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A computational fluid dynamic modelling approach to assess the representativeness of urban monitoring stations

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HIGHLIGHTS

- Methodology to reconstruct NOx maps around urban air quality stations using CFD simulations
- Application of the methodology to two urban air quality stations in Spanish cities
- Evaluation of the spatial representativeness (SR) of urban air quality stations

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ABSTRACT

Air quality measurements of urban monitoring stations have a limited spatial representativeness due to the complexity of urban meteorology and emissions distribution. In this work, a methodology based on a set of computational fluid dynamics simulations based on Reynolds-Averaged Navier–Stokes equations (RANS-CFD) for different meteorological conditions covering several months is developed in order to analyse the spatial representativeness of urban monitoring stations and to complement their measured concentrations. The methodology has been applied to two urban areas nearby air quality traffic-oriented stations in Pamplona and Madrid (Spain) to analyse nitrogen oxides concentrations. The computed maps of pollutant concentrations around each station show strong spatial variability being very difficult to comply with the European legislation concerning the spatial representativeness of traffic-oriented air quality stations.

1. Introduction

In urban areas, air quality assessment is usually based on measured pollutant concentrations from networks of urban monitoring stations. It is based on the assumption that the pollutant concentration in a region around the station does not differ significantly than the concentration measured at the station. The European Air Quality Directive (EC/2008/50), for example, specifies that "…a sampling point must be sited in such a way that the air sampled is representative of air quality for a street segment no less than 100 m in length at traffic-oriented sites…". However, the complex air flow patterns caused by the urban morphology (streets and buildings), and the irregular spatial distribution of traffic emissions, generate strong spatial gradients in the concentration fields inside the urban canopy layer. As a consequence, the scientific questions that motivate this paper are:

> Can a point measurement be representative of the air quality in a certain urban area (streets, squares or district)? Is there a methodology to estimate the representativeness of an urban monitoring station? More broadly, how can we link the concentration measured in a certain point with the 3D field of concentrations or with the 2 m concentrations (air breathed)?

These questions are very relevant if we want to know the quality of the air breathed by citizens. Moreover, they will allow clarifying whether an urban air quality station can be really representative as stated by the Directive or not. This study is addressed to traffic stations where the highest values of concentration are found.

European projects have devoted efforts to tackle the station representativeness question, for example, the European project AIR4EU developed between 2004 and 2006 or presently FAIRMODE (Forum for air quality modelling in Europe), in which there is a specific working group dealing with the combination of measurements and models and spatial representativeness of air quality stations.

An answer to the station representativeness questions can be obtained by organizing specific measurement campaigns with a large amount of passive samplers deployed around a monitoring station during weeks or months. The advantage is that these samplers are cheaper and smaller than the standard monitoring station itself, and can be installed easily. The disadvantage is that they can provide only long term concentration averages (over weeks or months) (Krochmal and Kalina, 1997; Liu et al., 1997; Galan Madruga et al., 2001; Parra et al., 2009). In addition, wind tunnel experiments can be carried out to

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investigate the representativeness of monitoring stations, as done by Repschies et al. (2007) for wind measurements in urban areas.

Alternatively, there are methodologies based on the use of models and/or some surrogate indicators related to emission sources distribution. For example, Janssen et al. (2008, 2012) have used land use data to take into account the local influence of the air pollutant concentrations measured at specific stations, in their methodology for air quality assessment in Belgium. Other methodologies are based on climatic-topographic criteria, which can be recommended specially for rural background stations (European Commission, 2011). Spangl et al. (2007) made a very complete review of the criteria and methods for air quality classification and representativeness estimate. Other authors have used models for estimating spatial representativeness of air quality stations ranging from rural to urban stations, including few studies for stations located in streets, as those of Lohmeyer et al. (2005) or Schatzmann et al. (2006). Vardoulakis et al. (2005) used parametric street-canyon models to check how they simulate the spatial distribution of pollutants near an urban air quality station where experimental campaigns were carried out. Other authors have used more complex models as computational fluid dynamic (CFD) to study the distribution of pollutants in streets, taking advantage of the high resolution of those models (Schlünzen et al., 2003; Parra et al., 2010; Santiago et al., 2010; Buccolieri et al., 2011, among others).

There is a consensus in the scientific community that CFD models are needed to simulate the complex flow and dispersion influenced by the presence of buildings (Schatzmann et al., 2010). The CFD models resolve explicitly the flow and pollutant dispersion around urban obstacles (building, trees…) on spatial domains with a size of several hundreds of meters. They need a very dense computational grid with high resolution (order of meters or finer). There are several types of CFD depending on the phenomena parameterized, that have different computational requirements. The cheapest one in terms of computational burden, solves the Reynolds Averaged Navier–Stokes (RANS) equations, and parameterizes all the turbulent motions. It provides steady-state simulations for fixed inlet wind and boundary conditions, and in general it is considered accurate for the estimate of the mean concentration. More refined approaches are Large Eddy Simulation (LES) that parameterise small eddies (in general smaller than the grid size) and resolves explicitly the largest turbulent eddies or Direct Numerical Simulation (DNS) that resolves all the turbulent motions. These last two techniques can provide not only the mean, but also the higher order statistics. However, the disadvantage is that the computational time is significantly larger than for RANS (at least a factor 100 for LES and even more for DNS). For many applications, including the one proposed in this article, the mean is the most relevant information, and the RANS approach is a good compromise between accuracy and CPU time (Santiago et al., 2007, 2008, 2010; Parra et al., 2010).

In this paper, we propose a methodology based on CFD simulations for different inlet wind directions and several simple assumptions (non-reactive pollutants, negligible thermal effects, etc.) to estimate the spatial representativeness of urban air quality stations. The advantage is that it can provide 3D fields of concentration with virtually any time resolution (from hours to years). Concerning the type of CFD model used, two aspects must to be taken into account: CPU time and accuracy. As commented previously, LES is able to reproduce more accurately the atmospheric wind flow, however, CPU time required is much higher than for RANS (about two order of magnitude). In this work, we are interested in the mean concentration fields and a large number of CFD simulations (one for each wind direction, 16 in total) are needed. Dejoan et al. (2010) simulated the concentration field measurements within an array of shipping containers (MUST experiment, Biltoft, 2001) using LES and RANS. The differences between LES and RANS and experimental concentration were partly explained by small fluctuation of inlet wind direction. Taking into account that for the methodology proposed in this study we use only a discrete number of CFD simulations (16 inlet wind directions) and the evaluation of spatial variability carried out of the whole methodology using RANS as CFD model by Parra et al. (2010) for a large period of time (explained further on in Section 3), a RANS model is selected to run the set of simulations with different wind directions. This methodology (described in Section 2) is an extension of the methodology proposed in Parra et al. (2010), and it has been applied to two locations with very different characteristics: a monitoring station located in a central part of a small Spanish city (Pamplona, North of Spain, (Location 1)) and a station located close to a big park in Madrid (Location 2). Results are presented and discussed in Section 3. Conclusions are in Section 4.

2. Methodology

For the purpose of this study (representativeness of urban monitoring stations), maps of time averaged pollutant concentration nearby the urban monitoring station are needed. Frequently, air quality limit values are associated to large periods of time and therefore pollutant concentrations should be averaged for large period of time. In addition, these maps should have spatial resolution high enough (~m) to catch the strong spatial heterogeneities in the distribution of pollutants inside the streets. Taking into account that it is not possible (within a suitable CPU time) to run an unsteady CFD model for these large periods of time, the solution proposed is to run with a steady CFD model only a set of inlet wind directions and use a numerical combination of these to compute the final results. This methodology was developed by Parra et al. (2010). A brief description and the modifications made in this paper are explained in the next sections, together with a description of the two locations investigated. This study is focused to nitrogen oxides concentration around two traffic-oriented air quality stations in Pamplona and Madrid.

2.1. Modelling approach

Numerical simulations were based on the steady state Reynolds-averaged Navier–Stokes equations (RANS) and k–ε turbulence models using STARCCM+ (from CD-Adapco) code. The pollutant concentration was simulated using additional transport equations for passive scalars. More information about the models and a discussion about the selection of RANS turbulence scheme can be found in Santiago et al. (2007) and Parra et al. (2010). The particular modelling setups for the two locations are explained in the next section.

The wind flow and the dispersion of several passive tracers inside the urban zones studied is simulated for 16 different inlet wind directions, i.e. from 0° to 360° with an increment of 22.5° (N is for 0°, NNE for 22.5° and so on). The notation used is sector 1 for N, sector 2 for NNE and so on, clockwise. The passive tracers represent traffic emissions and they are all released at the same rate from line sources in different streets (one passive tracer for each street). The total concentration $C_{total}(t)$ at hour t in a certain point, is the sum of the concentration of each tracer (i), corrected to account for the emissions and wind speed of this hour, and it can be written as:

$$C_{total}(t) = M\frac{1}{v_{in}(t)}\sum_i C_i(Sector(t))\cdot\frac{L_i}{Vsource_i}N_i(t) \tag{1}$$

where,

- $Sector(t)$ is the wind direction sector at hour t.
- i indicates the tracer emitted in street i.
- $C_i(Sector(t))$ is the concentration computed for $Sector(t)$ for a given emission from street i and for a reference 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.