CFD and Mesoscale Air Quality Applications in Urban Environments: Madrid Case Study

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Abstract: - In this contribution we show the implementation of an adapted CFD code, developed by the University of Karlsruhe (Germany) and a mesoscale air quality modelling system composed by MM5 (PSU/NCAR) and CMAQ (EPA, US) and an emission model EMIMO, developed by the Technical University of Madrid (UPM). The system includes a cellular automata model, CAMO, developed by UPM as part of the traffic emission system in order to accommodate the high spatial and temporal resolution emission datasets which are required by the CFD model. The CFD and emission system is called MICROSYS. The mesoscale meteorological and air quality dispersion model provides the boundary and initial conditions for MICROSYS. Different scenarios have been tested based on the reduction of traffic cars and increase of public transportation. The results show that the MICROSYS and the mesoscale air quality modelling system provide detailed and sensitive results to the different scenarios. The results show that the system can be used for analyzing many different situations in urban environment with a high level of detail and could be used as a management tool for air quality impact studies at urban level.

Key-Words: - CFD, air quality, mesoscale, cellular automata.

1 Introduction

Important advances on Computational Fluid Dynamics models and Air Quality Modelling Systems have occurred during the last years. The increase on computer capabilities and on the knowledge of turbulence parameterization and numerical schemes has also been very important during the last ten years. On the other hand, there is a considerable public interest on information related to the "real" pollution they are exposure on when they are walking in the street going to work or even during the period they are driving a car from/to work or other daily activities. At street level the differences in the concentration values at both sides of a street can be important, particularly, for instance, on relation to photochemical production during summer time in Mediterranean regions. In this contribution we have used the CFD model MIMO (U. of Karlsruhe (Germany)) and the mesoscale air quality modelling system MM5-CMAQ-EMIMO (NCEP / EPA / Technical University of Madrid) to simulate the impact of different emission reduction scenarios in the downtown area of Madrid City. These complex systems could evaluate the impact of several urban strategic emission reduction measures such as reduction of private traffic, increase of public transportation, impact on introduction of new fuel cell vehicles, etc. Also, they could be used for analysis of pollution concentrations at different heights (buildings) and on different areas of urban neighbourhoods. Air dispersion in urban areas is affected by atmospheric flow changes produced by building-street geometry and aerodynamic effects. The traffic flow, emissions and meteorology are playing also an important role. Microscale air pollution simulations are a complex task since the time scales are compared to the spatial scales (micro) for such a type of simulations. Boundary and initial conditions for such a simulations are also critical and essential quantities to influence fundamentally the air dispersion results. Microscale Computational Fluid Dynamical Models (CFDM) are playing an increasing role on air quality impact studies for local applications such as new road and building constructions, emergency toxic dispersion gases at urban and local scale, etc. Microscale air dispersion simulations are applied to predict air-flow and pollution dispersion in urban areas.

In this contribution we have applied the microscale dispersion model MIMO [8] to simulate different emission reduction scenarios in Madrid (Spain) related to the vehicle traffic conditions. The MIMO CFD code has been adapted and incorporated into a mesoscale air quality modelling system (MM5-CMAQ-EMIMO) to fit into the one-way nesting structure. MM5 is a meteorological mesoscale model developed by Pennsylvania State University (USA) and NCAR (National Centre for Atmospheric Research, USA) [4]. The CMAQ model is the Community Multiscale Air Quality Modelling System developed by EPA (USA) [1] and EMIMO is the Emission Model [6]. MM5 is a well recognized non-hydrostatic mesoscale meteorological models which uses global meteorological data produced by global models such as GFS model (NCEP, USA) to produce high resolution detailed three dimensional fields of wind, temperature and humidity which are used in our case as input for the photochemical dispersion model CMAQ [5]. In addition of MM5 output data, EMIMO model produces for the specific required spatial resolution, hourly emission data for different inorganic pollutants such as particulate matter, sulphur dioxide, nitrogen oxides, carbon monoxide and total volatile organic compounds VOC's. The VOC's are splitted according to SMOKE (Sparse Matrix Operator Kernel Emissions) [7] and [3]. The CFD and mesoscale models solve the Navier-Stokes equations by using different numerical techniques to obtain fluxes and concentrations at different scales. Mesoscale air quality models cover a wide range of spatial scales from several thousands of kilometres to 1 km or so. In this contribution we have applied the MM5-CMAQ-EMIMO models over Madrid domain to obtain detailed and accurate results of the pollutant concentrations at this spatial resolution and the MIMO CFD model over a 1 km x 1 km domain with several spatial resolutions (2 m – 10 m) and different vertical resolutions. MM5-CMAQ-EMIMO data serves as initial and boundary conditions for MIMO modelling run.

In Figure 1 we observe the spatial architecture for the application of the MM5-CMAQ-EMIMO mesoscale air quality modelling system. In figure 2 we show a detailed diagram of the EMIMO modelling system. EMIMO is currently operating with the so called Version 2 which includes the CLCL2000 (European Land Use database) with 44 different landuse types with 100 m spatial resolution. EMIMO 2.0 also uses the CIESIN 30'' [2], population database and the Digital Chart of the World 1 km land use database to produce adequate emission data per 1 km grid cell per hour and per pollutant. In order to apply the EMIMO CFD model, we need detailed information related to the building structure in the 1 km grid cell. This information is shown in Figure 3 for the whole of the Madrid Community (Spain). The height of the buildings is not included in this file and it has been estimated directly for this experiment. A cellular automata traffic model (CAMO) has been developed. CAMO – which has been included into the EMIMO modelling system – is based on transitional functions defined in a discrete interval t as follows:

$$s(t+1) = p(s(t), a(t)) \quad (1)$$

$$u(t) = \nu(s(t)) \quad (2)$$

where s(t+1), s(t) is a defined sate, a(t) is an input symbol and u(t) is an output symbol. We have used the Moore neighbourhood with 8 different surrounding cells where each cell – representative of a vehicle – can move on. The whole system focusing on the 1 km x 1 km urban area in Madrid downtown is called MICROSYS system. We have selected a subdomain of 300 x 300 m with 5 m spatial resolution and 15 vertical layers for this particular experiment The first 10 layers are equally spaced with 5 m spatial resolution up to 50 m in height and the last five layers are located at 55, 61.55, 68.20, 75.52 and 83,58 m in height.

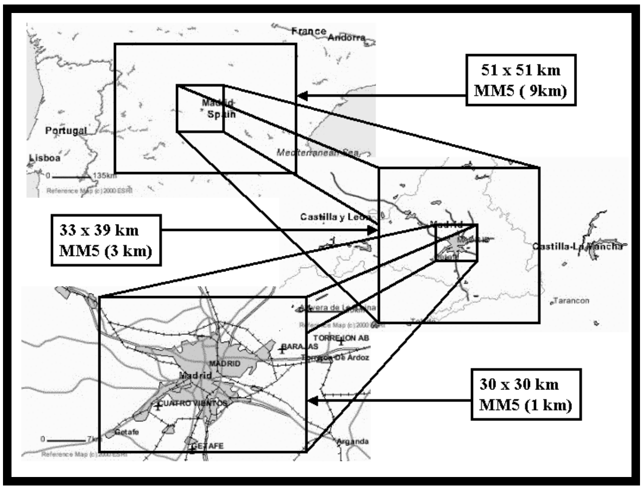

Figure 1. MM5-CMAQ-EMIMO architecture for this application.

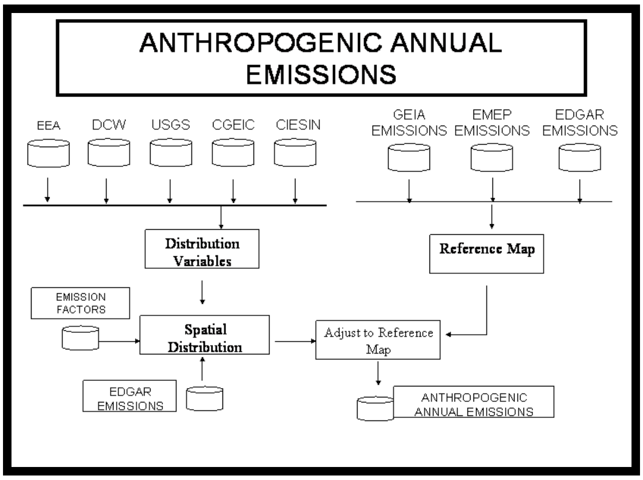

Figure 2. EMIMO model basic architecture.

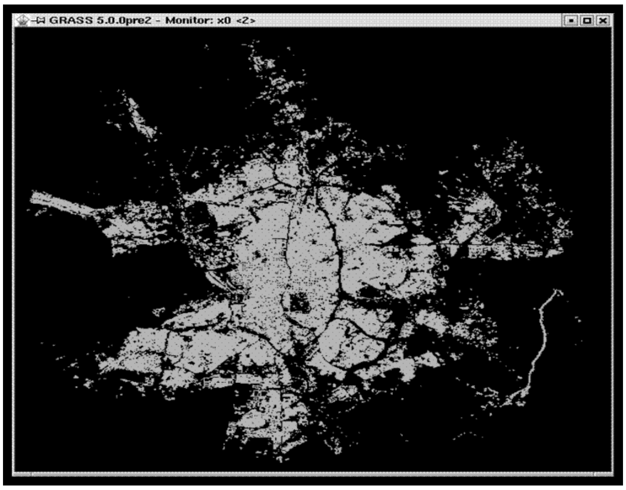

Figure 3. E00 vector file for Madrid Community.

Figure 4. Subdomain view for this experiment in Madrid City downtown area.

2 Results

We have done several tests. A preliminary test for July, 8, 2002 at 14:00 is shown in Figure 5 for NO2 data. In Figure 6 we show the results for the May, 20, 2003 at 10:00 hors. Complete different wind pattern is shown in both figures. Northern winds are presented early morning on that day and Southern winds are shown at 14:00 on the same day. The complexity of the wind pattern structure is clear from both pictures. In this experiment the prognostic mode has been used for producing both figures 5 and 6. In a further application, the system was applied to produce test results for a synthetic experiment related to the impact of different emission reduction scenarios and shown in Internet into the OSCAR EU project (EVK4-CT2002-00083 OSCAR). In this particular application, the system was run for different domains and scenarios in Helsinki (Finland), London (United Kingdom) and Madrid (Spain). In the case of Madrid, two different emission scenarios have been run: a) Normal traffic conditions and b) decreasing in 30% the total number of private cars and increasing in 15% the total number of public buses. Figure 7 shows the NO2 percentages obtained as differences between the scenario b) and scenario a) divided by the concentrations obtained in scenario a). We observe on the lower left corner a detail of a street angle located in the southern area of the square. In the whole domain the impact of reducing 30 % the total number of private cars and increasing in 15% the total number of public buses has an increase on the air pollution on 40 % on very specific areas (normally in the areas located near de buildings in the square or in specific hot spots in the streets. Most of the values for the "open" areas in the square and streets are on the negative side so that we have a reduction on NO2 concentrations when implementing the emission reduction strategy for this experiment described in scenario b). In Figure 8 we see two details of the Figure 7 when we zoom-in into the central and north areas of the domain. We observe that in the square itself most of the data is on the negative side with reductions up to 3.2 % but in the north area we observe that in the street on the left there are two hot spots with the maximum increase and decrease - +40 % and -30 % - which gives us a good confidence on model behaviour.

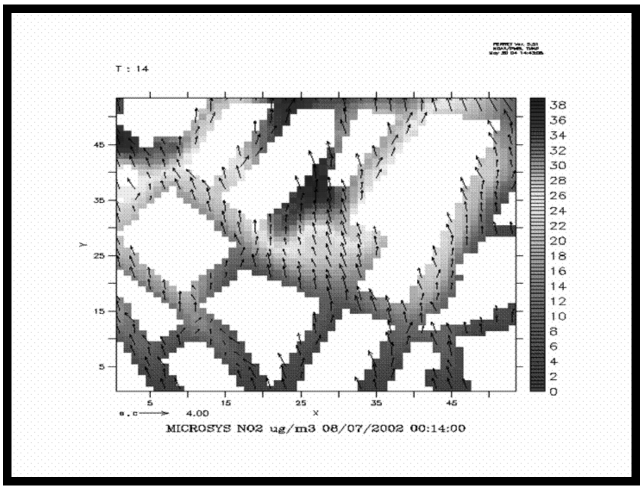

Figure 5. NO2 concentrations at 14:00 July, 8, 2002 produced by MIMO.

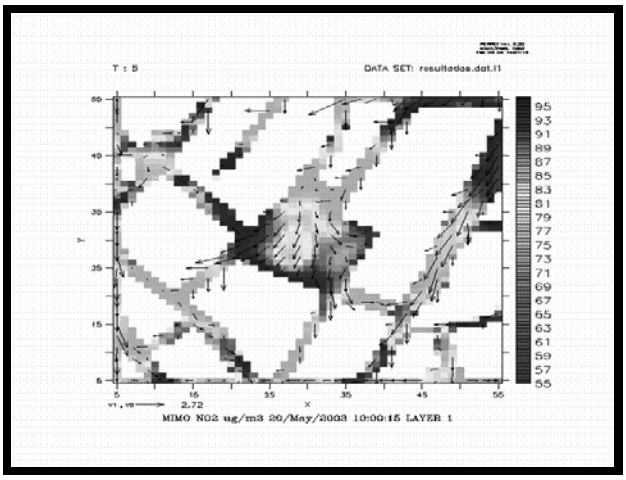

Figure 6. NO2 concentrations at 10:00:15 May, 20, 2003 produced by MIMO.

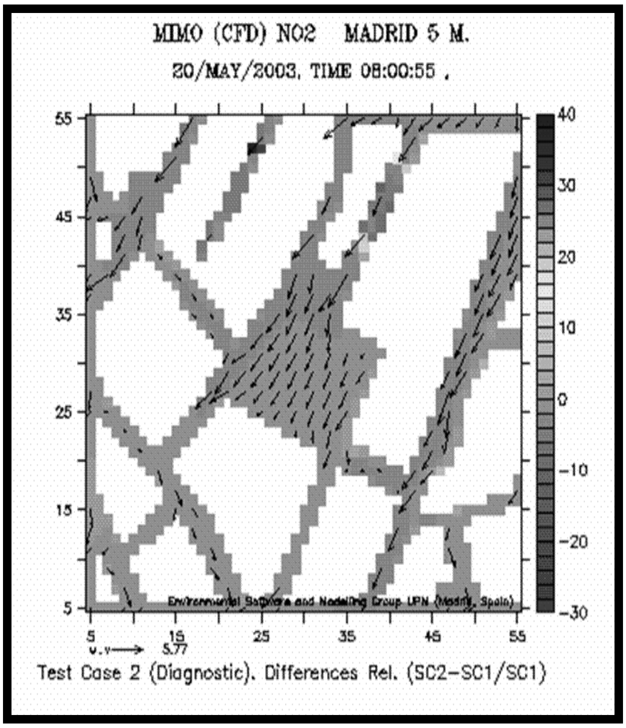

Figure 7. MIMO CFD results for NO2 at 08:00:55 May, 20, 2003 for the differences between scenario b) and scenario a) in percentage respect scenario a). Differences between +40 % and -30% are found. Most of the highest differences are found in the corners of the streets as expected due to the complexity of the turbulence on those areas.

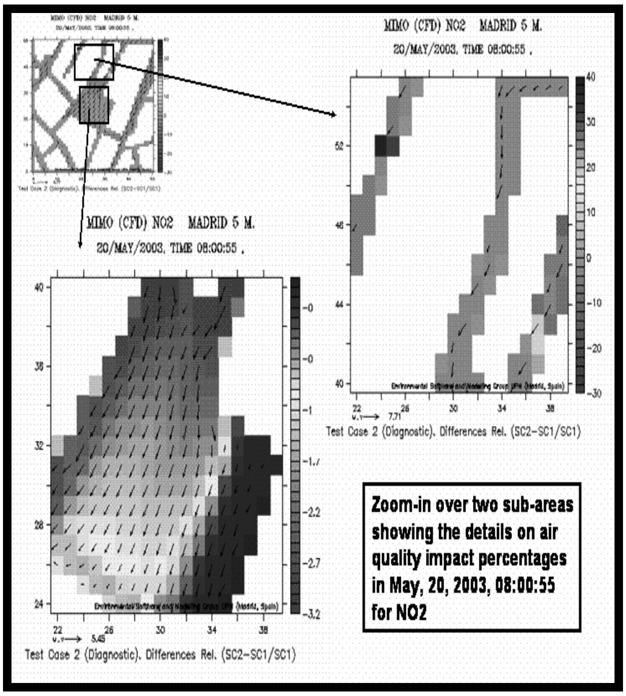

Figure 8. Zoom-in over two sub-areas in model domain for NO2 percentage impact when implementing scenario b) compared with scenario a). Left lower image shows that in square most of the impacts are on the negative side up to -3.2 % reductions on NO2 concentrations. In the upper-right image, we observe that two grid cells are "hot spots" with the highest increases and decreases in percentage (+40 % and -30 %).

3 Conclusion

The MM5-CMAQ-EMIMO modelling system has been used to provide detailed initial and boundary conditions to a system called MICROSYS which is composed by the MIMO CFD microscale dispersion model and CAMO which is a cellular automata traffic model. The results show that the air quality modelling system offers realistic results although no comparison with eddy-correlation measurement system has been performed in the area. The tool can be used for many air quality impact studies but in particular for traffic emission reduction strategies.

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References:

[1] Byun, D.W., J. Young, G. Gipson, J. Godowitch, F. Binkowsky, S. Roselle, B. Benjey, J. Pleim, J.K.S. Ching, J. Novak, C. Coats, T. Odman, A. Hanna, K. Alapaty, R. Mathur, J. McHenry, U. Shankar, S. Fine, A. Xiu, and C. Lang, 1998. Description of the Models-3 Community Multiscale Air Quality (CMAQ) model. *Proceedings of the American Meteorological Society 78th Annual Meeting Phoenix, AZ, Jan. 11-16, 1998*. pp. 264-268.

[2] CIESIN, 2004. Center for International Earth Science Information Network (CIESIN). Global Rural-Urban Mapping Project (GRUMP): Urban/Rural population grids. Palisades, NY: CIESIN, Columbia University. http://sedac.ciesin.columbia.edu/gpw/.

[3] Coats, C.J., Jr. 1995. High Performance Algorithms in the Sparse Matrix Operator Kernel Emissions (SMOKE) Modelling System, *Microelectronics Center of North Carolina, Environmental Systems Division, Research Triangle Park, NC*, 6 pp.

[4] Grell, G., J. Dudhia, and D. Stauffer 1994: A Description of the Fifty Generation Penn State/NCAR Mesoscale Model (MM5). *NCAR Tech. Note, TN-398+STR*, 117 pp.

[5] San José R., Prieto J.F., Castellanos N. and Arranz J.M. (1997) Sensititivity study of dry deposition fluxes in ANA air quality model over Madrid mesoscale area, *Measurements and Modelling in Environmental Pollution, Ed. San José and Brebbia*, pp. 119-130.

[6] San José R., Peña J.I., Pérez J.L. and González R.M. (2003) EMIMO: an emission model. 292-298. ISBN: 3-540-00840-3 Springer-Verlag.

[7] Williams, A., M. Caughey, H.-C. Huang, X.-Z. Liang, K. Kunkel, Z. Tao, S. Larson, and D. Wuebbles, 2001: Comparison of emissions processing by EM-S95 and SMOKE over the Midwestern U.S. *Preprint of International Emission Inventory Conference: One Atmosphere, One Inventory, Many Challenges*. Denver, Colorado, May 1-3, pp. 1-13.

[8] Ehrhard, J., Khatib I.A., Winkler, C., Kunz, R., Moussiopoulos, N. and Ernst, G. (2000). The microscale model MIMO: development and assessment. *Journal of Wind Engineering and Industrial Aerodynamics*, 85, 163-176.