H13-37
PERFORMANCE OF DIFFERENT MODELS TO EVALUATE ATMOSPHERIC DISPERSION IN CALM WIND CONDITIONS

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Abstract: This study investigates the performance of different air pollution dispersion models in wind calm conditions. The models have been applied to two case studies: the cities of Modena and Reggio Emilia, both placed in the Po river valley (Northern Italy), an area characterized by prevailing weak wind conditions. The emission sources are the municipal waste incinerator of Modena and the Turbo Gas plant of Reggio Emilia. Total suspended particulate (TSP) concentration levels are estimated by three models: the gaussian Industrial Source Complex (ISC3) and WinDimula 3.0 models, and the langrangian particle model SPRAY. The performances of the models have been compared: ISC3 provides less reliable results, while SPRAY and WinDimula 3.0 have shown a good capability to describe a domain characterized by wind calm conditions and SPRAY simulation performs significantly better in the vicinity of the source.

Keywords: *Dispersion models, air quality, wind calm conditions.*

INTRODUCTION

Air pollution dispersion models are largely applied to describe the distribution of pollutants, in order to identify the contribution of different emitting sources and to forecast their impact on air quality. Italian law (DL 351/99) allows the application of these models. The models available are many, with different degrees of complexity and different performances; the simulation of pollutant dispersion by different models may produce not comparable results in some typical atmospheric conditions, such as wind calm, during which the dispersion processes are mainly driven by turbulence. Wind calms and high pressure conditions enhance pollutant accumulation in the atmosphere, leading to deterioration in air quality.

The lagrangian particle model SPRAY and the gaussian ISC3ST and WinDimula models have been tested in the present study. The atmospheric dispersion of total suspended particulate (TSP) emitted from two point and steady state sources has been simulated with both the lagrangian and gaussian models. The sources considered in the study are the stacks of the municipal waste incinerator of Modena and of the Turbo Gas plant of Reggio Emilia. The cities of Modena and Reggio Emilia are located in the central part of the Po river valley (Northern Italy), an area characterized by flat topography and prevailing conditions of weak winds, often occurring in autumn and winter seasons. The time period covered by each simulation is one year. Wind calm conditions (i.e. wind speed lower than 2 m/s) occurred for about 78% of the simulation time in Reggio Emilia and about 30% in Modena site (Database CALMET-SIM).

The main purpose of the application of SPRAY, ISC3ST and WinDimula was to analyze and compare the differences between the concentration distribution patterns of TSP in air at ground level simulated by the three models, with major attention to the vicinity of the source. The evaluated maximum concentrations of TSP are always well below the threshold levels established by Italian law and are generally very low, having negligible effects on the air quality.

DISPERSION MODELS

The package Aria Industry is composed of three main models: the dispersion model SPRAY, the diagnostic meteorological model MINERVE (Geai, P., 1987; ARIA Tech., 2001) and the turbulence model SURFPRO (ARIANET, 2007). SPRAY (Arianet, 2007; Tinarelli, G. *et al.*, 1998) is a 3D lagrangian stochastic particle dispersion model able to simulate air pollution dispersion and deposition-decay phenomena in non homogenous, non stationary conditions and over complex topography (Thomson, D.J., 1987). SPRAY supplies a 3D concentration field subdivided into grid cells vertically structured into terrain-following layers separated using a logarithmic progression.

The model WinDimula 3.0 (Cagnetti, P. and M.C. Cirillo, 1982; Cirillo, M.C. *et al.*, 1986) is an atmospheric multisource gaussian steady-state dispersion model of non reagent pollutants generated by point, line and area sources. The model may operate over complex topography. Short time (ST) and long time (LT) version are available. Calm conditions are treated (for wind speed < 1 m/s) by means of the Cirillo-Poli algorithm (Cirillo, M.C. and A.A. Poli, 1992).

The dispersion model ISC3 (US EPA, 1995) is a steady-state gaussian model allowing to assess pollutant concentrations from point, area and volume sources; it may operate in ST and LT modality. ISC3 is mainly suitable for preliminary investigations based on the average meteorological conditions seasonally occurring in the studied site. A treatment of the calms is not included; wind speeds lower than a given value may be neglected or set equal to it. The two gaussian models supply a 2D concentration field at a user-specified height.

STUDIED DOMAINS, SOURCES FEATURES AND METEOROLOGICAL DATASET

The model domain for Modena site covers an area of 15x15 km^2; the center of the domain is in the emission source. The domain origin (South-West corner) is located at cartographic coordinates 646613 m East and 4942233 m North (UTM33-WGS84). The computation grid has a regular step of 100 m. Spray divides the domain into 25 layers from the ground to 1500 m; only the concentration field at 10 m is calculated by ISC3 and WinDimula. The simulation period spans over one year, from October 1st, 2006 to September 30th, 2007.

The emission source is a municipal incinerator with three combustion lines and a whole waste treatment capacity of 120 000 t/y. The stack is simulated as a point source. The concentration of TSP in the emission flow rate of the plant has been put equal to the maximum established by Italian law (D.L. 133/05).

The computational domain for Reggio Emilia site is 20x20 km^2, with a resolution of 500 m. The domain origin (South-West corner) is located at cartographic coordinates 617777 m East and 4942835 m North (UTM32-ED50), with the emission source in the domain center. The computational grid has the same features reported above.

The simulation period spans over a year, from September 1st, 2004 to August 31st, 2005. The emission source is the stack of a Turbo Gas plant with a combustion thermal power of 129.6 MW. The emission of TSP results from the measured concentration in the maximum flow rate for the plant; the data have been supplied by the utility manager.

The simulations were performed using meteorological data acquired by Osservatorio Geofisico of the University of Modena and Reggio Emilia (Modena, Italy) and meteorological data simulated by CALMET model provided by the Emilia-Romagna Meteorological Service. Hourly meteorological data were given as input to the models MINERVE and SURFPRO for the simulation with Spray. ISC3 and WinDimula models operated in short-term modality. The meteorological data at the source used by the gaussian models were extracted from the MINERVE database. The SPRAY, ISC3 and WinDimula simulations result from the average of hourly runs, due to hourly meteorological data. The WinDimula model was applied only to the Modena scenario.

RESULTS AND DISCUSSION

The average concentration levels and concentration maps at the ground obtained from the one-year-long simulation runs resulted very similar for the three models; this outcome indicates that at the time scale of a year the spatial concentration patterns are substantially the same. For this reason the subsequent analysis involved the simulation results for a shorter time length.

Modena case

The simulation runs have been divided into two periods: the first from Oct. 01 to 27, 2005 (autumn, poor dispersion conditions), the latter from June 01 to July 20, 2006 (summer, meteorological conditions more favorable to pollutant dispersion). The ISC3 model simulations are performed setting all the wind speed values < 1 m/s equal to 1 m/s.

The first period is characterized by low mixing layer heights (100-200m) and high occurrence (85 %) of wind calm events; the wind speeds are generally very low, with only the 0.3 % resulting > 5 m/s.

The simulations performed by the three models show relevant differences in the spatial distribution patterns of the TSP plumes and in the maximum concentration levels, whereas the difference in average TSP concentration at ground level for the whole period resulted below 10%.

The SPRAY concentration maps show larger areas among the isopleths for concentration values < 0.08 $\mu g/m^3$ and small areas where the concentration increases rapidly (higher concentration gradient). ISC3 and WinDimula maps show a more homogeneous and steady decrease of the areas among the concentration isopleths. If a cut-off level in TSP concentration of less than 0.05 $\mu g/m^3$, is considered, the surface covered by the plume corresponds to 16.3 % of the whole domain area in the SPRAY map, 21.3 % in ISC3 and 18.5 % in WinDimula respectively (Fig. 1, left).

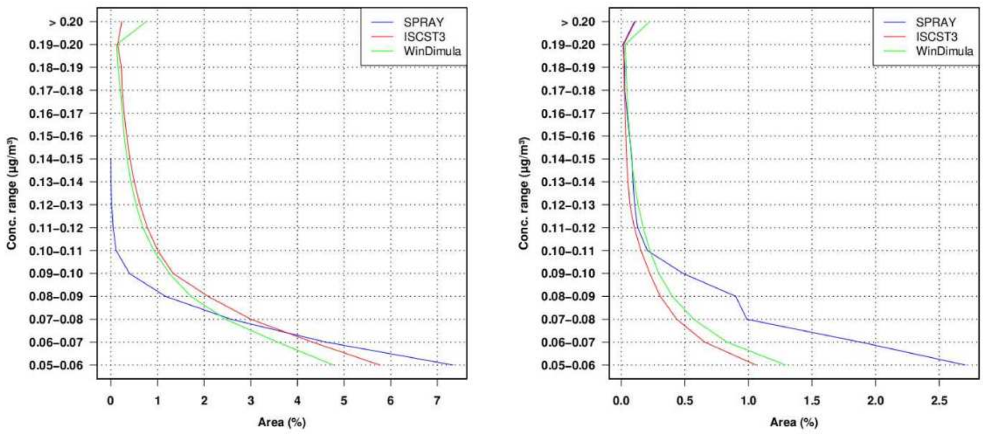

Figure 1. Areas (in percentage of the whole domain area) included between concentration isopleths at the ground for the simulations performed with SPRAY, ISC3 and WindDimula for the Modena case study and for the two tested periods: from October 1st, 2005 to October 27th, 2005 (left) and from June 1st, 2006 to July 20th, 2006 (right).

For all three models the plume shape (Fig. 2) is stretched along the main axis of the Po valley (approximately from West to East). The lagrangian plume boundaries spread irregularly, due to the stochastic motion component that well simulates turbulent dispersion, whereas the less realistic gaussian plumes are excessively stretched windward by weak winds (speed < 1 m/s). The concentration maxima calculated by the gaussian models fall approximately in the same point (black dots in Fig. 2), close to the source; the SPRAY maximum is placed about 1500 m from them, farther from the source, and its concentration value is lower.

WinDimula describes better than ISC3 the upwind zone closest to the source, even if the concentration values obtained by the Cirillo-Poli algorithm may be overestimated: the number of wind speed < 1 m/s events are uniformly assigned to the direction of the first upper class of wind speed, increasing its occurrence.

Hourly concentration and wind speed values are quite well correlated in WinDimula simulations and scarcely correlated in ISC3 (r = 0.58 and r = 0.40 respectively), in disagreement with the gaussian diffusion equation (Oke,T.R., 1978); a more realistic very low anti correlation (r = - 0.18) results from SPRAY.

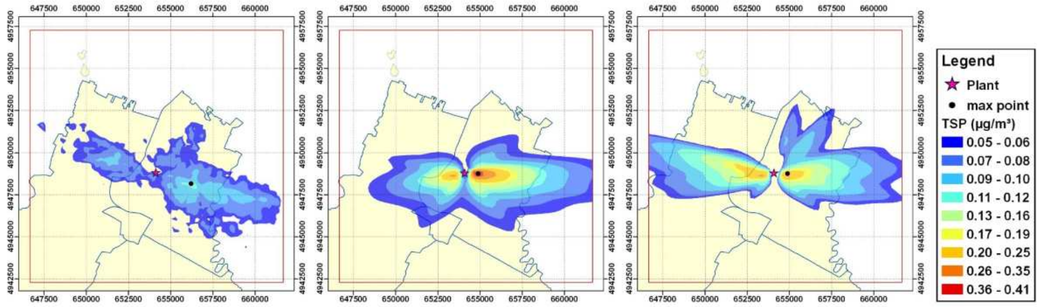

Figure 2. TSP concentration plumes at the ground from the simulations performed with SPRAY (left), WinDimula (centre) and ISC3 (right) for the Modena case study, from October 1st, 2005 to October 27th, 2005. Points of maximum concentration are also reported (black dots).

The different performance of SPRAY compared to the gaussian models in wind calm conditions has been further investigated limiting the TSP dispersion to a four-day-long simulation period, contained in the tested one, with wind speed constantly < 2m/s; the simulated concentration maps at ground level have been evaluated through each model. In figure 3 are presented the four-day-period concentration values along a circumference, centered in the source and with a radius of 1 km and 2.5 km.
The concentrations extracted along the 1-km-radius circumference have mean values of results 0.08 µg/m^3 for SPRAY, 0.09 µg/m^3 for ISC3 and 0.13 µg/m^3 for WinDimula. The plot in Fig. 3 (left) shows higher concentrations estimated by WinDimula and ISC3 due to weak westerly wind episodes, whose effect is emphasized by the gaussian models. SPRAY simulation is more reliable, with a quasi random variability of the concentration values around the source. SPRAY simulates a similar behavior also at 2.5 km from the source (Fig. 3, right). The gaussian models encounter major difficulties in the simulation near the source, while they perform better far from it: in fact along the 2.5-km-radius circumference the simulations of the three models show a higher agreement and the average concentration level is very similar: 0.080 µg/m^3 (SPRAY), 0.076 µg/m^3 (ISC3) and 0.075 µg/m^3 (WinDimula).

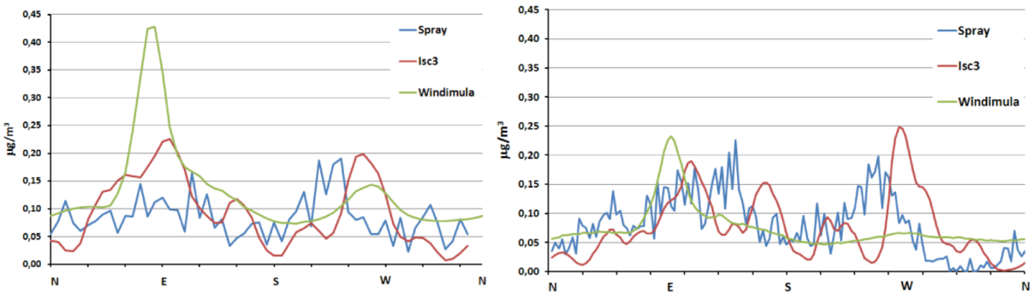

Figure 3. Concentration values at the ground from four consecutive days of wind calm (October 2005) along a circumference centered at the source with 1 km radius (left) and along a circumference with a 2.5 km radius (right), from the simulations performed with SPRAY, ISC3 and WindDimula (Modena case study)

<u>In the summer period</u> the average mixing height is 800 m and wind calms (0-2 m/s) occur for 20 % of the whole period, with only 3% of events of wind speed < 1 m/s. The more relevant role of wind transport in pollutant dispersion determines similar concentration distribution patterns for the three models and lower plume surfaces at ground level: if a cut-off level in TSP concentration of less than 0.05 µg/m^3, the plume surface is 7.5 % of the whole domain for the SPRAY simulation, 3.3 % for the ISC3 and 4.6 % for the WinDimula (Fig. 1, right). The SPRAY plume surface mainly results from larger areas among the concentration isopleths for TSP < 0.08 µg/m^3, as in the previous period, due to the effect of turbulent mixing simulated by this model. The concentration maxima for the gaussian models are slightly higher than for SPRAY and are placed about 300 m from it. The concentration values are correlated with the wind speed in WinDimula (r = 0.44) and also in ISC3 (r = 0.46) simulation, while no significant correlation results from SPRAY data.

Reggio Emilia case

Wind calm conditions (wind speed less than 2 m/s) occurred in Reggio Emilia for about 78% of the studied year. Of the remaining 22% wind events, about 15% correspond to wind speed lower or equal to 3 m/s. As in the Modena case, two shorter simulation periods were examined.
The first period spans from Nov. 27th, 2004 to Dec. 24th, 2004 and is characterized by critical meteorological conditions: 91% wind calm, low values of the mixing height (100-200 m) and cloud cover that reduces the diurnal temperature variation; in the second period, from May 9th, 2005 to June 21st, 2005, the mixing height values (> 800 m) and a minor occurrence of wind calms (51 %) promote pollutant dispersion in the atmosphere.
The ISC3 model concentration fields are calculated neglecting wind speed values < 2 m/s.
The TSP concentration values are always very low, due to the low emission rate of the source; <u>during the first period</u>, due to the persistence of conditions not favorable to dispersion, the highest average concentration values over the whole examined year are reached. The pollutants accumulate in atmosphere close to the plant.
In this period the prevalent and very weak wind component blew from West. The situation is well simulated by SPRAY (Fig. 4, right), whose concentration map shows a plume enlarged by turbulence, slightly driven eastward of the source. The ISC3 simulation (Fig. 4, left) defines a not reliable plume stretched at North East of the plant; the concentration level results one

order of magnitude lower than in the SPRAY simulation and the source point is not included the plume. The correlation between the results of the two simulations is poor (r = 0.36).

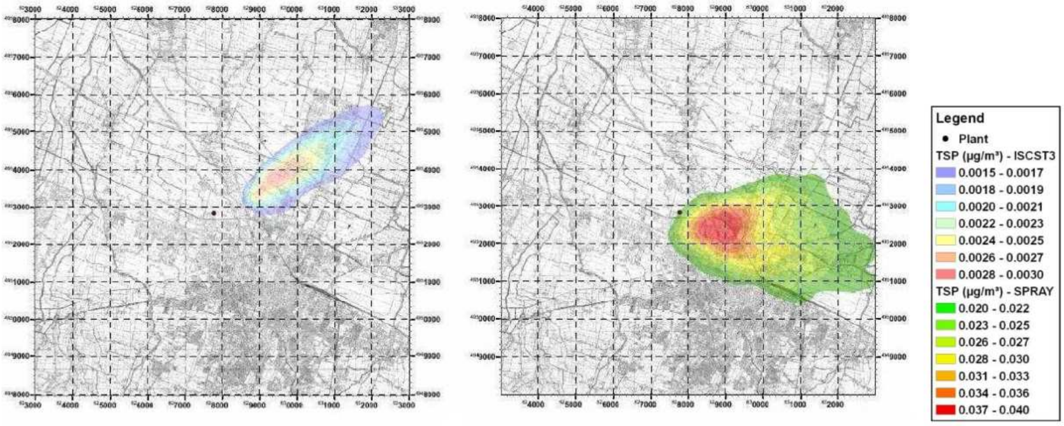

Figure 4. TSP concentration plumes at ground level emitted from the Reggio Emilia Turbo Gas source (center point of the domain) simulated by ISC3 (left) and SPRAY (right), from November 27th 2004 to December 24th, 2004.

<u>In the second period</u>, meteorological conditions favorable to pollutant dispersion and few episodes of wind calms lead to a higher agreement between the SPRAY and ISC3 simulation (Fig. 5). The plume shape and spatial distribution are similar and the concentration values are comparable, even if they result higher for ISC3 compared to SPRAY evaluation. The correlation between the results of the two simulations is better (r = 0.53).

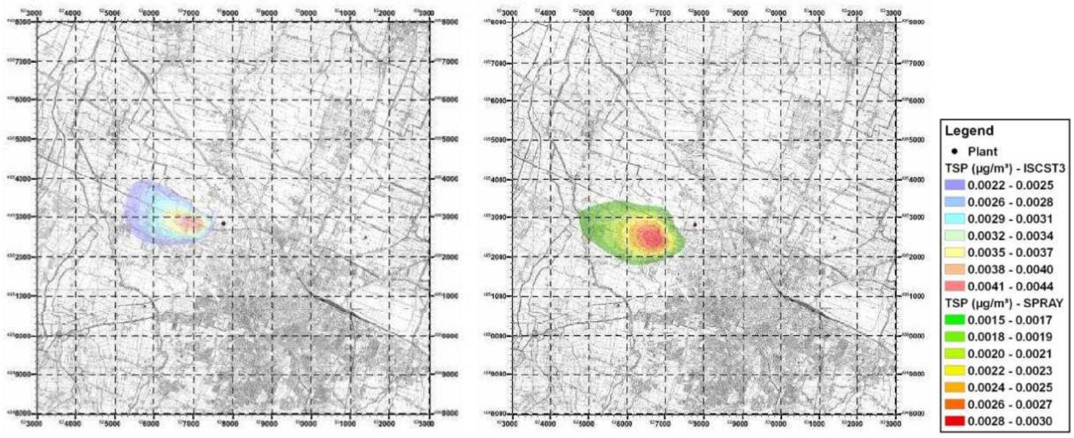

Figure 5. TSP concentration plumes at ground level emitted from the Reggio Emilia Turbo Gas source (center point of the domain) simulated by ISC3 (left) and SPRAY (right), from May 09th, 2005 to June21st, 2005.

CONCLUSIONS

This work has tested the performance of three models, SPRAY, ISC3 and WinDimula, to simulate the dispersion of a chemically inert pollutant continuously emitted at a steady rate from a point source. Two case studies have been investigated and in both of them the three models have been supplied with the same source and meteorology data set.

Yearly and monthly simulation runs have been used: both prevalent wind calm condition periods and high dispersion condition periods have been examined. The concentration maps from the three models are in agreement for simulation runs over a year and also for shorter simulation periods, if wind calm episodes are infrequent.

When critical conditions prevail during the simulation period, ISC3 and WinDimula do not perform as well as SPRAY. ISC3 does not include a calm condition treatment, and WinDimula introduces it only for wind speed < 1 m/s; it emphasizes the effect of too weak winds (with speed < 2 m/s), simulating plumes that are stretched rather far from the source. The maximum concentration points are close to the source, while the plumes affect marginally or exclude (ISC3 simulation) the source zone at ground level. The concentration field resulting from ISC3 depends strongly on the conditions for wind speed. In the Modena scenario all wind speed values < 1 m/s have been set equal to 1 m/s, while in the Reggio Emilia scenario wind speed values < 2 m/s have been neglected. Both conditions are not very realistic, leading to an overestimation of maximum concentration values in Modena, whereas the concentration map simulated in the Reggio Emilia scenario by ISC3 is clearly underestimated.

The WinDimula simulation of wind calms is performed using the Cirillo-Poli algorithm. This method uniformly assigns the number of weakest winds events (speed < 1 m/s) to the direction of the first upper class of wind speed: it is a rather forced assumption, because, during the calms, weak winds may blow in any direction. The frequencies of the first class winds are then increased using this algorithm, and the maximum concentration values close to the source are for this reason frequently overestimated.

In wind calm conditions the advective transport is reduced and the pollutants are homogeneously distributed over the whole mixed layer depth, where they accumulate also very close to the source. The lagrangian simulation describes more satisfactorily this situation: the size and the shape of the plume are mainly determined by the turbulent mixing and the

concentration field at ground level is more uniform. The area covered by the lagrangian plume at ground level is lower than the gaussian plume surfaces and also the maximum concentration values calculated by SPRAY are lower.
These results confirm that ISC3 and WinDimula are mainly suitable for climatologic application over long time period; ISC3 should not be applied during wind calm conditions, WinDimula performs better than ISC3, while SPRAY gives the most reliable simulation of the air quality deterioration due to pollutant emission in wind calm conditions.

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