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Impact of vehicular emissions in an urban area of the Po valley by microscale simulation with the GRAL dispersion model

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Abstract. This work sets out the test of the GRAL model (Graz Lagrangian Model, vs.18.1) in the urban area of Modena (Po valley, Northern Italy). The simulation domain sizes 2 000 x 3 000 m² and it features ‘microscale’ cells of 4 x 4 m². The simulation focuses on an intersection featured by large traffic flows next to a school and a regulatory air quality monitoring station classified as an urban traffic site. The model is a lagrangian particle dispersion model and it takes into account the presence of buildings as obstacles and generating microscale wind fields accordingly, making this class of model suitable for investigating spatial pattern of atmospheric pollution in urban areas where local accumulation might occur. The simulation investigates traffic emissions of nitrogen oxides (NO_x) over the period October 29 to November 10, 2016, when direct measurements of traffic flow were collected by four one-channel doppler radar traffic counters. These counters provided continuous estimate of vehicle length, speed and number. These latter data were combined with available traffic flows at rush hour by PTV VISUM mobility software and the fleet composition of the municipality to estimate the total NO_x emissions by vehicular traffic over the roads included in the simulation domain. NO_x simulated concentrations showed a moderate correlation with the NO_x observations at the nearby monitoring site. To have a better insight on the potential and the limitations of the GRAL model, its results will be compared with the output of the lagrangian particle dispersion model PMSS over the same area.

1. Introduction

The Po valley is a European hotspot area for air quality, due to its recurrent wind calm episodes and high pressure conditions that lead to persistence of high concentrations of atmospheric pollutants, even at remote rural sites. Despite the decrease in PM₁₀ and PM_{2.5} concentration over the long term throughout the valley [1][2], the strong anthropic pressure in this area, together with its characteristic climatic conditions, increase the persistence and the homogenization of the regional air masses.

This latter results in a significant impact by emission sources in the valley, affecting also rural areas distant from the metropolitan areas and strong emissions [3][4][5]. The main source of NO_x across the valley is vehicular traffic [2], although occasionally urban point emissions may have a non-negligible impact [6]. Therefore atmospheric pollution by NO_x is of main concern in the Po valley because of its rapid conversion to harmful atmospheric particles and of its critical level according to European and WHO air quality guidelines. One of the most successful tools in investigating impact on



air quality by emission sources are numerical models and, among these, lagrangian particle dispersion models (LPDM) showed very good performance under the meteorological settings typical of the Po valley [7] and under complex settings in general [8]. Moreover LPDM showed a good performance in investigating air quality in dense urban areas, since they can take into account the presence of buildings if operated on a fine simulation grid, e.g. of few meters (microscale).

This study presents a preliminary test of the Graz Lagrangian Model GRAL v.18.1 [9], a freely-available LPDM. The model was applied to simulate the fate of vehicular emissions within a part of the urban area of Modena, a town of 180 thousand inhabitants in the Po Valley (Northern Italy).

GRAL has been accurately described and validated in reference 10 and is able to perform simulations at microscale. GRAL has been successfully applied to assess the impact of emissions in other urban areas [11].

The main goal of this study is to verify the suitability of the procedure used to investigate the fate of vehicle traffic NO_x emissions in urban areas.

2. Experimental and Methods

2.1. Investigated site

Simulation domain was set to an area of 2 000 x 3 000 m² (inner box in Figure 1.), which includes several main roads, as well as a busy intersection of the city south-west ring road of the city. Direct measurements of the traffic flow were carried out continuously on the road with the highest traffic of the domain (Figure 2.) by the means of four doppler radar traffic counters (Easy Data SDR). The radar traffic counters recorded the time, the length and the speed for each passing vehicle. This very busy four-lane road, near the intersection with the ring road, was monitored from October 29th to November 10th 2016. Each one of the four lanes was monitored by a single one-channel doppler radar.

The hourly atmospheric concentration of NO_x was provided by the regulatory air quality station, classified as a urban traffic station, which is part of regional air quality monitoring programme and is managed by the regional environmental agency (ARPAE). This station is sited in the same street section as the Doppler radars, although few meters from off the road, within the grounds of a school (Figure 2.).

2.2. Emission data

Traffic emissions were based upon a combination of the direct measurements of traffic by radar counter with model estimates of traffic flows. These latter were based upon the traffic analysis model PTV Visum (PTV Group, Karlsruhe, Germany) one of the most used and recommended traffic simulation models for the integrated planning system [12]. Results of these simulations were provided by the Municipality of Modena and consist in the flow of light and heavy vehicles at peak time (from 7:30 to 8:30), along with their respective mean speed. These simulations refer to the year 2010 and include most of main roads in the Modena urban area. These street-specific traffic flows at peak hour were used in this study, since direct measurement of traffic were available only in 1 street.

Real traffic flow recorded by doppler radar were used to estimate hourly traffic modulations across the whole simulation period and were applied to the traffic fluxes provided by PTV Visum. This allowed to fully describe the traffic flow across the simulation domain for the investigation period. Moreover the modulation by Doppler radar was vehicle type dependent, since the radar allowed to produce a classification of each counted vehicle by measuring its length (i.e. motorbike, passenger car, light duty vehicle and heavy duty vehicle/bus)

The traffic estimates generated by the combination of experimental and simulated data, were used as input for TRAFFIC Emission Factors Improved Calculation (TREFIC, Arianet srl, Milan, Italy), an emission model implementing the COPERT IV official methodology, able to calculate for each road segment the NO_x atmospheric emissions in terms of pollutant mass per unit road length per hour. In order to produce this latter estimate, TREFIC split the vehicles flows proportionally to each type of vehicle in Modena accordingly to the local vehicular fleet composition, provided by Automobile Club

Italia for the year 2015 [13]. This fleet composition accounts for the number of vehicles for each fuel supply (e.g. diesel, gasoline, LPG, CNG), engine capacity, load displacement and EURO emission standard.

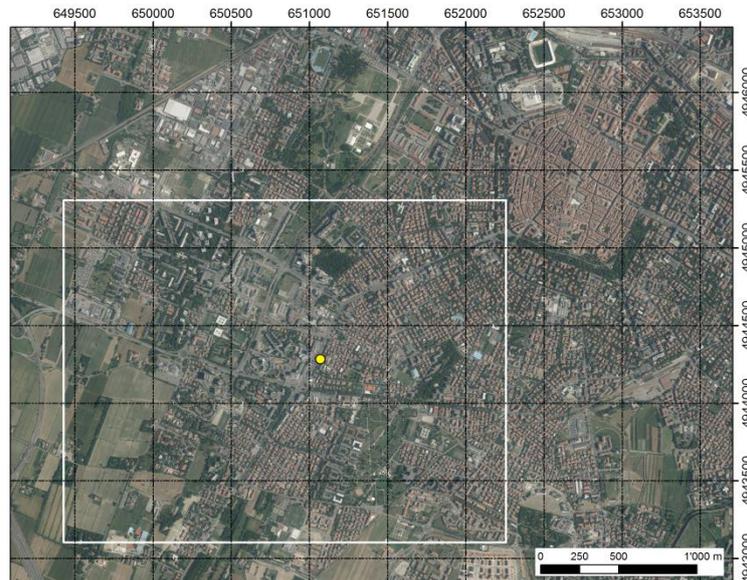


Figure 1. Satellite orthophoto of the city of Modena and of the simulation domain in the inner white box.

Red lines in Figure 2. show the roads for which the emissions were considered, along with the position of the radars and of the air quality station. The computational domain inside the white box extends beyond the considered road, since the GRAL model omits emissions and buildings at the model boundaries.

2.3. Model setup and meteorological data set

The model domain is 2000 m x 3000 m. The grid for the computation of flow extends vertically of 23 meter from the ground and it is divided in 10 layers having a thickness of 2 – 3 m. The concentration grid extends vertically from the surface of 6 m, with 2 layers with a thickness of 3 m. The model was performed in prognostic mode [11] with a horizontal grid resolution of 4 m. In the prognostic mode, the flow is explicitly calculated by the direct integration of a set of prognostic equations [9] and the microscale wind fields are generated by taking into account also the buildings. The volumes of buildings and the geometry of the roads were outlined by a high resolution 3D vector cartography (UVL_GPG) available for the domain [14].

A receptor, located to the point of the urban traffic station 4 m from the ground, was used in comparison with the observations, because the ARPAE input of the inlet of the NO_x analyser of the air quality monitoring station was at about that height. The model was run using hourly input data and generated hourly estimates of NO_x.

Meteorological input data can be provided to GRAL as raw or as categorized data. In this study we tested both options. In the first trial the raw meteorological values were used, i.e. hourly data of wind speed and direction provided by COSMO model mesoscale simulations performed by ARPAE weather service (i.e. “NO CLASSIFICATION” option).

In the second trial we used the simplest way to provide meteorological input data to GRAL: the hourly simulated weather conditions are firstly classified according to a lookup table depending on the wind direction, wind speed and atmospheric stability class and the frequency of each class of weather condition is calculated in permil. The wind direction is randomly selected within the range of each

sector. GRAL uses the data of each row for initialization and then calculates an almost stationary flow field. GRAL automatically calculates all wind flow fields accordingly [11][15].

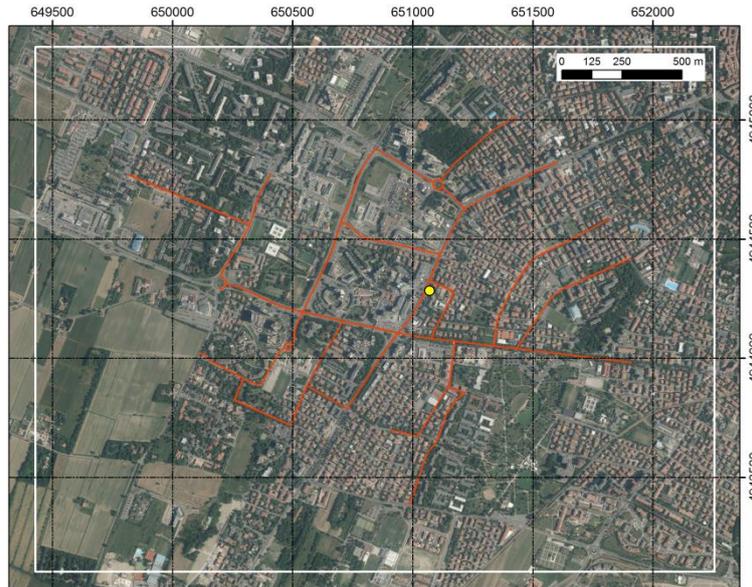


Figure 2. Model domain with location of the air quality station and of the Doppler radars (yellow dot) and of the streets included in the estimate of traffic emissions.

3. Experimental and Methods

Specific separated simulations were performed for each day of the investigated period, since input data was specific to each day. Moreover it was not possible to perform a single run for the whole period since it was too computationally demanding and GRAL does not allow the possibility to perform a model restart. Hourly NO_x concentration maps were generated for the whole domain at 3 m and 6 m above the ground for each day. The r Pearson's coefficient of linear correlation between the simulated and observed NO_x concentration at the air quality station are reported in Table 1.

Correlation resulted acceptable, occasionally very good, during days with stationary meteorological conditions, peaking on November 8th with $r = 0.79$; on the contrary, r was low in days with variable meteorology.

Table 1. Pearson's correlation coefficient between simulated and observed NO_x level at the air quality station, along with Mean Bias Error and ΔNO_x

| Day | Pearson's <i>r</i> | Mean Bias Error (μg/m ³) | Mean ΔNO _x (μg/m ³) |
|-------------|--------------------|---|---|
| 29 October | 0.62 | -90.2 | 21.3 |
| 30 October | 0.41 | -50.1 | 10.9 |
| 31 October | 0.41 | -71.9 | 35.8 |
| 01 November | -0.26 | -32.8 | 18.3 |
| 02 November | 0.31 | -67.3 | 30.4 |
| 03 November | -0.30 | -170.8 | 38.5 |
| 04 November | 0.33 | -81.4 | 33.2 |
| 05 November | 0.08 | -68.9 | 27.8 |
| 06 November | -0.03 | -34.8 | 16.6 |
| 07 November | 0.26 | -109.6 | 37.1 |
| 08 November | 0.79 | -106.9 | 12.1 |
| 09 November | 0.63 | -103.3 | - |

The mean bias error (MBE) was also estimated for each simulation day and included in Table 1. As expected the bias is largely negative, since GRAL includes only traffic emissions. Following a Lenschow approach [16], notwithstanding its large and well-known limitations [17], the MBE should be more properly compared to the difference in NO_x levels between the urban traffic station and the corresponding urban background station for the same urban area. The daily mean of this latter difference, namely ΔNO_x, was compared to the MBE and it confirms the non-negligible underestimation of NO_x levels by GRAL, with an overall mean difference between MBE and ΔNO_x of $-54.8 \mu\text{g}/\text{m}^3$.

The sources of this underestimation are several: the uncertainty in the estimate of the vehicular emissions, the quality in the meteorological simulation, the lack of chemical modelling in GRAL. Moreover significant part of the model underestimation is due to the non-ideal representativity of the two urban stations of Modena: the urban traffic and urban background sites share a highly similar source mix and an analogous impact by traffic and secondary pollutants [18], i.e. they are not fully suitable for an analysis based on a Lenschow approach.

Figure 3. shows the time series of simulated and observed NO_x levels by combining all single-day concentrations, resulting in a linear correlation of 0.14. Some unrealistic peaks in NO_x were occasionally generated by the model, hinting to GRAL difficulties during rapid meteorological transitions, e.g. on November 5th at 11:00. This shortcoming was previously observed in other studies [11].

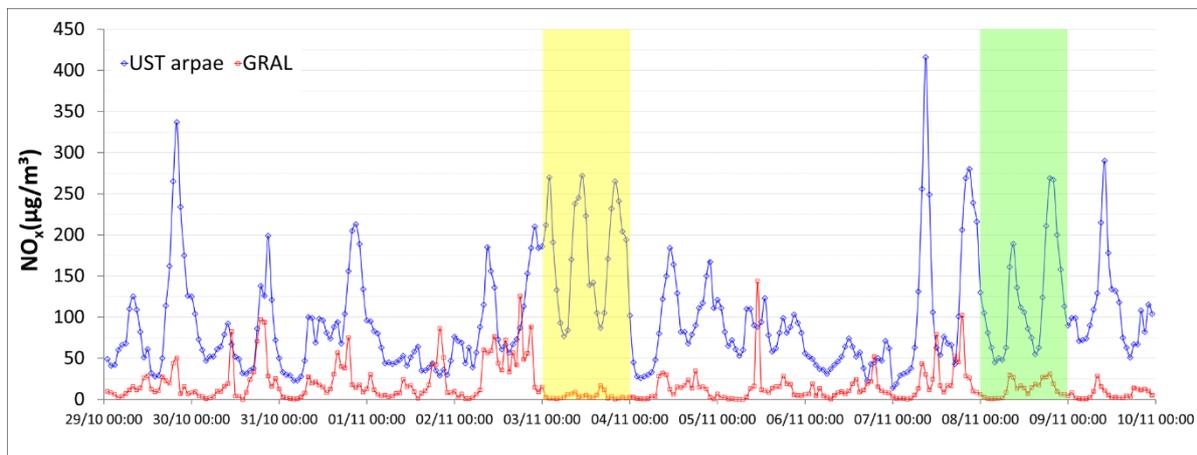


Figure 3. Hourly time series of observed and simulated concentration of NO_x : the former by the urban traffic station (UST arpae) and the latter by GRAL. Two periods are highlighted, one featured by low correlation in yellow (3 November) and one featured by high correlation in green (8 November).

In Figure 3, two days are highlighted: in yellow a period of very low correlation (November 3rd) and in green a period featured by high correlation (November 8th): in order to understanding the cause of this difference in performance, the meteorology of these two days were analysed in detail.

3.1 Thursday, November 03, 2016

November 3rd is featured by maximum wind speed of 4.6 m/s, with the 8.33 % occurrence of wind calms (i.e. wind speed < 1 m/s). Largest simulated concentration peaked at $16.5 \mu\text{g}/\text{m}^3$ (Figure 4), although this is an evident unrealistic peak during the rapid change in wind speed in the afternoon, which conversely lead to a drop in observed NO_x levels. Linear correlation for this day of simulation results $r = -0.30$, with a standard deviation in wind speed of 1.2 m/s.

In the second simulation test, using the stability classes instead of providing directly to the model the scale parameters for turbulence, the correlation does not change significantly, resulting in $r = -0.25$. In this case, simulated concentrations are larger than in the previous setup, exhibiting a peak at $28.4 \mu\text{g}/\text{m}^3$, but the pattern of the simulated concentration is not significantly different (Figure 5).

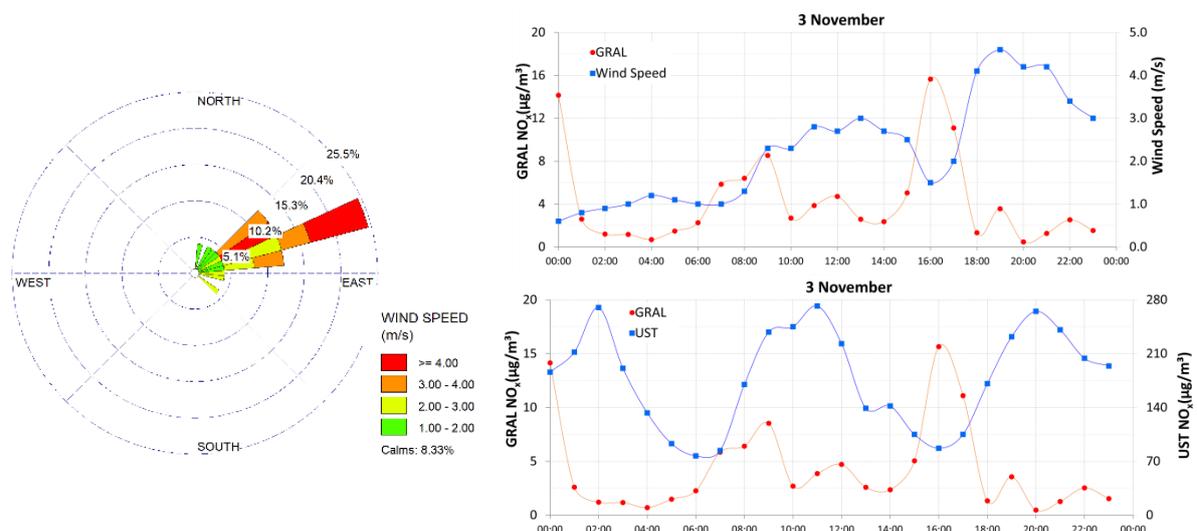


Figure 4. Wind rose, at left, and hourly evolution concentration NO_x (at 4 m) and wind speed at right.

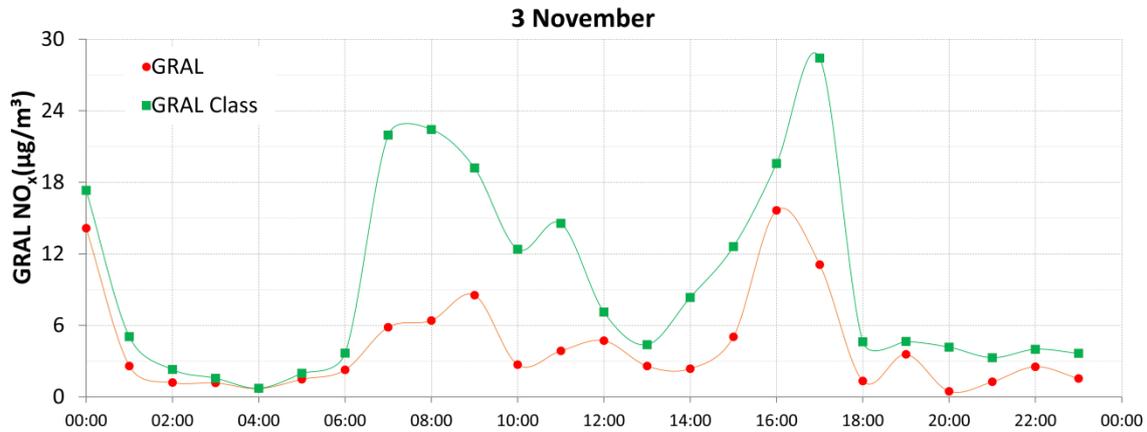


Figure 5. Hourly evolution concentration NO_x no classification (red) and with classification (green).

3.2. Tuesday, November 08, 2016

Meteorology on November 8th was featured by maximum wind speed of 2.9 m/s and with the 4.7 % occurrence of wind calms. Wind intensity is fairly constant, with a standard deviation of only 0.45 m/s. This weather conditions allowed to have a correlation between simulated and observed NO_x of $r = 0.79$ (Figure 6.). Also in this case the simulation was repeated using the Pasquill-Gifford stability classes, and similarly to November 3rd the correlation increase slightly, up to $r = 0.81$, and also the simulated NO_x levels increase (Figure 7.).

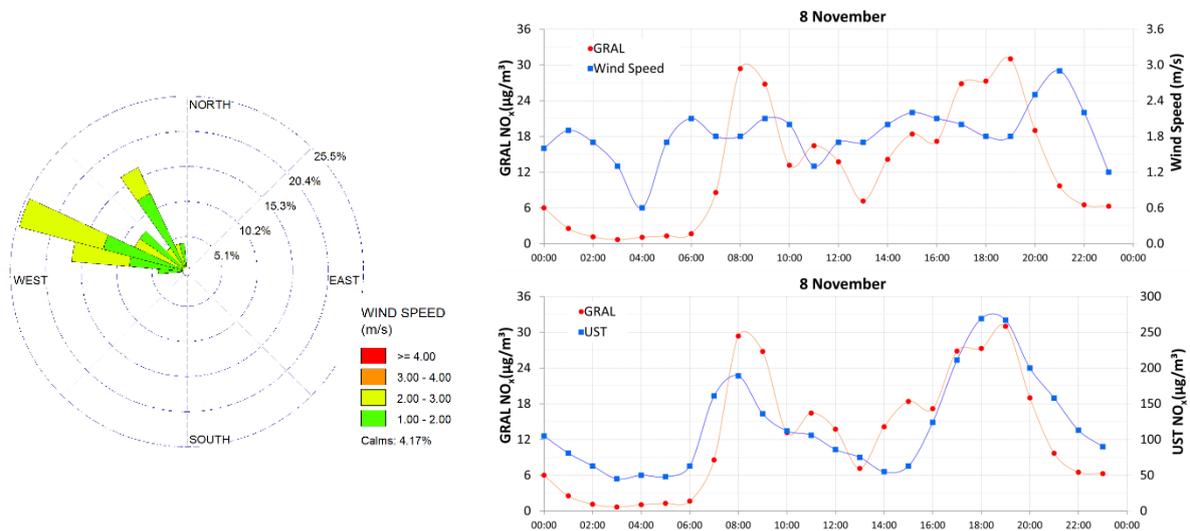


Figure 6. Wind rose, at left, and hourly evolution concentration NO_x (at 4 m) and wind speed at right.

Further tests were performed aiming to increase the performance of the model, e.g. performing runs over more than one day (Figure 8.), although the overall linear correlation did not show significant improvement ($r = 0.16$).

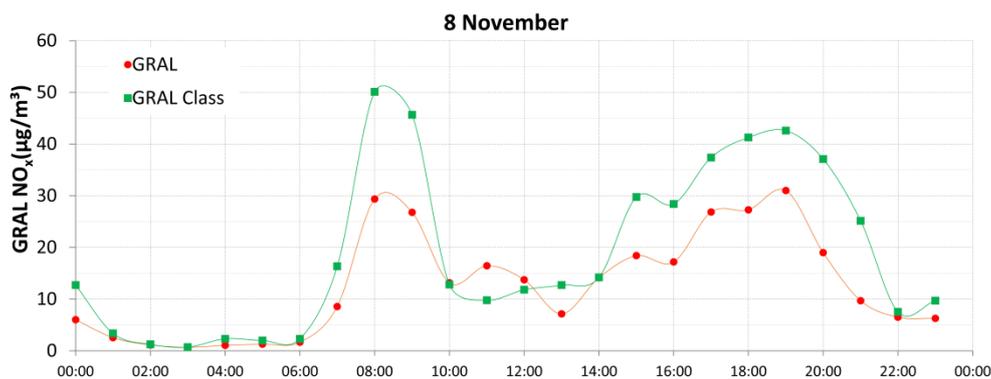


Figure 7. Hourly evolution concentration NO_x using GRAL without providing explicitly the stability classes (red) and with the explicit stability classes (green).

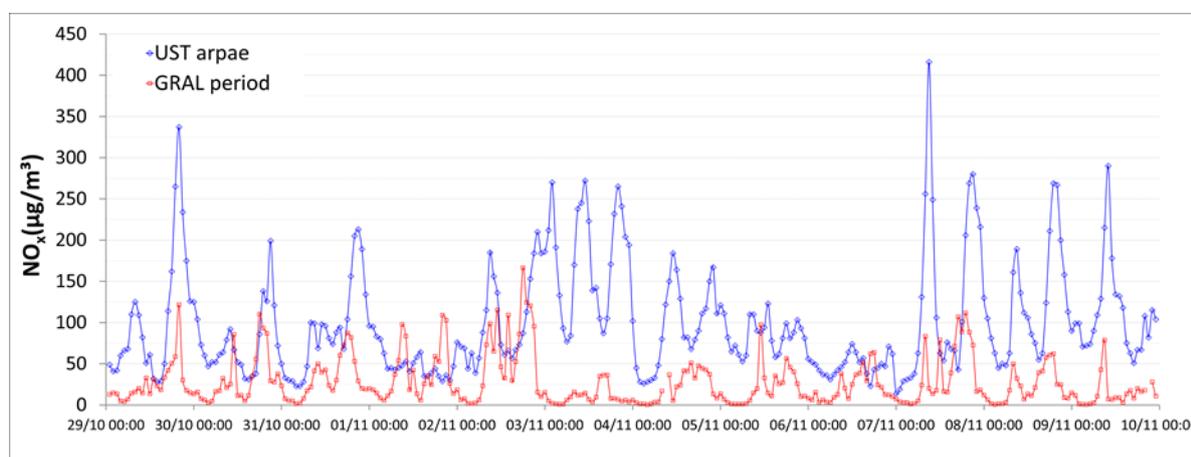


Figure 8. Hourly observed concentration of NO_x at the urban traffic site UST (blue) along with hourly simulated concentration of NO_x (red) by GRAL from October 29 to November 09, 2016.

4. Conclusion

The Graz Lagrangian Model GRAL was tested to estimate the impact of vehicular traffic in Modena, a city in the Po valley (Northern Italy). The model exhibited a general underestimation and some conflicting results, featured by a good performance during steady weather conditions, and occasional unrealistic peaks during rapid changes in wind speed, indicating some limitations of its steady state approximation. This behaviour is amplified by its application to specific days instead of an application using climatological data. Previous simulations for this same test case by the Lagrangian Particle Dispersion Model PMSS (Arianet, Italy and Aria Technologies, France) were available [19]: these show somewhat larger correlation coefficient between observed and simulated data for this test case, compared to GRAL.

Future tests will include the performance of a single simulation over the whole period and simulations under different meteorological conditions or in different locations.

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