2 for the crosswind integrated concentrations. Following Hanna and Paine (1987), we considered the ground level concentrations measured at three arcs with radius 2, 5, 10 km. The comparison is performed in terms of maximum of concentration and cross wind integrated concentrations on the three arcs. The SPRAYWEB simulation refers to time period 15-18 (LST). We compared the obtained results with the measurements, in term of the following statistical indexes: mean, correlation coefficient (COR), normalised mean square error (NMSE) and fractional bias (FB). The first line indicates the expected value for a “perfect model” where mean and standard deviation are calculated from the measured data provided in the Bull Run data set.

Table 1. Maximum of ground level concentration

	Mean (μg/m^2)	**CORR**	**NMSE**	**FB**
Measured	256.333	1.000	0.000	0.000
Simulated	288.714	0.928	0.017	0.119

Table 2. Crosswind integrated concentration

	Mean (μg/m^2)	**CORR**	**NMSE**	**FB**
Measured	6625.421	1.000	0.000	0.000
Simulated	5149.403	0.903	0.219	-0.250

CONCLUSION

The statistical indexes presented in Table 1 and Table 2 exhibit a good agreement between the measures and the simulation results. The correlation is very high both for the maximum of concentration at ground and the crosswind integrated concentration. The normalised mean square error is smaller for the maximum of ground level concentration but the value for the crosswind integrated concentration is acceptable as well. The fractional bias shows a slight overestimation for the maximum and an underestimation for the crosswind integrated concentration.

Future developments would include the following features:

- several PBL schemes available in WRF will be tested in order to understand which one is the most appropriated to build the model chain with SPRAYWEB
- different turbulence parameterisation will be implemented in the interface code.
- new plume rise schemes (Alessandrini et al., 2013; Bisignano and Devenish, 2015) will be developed in SPRAYWEB.

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