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Quantifying road traffic impact on air quality in urban areas: A Covid19-induced lockdown analysis in Italy☆

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ABSTRACT

Covid19-induced lockdown measures caused modifications in atmospheric pollutant and greenhouse gas emissions. Urban road traffic was the most impacted, with 48–60% average reduction in Italy. This offered an unprecedented opportunity to assess how a prolonged (~2 months) and remarkable abatement of traffic emissions impacted on urban air quality. Six out of the eight most populated cities in Italy with different climatic conditions were analysed: Milan, Bologna, Florence, Rome, Naples, and Palermo. The selected scenario (24/02/2020–30/04/2020) was compared to a meteorologically comparable scenario in 2019 (25/02/2019–02/05/2019). NO_2, O_3, $PM_{2.5}$ and PM_{10} observations from 58 air quality and meteorological stations were used, while traffic mobility was derived from municipality-scale big data.

NO_2 levels remarkably dropped over all urban areas (from −24.9% in Milan to −59.1% in Naples), to an extent roughly proportional but lower than traffic reduction. Conversely, O_3 concentrations remained unchanged or even increased (up to 13.7% in Palermo and 14.7% in Rome), likely because of the reduced O_3 titration triggered by lower NO emissions from vehicles, and lower NO_x emissions over typical VOCs-limited environments such as urban areas, not compensated by comparable VOCs emissions reductions. PM_{10} exhibited reductions up to 31.5% (Palermo) and increases up to 7.3% (Naples), while $PM_{2.5}$ showed reductions of ~13–17% counterbalanced by increases up to ~9%. Higher household heating usage (+16–19% in March), also driven by colder weather conditions than 2019 (−0.2 to −0.8 °C) may partly explain primary PM emissions increase, while an increase in agriculture activities may account for the NH_3 emissions increase leading to secondary aerosol formation. This study confirmed the complex nature of atmospheric pollution even when a major emission source is clearly isolated and controlled, and the need for consistent decarbonisation efforts across all emission sectors to really improve air quality and public health.

1. Introduction

Following the coronavirus disease (Covid19) outbreak and its pandemic spread worldwide, several restrictive measures have been taken by governments. In Italy, the first confirmed case of infection was detected on February 20, 2020 in Codogno (Collivignarelli et al., 2020), a small town in the Lombardy region located about 50 km from Milan. On 21st February, the government adopted the first restrictive measures limiting travel, social, cultural, and economic activities, that were applied over 11 small municipalities in Lombardy and Veneto regions and involved about 50,000 people. On 4th March, schools and universities were closed over the whole country. To contain the rapid spread of the infection, particularly in the northern regions, on 8th March the government enforced the first lockdown measures over a large part of northern Italy, including restriction of home-work mobility. These measures involved 16 million people, about 1/4 of the whole Italian population. This local lockdown was extended to the entire country on 11th March and was maintained until May 3, 2020 (Fig. S1). Since late February 2020, Italy progressively shut down commercial activities and workplaces, limited travel, and forced people to stay home, so that main production sectors and population lifestyle were both strongly impacted. Anthropogenic activities drastically

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changed, together with pollutant emissions generated by the corresponding source categories, with a consequent expected significant change in air quality conditions.

Recently, several studies were focused on the impacts of Covid19 lockdown on air quality in different regions worldwide. Air quality changes during the 2020 lockdown have been either compared against the pre-lockdown period (e.g. Tobías et al., 2020; Mahato et al., 2020; Huang et al., 2020; Wang and Su, 2020; Rodríguez-Urrego and Rodríguez-Urrego, 2020; Agarwal et al., 2020) or against a mirrored period occurring during the previous year(s) (e.g. Chauhan and Singh, 2020; Chen et al., 2020; Sicard et al., 2020; Kerimray et al., 2020; Sharma et al., 2020; Shrestha et al., 2020; Singh and Chauhan, 2020; Shakoor et al., 2020; Connerton et al., 2020). The first approach is probably arguable, as the influence due to the changing meteorological conditions (e.g. Jan.–Feb. vs. Mar.–Apr.) is completely disregarded, while the second offers the advantage of referring to a period with similar weather conditions. Taking a step further, Collivignarelli et al. (2020) even constructed, after categorizing main observed meteorological variables based on their distribution, a reference period meteorologically comparable with the lockdown period.

A limitation in most of such studies is the lack of quantification of road traffic mobility change during lockdown. Across all countries, transportation was by far the sector mostly impacted by the pandemic-induced restriction measures. Both inside and outside the urban areas, a large reduction in road traffic and associated pollutant emissions occurred. Therefore, although under tragic circumstances, as also noted by Kerimray et al. (2020) and by Collivignarelli et al. (2020), Covid19-induced severely restrictive measures offered a unique and unprecedented opportunity to assess how a substantial abatement of road traffic results in air quality changes in urban areas. A comprehensive and consistent mobility dataset may be obtained by using big data based on digital traces collected from smartphone users (Pepe et al., 2020). Big data are generally referred to as high-volume, high-velocity and/or high-variety sets of information that grow at ever-increasing rates. Particularly during the Covid19 pandemic, several companies have published periodic mobility reports based on location data collected through their services, including Google (2020) and TomTom (2020), or have shared their data thanks to suitably developed analytical platforms, including Apple (2020), Cuebiq (2020), and EnelX & Here (2020) that provided the data used here.

The goal of the present study is twofold: (i) to assess how urban air quality changed in Italy following the Covid19-induced lockdown measures; (ii) to quantify the contribution due to road traffic emissions to atmospheric pollution in urban areas. Two temporal scenarios have been defined: a “lockdown” scenario in 2020, when the Covid19-induced restrictive measures greatly affected traffic mobility, and a baseline scenario, corresponding to basically undisturbed traffic mobility conditions during the same period of the year in 2019. The analysis focused on six major cities lying along a climatic gradient in Italy: Milan, Bologna, Florence, Rome, Naples, and Palermo. Daily observations of air pollutants such as nitrogen dioxide (NO_2), ozone (O_3), and particulate matter with an aerodynamic diameter lower than 2.5 μm ($PM_{2.5}$) and 10 μm (PM_{10}), and meteorological parameters were obtained, while big data at municipality scale have been used to derive traffic mobility over all the urban areas.

2. Materials and methods

2.1. Study areas

The analysis focused on six urban areas in Italy: Milan, Bologna, Florence, Rome, Naples, and Palermo (Fig. 1). These cities were selected to obtain a representative picture of urban air quality conditions at national level: they fall among the eight most populated cities in Italy, and – since located north to south of the peninsula – are affected by very different climatic conditions, thus encompassing all possible atmospheric dispersion conditions at a country scale. The main characteristics of these urban areas are reported in Table S1. Since belonging to different climatic zones, the selected urban areas must also comply with different regulations for residential heating usage (DPR no. 412 of August 26, 1993), as detailed in Table S2. These regulations include: (i) a maximum of 14 h from Oct. 15th to Apr. 15th for Milan and Bologna (falling onto E-zone); (ii) 12 maximum hours from Nov. 1st to Apr. 15th for Florence and Rome (D-zone); (iii) 10 maximum hours from Nov. 15th to Mar. 31st for Naples (C-zone); (iv) 8 maximum hours from Dec. 1st to Mar. 31st for Palermo (B-zone).

2.2. Data collection

The analysis was based on air quality, meteorological and road mobility observations. NO_2, $PM_{2.5}$ and PM_{10} data were obtained from urban traffic (UT) and urban background (UB) air quality stations, while O_3 data were obtained from suburban background (SB) and UB stations.

Meteorological data were collected from stations located in the urban areas or in the nearby airports, including air temperature (*T*), relative humidity (*RH*), wind speed (*WS*), wind direction (*WD*), rainfall (*Rain*), and global solar radiation (*Rad*). Since *Rad* was not available at met stations of all urban areas, satellite data from the Copernicus Atmosphere Monitoring Service (CAMS, 2020) have been used. Reliability of CAMS satellite irradiation was assessed by applying a linear regression against solar radiation measured at the Florence meteorological station on the period 01/01/2019–30/04/2020, that gave an R^2 value of 0.970. A further variable – cloud cover (*CC*) – was estimated as a function of ground-observed global irradiation on horizontal plane (*GHI*) and clear sky *GHI* (GHI_{clear}), both retrieved from CAMS data, by inverting the expression of Kasten and Czeplak (1980):

$$GHI\ /\ GHI_{clear} = 1 - 0.75 * CC^{\,3.4} \tag{1}$$

Since $PM_{2.5}$ and PM_{10} were available as daily average concentrations, all the other air quality and meteorological observations have been averaged from hourly to daily values. The wind regime over each urban area has been addressed by calculating the wind roses based on concurrent observations of *WS* and *WD* at time resolution higher than daily, thus using: 1-h values for Milan, Bologna, Florence, and Rome; 10-min values for Naples and Palermo. The full list of air quality and meteorological stations (58) that were used is reported in Table S3, also showing stations' coordinates, type and measured parameters.

Road mobility data have been derived in terms of daily normalized variations with respect to a baseline mobility scenario (13/01/2020–02/02/2020), using data made available across the period 07/02/2020–30/04/2020 by the online platform developed for Italy by EnelX & Here. Usefulness of these data lies in that their fine granularity allows to derive mobility data at municipality level. A comparison with traditional traffic counters was made to validate such data products, comparing daily mobility variations over the municipality of Milan in the period 07/02/2020–30/04/2020 against road vehicle entries to the city-centre restricted area (C-area) collected in the same period by the Municipality of Milan (2020a) over 42 gateways recording half-hourly traffic volumes. As a result, $R^2 = 0.972$, mean bias of 0.8% and root mean square error of 5.7% were achieved.

To obtain a comprehensive figure of the role played by different

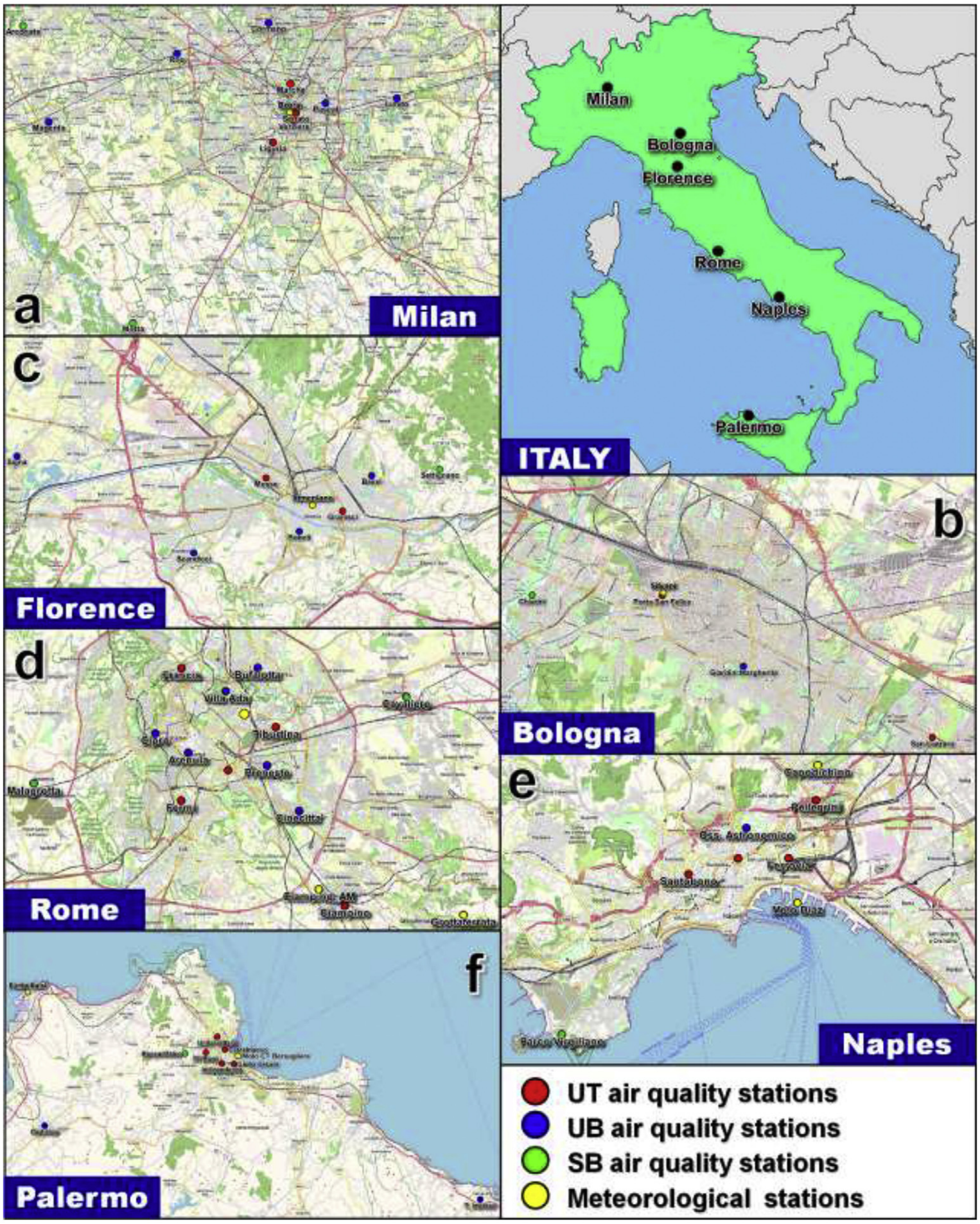

Fig. 1. Map of the urban study areas in Italy, also showing location of air quality and meteorological stations: (a) Milan; (b) Bologna; (c) Florence; (d) Rome; (e) Naples; (f) Palermo. (Cartography source: Open Street Map).

emitting categories, data extracted from the most updated versions of the following regional emission inventories have been also analysed: Milan (updated to the year 2017, ARPA Lombardia, 2020); Bologna (year 2015, ARPA Emilia-Romagna, 2020); Rome (year 2015, ARPA Lazio, 2020). Unfortunately, quite outdated inventory versions are currently available for Palermo (year 2012) and Florence (year 2010), which have therefore been withdrawn as well as inventory for Naples, whose data – although updated to 2016 – are not publicly available. Furthermore, official statistics by nationwide operators have been also consulted, including ANAS (https://www.stradeanas.it), the largest national operator of the extra-urban road network, and Atlantia (https://www.atlantia.it), the Italian operator of the toll motorway network.

2.3. Methods

In order to quantify the impact caused by road traffic on air quality in urban areas, a straight comparison has been performed between data observed across a period of strongly modified traffic mobility and a period of undisturbed ("baseline") mobility. The first scenario (2020) was set from February 24, 2020 to April 30, 2020 to meet the following criteria: (i) to include the very start of the Covid19-induced restrictive measures taken in Italy, thus capturing the beginning of progressive traffic reduction; (ii) to last until the end of the most restrictive lockdown measures (i.e. 03/05/2020); (iii) to include the end of the period when residential heating plant usage is regulated for the coldest urban areas (Apr. 15th, Table S2). The second scenario (2019) was selected as a mirrored (Mondays to Sundays) period during the previous year, thus spanning from February 25, 2019 to May 02, 2019.

Overall, datasets for each period included a total of 67 daily records. Daily time series of the following 15 variables have been analysed: (i) for meteorology, *T*, *RH*, *WS*, *Rain*, *Rad*, and *CC*; (ii) for road traffic, normalized mobility variations by day of week with respect to a baseline scenario; (iii) for air quality, concentrations of O_3 at SB and UB stations as well as concentrations of NO_2, $PM_{2.5}$ and PM_{10} at UT and UB stations. When multiple air quality stations of a given type were available in the monitoring network of an urban area, pollutant concentrations have been averaged across all stations of the same type (Table S3).

The EnelX & Here mobility data are expressed as normalized variations with respect to a baseline scenario spanning January 13, 2020 to February 02, 2020). To verify that such 2020 baseline mobility data are also representative of the 2019 baseline period used here, road vehicle entries to the C-area collected by the Municipality of Milan in the period 13/01/2020–02/02/2020 have been correlated to those collected during the period 14/01/2019–03/02/2019, returning an R^2 of 0.890 and normalized mean bias of −1.9%. Since 2020 EnelX & Here mobility big data in Milan are strongly correlated to locally observed vehicle entries ($R^2 = 0.974$, see section 2.2), they can therefore be assumed as representative of the baseline 2019 traffic scenario (25/02/2019–02/05/2019).

Since this study is focused on the role played by local anthropogenic emission sources (markedly, road traffic), those events (if any) involving long-range transcontinental air pollutant transport have been withdrawn from the analysis. For each period, the statistics of all time series have been computed using the "R-stat" environment (R Core Team, 2020), while the frequency distribution was analysed in terms of boxplots using the "boxplot" function implemented in the R Graphics Package (2020).

3. Results

3.1. Overview

Time series of traffic mobility observed 10/02/2020–30/04/2020 over all the municipalities expressed as values by day of week normalized to the baseline scenario (13/01/2020–02/02/2020) are shown in Fig. 2. Following the analysis described in section 2.3, this 2020 baseline scenario is considered as representative of the mobility conditions across the whole 2019 baseline period.

Fig. 2 clearly indicates that mobility trends start to decrease after the first local restrictive measures were introduced (February 21, 2020 onwards). Since March 08, 2020, the most restrictive (lockdown) measures were adopted over a large part of northern areas, including the whole Lombardy region and thus Milan, which was the first large urban area in the country experiencing the lockdown. After the start of the lockdown at national level (March 11, 2020), mobility trends prove to be very similar across all cities.

Table 1 summarizes mean daily values of all variables across the two scenarios along with corresponding change rates. Across both scenarios in 2019 and 2020, one event of desert dust intrusion due to long-range transportation has been registered, affecting the whole Italian peninsula from 28 to March 31, 2020 to such an extent that abnormally high PM_{10} concentrations were recorded. Therefore, applying the approach described in section 2.3, these unusual events across the period 2020 were removed from the analysis. A similar choice was taken, e.g., by Collivignarelli et al. (2020).

In Figs. S2–S7, the 2019 vs. 2020 air quality comparison is shown through the boxplots of NO_2, O_3, PM_{10} and $PM_{2.5}$ daily concentrations measured by station type over all urban areas. In order to have an immediate quantification of the differences by period affecting all analysed variables and the possible relations with meteorology and traffic, in Fig. 3–8 the boxplots of 2020-to-2019 change rates are plotted for the same pollutant concentrations as well as for main meteorological parameters (*T* and *WS*) and road traffic mobility. In Figs. S8–S13, the wind roses observed across scenarios 2019 and 2020 over each urban area are plotted.

3.2. Milan

Milan was one of the cities most severely affected by the pandemic at national and even global level, as well as the first large city after Wuhan where lockdown measures were enforced. Therefore, as expected, it experienced on average the highest 2020-to-2019 mobility reduction among the cities analysed here. As shown in Fig. 2, in the period 24/02/2020–30/04/2020 traffic mobility dropped up to 93%, overall averaging 60% (Table 1). In the boxplot of 2020-to-2019 change rate, traffic mobility distribution exhibited a median value of −69% (Fig. 3). The 2020 period was slightly colder than 2019, as *T* decreased on average by 0.5 °C, and slightly less windy, as *WS* reduced by 6.6% (Table 1). No appreciable change occurred neither in *Rain* nor in *Rad* or in *CC*. Wind roses were apparently similar across 2019 and 2020 (Fig. S8). A clear reduction in NO_2 was observed (Fig. S2a), higher at UB (−34.8%) than at UT (−24.9%) stations (Table 1). By contrast, O_3 increased at both types of station (Fig. S2b) by an average of 11.4% (UB) and 12.7% (SB), exhibiting an increase of 17% in the median value of the

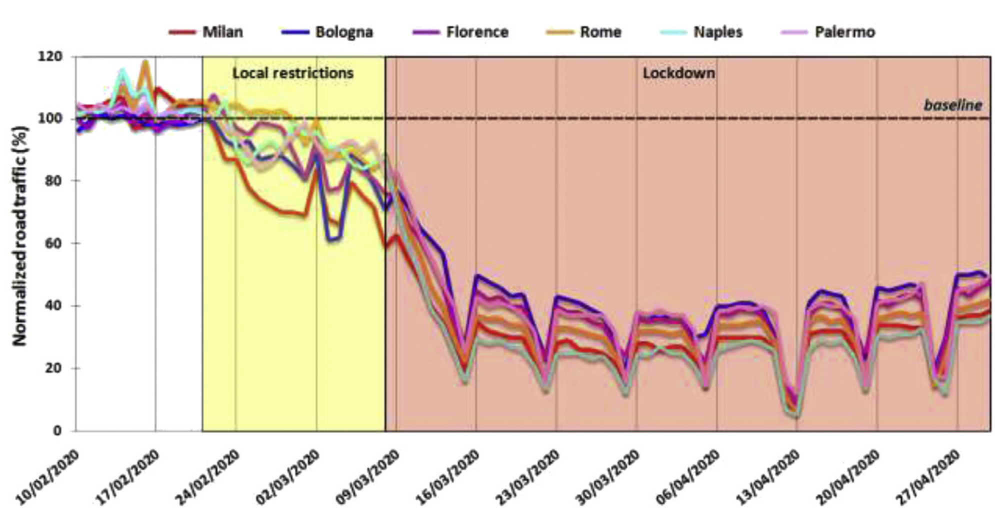

Fig. 2. Time series of daily road traffic mobility observed over the municipalities of the study areas (10/02/2020–30/04/2020). Values are normalized by day of week to those observed 13/01/2020–02/02/2020 taken as baseline scenario (shown as dashed line, traffic = 100%). The periods of local restrictions (21/02–07/03) as well as of local and national lockdown measures (08/03–30/04) are also shown. Mobility data source: EnelX & Here (2020).

Table 1
Mean values by study area and period of meteorological parameters, road traffic and pollutant concentrations observed on a daily basis at all stations. Corresponding 2020-to-2019 change rates (%) are reported in italics[a, b,c].

Variable	Study area											
	Milan		Bologna		Florence		Rome		Naples		Palermo	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
Meteorology												
T (°C)	13.8	13.1	13.3	12.5	13.3	12.7	12.7	12.5	13.5	13.1	14.3	15.5
		−5.1		*−6.0*		*−4.5*		*−1.6*		*−3.0*		*+8.4*
RH (%)	52.7	53.4	51.5	50.0	51.0	48.9	67.6	70.4	68.1	69.6	72.3	70.3
		+1.3		*−2.9*		*−4.1*		*+4.1*		*+2.2*		*−2.8*
WS (m/s)	1.98	1.85	2.75	2.74	2.40	2.30	2.70	2.60	2.80	2.70	5.00	5.00
		−6.6		*−0.4*		*−4.2*		*−3.7*		*−3.6*		*0*
Rain (mm)	1.5	1.6	1.1	0.7	1.2	0.7	1.2	1.5	NA	NA	NA	NA
		+6.7		*−36.4*		*−41.7*		*+25.0*		*NA*		*NA*
Rad (W/m^2)	175.8	170.5	189.3	192.1	192.2	191.2	197	199.1	199.3	196.1	211.3	194.2
		−3.0		*+1.5*		*−0.5*		*+1.1*		*−1.6*		*−8.1*
CC (%)	66.7	67.9	64.2	62.2	65.6	63.3	63.7	61.4	63.9	64.4	61.3	66.1
		+1.8		*−3.1*		*−3.4*		*−3.5*		*+0.8*		*+7.8*
Normalized road traffic (%)	1.00	0.40	1.00	0.52	1.00	0.50	1.00	0.48	1.00	0.42	1.00	0.52
		−60		*−48*		*−50*		*−52*		*−58*		*−48*
Pollutant concentrations by station type (μg/m^3)												
NO_2 (UT)	47.3	35.5	40.9	24.6	46.9	26.3	48.5	25.8	47.0	24.8	50.5	34.3
		−24.9		*−39.9*		*−43.9*		*−46.8*		*−47.2*		*−32.1*
NO_2 (UB)	42.2	27.5	18.7	14.0	20.1	14.6	38.7	22.6	24.7	10.1	18.8	21.3
		−34.8		*−25.1*		*−27.4*		*−41.6*		*−59.1*		*+13.3*
O_3 (SB)	51.9	58.5	48.7	52.7	73.8	72.9	49.5	56.8	70.9	73.8	73.7	83.8
		+12.7		*+8.2*		*−1.2*		*+14.7*		*+4.1*		*+13.7*
O_3 (UB)	48.1	53.6	52.8	52.5	63.4	61.6	50.2	54.2	61.6	51.3	69.5	69.5
		+11.4		*−0.6*		*−2.8*		*+8.0*		*−16.7*		*0*
PM_{10} (UT)	30.3	28.0	22.2	21.3	22.8	17.9	26.4	23.2	23.2	23.8	30.5	20.9
		−7.6		*−4.1*		*−21.5*		*−12.1*		*+2.6*		*−31.5*
PM_{10} (UB)	28.5	29.0	19.1	17.5	18.3	16.8	24.6	21.5	26.0	27.9	18.0	14.3
		+1.8		*−8.4*		*−8.2*		*−12.6*		*+7.3*		*−20.6*
$PM_{2.5}$ (UT)	19.3	20.7	13.6	14.0	14.7	12.2	13.9	14.3	13.2	14.4	NA	NA
		+7.3		*+2.9*		*−17.0*		*+2.9*		*+9.1*		*NA*
$PM_{2.5}$ (UB)	20.9	18.1	10.8	11.2	11.4	11.4	12.6	12.9	12.0	12.5	NA	NA
		−13.4		*+3.7*		*0.0*		*+2.4*		*+4.2*		*NA*

[a] 2019-period: 25/02/2019–02/05/2019; 2020-period: 24/02/2020–30/04/2020. Sample size for each period: 67 records.
[b] Code for air quality station type: UT, Urban Traffic; UB, Urban Background; SB. Suburban Background.
[c] Not Available (NA) data: Rain (Naples, Palermo); $PM_{2.5}$ concentrations (UT & UB, Palermo).

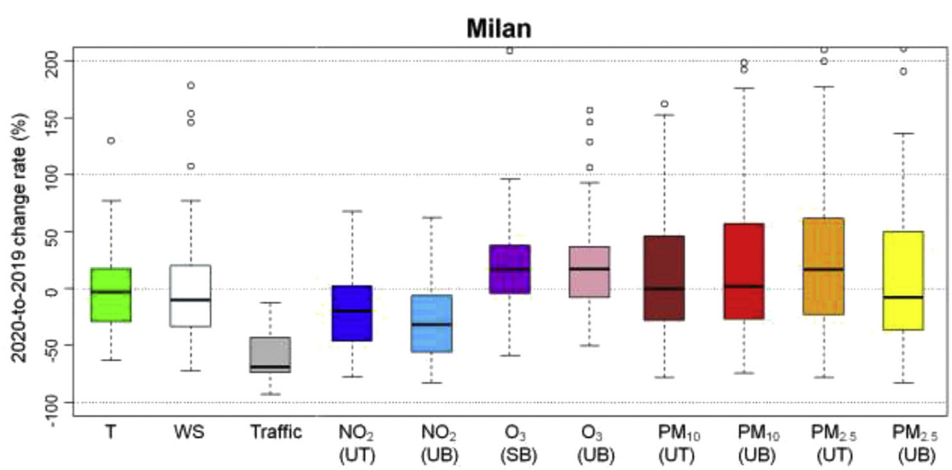

Fig. 3. Boxplots of 2020-to-2019 change rates of daily observations in Milan: concentrations by station type of NO_2, O_3, PM_{10} and $PM_{2.5}$; air temperature (T); wind speed (WS); road traffic. Boxplots are delimited by the first (Q_1) and third (Q_3) distribution's quartiles, while the black line inside the box denotes the median value (Q_2). Lower whisker is Q_1–1.5*IQR, while upper whisker is Q_3+1.5*IQR, where the interquartile range (IQR) is Q_3–Q_1. Circles outside the whiskers denote outlier data.

distributions (Fig. 3). PM_{10} remained basically unchanged (Fig. S2c), showing a 7.6% reduction (UT) and a 1.8% increase (UB), while $PM_{2.5}$ (Fig. S2d) exhibited a median increase of 17% at UT stations and a median decrease of 8% at UB stations (Fig. 3).

3.3. Bologna

Opposite to Milan, Bologna experienced the smallest mobility reduction with respect to the previous year: −48% on average (Table 1) and −56% in terms of median value (Fig. 4). On average, *T* reduced by 0.8 °C, *WS* by 0.4%, *Rain* by 36.4%, and *CC* by 3.1% (Table 1). As in Milan, no appreciable change was observed in the wind regime (Fig. S9). A significant drop in NO_2 was recorded (Fig. S3a), higher at UT (−39.9%) than at UB (−25.1%) stations. O_3 remained basically unchanged (Fig. S3b), although exhibiting a slight average increase at SB stations (+8.2%). Boxplots show that PM_{10} remained substantially unchanged (Fig. S3c), and that $PM_{2.5}$ slightly increased (Fig. S3d), with distribution's median value of 9% at both types of station (Fig. 4).

3.4. Florence

In 2020, Florence's traffic mobility reduced on average by 50% with respect to the same period in 2019 (Table 1), with a distribution's median reduction of 60% (Fig. 5). Similarly to Bologna, the year 2020 was slightly colder than 2019 (−0.6 °C), less windy (−4.2%), less cloudy (−3.4%), and less rainy (−41.7%, Table 1): this significant *Rain* reduction did not reflect on *Rad*, that did not appreciably change (−0.5%). The 2019-to-2020 wind rose comparison basically shows the same prevailing wind directions, although in 2020 NE winds proved to be slightly stronger and more frequent than in 2019 (Fig. S10). As in Bologna, a clear NO_2 decrease was observed (Fig. S4a), most pronounced at UT (−43.9%) than at UB (−27.4%) stations (Table 1). Again similarly to Bologna, O_3 levels did not significantly change (Fig. S4b), exhibiting an average reduction of 1.2% at SB and 2.8% at UB stations. A decrease averaging 21.5% was observed for PM_{10} at UT stations, and 8.2% at UB stations (Table 1, Fig. S4c). A comparable decrease (17%) was recorded on average for $PM_{2.5}$ at UT stations, while no variation resulted at UB stations (Fig. S4d). This outcome is confirmed by the boxplots of PM_{10} and $PM_{2.5}$ time changes at UB stations (Fig. 5), as the median values of their distribution clearly indicate no variation.

3.5. Rome

In Rome, 2020 road mobility varied between −5 and −94% with respect to 2019, overall averaging −52% (Table 1). As shown by the boxplot in Fig. 6, the distribution of mobility change rate is strongly skewed to the left, exhibiting a median reduction of 65%. Meteorological conditions were basically the same as in the previous year, with marginal reduction in *T* (0.2 °C), *WS* (3.7%), and *CC* (3.5%), while *Rain* increased by 25% (Table 1). Wind roses were again quite similar between 2019 and 2020 (Fig. S11). NO_2 dropped to a higher extent than in Milan, Bologna and Florence (Fig. S5a), averaging 46.8% at UT and 41.6% at UB stations (Table 1). NO_2 strong reduction is counterbalanced by a slight O_3 increase (Fig. S5b), averaging 14.7% at SB and 8% at UB stations. The boxplots of O_3 change rates (Fig. 6) show median values increasing by 18% at SB and 5% at UB stations. PM_{10} exhibit a slight and comparable decrease at both types of station (medians of 12–13%, Fig. S5c), while $PM_{2.5}$ did not appreciably change with respect to the previous year (Fig. S5d).

3.6. Naples

During the 2020 scenario, traffic mobility in Naples dropped up to 95% (Fig. 2), overall averaging 58% (Table 1). While average mobility reduced the most in Milan (see section 3.2), Naples was the urban area with the highest reduction median value of −72% (Fig. 7). Naples was affected by a meteorological regime comparable to the previous year, as on average *T* reduced by 0.4 °C and *WS* by 3.6%, while *Rad* and *CC* remained basically unchanged (Table 1). The wind rose comparison again indicates no appreciable variation, although in 2020 SW winds were slightly weaker and less frequent than in 2019, and NE winds slightly stronger (Fig. S12). NO_2 showed the highest reduction among all the considered urban areas (Fig. S6a), averaging 47.2% at UT and 59.1% at UB stations (Table 1). O_3 exhibited a contrasting behaviour, as slightly increasing at SB and slightly decreasing at UB stations (Fig. S6b). PM_{10} and $PM_{2.5}$ resulted in a slight increase at both types of station (Figs. S6c and S6d), with the boxplots of their change rate reporting median increases of 4–8% for PM_{10}, and of 6% for $PM_{2.5}$ concentrations (Fig. 7).

3.7. Palermo

In 2020, traffic mobility pattern in Palermo was quite similar to the one affecting Bologna (Fig. 2), also featuring the same average reduction with respect to 2019 (48%, Table 1). The full distribution of mobility change rate returned a median value of −60% (Fig. 8). Unlike in all other cities, in Palermo *T* on average significantly increased (+1.2 °C), while no change was observed for *WS* (Table 1); an 8.1% decrease occurred in *Rad* observations and a concurrent increase (+7.8%) in *CC* observations. Local wind roses do not exhibit a significant change between the two periods (Fig. S13). NO_2 exhibited a contrasting pattern (Fig. S7a), as decreasing at UT stations (−32.1%), while increasing at UB stations (+13.3%, Table 1). O_3 increased at SB stations (+13.7%), while remained unchanged at UB stations (Fig. S7b). Palermo was affected by the highest PM_{10} concentrations reductions among the cities analysed here (Fig. S7c), averaging 31.5% at UT and 20.6% at UB stations (Table 1). Within the

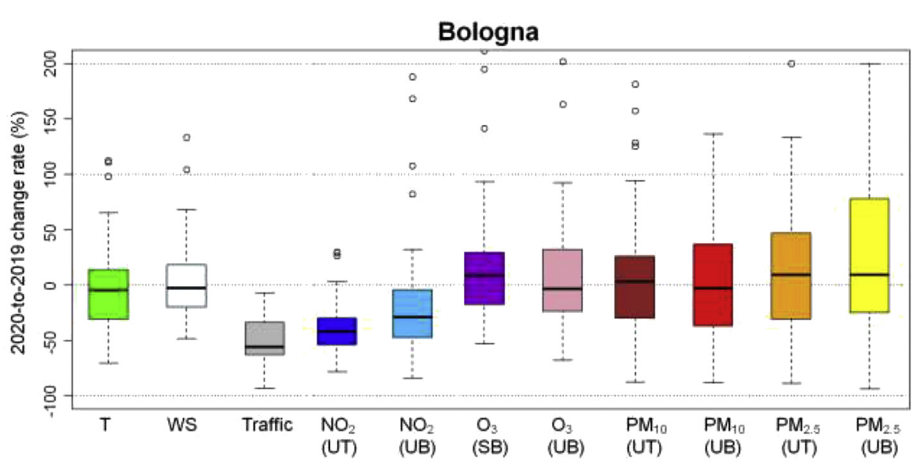

Fig. 4. Similar to Fig. 3, but for the city of Bologna.

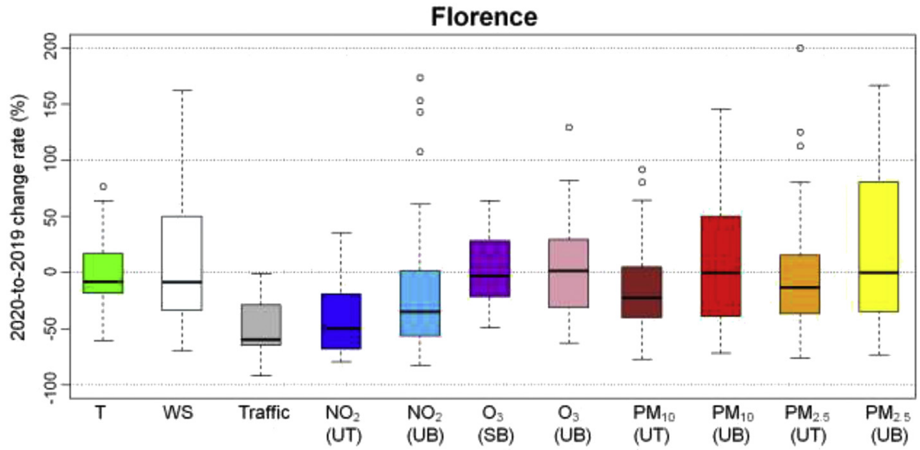

Fig. 5. Similar to Fig. 3, but for the city of Florence.

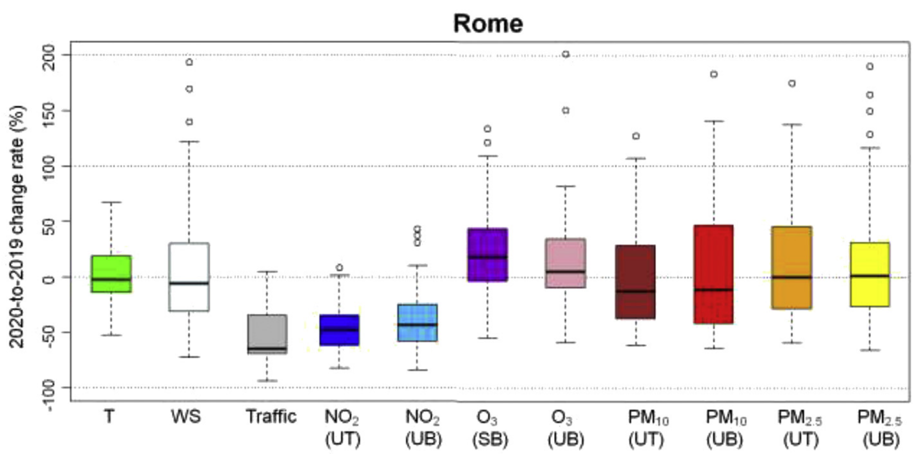

Fig. 6. Similar to Fig. 3, but for the city of Rome.

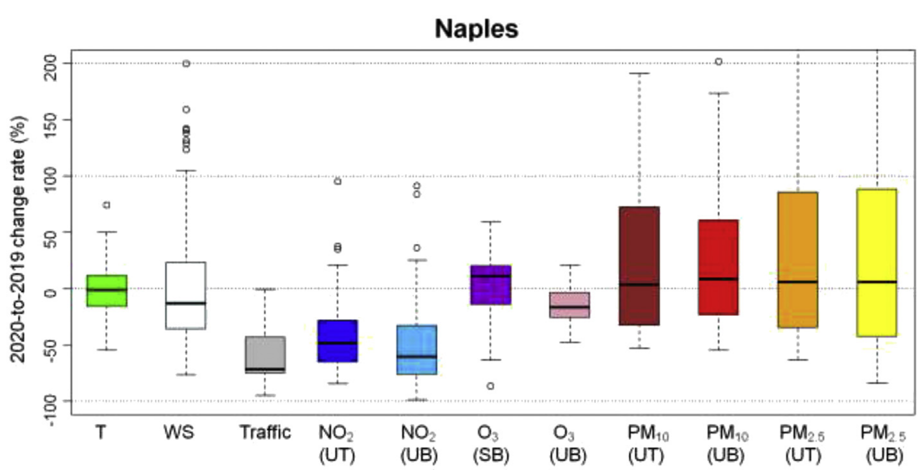

Fig. 7. Similar to Fig. 3, but for the city of Naples.

Palermo air quality monitoring network, $PM_{2.5}$ concentrations were only recorded by industrial stations, so that no observation either at UT or UB stations was available.

4. Discussion

Mobility reduction during the lockdown was observed both in urban areas and along extra-urban roadways. In fact, EnelX & Here mobility data at municipality scale (Fig. 2) are strongly correlated to

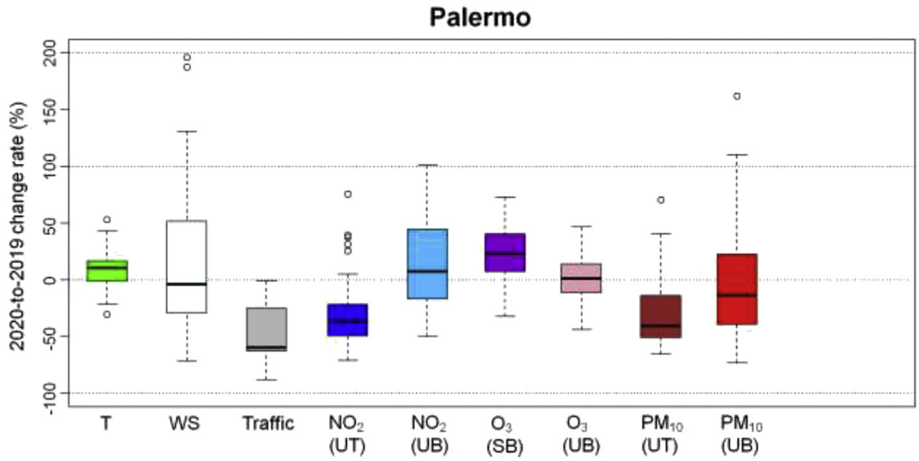

Fig. 8. Similar to Fig. 3, but for the city of Palermo. Daily $PM_{2.5}$ concentrations not available at both UT and UB stations.

the same data at province scale (r = 0.985–0.998). These traffic data are moreover consistent with vehicle count observations collected by ANAS, reporting that total extra-urban road traffic decreased by 55% in March (ANAS, 2020a) and 75% in April (ANAS, 2020b) with respect to the previous year. According to statistics by Atlantia (2020), overall road traffic on all countrywide motorways dropped by 64.5% in March and 80.1% in April. Therefore, EnelX & Here mobility data used here can be taken as an excellent proxy of both traffic-related emissions from within the study domain and traffic-related pollutant contribution from outside the domain (boundary conditions). Analysing other typical pollutant emission categories, an average drop in combustion in energy and transformation industries was also observed during the lockdown. According to statistics by ENEA (2020), in March 2020 electric energy demand decreased in Italy by 17% with respect to March 2019. The weight of energy and transformation industries on pollutant emissions is however secondary: for NO_x, e.g., they contribute to overall emissions by 15.7% in Rome, 10.3% in Milan, and 3.5% in Bologna; for primary PM_{10}, they contribute by 7.9% in Milan, 1.4% in Bologna, and 0.9% in Rome. By contrast, residential emissions may have been likely stable or even increased due to the lockdown and smart working conditions. At the global level, Le Quéré et al. (2020) reported decreases in all the emission categories except residential, that showed a moderate increase. Wind roses calculated for all urban areas indicate no appreciable change in 2020 with respect to the previous year (Figs. S8–S13): this means no significant variation in the prevailing wind directions and wind strength, and thus in the dynamics of air pollutant advection from both inside and outside each city domain. Therefore, urban air quality in 2020 was likely affected by the same sources as in 2019.

NO_2 concentrations significantly dropped over all urban areas in 2020 with respect 2019, as a result of the very large traffic mobility reduction (Table 1). This outcome was expected based on emission inventory data, indicating that the road transport sector contributes to overall NO_x emissions by 53.9% in Rome (ARPA Lazio, 2020), 68.3% in Milan (ARPA Lombardia, 2020), and 77.5% in Bologna (ARPA Emilia-Romagna, 2020). Agreeing with similar studies in the literature (e.g. Sicard et al., 2020), current NO_2 decrease was generally higher at UT stations (24.9–47.2%), i.e. where the highest NO_2 levels are normally recorded (40.9–50.5 $\mu g/m^3$ in 2019). By comparison, at UT stations in Nice (France) and Valencia (Spain) Sicard et al. (2020) observed even stronger NO_2 decreases (~65%). Following a study across 28 US locations, Chen et al. (2020) reported average NO_2 decreases ranging from 5% (Cheyenne) to 49% (Las Vegas), including Atlanta (−15%), Los Angeles (−34%), Boston (−36%), and New York (−41%). In China, Shakoor et al. (2020) observed NO_2 reductions of 25.6% in Beijing, and 43.8% in Shanghai. In Naples, the city where the highest median traffic reduction was observed (72%), the largest absolute NO_2 reduction among UB stations was recorded (59.1%). By contrast, although the remarkable road traffic abatement (−60%), a fairly limited NO_2 overall decrease (−24.9 to −34.8%) was recorded in Milan, likely because of the limited "room for reduction" resulting from the strict measures adopted over most of Milan urban area, where diesel vehicles up to Euro 4 are banned since February 2019 (Municipality of Milan, 2020b). A contrasting outcome resulted in Palermo, where a slight increase (13.3%) was observed in NO_2 concentrations at UB stations (Table 1 and Fig. 8). In all urban areas, the overall reduction of NO_x concentrations (Fig. 3–8) was lower than the reduction of total traffic (Fig. 2). This outcome may be explained by the fact that heavy-duty traffic reduced by a lower amount than passenger cars traffic. ANAS reported that heavy-duty traffic reduced by 24.8% in March 2020 and 39% in April 2020, compared to corresponding total traffic reductions of 55% and 75% (ANAS, 2020a,b). Also at the urban level, the increase in delivery and e-commerce have likely led to moderate reductions of heavy duty vehicles, that are mostly diesel-fuelled and produce higher NO_x emissions than passenger cars: in Bologna, for example, heavy-duty vehicles emit 54.3% of overall road transport NO_x emissions, while passenger cars emit 31.3% (ARPA Emilia-Romagna, 2020). Over most urban areas, the *CC* comparison showed minor changes (within 3.5%) in 2019 vs. 2020 (Table 1). The drop in NO_2 levels generally affected *CC* to a minor or even negligible extent, except for Palermo, where interestingly, the NO_2 increase at UB stations resulted in a quite comparable increase in *CC* (+7.8%). This confirms findings, e.g., from Cui et al. (2018), who reported a weak positive correlation between *CC* and NO_2 concentrations during the heating period.

O_3 concentrations slightly decreased in Naples (Fig. 7), remained basically unchanged in Bologna (Fig. 4) and Florence (Fig. 5), and increased in Milan (Fig. 3), Rome (Fig. 6), and Palermo (Fig. 8). O_3 increases were generally higher at SB stations (up to 13.7% in Palermo and 14.7% in Rome, Table 1) than at UB stations (up to 8% in Rome and 11.4% in Milan). This outcome is consistent with findings reported from similar studies in the literature. Sicard et al. (2020) found O_3 increases of 2.4% in Valencia and of 24% in Nice, while increases up to 17% were observed by Sharma et al. (2020) in India, particularly over central and eastern regions. Comparable O_3 increases were registered by Chen et al. (2020) in NewYork (8%) and

Las Vegas (17%), as well as by Connerton et al. (2020) in Paris, France (12%) and São Paulo, Brazil (30%). As remarked, e.g., by Tobías et al. (2020), the main cause of this O_3 increase could be the reduction of nitrogen oxide (NO) emitted from road vehicles, leading to a lower O_3 consumption (or titration, $NO + O_3 = NO_2 + O_2$). Observational evidences of similar O_3 increases triggered by Covid19-induced NO_x emission reductions in eastern China have been reported by Huang et al. (2020). This phenomenon is exacerbated by the fact that urban areas are typically VOCs-limited environments, as opposed to rural areas, which are mainly NO_x-limited. As well-known in the literature from the typical O_3 isopleth diagram (e.g., Seinfeld and Pandis, 2016), a reduction of NO_x concentrations in VOCs-limited environments may worsen O_3 pollution if not coupled with a concurrent (and comparable) reduction of VOCs (Sharma et al., 2020). An increase in solar irradiation can be safely excluded from possible drivers of O_3 increase through photochemistry, as no appreciable variation was observed in any city for this parameter (Table 1). Moreover, since O_3 is generally highly correlated to *T* (Mavroidis and Ilia, 2012) and *T* slightly decreased in almost all urban areas in 2020 with respect to 2019 (from 1.6 to 6%, Table 1), the hypothesis of O_3 increase in 2020 being caused by a different temperature can be also safely ruled out. For Palermo, where *T* increased by 1.2 °C, the opposite applies.

According to several similar studies in the literature, PM_{10} levels decreased to a lesser extent than expected during the lockdown, with reductions up to 31.5% (Palermo) as well as increases up to 7.3% (Naples, Table 1). Sicard et al. (2020) reported an overall PM_{10} decrease of 6% in Nice. Larger PM_{10} reductions (~31%) were recorded by Sharma et al. (2020) over 22 cities in India, while a reduction of 60.5% was reported by Mahato et al. (2020) for the megacity of Delhi. Remarkable PM_{10} reductions were also registered in Los Angeles (−57%) by Chen et al. (2020), and in Beijing (−79%) by Shakoor et al. (2020). In Italy, the share of primary PM_{10} emissions from road traffic is particularly high in Bologna (83.8%), while significantly lower in Rome (54.3%) and Milan (44.6%); by contrast, the contribution from heating plants is 38.5% in Rome, 25.5% in Milan, and 10.1% in Bologna. However, these shares significantly change in the period when heating systems are turned on: in Milan, for example, the weight of PM_{10} emissions from heating may reach 45% in February and 37% in March (ARPA Lombardia, 2020). The lockdown-induced generalized abatement of road traffic emissions of $PM_{2.5}$ and PM_{10}, as well as of emissions of secondary aerosol precursors such as NO_x and SO_2, both inside and outside the urban areas, have been counterbalanced by an increase in PM emissions from home activities such as domestic heating and biomass burning. This hypothesis is supported by the statistics reported by ENEA (2020), indicating that in March 2020 household consumption over the whole country increased with respect to March 2019 by 15% for natural gas, 21.8% for liquid propane gas (LPG), and 31.5% for gasoil. If combining statistics by ISPRA (2017) on fuels used for residential heating in Italy, this roughly corresponds to an overall household consumption increase ranging 16–19%. This increase was also driven by meteoclimatic reasons, as *T* decreased on average by 0.2 °C (Rome) to 0.8 °C (Bologna, Table 1) with respect to the corresponding period in 2019. This hypothesis seems to be confirmed in Palermo, where the relevant *T* increase (+1.2 °C) required a lower household heating usage, and thus lower emissions of primary PM: as a result, Palermo proved to be the urban area where during the 2020 lockdown PM_{10} levels decreased the most both at UT and UB stations. The unexpected increase in PM_{10} concentrations in Italy may also be accounted for by the increase in emissions of ammonia (NH_3), which is a recognised precursor of secondary aerosol (Gualtieri et al., 2018; Huang et al., 2020). NH_3 emissions mostly result from agriculture activities (e.g., 61.8% in Bologna, 71.2% in Rome, and 93.7% in Milan), that, according to gasoil consumption statistics by the Italian Ministry of Economic Development, increased during the lockdown with respect to the corresponding months in 2019.

A far larger population fraction at home and a colder weather did not only lead to higher consumption of gas-combustion plants, but also of biomass heating systems, which are well-known large emitters of PM_{10} and particularly $PM_{2.5}$ (Nava et al., 2015; Gualtieri et al., 2015). In the city of Bologna, for example, wood and biomass heating systems account for 86.2% of overall $PM_{2.5}$ emissions from heating plants (ARPA Emilia-Romagna, 2020). In Milan, primary $PM_{2.5}$ emissions from heating may reach 51% in February and 43% in March (ARPA Lombardia, 2020). This scenario could explain why $PM_{2.5}$ decreased to a lesser extent than PM_{10} (Table 1). If considering UT stations, $PM_{2.5}$ only reduced in Florence (−17%), similarly to the value (−21%) found by Kerimray et al. (2020) in Almaty (Kazakhstan) and to the value (−29%) observed at UT stations by Sicard et al. (2020) in Valencia. Comparable $PM_{2.5}$ reductions were registered in Shanghai (−27%) by Shakoor et al. (2020), Paris (−28%) by Connerton et al. (2020), and New York (−29%) by Chen et al. (2020). Among UB stations, only in Milan a $PM_{2.5}$ reduction (−13.4%) was observed, while elsewhere $PM_{2.5}$ concentrations matched or exceeded the 2019 amounts. A further reason partly accounting for the generalized concentration increase is the overall lower windy conditions affecting the period 2020 with respect to the previous year, as *WS* regularly reduced in all urban areas, particularly in Milan (−6.6%).

5. Conclusions

During the Covid19-induced lockdown period, Italy experienced an unprecedented abatement of road traffic with respect to the previous year, not only within major urban areas (48–60%), but also over the extra-urban road network (55–75%) and on the entire motorway network (64.5–80.1%). This abatement was extensive both in time and space, occurring for 50 consecutive days both inside the urban areas and outside the domains (boundary conditions). This enabled to address a typical "what-if" emission scenario analysis, driven by real-world events instead of being setup by means of theoretical assumptions.

This study confirmed the complex nature of atmospheric pollution. Even when a major driver of pollutant emissions is clearly isolated and controlled, the strong non-linearity of atmospheric processes and the prominent role played by meteorological conditions in pollution formation and removal should be taken into account. This study demonstrated that, at least in economically developed countries, a radical traffic ban extended to the whole country for about 2 months only significantly reduced NO_2 levels. $PM_{2.5}$ and PM_{10} concentrations, whose containment is generally enforced adopting traffic restriction measures in urban areas, were affected to a minor extent. Stable and permanent rather than temporary actions, such as the 2020 lockdown, are needed to reduce emissions to the atmosphere across all relevant categories and species in a true decarbonisation effort, to obtain significant benefits on air quality and public health.

Credit author statement

Giovanni Gualtieri: Conceptualization, Methodology, Software, Investigation, Data Curation, Writing - original draft. **Lorenzo Brilli**: Data Curation, Visualization, Writing - review & editing. **Federico Carotenuto**: Data Curation, Writing - review & editing. **Carolina Vagnoli**: Writing - review & editing. **Alessandro Zaldei**: Writing - review & editing. **Beniamino Gioli**: Conceptualization, Investigation, Data Curation, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2020.115682.

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