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Enhanced air quality modelling through AUSTAL2000 model in Milan urban area

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Abstract. Atmospheric dispersion models are a useful tools to assess air quality and emission source contributions in urban areas. Eulerian chemical and transport models (CTMs) can assess the regional background, that is the baseline level in the region of the city, and the urban background, that is the increment of concentration due to the emissions of the city, but they are not able to properly assess the very local contribution of emission sources at pollution hotspots within the city, because of their relatively large grid step. For the assessment of local sources' contribution, Lagrangian dispersion models can be profitably used, especially when high spatial resolution modelling is required. Actually, Lagrangian models rely on a more realistic spatialization of urban emissions, unevenly distributed because of the road network layout (for traffic emissions) and of the built environment structure (for space heating emissions); additionally, Lagrangian models also account for wind field modifications induced by buildings. In this work, air quality modelling results for fine particles (PM2.5) in the city centre of Milan obtained by means of the AUSTAL2000 Lagrangian model are compared with those of CAMx Eulerian model. Model simulations where performed for a 1.7x1.7 km^2 area in Milan and focused on three receptor points selected in order to represent sites with both different features in terms of the surrounding built environment and different exposure to the local emission sources. Namely, the receptors correspond to a green area, to a residential and shopping area near Milan main square, and to a congested crossroad on the inner ring road of the city centre. Comparison results show that the outcome of the Eulerian model at the local scale is only representative of a background level, similar to Lagrangian model's outcome for the green area receptor, but fails to reproduce concentration gradients and hot-spots, driven by local sources' emissions.

1. Introduction

Ambient air quality in urban areas represents a significant public health problem because of the negative impacts on respiratory and cardiovascular health and because of premature deaths as a result of population exposure to atmospheric pollutants [1] [2] [3]. Air quality monitoring networks provide accurate data for the concentration levels at fixed measurement sites, in order to check the compliance with air quality limits. However, measurements sites are limited in number and, even though located at site supposedly representative of the different urban microenvironments (i.e.: urban background sites, urban traffic-exposed sites, residential areas), they may fail in properly assessing the actual air quality over the whole urban area [4]. Atmospheric dispersion models are useful tools to assess air quality and emission sources' contributions to the pollutant concentration levels in urban areas [5] [6] [7]. The EU

Directive 2008/50 on air quality [8] defines a range of situations, with regard to air quality limits compliance, where models can be applied for assessment instead of, or in combination with, fixed measurements; nevertheless, modelling can be profitably used to supplement air quality data at fixed measurement sites.

Air quality modelling in urban areas is quite challenging for a number of reasons. First, because concentration levels are not solely due to local emissions but are also determined by the emissions in the surroundings or, in some circumstances, of the entire region of the urban area. Actually, concentration levels of atmospheric pollutants can be regarded as the result of three overlapping contributions: a regional background, that represents the baseline level in the surroundings/region of the urban area, an urban background, that represents the increment of concentration due to emission of the urban area itself, and the very local contribution of emission sources at pollution hotspots within the urban area [9]. Second, because the pollutants of interest may be result from secondary formation processes, like O_3, NO_2 and, partially, fine particulate matter (PM). Third, because the spatial distribution of the two main emission sources in urban areas (i.e.: road traffic and space heating) depends on the urban structure of the built environment. Finally, because the built environment itself can negatively affect the dispersion of the locally emitted polluted, namely with local modifications of the wind conditions induced by buildings and with urban canyon structures favoring the built-up of the pollutants at emission hot-spots.

Eulerian chemical and transport models (CTMs), usually applied for air quality modelling at the regional scale, can cope with the first two issues: regional and urban background concentration levels for both primary and secondary pollutants can be reasonably well estimated. Nevertheless, because of their relatively large grid step (i.e.: low spatial resolution in both sources' spatial distribution and estimated concentration values) CTMs are not able to properly reproduce the local contribution of urban sources. Conversely, Lagrangian dispersion models (LMs) can be profitably used for the assessment of local sources' contribution, especially when high spatial resolution modelling is required at relatively small spatial scales. Actually, LMs rely on a more realistic spatialization of urban emissions, unevenly distributed because of the road network layout (for traffic emissions) and of the built environment structure (for space heating emissions), and can account for wind field modifications induced by buildings. As drawbacks, LMs do not include comprehensive gas and aerosol chemistry modules for secondary pollutants assessment and cannot be used for regional scale modeling due to their computational burden.

This work is focused on air quality modelling at the very local scale within an urban area, intended to assess the extent and the spatial variability of the third of the abovementioned contributions to the urban concentration levels. In particular, the work highlights the enhancements in the reconstruction of the spatial distribution of the concentration of fine particles (PM2.5) in the city centre of Milan, obtained by means of AUSTAL2000 Lagrangian model in comparison with those of CAMx Eulerian model. Modelling results are presented for three receptors selected in order to represent urban sites characterized by both different features in terms of the surrounding built environment and by different exposure to the local emission sources.

2. Materials and methods

2.1. Air quality models
In this work the Comprehensive Air Quality Model with Extensions (CAMx v6.30) [10] was used as Eulerian chemical and transport model (CTM) and AUSTAL2000 model (AUSTAL2000 v2.6.9) [11] as Lagrangian local-scale model (LM). Results of the model simulations are reported for a 1.7 x 1.7 km^2 study area that covers part of Milan city centre. The study area corresponds to one single cell of CAMx modelling domain and is characterized by a heterogeneous urban pattern with road arches separating the densely built up commercial and residential area (Figure 1). Actually, CAMx was run over a larger domain, including the study area and the whole metropolitan area of Milan (still at 1.7 x 1.7 km^2 resolution). Thanks to the PSAT Source Apportionment Tool [12] embedded in CAMx, it was possible

to assess the impact of the emission sources located in the study area on the air quality in the area itself, so that the contributions to the ambient concentration levels estimated by CAMx and by AUSTAL2000 could be properly compared.

Three receptors were selected in the study area order to represent sites with a different exposure to the local emission sources: namely, they correspond to a green area (PARK), to a residential and shopping area near the main cathedral square (DUOMO), and to a congested crossroad on the inner ring road of the city centre (TRAFFIC).

Input meteorological data for the study area were reconstructed by Weather Research and Forecasting meteorological model (WRF v3.4.1) [13] for calendar year 2010. WRF model output was further processed by the diagnostic wind field model TALdia in order to obtain the input meteorological fields for AUSTAL2000, that account for the features of the urban canopy at 20x20 m^2 grid resolution.
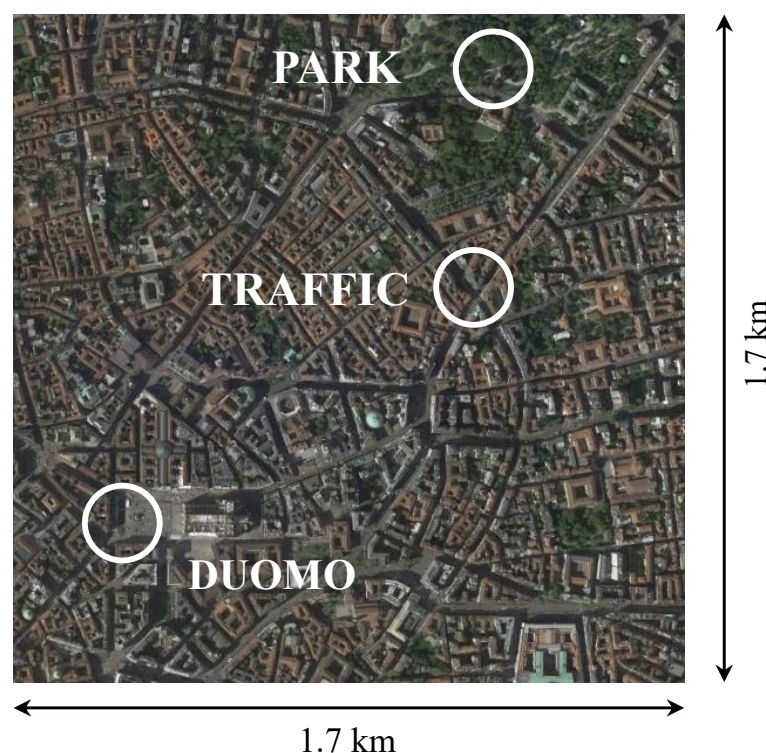

Figure 1. Location of the selected receptors in the study area.

2.2. Emission data

Emissions were derived from inventory data for the city of Milan provided by the Lombardy region inventory based on INEMAR methodology (INEMAR) [14]. Inventory data were firstly processed using the Sparse Matrix Operator for Kernel Emissions model (SMOKE v3.5) [15] in order to obtain the hourly time pattern of the emissions gridded over the CAMx cells. According to emission inventory data, commercial and residential heating (SNAP category 02) and road traffic (SNAP category 07) are responsible for more than 90% of the emissions in the study area; thus, this work is focused on the contributions to PM2.5 ambient levels due to the emissions from these two source categories. For the AUSTAL2000 simulations the emissions of the study area were spatially distributed based on urban land use information gridded at 20 x 20 m^2 cell resolution. Commercial and residential heating emissions have been equally split among all the cells associated to buildings, because specific information on the energetic system and performance of the real buildings was lacking. Each building was associated to a stack represented as a point source at the building rooftop height. Road traffic was dealt with as ground-level linear source, proportionally splitting its emission among all the road arches of the study area based

on road network and traffic data provided by the Mobility Agency of Milan (AMAT) [16]. Namely, for each single road arch the emissions have been computed as fraction of the total emissions of the study area weighted based on an aggregate street variable (ASV) given by the product of the arch length and of its traffic flow.

3. Results and discussion

3.1. Annual and seasonal average contributions

The estimated contributions of the emission sources located within the study area to the ambient PM2.5 levels at the three receptors resulting from CAMx and AUSTAL2000 simulation are compared in Figure 2. CAMx local concentrations at the three receptors are computed by means of a weighted-distance bilinear interpolation of the four 1.7 km^2 cells surrounding each receptor. Differently, thanks to its spatial resolution, AUSTAL2000 really calculates concentrations at the receptors points. Even though the features of the urban receptors change radically, the comparisons points out the relatively "flat" output of CAMx, with very limited spatial variability of PM2.5, both for the annual and for the seasonally averaged (cold season: Jan-Mar; warm season: Jun-Aug) concentrations. Conversely, AUSTAL2000 results highlight the difference between the receptor strongly affected by local sources (TRAFFIC) and the receptors less exposed to traffic emissions (DUOMO) and located in an urban background site (PARK). PM2.5 concentrations estimated by CAMx vary in rather narrow ranges (0.7-1.1 µg/m^3 on annual basis, 1.2-1.9 µg/m^3 in wintertime, 0.4-0.6 µg/m^3 in summertime). AUSTAL2000 results display variations in the order of a 2x factor between DUOMO and PARK (0.65 µg/m^3 vs.1.46 µg/m^3 on annual basis, 1.2 µg/m^3 vs. 2.6 µg/m^3 in wintertime, 0.3 µg/m^3 vs. 0.6 µg/m^3 in summertime) and, in turn, between TRAFFIC and DUOMO. Cold season concentration at TRAFFIC is twice as high as at DUOMO (5.32 µg/m^3 vs. 2.60 µg/m^3) but up to four times higher in the warm season (2.44 µg/m^3 vs. 0.58 µg/m^3).

Table 1. Estimated total annual and seasonally averaged contributions to PM2.5 ambient levels at the three receptors from emission sources located within the study area.

Receptor	Period	CAMx PM2.5 (µg/m^3)	AUSTAL2000 PM2.5 (µg/m^3)
PARK	Annual	0.71	0.65
	Cold season	1.25	1.17
	Warm season	0.37	0.28
DUOMO	Annual	1.07	1.46
	Cold season	1.87	2.60
	Warm season	0.61	0.58
TRAFFIC	Annual	0.90	3.80
	Cold season	1.58	5.32
	Warm season	0.47	2.44

In spite of the abovementioned limits of CAMx and notwithstanding the two models are based on different approaches, their results are in rather good agreement at PARK receptor: estimated PM2.5 concentrations are 0.65 µg/m^3 vs. 0.76 µg/m^3 for the annual average, 1.17 µg/m^3 vs. 1.32 µg/m^3 for the cold season average, and 0.28 µg/m^3 vs. 0.40 µg/m^3 for the warm season average. Deviations between model outputs become larger and larger as the density of emission sources nearby the receptor increases (i.e.: from PARK to DUOMO and from PARK to TRAFFIC receptor). At DUOMO, AUSTAL2000 results for the annual and the for the cold season average are 40% higher than CAMx (1.46 µg/m^3 vs. 1.07 µg/m^3 and 2.60 µg/m^3 vs. 1.87 µg/m^3, respectively); only in the warm season the two models

provide similar concentration levels (about 0.6 µg/m^3). At TRAFFIC, AUSTAL2000 predictions are from about three (5.32 µg/m^3 vs. 1.58 µg/m^3 in wintertime) up to almost six times higher (2.44 µg/m^3 vs. 0.47 µg/m^3 in summertime) than those of CAMx. Thus, CAMx results can be regarded as concentrations levels representative of receptors not directly exposed to local emissions but poorly representative of both residential areas and, most of all, of traffic exposed receptors, where the impact of local sources is strongly missed. The limitation of CAMx in properly accounting for the impact of local sources is also highlighted by the fact that CAMx estimates the highest contribution at DUOMO whilst AUSTAL2000 at TRAFFIC and by the smaller spatial concentration gradients among the three receptors.
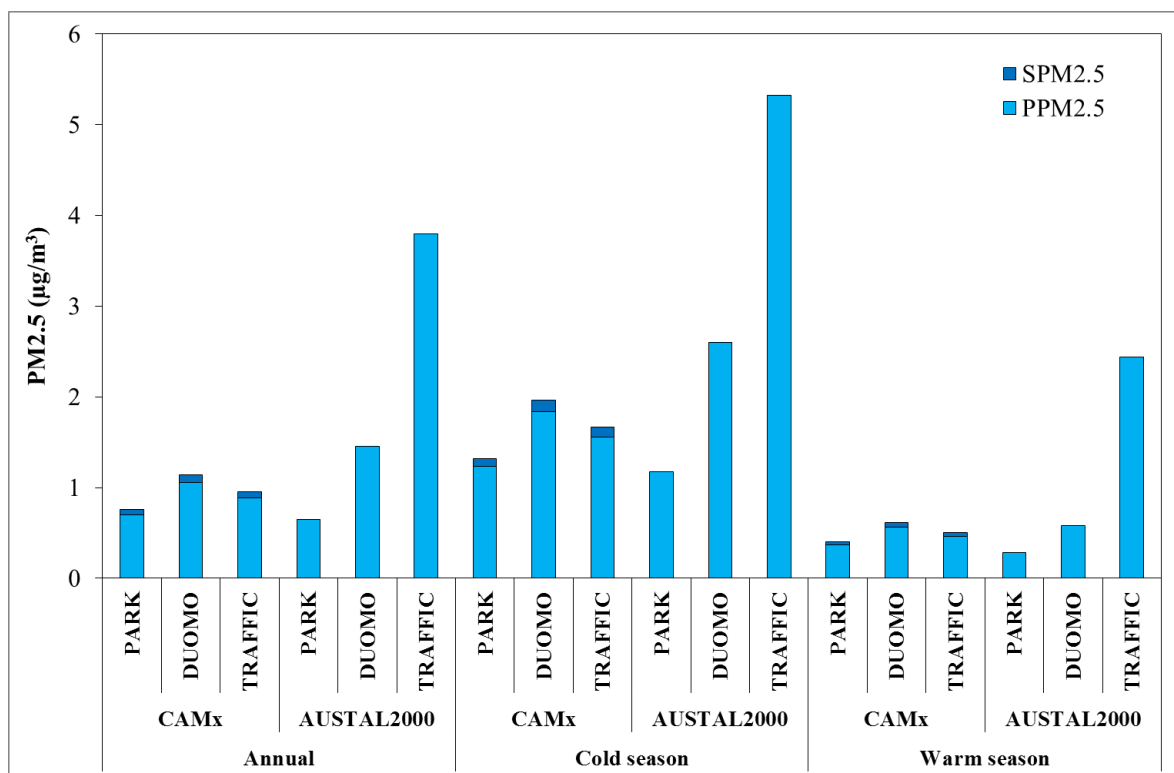

Figure 2. Estimated contributions to PM2.5 concentration levels at the urban receptors from emission sources within the study area. (Cold season: Jan.-Mar. and Oct.-Dec.; Warm season (Apr.-Sep.)

These outcomes are a direct consequence of the different spatialization degree of the local emissions adopted by the two models: AUSTAL2000 locates road traffic and domestic heating emissions in correspondence with the arches of the urban street network and of the built areas; conversely, CAMx evenly distributes the emissions all over the study area. Moreover, as already mentioned, CAMx concentrations values at the receptors come from a distance-based weighed average of the concentrations computed for the four nearest grid cells at 1.7 km^2 resolution. Therefore, CAMx is not able to reflect the local features of the receptor sites.

The drawback of AUSTAL2000 results is that they neglect the secondary fine PM generated by precursors emissions from the sources in the study area, because the model does not handle aerosol chemistry. Conversely, CAMx is able to reproduce the secondary formation of aerosols and to provide separate predictions for the primary and secondary PM2.5. However, in literature the contribution of local precursor emissions to local concentration of secondary PM is reported to be substantially negligible [17]. Actually, as shown in Figure 2, in our work the contribution of secondary PM (SPM) to the total PM2.5 is very limited, roughly in the order of 7%. Thus, AUSTAL2000 enhanced capability of better reproducing the variability of the concentration levels at the urban scale, according to receptors'

exposure to the local emission sources, almost totally offsets the limitation of the neglected secondary PM formation processes.

3.2. Time patterns of daily contributions

Further insight on the models' performance comes from the comparison of the time patterns for the daily averaged concentrations. The inspection of Figure 3, 4, and 5 clearly highlights that both models reconstruct the same seasonal pattern, with higher contribution in the cold season and lower contributions in the warm season. Other than from the different dispersive conditions of the atmosphere, the pattern is mainly driven by the seasonality that affects sources' activity, with domestic heating emissions in addition to traffic emissions in the cold season. In spite of the fluctuations in the estimated concentration levels, the annual time series are quite correlated, with R^2 values ranging between 0.45 and 0.56 (Table 2). Correlation becomes stronger in the warm season (up to R^2 values about 0.7 at all the receptors), but falls down to $R^2 = 0.31\text{-}0.38$ in the cold season, when the fluctuations in AUSTAL2000 estimates become much larger than those predicted by CAMx.

Figure 3 and 4 show the good agreement between models' predictions, especially during the warm season. Conversely, Figure 5 points out the relevant and systematic departures between models' estimates throughout the whole year at TRAFFIC receptor, with values computed by AUSTAL2000 always on top of those resulting from CAMx simulation. Differently form the two other receptors, at TRAFFIC models' prediction differ not only in the cold season but also in the warm season, when AUSTAL2000 values are about 2 $\mu g/m^3$ higher than those of CAMx on the average but occasionally also up to 4 $\mu g/m^3$. Such different values obtained at the TRAFFIC receptor for the warm season, when traffic is the only active local source in the area, confirm that CAMx is systematically unable to reproduce the impact of traffic emissions at the very local scale.
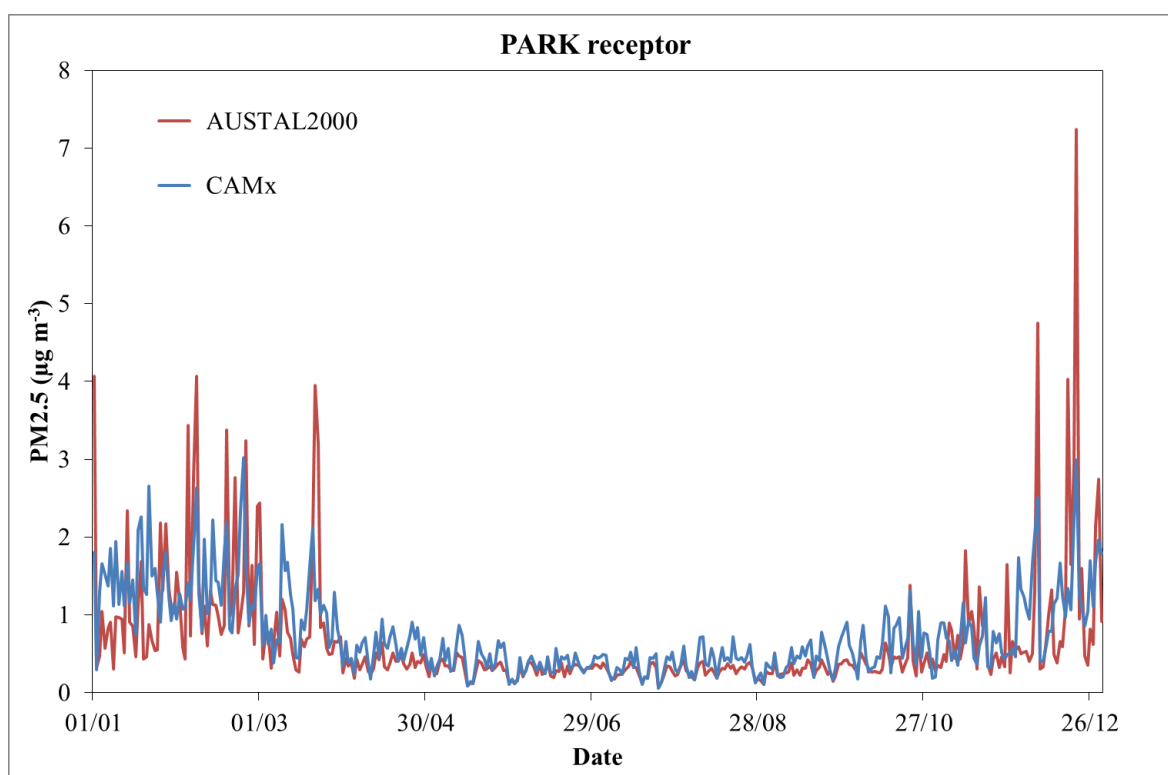

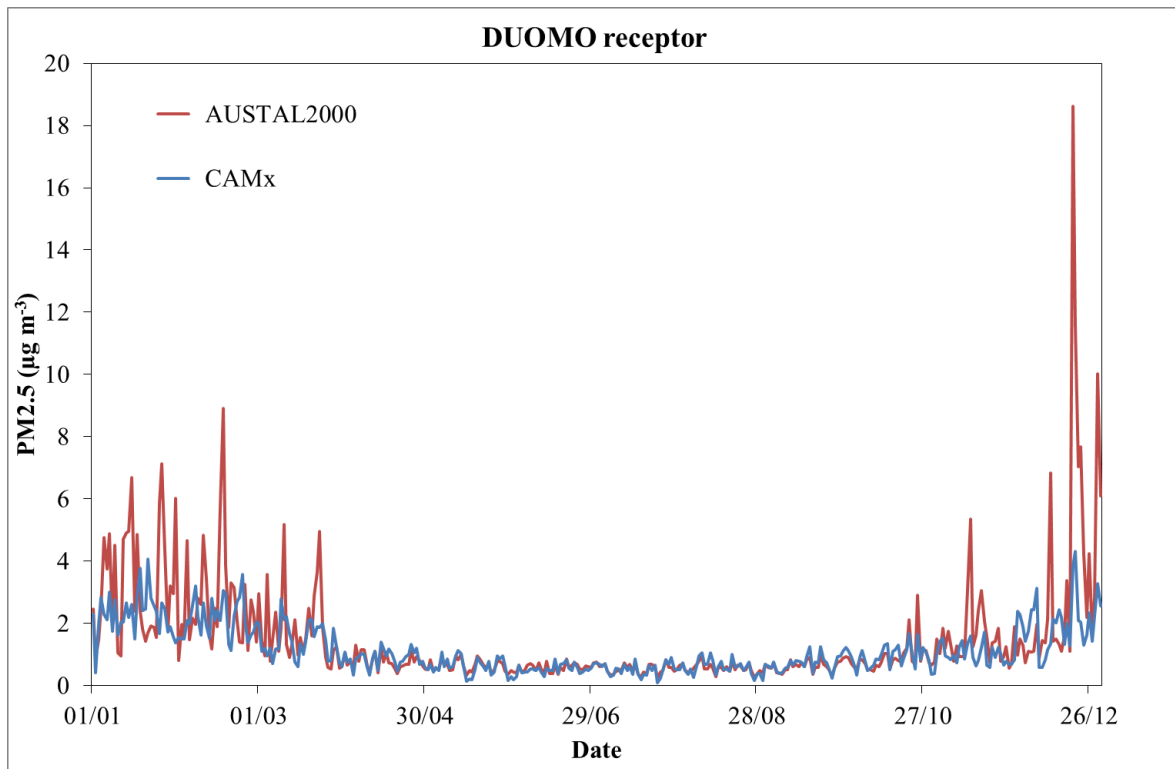**Figure 3.** Time pattern of daily averaged PM2.5 estimated contributions at PARK receptor.

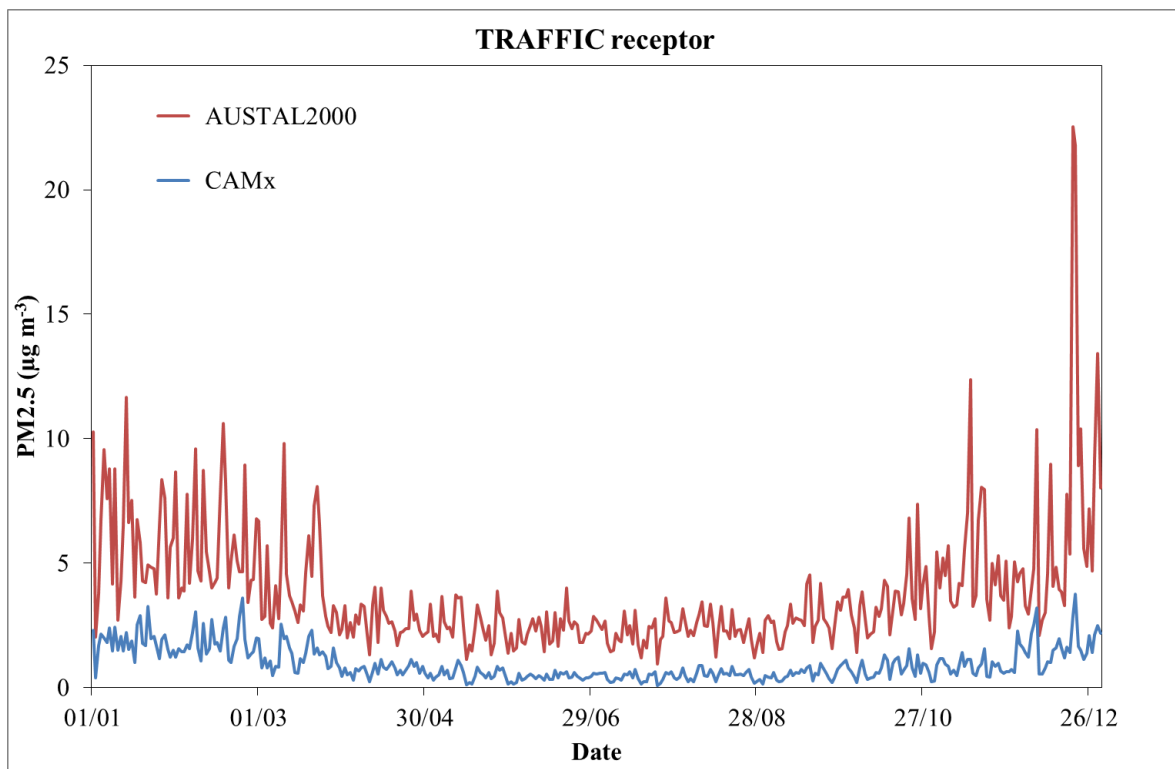**Figure 4.** Time pattern of daily averaged PM2.5 estimated contributions at DUOMO receptor.

Figure 5. Time pattern of daily averaged PM2.5 estimated contributions at TRAFFIC receptor.

Table 2. R^2 values for the time series of daily average concentrations estimated by CAMx and AUSTAL2000.

Period	PARK	DUOMO	TRAFFIC
Annual	0.47	0.45	0.56
Cold season	0.35	0.31	0.38
Warm season	0.72	0.70	0.69

4. Conclusions

The enhancements in the reconstruction of the impact of local emissions on PM2.5 concentration levels in the city centre of Milan obtained by means of AUSTAL2000 Lagrangian model in comparison with those of CAMx Eulerian model have been investigated for three urban receptors characterized by both different features in terms of the surrounding built environment and by different exposure to the local emission sources. In comparison with the Eulerian model, the Lagrangian model relies on a better spatial distribution of road traffic and space heating emission within the study area, unevenly distributed because of the road network layout and of the built environment structure. Such a refinement in the spatialization of local emissions allows the Lagrangian model to reproduce more realistically the variability of concentration levels among the urban receptors, according to their actual exposure to local sources. For the presented case-study of Milan city centre, the AUSTAL2000 Lagrangian model results in almost a 6x factor between PM2.5 annual average at the traffic exposed receptor and at the background receptor in a green area. Conversely, the CAMx Eulerian model, missing the impact of local traffic at the former receptor, predicts only a 26% difference. In practice, the outcome of CAMx at the local scale is only representative of a background level, similar to AUSTAL2000 outcome for the green area receptor, but fails to reproduce concentration gradients and hot-spots, driven by local sources' emissions.

These results suggest that a more accurate assessment of the air quality in urban areas could be obtained by means of a hybrid modeling system, which couples an Eulerian chemical and transport model with a local-scale Lagrangian model. In such a system the estimated concentration levels come from the superposition of the regional and the urban background contributions of emission sources located outside the local-scale urban domain, both assessed by the Eulerian model, and of the contribution of the sources located within this latter domain, assessed by the Lagrangian model with a higher accuracy for the spatial variability at the local scale.

Acknowledgements

References

[1]   World Health Organization (WHO) 2016. *Ambient air pollution: A global assessment of exposure and burden of disease* (Geneva, Switzerland)
[2]   Kelly FJ and Fussel JC 2015 *Environ. Geochem. Health* **37** 631-649
[3]   World Health Organization (WHO) Regional Office for Europe, 2013. *Review of evidence on health aspects of air pollution - REVIHAAP project, technical report*
[4]   Duyzer J, van der Hout D, Zandveld P and van Ratigen S 2015 *Atmos. Environ.* **104** 88-101
[5]   Ciarelli G et al. 2017 *Atmos. Chem. Phys.* **17** 7653-7669
[6]   Squizzato S, Cazzaro M, Innocente E, Visin F, Hopke P and Rampazzo G 2017 *Atmos. Res.* **186** 51-62
[7]   Pirovano G, Colombi C, Balzarini A, Riva GM, Gianelle V and Lonati G 2015 *Atmos. Environ.*

        106 56-70

[8]   European Union, 2008. Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. *Official Journal of the European Union*, L 152, 11.6.2008, 1-44

[9]   Lenschow P, Abraham HJ, Kutzner K, Lutz M, Preuss JD and Reichenbächer W 2001 *Atmos. Environ.* **35** 123-133

[10]   Environ 2016. CAMx (Comprehensive Air Quality Model with extensions) User's Guide Version 6.3. ENVIRON International Corporation, Novato, CA.

[11]   Janicke consulting 2014 AUSTAL2000 Program Documentation of Version 2.6 2014-02-24. Federal Environmental Agency (UBA), Dessau-Roßlau (Germany).

[12]   Skamarock WC et al. 2008 *A Description of the Advanced Research* WRF Version 3, NCAR Technical Note NCAR/TN-475+STR, Boulder, Colorado

[13]   Yarwood G, Morris RE and Wilson GM 2004 *Proceedings of the 27th NATO/CCMS International Technical Meeting on Air Pollution Modeling and Application*

[14]   ARPA Lombardia 2015. INEMAR, Inventario Emissioni in Atmosfera: emissioni in Regione Lombardia nell'anno 2012 - revisione pubblica. ARPA Lombardia Settore Monitoraggi Ambientali

[15]   University of North Carolina at Chapel Hill (UNC) 2013 SMOKE v3.5 User's manual.

[16]   AMAT Comune di Milano 2016 [Online] available: http://www.amatmi.it/it/documenti/dettaglio/16/)

[17]   Amann M et al. 2011 *Environ. Modell. Softw.* **26** 1489-1501