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Development and application of a high resolution hybrid modelling system for the evaluation of urban air quality

N. Pepe [a, b, *], G. Pirovano [a], G. Lonati [b], A. Balzarini [a], A. Toppetti [a], G.M. Riva [a], M. Bedogni [c]

[a] RSE Spa, Via Rubattino 54, 20134 Milano, Italy
[b] Department of Civil and Environmental Engineering, Politecnico Milano, Milano 20133, Italy
[c] AMAT, Via T. Pini 1, 20134 Milano, Italy

HIGHLIGHTS

- Hybrid modelling system developed at the urban local scale.
- Hourly model output at 20 × 20 m space resolution for urban area.
- Improvement in model bias despite slightly worsened time correlation.
- Weaknesses and strengths of the system are pointed out and discussed.
- Estimated NO_X background accounted for about 75% in Milan area domain.

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ABSTRACT

A hybrid modelling system (HMS) was developed to provide hourly concentrations at the urban local scale. The system is based on the combination of a meteorological model (WRF), a chemical and transport eulerian model (CAMx), which computes concentration levels over the regional domains, and a lagrangian dispersion model (AUSTAL2000), accounting for dispersion phenomena within the urban area due to local emission sources; a source apportionment algorithm is also included in the HMS in order to avoid the double counting of local emissions.

The HMS was applied over a set of nested domains, the innermost covering a 1.6 × 1.6 km^2 area in Milan city center with 20 m grid resolution, for NO_X simulation in 2010. For this paper the innermost domain was defined as "local", excluding usual definition of urban areas. WRF model captured the overall evolution of the main meteorological features, except for some very stagnant situations, thus influencing the subsequent performance of regional scale model CAMx. Indeed, CAMx was able to reproduce the spatial and temporal evolution of NO_X concentration over the regional domain, except a few episodes, when observed concentrations were higher than 100 ppb. The local scale model AUSTAL2000 provided high-resolution concentration fields that sensibly mirrored the road and traffic pattern in the urban domain. Therefore, the first important outcome of the work is that the application of the hybrid modelling system allowed a thorough and consistent description of urban air quality. This result represents a relevant starting point for future evaluation of pollution exposure within an urban context.

However, the overall performance of the HMS did not provide remarkable improvements with respect to stand-alone CAMx at the two only monitoring sites in Milan city center. HMS results were characterized by a smaller average bias, that improved about 6–8 ppb corresponding to 12–13% of the observed concentration, but by a lower correlation, that worsened around 1–3% (e.g. from 0.84 to 0.81 at Senato site), due to the concentration peaks produced by AUSTAL2000 during nighttime stable conditions. Additionally, the HMS results showed that it was unable to correctly take into account some local scale features (e.g. urban canyon effects), pointing out that the emission spatialization and time modulation criteria, especially those from road traffic, need further improvement.

Nevertheless, a second important outcome of the work is that some of the most relevant discrepancies between modelled and observed concentrations were not related to the horizontal resolution of the dispersion models but to larger scale meteorological features not captured by the meteorological model,

* Corresponding author. Present address: Via Rubattino 54, 20134 Milano, Italy.
E-mail address: nicola.pepe@polimi.it (N. Pepe).

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especially during winter period. Finally, the estimated contribution of the local emission sources accounted on the annual average for about 25–30% of the computed concentration levels in the innermost urban domain. This confirmed that the whole Milan urban area as well as the outside background areas, accounting all sources outside the innermost domain, play a key role on air quality. The result suggests that strictly local emission policies could have a limited and indecisive effect on urban air quality, although this finding could be partially biased by model underestimation of the observed concentration.

1. Introduction

The impact assessment of environmental policies on air quality involves reactive pollutants, thus requiring chemical transport models (CTMs) and urban to regional domains, depending by the area of interest (Isakov et al., 2007; Denby et al., 2011; Martins, 2012). Urban areas are composed by heterogeneous elements and present densely built-up features, which can influence the spatial distribution of some pollutants such as NOx and NO_2, as well as the primary fraction of PM (EEA, 2015; Torras Ortiz and Friedrich, 2013). Due to their relatively low spatial resolution, CTMs cannot capture correctly the strong spatial gradients that can take place in urban areas, hampering a reliable evaluation of human exposure (Isakov et al., 2009; Batterman et al., 2014). The reconstruction of air quality variability within urban areas would require local scale models (LSMs); nevertheless LSMs alone are usually unable to reproduce chemical reactions and can not be applied over large domains (Stein et al., 2007; Lefebvre et al., 2011, 2013; Beevers et al., 2012; Isakov et al., 2014).

For all these reasons we developed an integrated hybrid modelling system (HMS) by combining the Comprehensive Air Quality Model (CAMx) with Extensions (ENVIRON, 2011), as chemical transport model, and the AUSTAL2000 (Janicke Consulting, 2014), as local scale model, according to a model nesting approach. The resulting HMS is a comprehensive and efficient modelling tool for urban air quality, capable of reconstructing the regional scale features of air pollution as well as the spatial variability of concentrations within urban areas, taking into account the building structures and the detailed spatial distribution of the emissions at the urban scale. In particular, this work is intended to define a standardized modelling chain that can use the same emission inventories and land use datasets, as well as meteorological inputs, for the CTM and LSM components of the HMS.

A case-study application of the HMS concerning the metropolitan area of Milan, with a specific focus over the city center, where the LSM was applied in cascade to the CTM in order to provide hourly NO_X concentration for a high resolution urban grid (20 × 20 m) for 2010, is presented and discussed.

The paper firstly describes the conceptual structure and the elements of the HMS. The following section is devoted to the evaluation of the performance of the CTM part of the HMS. Then the results of the LSM application are presented and compared with the corresponding CTM outcomes. HMS results at the Milan urban domain are then compared with observations. Finally the evaluation of the spatial variability of the fine scale concentrations is presented and discussed.

2. Methods

2.1. The hybrid modelling system

The hybrid system relies on two main components: the regional scale model CAMx and the local scale dispersion model AUSTAL2000. The modelling system also includes the Weather Research and Forecasting (WRF) meteorological model and the SMOKE emission model. Interactions between all models are shown in the flow chart of Fig. 1. All models and tools implemented in the modelling chain are based on open source codes. The modelling system has two main features:

- CTM and LSM input data consistency, i.e.: the two models share the same meteorological and emission data;
- solution to the double counting problem of local contribution, thanks to a source apportionment algorithm implemented in the CTM model the local sources' contribution is accounted for only by the LSM.

The modelling chain presents efficient features concerning computational time: 15 min/day with 8 core processors about CAMx outcomes while 4 min/day about AUSTAL2000 outputs with single core. Physical and chemical processes are described and quantified although AUSTAL2000 treats all pollutants as inert. Chemical schemes are implemented into CAMx, as described in setting section, and cover an important role overall at the basin scale; conversely, at the local scale the correct quantification of the dispersion phenomena is more important in order to compute backlog events, key features concerning exposition levels within urban areas. Thanks to its LSM component the HMS can accurately reproduce the spatial pattern of emission sources and reconstruct the spatial variability of pollutants concentrations. Thus, for example, the HMS is helpful to define critical zones for urban pollution and to assess the impact of air quality control policies, as the introduction of "Low Emission Zone" (Hellison et al., 2013; Morfeld et al., 2014), popular in big cities of Germany and England and adopted also in Milan since a few years.

Models setup and details on the output of the HMS are given in the following paragraphs with specific reference to the case-study for NO_X concentration in Milan city center.

2.2. WRF setup

The WRF model v3.4.1 (Skamarock et al., 2008) was setup using 30 vertical layers, with the first one reaching about 25 m from ground level; the top layer overcomes 15 km. Four horizontal nested grids were used, downscaling from a 3870 × 4140 km^2 domain covering Europe to a 1350 × 1530 km^2 domain over Italy, a 600 × 420 km^2 over the Po Valley and an 85 × 85 km^2 over a part of the Lombardy region, including the city of Milan. Each domain was gridded using different resolutions starting from 45 km as grid step down to 15 km, 5 km and 1.7 km for the last domain. Initial and boundary conditions were taken from ECMWF analysis fields at 0.5 × 0.5° grid size, both at ground level and at different pressure levels (http://old.ecmwf.int/products/data/archive/ECMWF_catalogue/index.html). Data included 3D and surface parameters