Evaluation of a CFD Modeling Approach by Means of an Intensive Experimental Campaign Using Passive Samplers in an Urban Area of Madrid

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1. Introduction

- Interaction between urban morphology and atmospheric processes induces complex flow fields and strong spatial heterogeneities of pollutant concentration patterns.
- Air quality applications (e.g. urban air quality assessment, network design, microscale air pollution abatement strategies, etc) usually needs long time series (e. g. 8-hours, 12-hours, 24-hours or even annual averages) and detailed maps of concentration.
- Parra et al. (2010), Santiago et al. (2011) and Santiago et al. (2013) developed a methodology based on a set of steady state RANS simulations for a range of wind directions, that allowed to compute average concentration maps over large periods of time (weeks, months) at microscale.
- **Main Objectives:**
  - To validate this methodology based on CFD-RANS for computing detailed maps of concentration using measurements of NO_2 from two intensive experimental campaigns lasting several weeks that were carried out deploying a large number of passive samplers distributed in a heavily trafficked district in the city center of Madrid.
  - To identify the limitations of methodology

2. Numerical methodology

- The methodology is based on to run only a set of scenarios using steady CFD-RANS simulations (STAR-CCM+ code from CD-Adapco). The final map of average concentration is made by means of a combination of the simulated scenarios. Pollutant concentration is computed assuming non-reactive pollutants.
- For wind speed higher than 2 m s^{-1} at 10 m height a concentration proportional to the observed one at time t is computed using CFD results and Eq. 1. Note that we do not obtain the observed concentration because the number of vehicles inside each street is used as proxy of traffic emissions:

$$C_{\text{Observed}}(t) - C_{\text{background}} \propto C_{\text{computed}}(Sector(t)) = \sum_i C_i(Sector(t)) \cdot \frac{L_i}{Vsource_i} \cdot N_i(t) \cdot \frac{1}{v_{in}(t)}$$

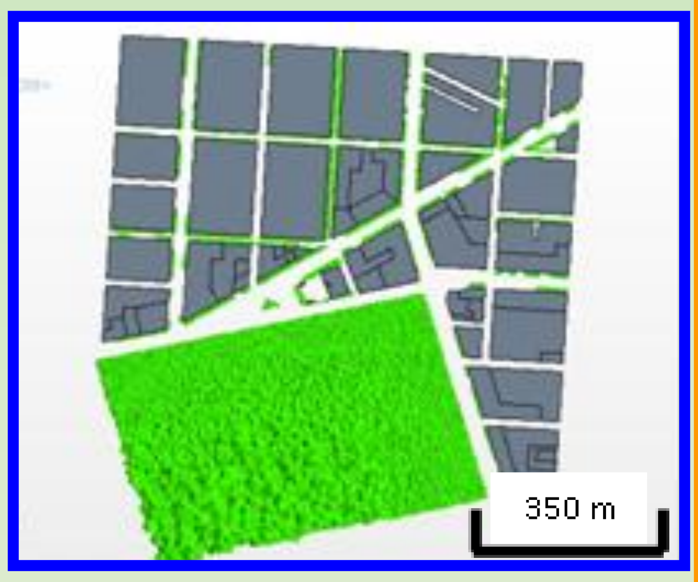
- $C_{\text{Observed}}(t)$ and $C_{\text{background}}(t)$: observed and background concentration at time *t; Sector (t): wind direction at time* k; *i: t*racer emitted inside each street, $C_i(Sector(t))$:concentration computed for *Sector*(*t*) for a given emission from street *i* and for a given inlet wind speed; L_i is the length of the street *i*, $Vsource_i$ is the volume of the row of computational cells where emission of the street *i* is located, N_i is the number of cars per unit time in street *i* and is the inlet wind speed.
- In the case of weak winds (lower than 2 m s^{-1}) the methodology was modified. For these cases, thermal effects are not negligible and we assume that the pollutant concentration is independent of wind direction and it is modelled depending on traffic intensity and mixing height along the day. This assumption allows taking into account indirectly the thermal effects.

3. Description of modeling domain, experimental campaigns and simulation setup

Aerial picture of the modeling domain (red line) including the location of the air quality monitoring station (blue dot)

3.1. Location and urban environment

- The urban area analyzed is located in Madrid City close to El Retiro park. In this zone there are several streets and avenues with intense road traffic and also there is a large green urban area (El Retiro). Buildings with different heights are located in this area; most of them have a height between 18 m and 24 m, although the tallest building is 90 m high approximately. A traffic air quality monitoring station (EA) is located in a garden very close to the sidewalk in the intersection of the two more important avenues. Meteorological data were provided by AEMET (Spanish Meteorological Agency) from the meteorological station located in El Retiro (the urban park South of EA station), approximately 200 m outside of the numerical domain. The urban park produces not negligible dynamical effects on pollutant dispersion



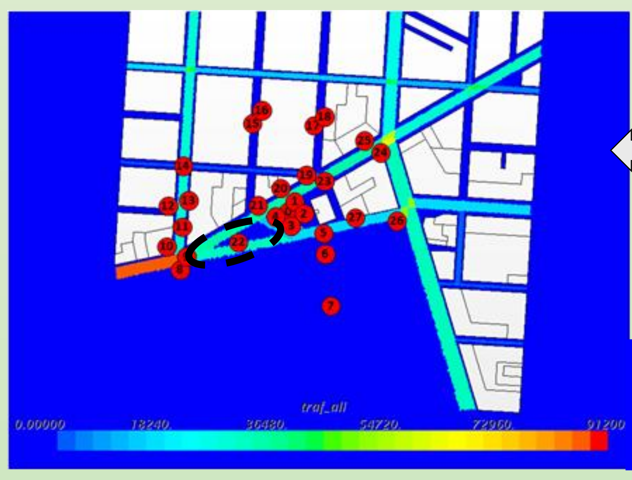
Modeled geometry of the domain including street and park vegetation

3.2. Simulation set-up

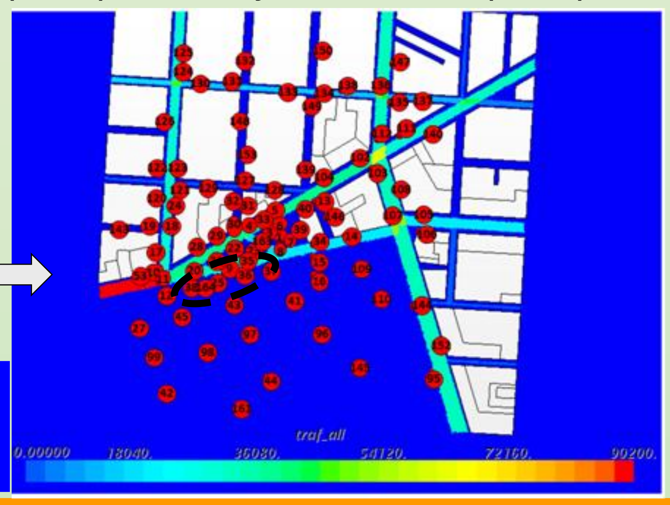
- Modelling domain: 700 m x 800 m, approximately.
- Hourly traffic data inside each street is estimated from the daily average traffic intensity (TI) data provided by the city council of Madrid, considering typical traffic patterns for different types of days (working days and weekend days) and the corresponding diurnal variation (TF).
- 29 passive tracers were released (one for each street) within the modelling domain.
- An irregular mesh of 3·10^6 grid points with a resolution of about 1 m3 close to the buildings is used.
- The dynamical effects of the vegetation are modelled considering trees as porous medium. More details can be found in Santiago et al. (2013), Santiago et al. (2014) and Krayenhoff et al. (2015).

3.3. Experimental campaigns

- Two different campaigns were carried out in this zone.
- The first campaign took place from January 26th to February 16th 2011. 26 passive samplers were deployed in the simulation domain.
- The second campaign was done from November 6th to December 1st 2014. In this campaign the number of passive samplers deployed within the modelling domain was increased to 95 .

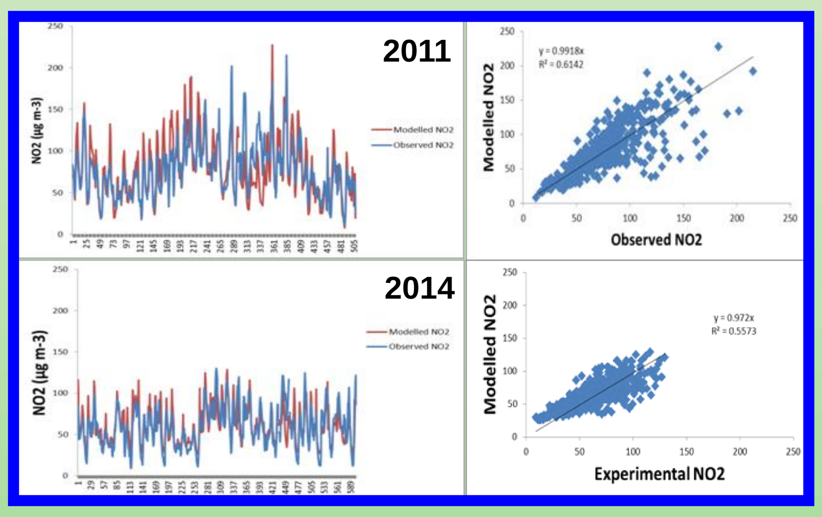


Daily mean traffic intensity for 2011 campaign (vehicles day^{-1}), location of passive samplers, and the zone B (dashed line).



Daily mean traffic intensity for 2014 campaign (vehicles day^{-1}), location of passive samplers and the zone B (dashed line).

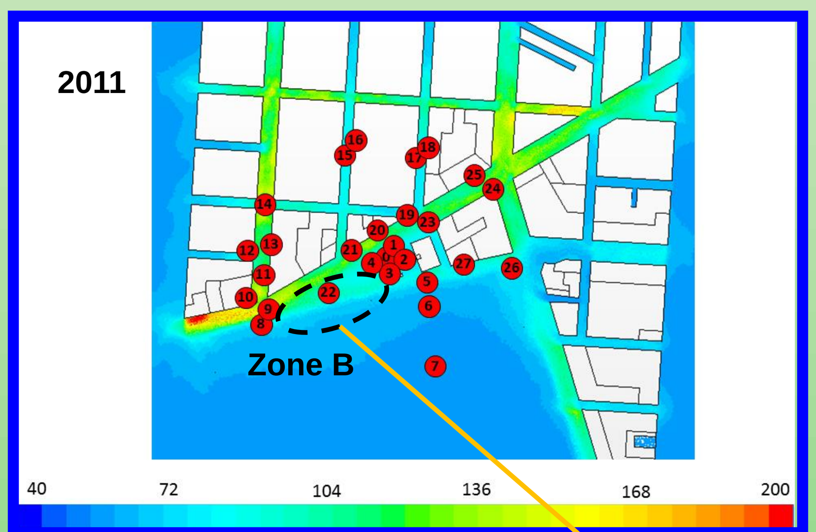
4. Results



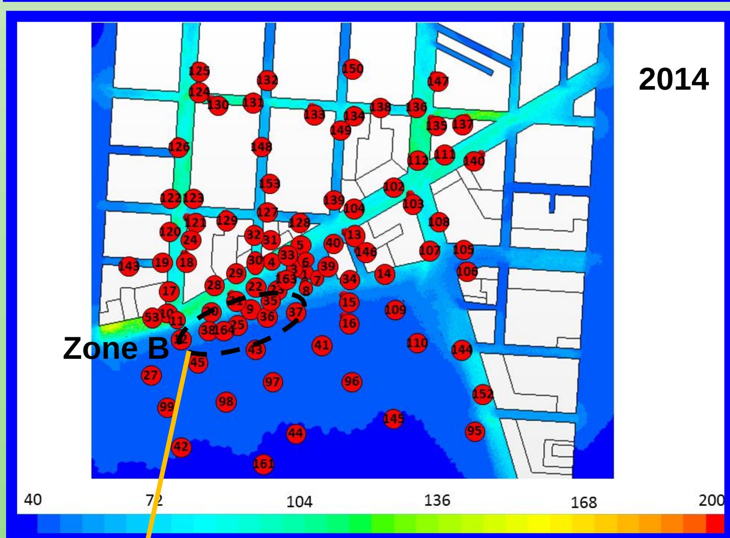
Comparison between modeled and measured hourly NO_2 concentrations recorded at EA air quality monitoring station. Left: Time series. Right: Scatter-plot.

- Modelled hourly data for NO_2 were compared with observed data in the air quality monitoring station (Figs. above) for both periods. The results were quite good showing that the simulated data fit well the observations.

Map of the time averaged NO_2 concentration in μg m^{-3} (508 hours) and location of passive samplers for 2011 campaign

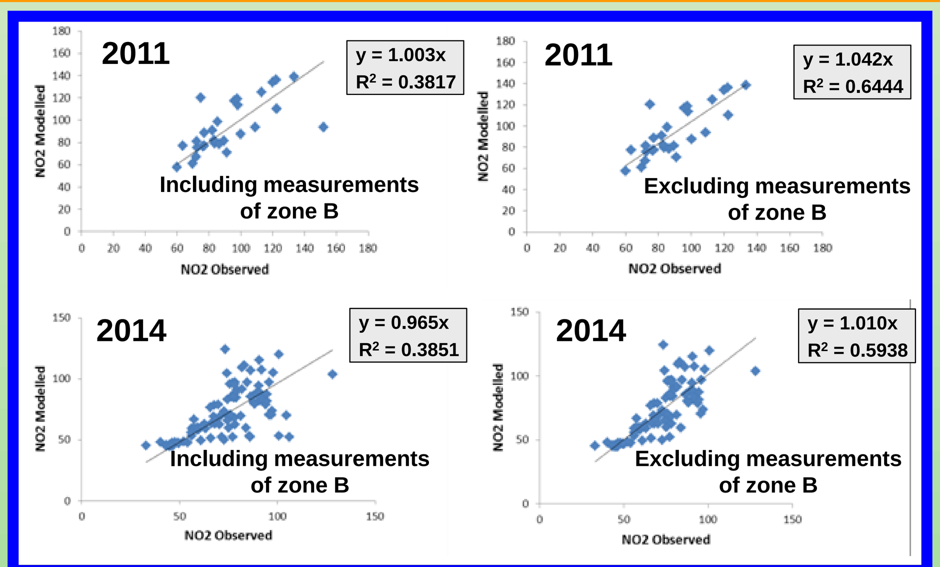


Map of the time averaged NO_2 concentration in μg m^{-3} (602 hours) and location of passive samplers for 2014 campaign



- Maps of the time averaged NO_2 concentrations were produced for the two experimental campaigns.
- Higher concentrations in 2011 campaign were observed are essentially due to a higher background concentration.

Image from google maps of the zone B



Left: Scatter plot with all measurements from passive samplers within domain.

Rigth: Scatter plot without passive samplers in zone B

- Model performance varies spatially. It was found good correlation if measurements in the zone B (zone marked with a dash line) are not considered.
- The problem found in the comparison with the zone B could be due to unrealistic emission representation in this particular area (e.g. real distribution of the street in this zone which is more complex than the distribution of the emissions (a triangle) used in the simulations).
- Taking into account the correlation obtained in the comparison, the methodology using CFD simulations seems to provide realistic NO_2 averaged concentration maps

5. Summary and Conclusions

- In the comparison with experimental data from two different campaigns, a good correlation between model estimates and measurements was obtained.
- It was observed that in a zone where the traffic distribution was not well estimated due to the complexity (tunnels, street forks,..), the model provided worse results in comparison with passive measurements.
- The methodology proposed is able to reproduce satisfactorily week-averaged pollutant concentration distribution (with resolution of the order of meters) in an urban area with heavy traffic and seems to be a useful tool to support the analysis of street-scale measures to improve air quality.
- Additional research efforts should be done to improve the representation of traffic emissions and the contributions from other sources though dynamic boundary conditions.

ACKNOWLEDGEMENTS

This study has been supported by the project TECNAIRE (S2013/MAE-2972) funded by The Regional Government of Madrid.

REFERENCES

- Borge, R, Lumbreras, J, Pérez, J, de la Paz, D, Vedrenne, M, de Andrés, JM, Rodríguez, ME, 2014: Emission inventories and modeling requirements for the development of air quality plans. Application to Madrid (Spain). Science of the Total Environment 466-467, 809-819.
- Parra MA, Santiago JL, Martín F, Martilli A, Santamaría JM, 2010: A methodology to urban air quality assessment during large time periods of winter using computational fluid dynamic models. Atmospheric Environment 44, 2089-2097.
- Santiago JL, Martín F, Martilli A, 2011: Representativeness of urban monitoring stations. 14th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Kos (Greece) 2-6 October.
- Santiago JL, Martín F, Martilli A, 2013: A computational fluid dynamic modelling approach to assess the representativeness of urban monitoring stations. Science of the Total Environment 454-455, 61-72.
- Santiago JL Martilli A, Martín F, 2014: Estimating the impact of street vegetation on air quality: a simple case with different types and position of vegetation. In: 16th International Conference on Harmonization within Atmospheric Dispersion Modelling for Regulatory Purposes, Varna (Bulgaria), 8-11 September 2014.
- Krayenhoff ES, Santiago JL, Martilli A, Christen A, Oke TR, 2015: Parametrization of drag and turbulence for urban neighbourhoods with trees. Boundary-Layer Meteorology (In press) DOI: 10.1007/s10546-015-0028-6.