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Air quality trends and implications pre and post Covid-19 restrictions

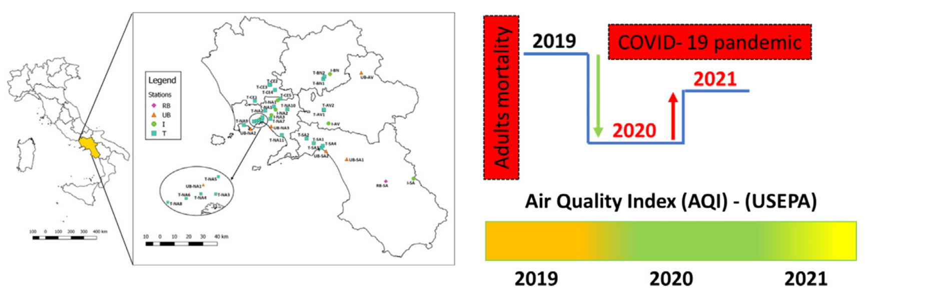
Alice Cardito [a], Maurizio Carotenuto [a,*], Antonella Amoruso [b], Giovanni Libralato [c], Giusy Lofrano [d]

[a] Department of Chemistry and Biology "Adolfo Zambelli", University of Salerno, via Giovanni Paolo II 132, 84084 Fisciano, SA, Italy
[b] Department of Physics "E. R. Caianiello", University of Salerno, via Giovanni Paolo II 132, 84084 Fisciano, SA, Italy
[c] Department of Biology, University of Naples "Federico II", via Vicinale Cupa Cinthia 26, 80126 Naples, Na, Italy
[d] Department of Movement, Human and Health Sciences, University of Rome Foro Italico, Piazza Lauro De Bosis 15, 00135 Rome, Italy

HIGHLIGHTS

- Air quality from good to moderately unhealthy over the three years
- PM_{10} and $PM_{2.5}$ resulted the less affected by the lockdown restrictions.
- NO_2 presented the highest reduction from 2019 to 2020.
- A significant decrement of adult mortality was observed in 2020.

GRAPHICAL ABSTRACT



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ABSTRACT

Air pollution causes millions of premature deaths every year. Thus, air quality assessment is essential to preserve human health and support authorities to identify proper policies. In this study, concentration levels of 6 air contaminants (benzene, carbon monoxide, nitrogen dioxide, ground level ozone, particulate matters) as monitored in 2019, 2020 and 2021 by 37 stations, located in Campania (Italy) were analysed. Particular attention has been paid to March–April 2020 period to get clues on the possible effects of the lockdown regulations, imposed in Italy from March 9th to May 4th to limit COVID-19 spread, on atmospheric pollution. Air Quality Index (AQI), an algorithm developed by the United States Environmental Protection Agency (US-EPA), allowed us to classify the air quality from moderately unhealthy to good for sensitive groups. The evaluation of air pollution impact on human health by using the AirQ+ software evidenced a significant decrement of adult mortality in 2020 respect to 2019 and 2021. Among the six pollutants considered, PM_{10} and $PM_{2.5}$ resulted the less affected by the lockdown restrictions. Finally, a comparison between NO_2 ground level concentration and the reprocessed Level 2 NO_2 tropospheric column concentration obtained from satellite surveys highlighted as concentration measured at the ground level stations can be strongly influenced by the station position and its surroundings.

1. Introduction

Air quality in urban and suburban areas around the world is strongly affected by pollution, which represent one of the major causes of health issues, mostly on the respiratory and cardiovascular systems, and determine negative impacts on the ecosystems (Al-Jeelani, 2014; Adame et al., 2020; Eskandari et al., 2020). Increasing levels of ozone (O_3), nitrogen dioxide (NO_2) and particulate matters (PM_{10} and $PM_{2.5}$), the most hazardous air pollutants (He et al., 2017; Adame et al., 2020), have been registered worldwide as consequence of the rapid strides in industrialization and increased vehicular traffic, which is the main anthropogenic emission source in urban areas (Al-Jeelani, 2014). The World Health Organization (WHO) has estimated that air pollution causes about 7 million premature deaths every year worldwide (World Health Organization (WHO), 2022a). According to the Institute for Health Metrics and Evaluation (Institute for Health Metrics and Evaluation (IHME), 2020), O_3 pollution was associated with 365,000 chronic

* Corresponding author at: Department of Chemistry and Biology "A. Zambelli", University of Salerno, Via Giovanni Paolo II, 132, Fisciano 84084, Salerno, Italy.
E-mail address: mcarotenuto@unisa.it (M. Carotenuto).

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obstructive pulmonary disease (COPD) premature death in 2019 and ambient O_3 was classified as a level-3 risk for human health. NO_2, the major pollutant involved in tropospheric O_3 production, is also directly damaging human health by increasing the risk of respiratory diseases (Guan et al., 2022). Several studies have shown the impact of PMs on the lung and systemic cardiovascular diseases (Liu et al., 2019; Danek et al., 2022). Benzene (C_6H_6) is released from burning coal and oil, gasoline service stations, and motor vehicle exhaust. According to the Agency for Toxic Substances and Disease Registry (Agency for Toxic Substances and Disease Registry (ATSDR), 2007), drowsiness, dizziness, headaches, as well as eye, skin, and respiratory tract irritation can result by acute (short-term) inhalation exposure of benzene. At high levels of exposure, benzene may cause unconsciousness and chronic (long-term) inhalation exposure is responsible of various disorders in the blood (Shallis et al., 2021). It is well known that carbon monoxide (CO) is harmful due to its ability to bind to haemoglobin in the blood, reducing the ability of blood to carry oxygen to the body's organs.

Starting from late 2019, the coronavirus disease (COVID-19), caused by the SARS-CoV-2 virus, started spreading from Wuhan, China all over the world (Hashim et al., 2021), determining a public health emergency of international concern on January 30th (World Health Organization (WHO), 2020a) and a pandemic on March 11th (World Health Organization (WHO), 2020b). Starting from April 2020, the pandemic had caused >500 million cases and 6 million deaths all over the word, making it one of the deadliest in the history (World Health Organization (WHO), 2022b). To stop its spread, many countries implemented preventive measures. The lockdown was one of the major actions adopted, with the suspension of most human activities (restrictions of vehicular traffic, halt of industrial and productive processes, closure of offices, non-essential businesses and educational institutes, imposition of curfews and social distancing). Air quality was directly affected by these restrictions, since anthropogenic sources, which are considered the largest contributor to air pollutants in urban areas, were strongly limited. The lockdown effects on air pollution were immediately evident from satellite observations, that showed a substantial decrease of air pollutants levels over China and other countries (Kerimray et al., 2020; Sannino et al., 2020; Toscano and Murena, 2020; Yadav et al., 2020; Orak and Ozdemir, 2021). Several studies showed a significant reduction of air pollution also by using the network of ground stations, as observed in the most urbanized areas of Italy (Toscano and Murena, 2020; De Angelis et al., 2021; Cucciniello et al., 2022). Most of studies focused on data related to the lockdown period and the one immediately before, taking in consideration only one pollutant. In this study, data collected over three years (2019, 2020, 2021) by the Environmental Protection Agency of the Campania Region (ARPAC) were compared to evaluate the effects of regulations enforced in Italy to limit the COVID-19 spread on the air quality not only during the rigid lockdown period (from March 9th to May 4th) but also when they were progressively reduced. In detail, the concentrations of six air pollutants (C_6H_6, CO, NO_2, ground level O_3, PM_{10} and $PM_{2.5}$) recorded on daily basis by 37 ground level monitoring stations located in 23 towns of the Campania region (Southern Italy) were analysed. The Air Quality Index (AQI) was calculated according to the method developed by United States Environmental Protection Agency (US-EPA) (1999) and the influence of air pollution on human health was carried out by AirQ+ software.

Although is well known that elevation, atmospheric properties, and orography can influence air pollutants concentrations and long-distance pollution migration, to evidence pattern differences between concentration at ground level and in the tropospheric column, the spatial distribution of NO_2 concentration, obtained through the interpolation of the values gathered by the ground monitoring stations, and those obtained by satellite data were compared at different dates.

2. Data and methods

2.1. Study area

The Campania region, located in Southern Italy, is one of the most densely populated regions of Europe (409 people per km^2, Italian National Institute of Statistics (ISTAT), n.d.). From an administrative point of view, it is divided into five districts: Naples (which is also the capital), Avellino, Benevento, Caserta, and Salerno. The districts of Naples and Caserta are the most urbanized, with about 4 million inhabitants, and the most industrialized. The monitoring ground stations have been classified as "Traffic (T)" when located in urban or suburban areas near high-traffic roads, "Industrial (I)" when located in industrial sites, "Urban Background (UB)" when located in urban or suburban areas far from emission sources, and "Rural Background (RB)" when located far from urban and suburban settings (Fig. 1 and Table S1).

More than half of the total (24 stations) were classified as T; UB and I stations were 6 respectively and only 1 station was classified as RB. The data, available on an hourly basis for all the parameters except for PM (where one daily measurement available for most of the stations), were collected from 2019 to 2021. No data were available for C_6H_6 and CO for the BR station. Meteorological data registered by sensors mounted on the ground level stations were reported in Table S2.

2.2. Data analysis

Statistical analysis and data plotting were performed using software R (v. 4.1.1), maps were obtained with open source software QGIS (v. 2.18.24), air quality index (AQI) was calculated according to EPA-USA method (United States Environmental Protection Agency (US-EPA), 1999), while to evaluate the effects of air pollution on human health, the software AirQ+ (v. 2.1.1), a tool developed by the WHO Regional Office for Europe (World Health Organization Regional Office for Europe, 2020) was used.

To get concentration spatial distribution maps, data were interpolated by using the Inverse Distance Weighting (IDW) tool implemented in QGIS. IDW method assumes that each measured point has a local influence that diminishes with distance: the measured values closest to the prediction location have more influence on the predicted value than those farther away. The approach is based on the following equations, which allows to estimate the value z at location x as the weighted mean of nearby observations (z_i):

$$z(x) = \frac{\sum_{i=1}^{n} w_i z_i}{\sum_{i=1}^{n} w_i} \tag{1}$$

$$w_i = |x - x_i|^{-\beta} \tag{2}$$

where $\beta \geq 0$, w_i is the i-th weight, and $|x - x_i|$ corresponds to the euclidean distance between the location of the point to be estimated and the location of observation points. The inverse distance power, β, determines the degree to which the nearer points are more effective then distant ones. In this work the value of $\beta = 2$.was used.

2.2.1. Air quality index

The AQI for each pollutant has been evaluated using the following equation:

$$I = \frac{I_{high} - I_{low}}{C_{high} - C_{low}}(C - C_{low}) + I_{low} \tag{3}$$

where C is the pollutant concentration, C_{low} and C_{high} are the limits of the concentration range that include C, whereas $I_{low}$and I_{high} are the AQI values corresponding to C_{low} and C_{high}, respectively (see Table S3). The daily AQI corresponds to the highest value among the indices evaluated for each pollutant. The calculation uses: 8-h average and 1-h average concentration measured as ppm for O_3, 24-h average concentration measured as $\mu g/m^3$ for PMs, 8-h average concentration measured as ppm for CO, and 1-h average concentration measured as ppm for NO_2 . In the original EPA-USA application, AQI is classified in six categories ranging from good to hazardous. However, to better highlight air quality differences, a wider number of categories were used as reported in Table S3.

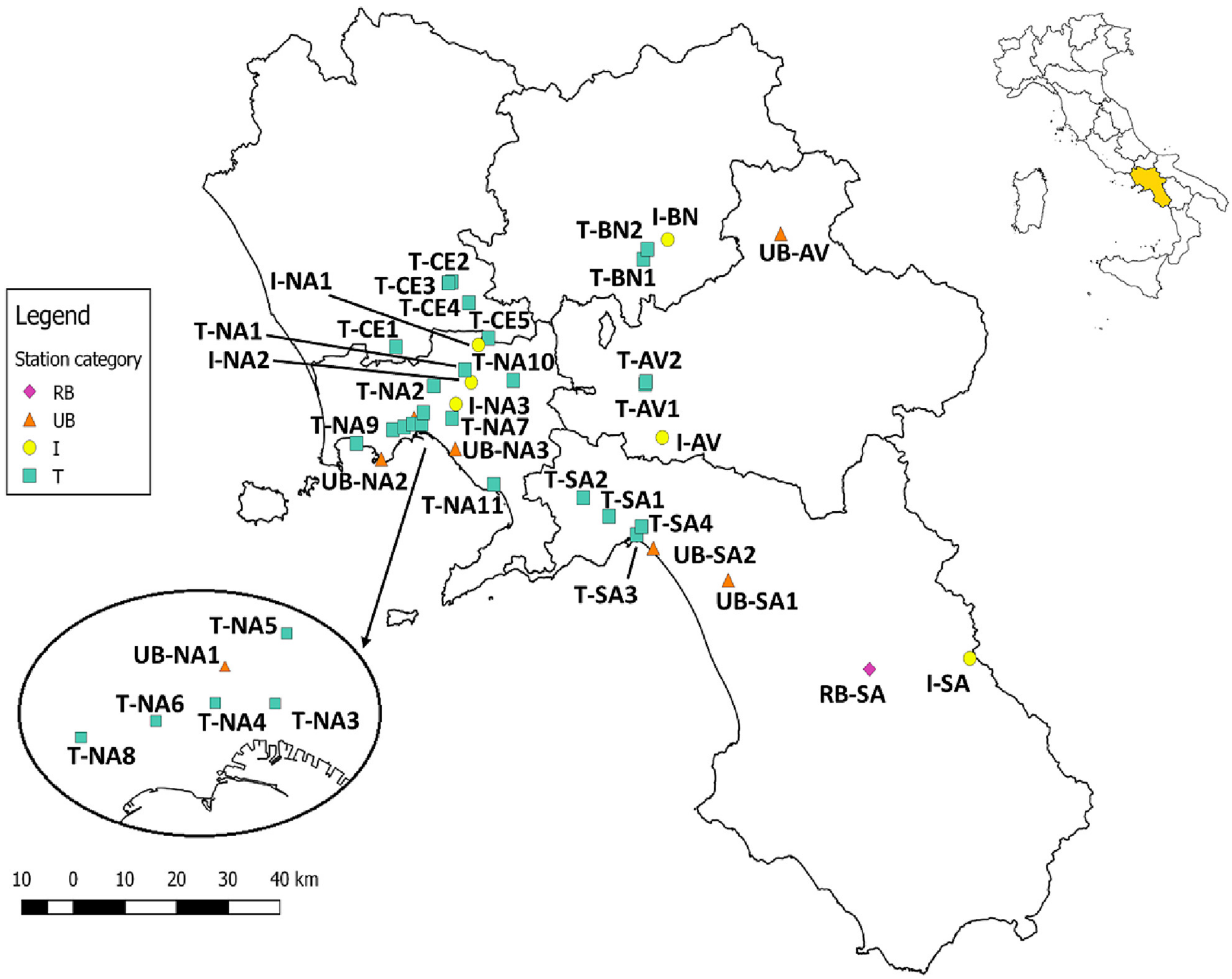

Fig. 1. Study area (RB: Rural Background, UB: Urban Background, I: Industrial; T: Traffic; AV: Avellino, BN: Benevento; CE: Caserta; NA: Naples, SA: Salerno).

2.2.2. Impact on human health

AirQ+ software can evaluate both the effects of short-term changes in air pollution (based on risk estimates from time-series studies) and the effects of long-term exposures (using life-tables approach and based on risk estimates from cohort studies). To run the software is necessary to provide: a relative risk and cut-off value for every considered pollutants (C_6H_6, ground level O_3, NO_2, PM_{10} and $PM_{2.5}$), data for the studied population (size and mortality data, both stratified by age), concentration values in the area for every considered pollutants (the annual average concentration for long-term exposure effects and daily average concentration for short-term exposure). The program output gives the percentage of cases for a given health endpoint respect to the exposure to a specific pollutant concentration. The algorithm used by the software has been reported in previous publications (Krzyzanowski, 1997; Toscano and Murena, 2021; Brito et al., 2022).

In the framework of this study, the model was applied to the 5 mean towns of the region, using the default values provided by WHO Regional Office for Europe (World Health Organization Regional Office for Europe, 2013) for the relative risk and cut-off value for every considered pollutants, the population data obtained by the Italian National Institute of Statistics data warehouse (ISTAT) and the concentration values obtained by ground level monitoring station of ARPAC.

2.2.3. Satellite images

Satellite images were sensed by Sentinel-5 Precursor, a European Space Agency (ESA) satellite inside the Copernicus program and were downloaded by EO Browser. Data were collected by TROPOMI (TROPOspheric Monitoring Instrument), a four spectrometers system that measures in the ultraviolet (UV), UV–visible (UV–VIS), near-infrared (NIR) and shortwave infrared (SWIR) spectral bands. Several important air quality and climate-related atmospheric constituents can be retrieved, including ozone, methane, formaldehyde, aerosol, carbon monoxide, nitrogen dioxide and sulfur dioxide. Sentinel-5 Precursor provides high spatio-temporal resolution data (pixel dimensions: 7 × 3.5 km) based on a single daily global coverage.

In this work, the reprocessed Level 2 NO_2 tropospheric column data for the period March 2019 – April 2021 have been used, focusing on the March–April period of each year to evaluate the lockdown effects. To compare ground level concentration and satellite data, only images without cloud coverage over the study area have been considered: six days (March 30th 2019, April 20th 2019, March 13th 2020, April 7th 2020, March 11th 2021, April 25th 2021) meet this condition. The concentration values obtained by satellite images were applied in the middle of the pixel. When two or more ground stations values were located inside the same image pixel, only the closest to the centre of the pixel was considered. Patterns of the NO_2 concentration in the tropospheric column were obtained through analogous IDW interpolation.

3. Results and discussion

3.1. Effects of 2020 lockdown on the concentration of air pollutants

Historical data on air quality in Campania region proved high air pollution levels, which often exceed the air quality standards (Barone et al., 2000; Toscano and Murena, 2021). However, as shown in Figs. 3–5 of Toscano and Murena (2021), a decreasing trend respect to NO_2, and a less evident one for PM_{10} and $PM_{2.5}$ is registered in the period ranging from 2003 to 2019. The main source of air pollution is road traffic, that contributes for about 49 %, 41 % and 24 % of CO, NO_x and PM_{10} total emissions respectively, followed by non-road traffic (harbors and airports) and oil and natural gas combustion (Iodice and Senatore, 2015a, 2015b).

Due to the reduced emissions as consequence of the strict regulations imposed on traffic and industrial activities, during the lockdown period an improvement of overall air quality was registered. Overall traffic flow in Campania was estimated to be reduced by 58 % (specifically, −60 % and − 29 % of light and heavy vehicles per day, respectively) (Toscano and Murena, 2020). Although a partial lockdown was imposed from November 2020 to June 2021, with limits on circulation, recreational and cultural activities, restaurants and cafes working hours, and schools and shops opening, in 2021 most human activities went back to normal. To evaluate the differences among the concentrations of the six pollutants in lockdown period of the considered years (2019, 2020 and 2021), the daily average were compared using a statistical hypothesis test, dividing the data by station category. Since the data did not follow a normal distribution (as checked with the Kolmogorov-Smirnov test), we applied the non-parametric Wilcoxon signed-rank test to compare two sets of data. Statistically significative differences (p-value <0.05) were found between 2019 and 2020 daily mean March–April concentrations of benzene, CO, NO_2 and O_3, for most groups. The exceptions were CO in UB sites, NO_2 in the RB site and O_3 in T sites. Benzene concentration decreased in both the UB and T sites (−28 % and −33 %, respectively), while showed an unexpected increment by +46 % in I stations. CO concentration decreased by −26 % in T sites, while increased by +23 % in I sites. Substantially lower NO_2 concentrations were found at all site categories (UB: −47 %, I: −42 %, T: −48 %). Finally, O_3 concentration showed a reduction in RB, UB and I sites (−25 %, −13 % and −40 %, respectively). Despite PM_{10} and $PM_{2.5}$ daily average concentrations didn't show significant differences between pre and during lockdown concentrations in all cases, the maximum daily values of PM_{10} concentration reached during March–April 2020 were substantially lower than the previous year's ones (see Table S4).

The same non-parametric Wilcoxon signed-rank test was applied to check for the presence of significative differences between 2020 and 2021 mean concentrations. Likewise, most pollutants showed significant differences (benzene in T sites, CO in UB and I sites, NO_2 for all station categories, O_3 in RB and I sites, and PM_{10} in the RB site), while for $PM_{2.5}$ p-value >0.05 in all cases. Benzene concentration increased again in T stations, by +40 %. CO concentration lowered by −20 % in UB sites and by −41 % in I sites. NO_2 concentration increased for all stations categories, reaching halfway values between 2019 and 2020 concentrations (RB: +57 %, UB: +63 %, I: +32 %, T: +43 %). O_3 concentration increased in the RB station (+9 %) and I stations (+62 %). Finally, PM_{10} incremented by +57 % in the BR site.

Fig. 2 shows the daily mean concentration values in March–April for each pollutant, by station category; the different letters associated to each box show significative statistical differences between the years, with a p-value threshold of 0.05. Full test results are presented in Tables S5 .

Overall, NO_2 presented the highest reduction from 2019 to 2020. The changes in concentration for each station are reported in Table 1, along with the minimum, maximum and mean concentration. The Wilcoxon test was applied to check for statistically significative differences between the NO_2 concentration observed in March–April during the three years, for every station. In most cases, p-value is <0.05, excepting I-BN, UB-NA2, T-NA9, RB-SA and T-SA1 2019–2020 comparison, and UB-AV, I-AV, T-BN1, I-NA3, T-NA9, T-SA3 and T-SA4 2020–2021 comparison. The higher reduction (−62 %) was observed in Salerno (T-SA3). Only one station (UB-NA2) registered a weak increase (+2 %). Conversely, in 2021 NO_2 concentration showed an increment in all but two sites (I-BN and T-NA8), compared to the values observed in March–April 2020.

The minimum, maximum and mean concentrations, as well as changes in concentration observed during the three years for each station relative to the other pollutants are reported in Tables S6-S9.

Reduction for most pollutants was associated to the suspension of the main emission sources (e.g., vehicular traffic and industrial activities), especially regarding NO_2, benzene and CO (Chu et al., 2021; Otmani et al., 2020; Sannino et al., 2020; Toscano and Murena, 2020; Yadav et al., 2020; Heintzelman et al., 2021; Mor et al., 2021). The PMs concentration might be less affected because of the increase in emissions caused by domestic cooking and the extension of the residential heating systems use, due to the sanitary emergency forcing people staying home (Gualtieri et al., 2020; Sannino et al., 2020; Toscano and Murena, 2020). Moreover, it has been reported that PMs has a different residence time in the atmosphere compared to gaseous pollutants and could be more affected by long distance transport (Otmani et al., 2020; Yadav et al., 2020). The smaller reduction of O_3 compared to the other pollutants was attributed to the less availability of NO_x, that limited its removal from atmosphere being a scavenger of O_3 (Collivignarelli et al., 2020; Gualtieri et al., 2020; Chu et al., 2021; Mor et al., 2021). Similar results were reported by Sannino et al. (2020) and Toscano and Murena (2020).

Fig. 3 shows the IDW interpolation of the average concentration of the six pollutants during the March–April 2020 period; as for NO_2, the difference of concentration from 2019 to 2020 is clearly visible, especially in urban areas.

3.2. Computation of the air quality index

The daily Air Quality Index (AQI) for the three years has been calculated on a restricted number of stations (17), where most NO_2, $PM_{2.5}$ and O_3, hourly concentration values were available for all the three years. Complete results are reported in Fig. S1. The AQI for 3 representative stations (urban background (UB-SA2), industrial (I-NA3) and traffic (T-NA2)), is presented in Fig. 4 through calendar plots: every square reports the category of the daily AQI value; the blank squares represent the days when there is no data available for any pollutant.

For each site, respect to all three years, the AQI score resulted mostly in the ranges from good (26 < AQI < 50) to moderate unhealthy for sensitive groups (101 < AQI < 125). In few cases (I-NA3, T-NA2, and T-NA10), the index reached extremely high values (>201) during winter. The overall air quality was better in background stations, even though some traffic sites showed healthier conditions than the others. According to AQI, the pollutants that have the major negative impact on air quality for all stations are $PM_{2.5}$ during cold months and O_3 during warm months. In different urban areas around the world, higher $PM_{2.5}$ concentration has been registered in winter respect to the summer (Gehrig and Buchmann, 2003; Kulshrestha et al., 2009; Huang et al., 2015). These monthly differences are driven by various factors, such as emission strength and meteorological conditions: firstly, the anthropogenic emission due to fossil fuel combustion and biomass burning for residential heating are higher during winter; furthermore, the increasing height of the boundary layer during summer results in a better dilution of the pollutants (Kulshrestha et al., 2009; Huang et al., 2015; Zhang et al., 2015; Xu et al., 2016; Wang et al., 2017). O_3 concentration follows the opposite trend, being highest during summertime and decreasing in cold months. The higher summer concentration is associated with the higher temperature and solar irradiance, that promote the photochemical production of O_3 in presence of its precursors (Khoder, 2009; Al-Jeelani, 2014). Another factor that strongly influences the ground level ozone concentration during the year is the local, regional, and global transport of pollutants: it has been assessed that fluxes coming from North America and Asia contribute significantly to Europe's O_3 budget, especially in spring and summer (Pippin et al., 2001; Auvray and Bey, 2005).

The higher AQI values observed on 1st January of every year (especially 2020) is likely caused by the New Year's celebrations, that strongly influence particulate matter concentration in the atmosphere. All sites show an improvement of air quality in summer 2020 compared to the summers

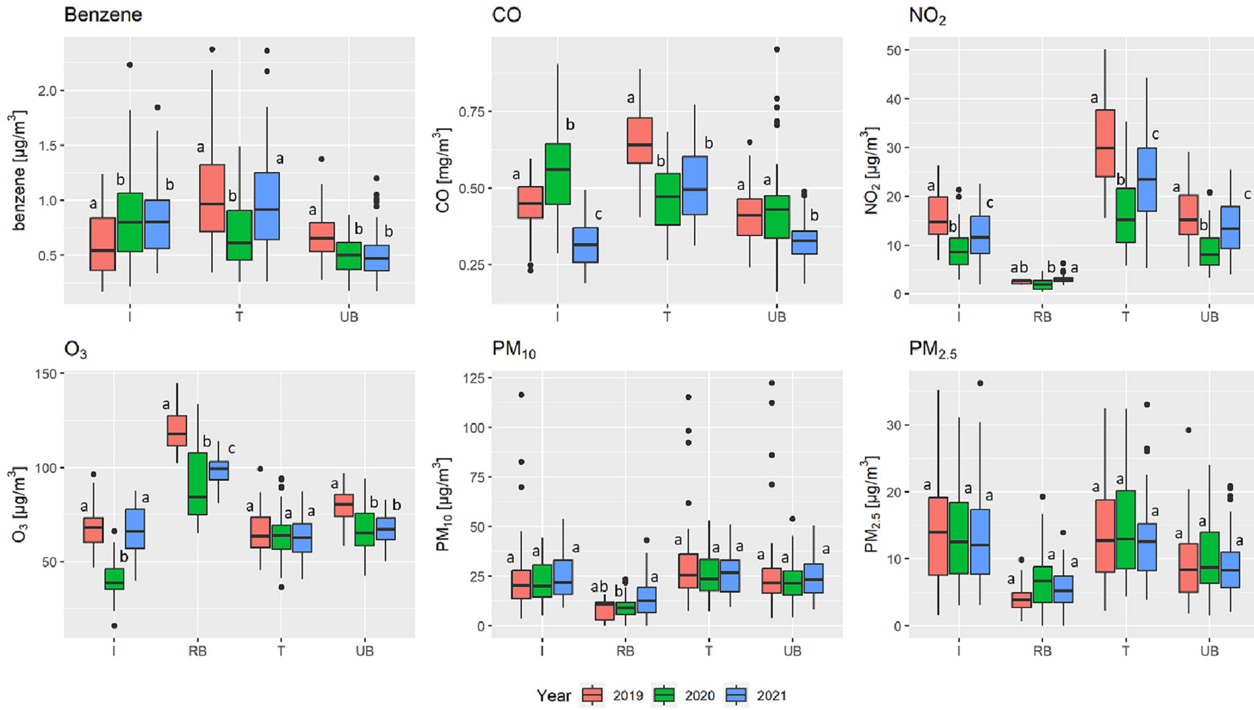

Fig. 2. Daily mean concentrations by station category (March–April). Different letters show statistically significative differences between the years (p-value threshold = 0.05).

Table 1
Minimum, maximum and mean (in parenthesis) NO_2 concentration, and changes during the three years (March–April period).

Station	2019 [µg/m³]	2020 [µg/m³]	2021 [µg/m³]	2019–2020 variation	2020–2021 variation
UB-AV	5.05–18.40 (10.75)	1.97–10.42 (4.45)	0.37–12.81 (4.75)	−59 %	7 %
I-AV	4.60–28.42 (14.10)	0.49–18.18 (6.17)	1.10–17.41 (7.45)	−56 %	21 %
T-AV1	6.80–46.53 (20.77)	1.25–36.22 (11.78)	2.66–32.45 (15.30)	−43 %	30 %
T-AV2	7.17–42.58 (18.28)	3.17–36.85 (11.64)	3.63–35.23 (15.97)	−36 %	37 %
I-BN	4.12–14.12 (9.07)	0.72–12.45 (8.24)	0.58–14.80 (6.37)	−9 %	−23 %
T-BN1	8.36–40.63 (20.82)	1.72–23.43 (8.41)	1.03–30.83 (11.86)	−60 %	41 %
T-BN2	11.09–41.37 (28.96)	4.08–25.75 (11.78)	4.61–30.90 (18.51)	−59 %	57 %
T-1CE	11.42–64.17 (31.22)	4.86–40.15 (16.97)	3.37–58.80 (25.42)	−46 %	50 %
T-2CE	7.37–49.43 (25.47)	3.71–22.59 (11.08)	3.34–31.60 (15.22)	−56 %	37 %
T-3CE	9.57–48.88 (21.46)	3.16–19.90 (9.63)	4.94–33.68 (17.24)	−55 %	79 %
T-4CE	6.08–48.50 (24.61)	1.81–24.86 (10.47)	2.67–38.87 (16.96)	−57 %	62 %
T-5CE	3.68–37.58 (20.43)	2.21–23.64 (10.50)	0.34–37.03 (16.14)	−49 %	54 %
UB-NA1	5.59–52.98 (24.19)	1.43–30.57 (10.67)	3.45–45.44 (18.29)	−56 %	71 %
UB-NA2	0.15–14.75 (4.96)	0.54–11.33 (5.06)	1.40–24.35 (9.39)	2 %	86 %
UB-NA3	1.54–42.00 (20.17)	1.42–33.11 (13.32)	5.55–39.03 (20.65)	−34 %	55 %
I-NA1	1.01–37.39 (18.89)	2.04–32.30 (14.25)	–	−25 %	–
I-NA2	5.22–35.97 (19.21)	2.36–24.71 (10.79)	2.25–36.38 (15.96)	−44 %	48 %
I-NA3	–	6.57–44.16 (21.54)	4.89–82.36 (27.08)	–	26 %
T-NA1	8.67–55.04 (28.76)	5.06–30.38 (14.84)	3.30–55.96 (26.02)	−48 %	75 %
T-NA2	12.20–61.24 (32.36)	4.59–44.47 (17.82)	3.36–58.77 (26.34)	−45 %	48 %
T-NA3	21.10–108.40 (61.49)	6.29–53.10 (27.06)	6.59–77.17 (40.10)	−56 %	48 %
T-NA4	22.97–101.37 (52.33)	4.83–55.98 (25.78)	6.73–72.02 (36.60)	−51 %	42 %
T-NA5	14.96–61.96 (35.89)	7.35–47.84 (22.65)	8.04–67.95 (36.53)	−37 %	61 %
T-NA6	22.16–63.95 (38.13)	7.23–47.22 (21.81)	8.42–65.04 (31.49)	−43 %	44 %
T-NA7	15.17–62.14 (39.86)	6.54–46.31 (23.35)	10.69–59.07 (35.38)	−41 %	51 %
T-NA8	–	0.58–49.95 (20.93)	1.09–43.87 (19.67)	–	−6 %
T-NA9	5.40–38.71 (17.81)	5.37–26.73 (16.35)	5.38–37.78 (18.45)	−8 %	13 %
T-NA10	10.59–49.13 (31.02)	5.47–47.41 (21.13)	2.91–50.30 (25.56)	−32 %	21 %
T-NA11	6.59–42.38 (22.62)	3.13–19.88 (10.12)	3.57–36.62 (16.53)	−55 %	63 %
RB-SA	1.90–2.93 (2.49)	0.41–4.73 (1.92)	1.82–6.23 (3.01)	−23 %	57 %
UB-SA1	8.23–38.49 (19.27)	5.67–17.84 (10.43)	3.48–33.56 (17.96)	−46 %	72 %
UB-SA2	3.24–45.40 (16.16)	1.03–20.02 (6.99)	3.36–27.99 (11.99)	−57 %	72 %
I-SA	7.38–35.09 (20.90)	3.41–21.54 (11.69)	3.16–31.85 (18.89)	−44 %	62 %
T-SA1	5.09–41.14 (21.39)	5.79–34.25 (18.11)	5.90–37.20 (21.19)	−15 %	17 %
T-SA2	1.94–50.27 (25.75)	1.54–35.95 (13.08)	2.63–45.40 (21.11)	−49 %	61 %
T-SA3	16.16–85.90 (44.94)	1.65–38.4 (17.22)	3.23–49.49 (20.48)	−62 %	19 %
T-SA4	12.07–92.07 (51.15)	4.28–54.59 (23.22)	3.93–52.66 (27.49)	−55 %	18 %

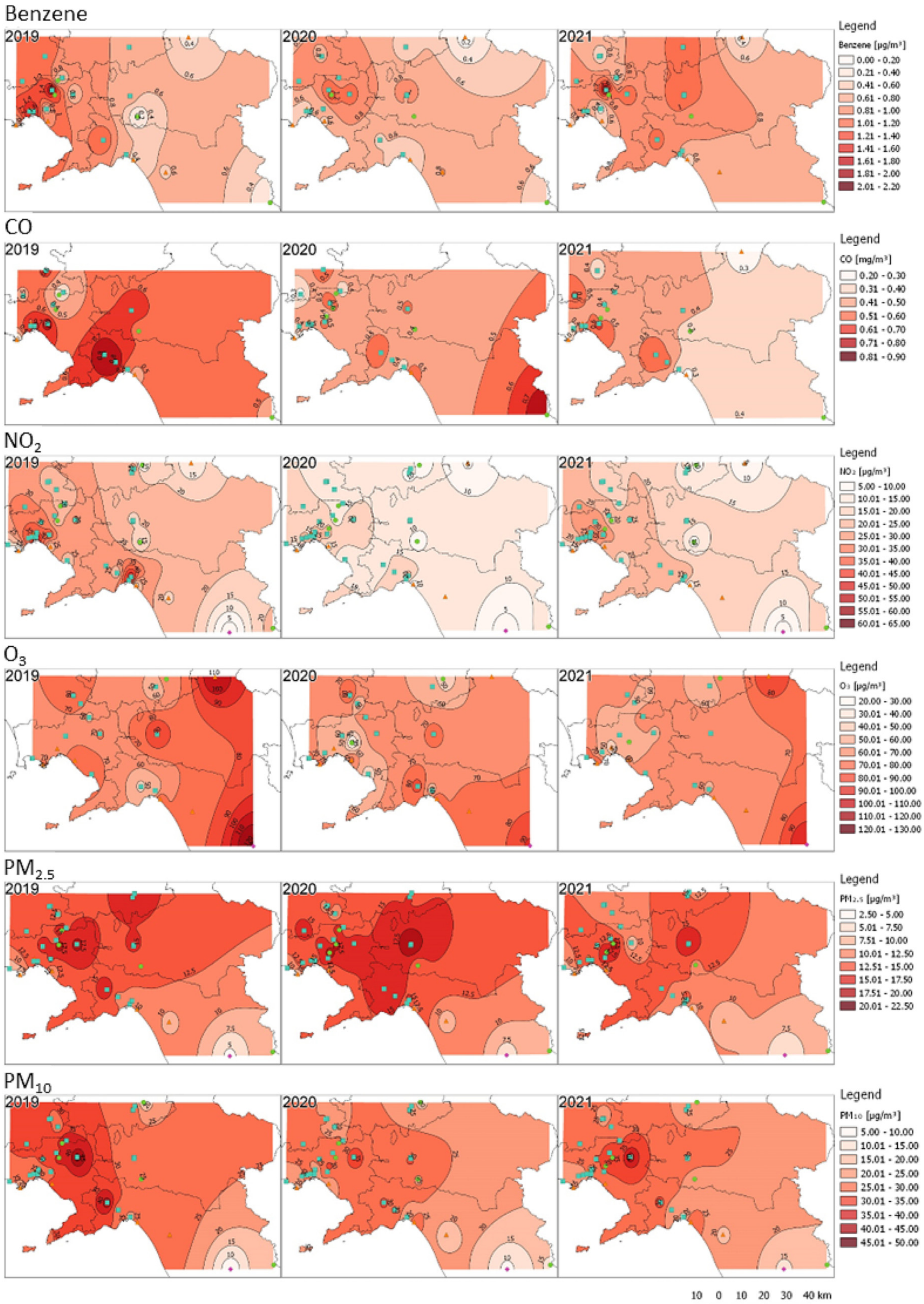

Fig. 3. IDW interpolation of the average concentration of the six pollutants (March–April period).

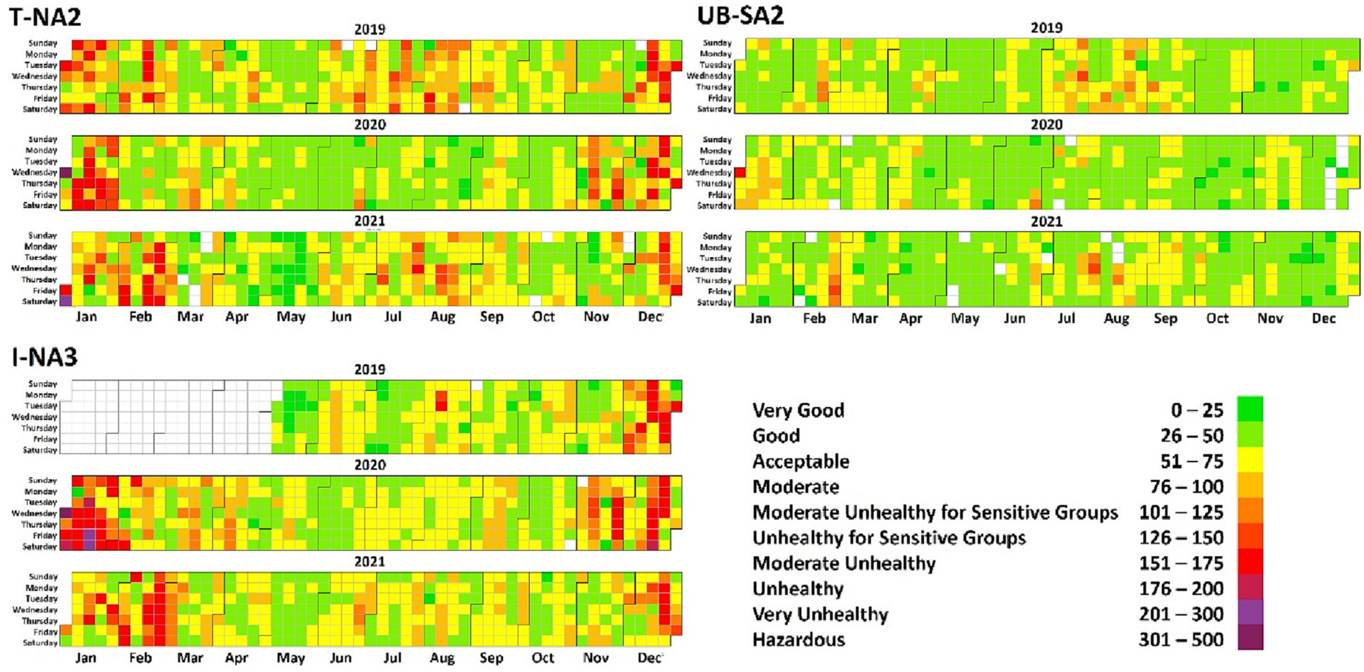

Fig. 4. Daily AQI values calculated for each day of the selected years in three representative stations.

2019 and 2021: this is due the lower values of O_3 concentrations, likely linked with the reduction of its precursors' (NO_x, VOCs, and CO) emissions caused by the lockdown restrictions.

3.3. Impact on human health

Campania has a higher than national average death rates due to cardiovascular diseases, respiratory diseases, and tumors (Toscano and Murena, 2021). By the AirQ+ software the impact of air pollution on human health was estimated evaluating the impact of C_6H_6 concentration on the incidence of leukemia; NO_2 and $PM_{2.5}$ concentration on adult (age 30+) mortality; tropospheric O_3 concentration on the number of deaths caused by respiratory diseases; PM_{10} concentration on the incidence of chronic bronchitis in adults (age 25+); $PM_{2.5}$ concentration on the number of deaths caused by ischemic heart disease for three age groups (35–39, 60–64, and 85–89). The effects of 2020 lockdown on the estimated proportion of deaths in adults attributable to NO_2 concentration were strongly evident (Fig. 5). Results relative to the other pollutants are reported in Figs. S2-S6.

A clear decrement of NO_2 impact on adult mortality can be observed in 2020 spring compared to the same months in 2019 and 2021. In Avellino, Benevento and Caserta, the estimated proportion of deaths attributable to NO_2 concentration dropped up to 0 % in April and May 2020. Among the five towns considered, Naples showed the smaller decrement (Fig. 4).

3.4. Comparison with satellite images

Fig. 6 shows the comparisons between the interpolation of NO_2 ground level concentration and the reprocessed Level 2 NO_2 tropospheric column concentration images, for the selected days (March 30th 2019, April 7th 2020, March 11th 2021). Further interpolations carried out on the remaining days without cloud coverage are reported in Fig. S7.

The comparison was quantified calculating the Pearson correlation coefficient R between every pair of concentration values for each day (30th March 2019: $R = 0.55$; 7th April 2020: $R = 0.64$; 11th March 2021: $R = 0.38$) (Figs. S8-S10). The weak correlation observed is likely related to the complex orography of the study area, which could instead influence the local weather and climate, increasing the variability of air quality and, much important, increase the vertical and horizontal inhomogeneity of NO_2 (Cersosimo et al., 2020). Furthermore, the NO_2 concentration measured at the ground level stations can be strongly influenced by the station position and its surroundings (source of pollution emissions, tall buildings, open areas, parks, etc.). Thus, ground stations data could be not adequate to carry out an interpolation to assess air quality at regional scale, especially when the orography of the territory is particularly complex and suffer spatial aliasing. The relatively large size of the TROPOMI pixels could also lead to an underestimation (overestimation) of higher (lower) NO_2 ground concentrations due to spatial averaging, while ground stations are more sensitive to pollution emissions at the surface, especially in urban and suburban areas (Ialongo et al., 2020).

4. Conclusions

Six contaminants responsible of air pollution have been analysed in the Campania region (Italy) for the years 2019, 2020 and 2021. The 2020 lockdown had a positive impact on air quality, causing a decrease of most pollutants' concentration during March and April compared to the previous year values; the most drastic change was observed for NO_2, which exhibited a concentration reduction between −42 % and −48 %, depending on the station category. Air quality was also noticeably better during summer, due to less O_3 precursors (NO_x, CO and VOCs). These improvements resulted also in an overall better AQI score and a lower impact of air pollution on mortality and the incidence of cardiopulmonary diseases. In 2021, NO_2 concentration increased again reaching halfway values between 2019 and 2020 concentrations (between +32 % and + 63 %, depending on the station category). Among the six considered pollutants, PM_{10} and $PM_{2.5}$ resulted the less affected by the lockdown restrictions imposed in 2020. Instead, the comparison between ground stations and satellite data evidenced that the latter are more suitable to be used for evaluating air quality on regional scale.

CRediT authorship contribution statement

- Alice Cardito: Investigation; Data curation; Formal analysis; Writing - Original Draft;

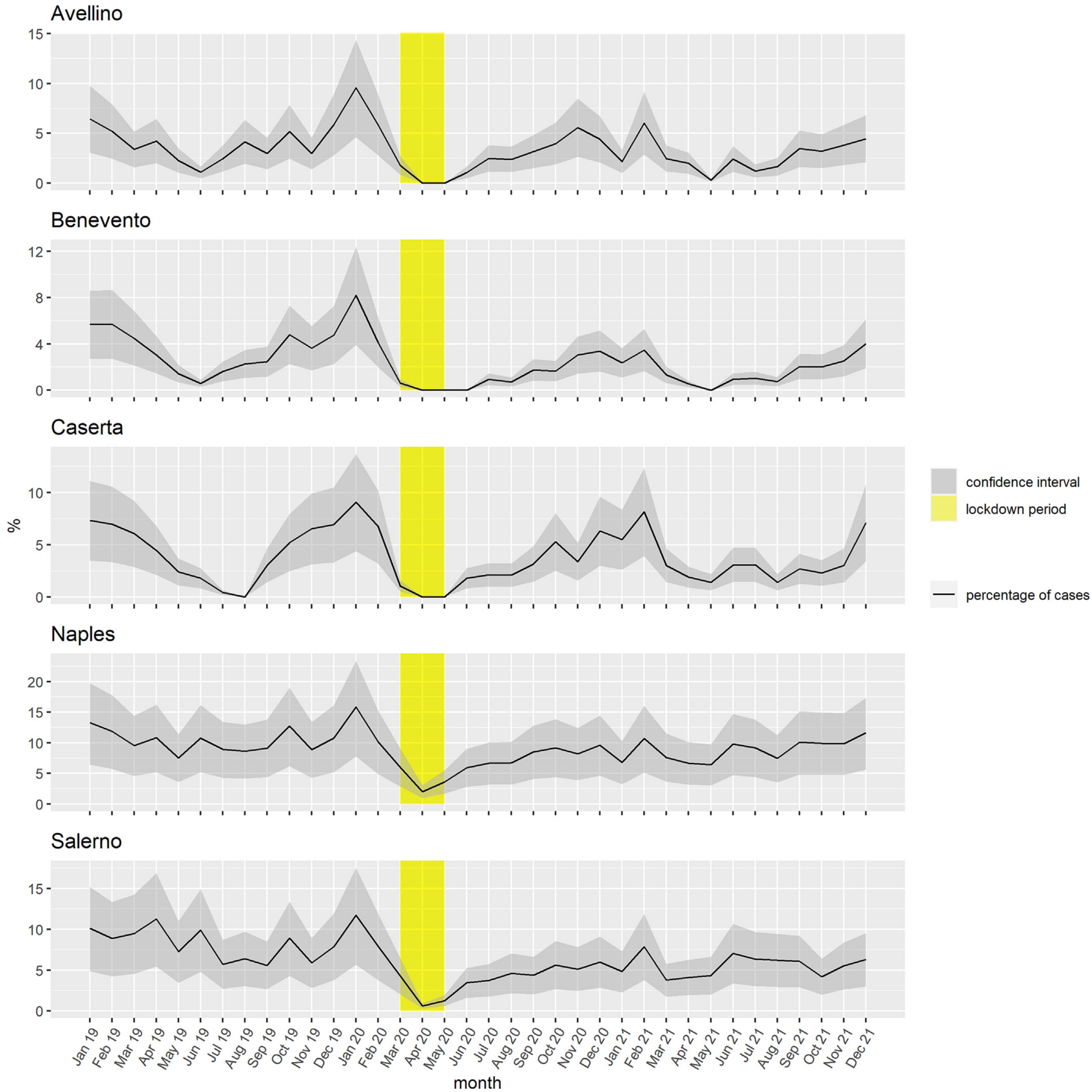

Fig. 5. Estimated proportion of deaths in adults (age 30 +) attributable to NO_2 concentration. Lockdown period is highlighted in yellow; the grey area is the 95 % confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Maurizio Carotenuto: Conceptualization; Formal analysis; Writing - Original Draft;
- Antonella Amoruso: Conceptualization; Validation
- Giovanni Libralato: Validation; Writing - Review & Editing;
- Giusy Lofrano: Methodology; Supervision; Review & Editing;

Data availability

Data will be made available on request.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.162833.

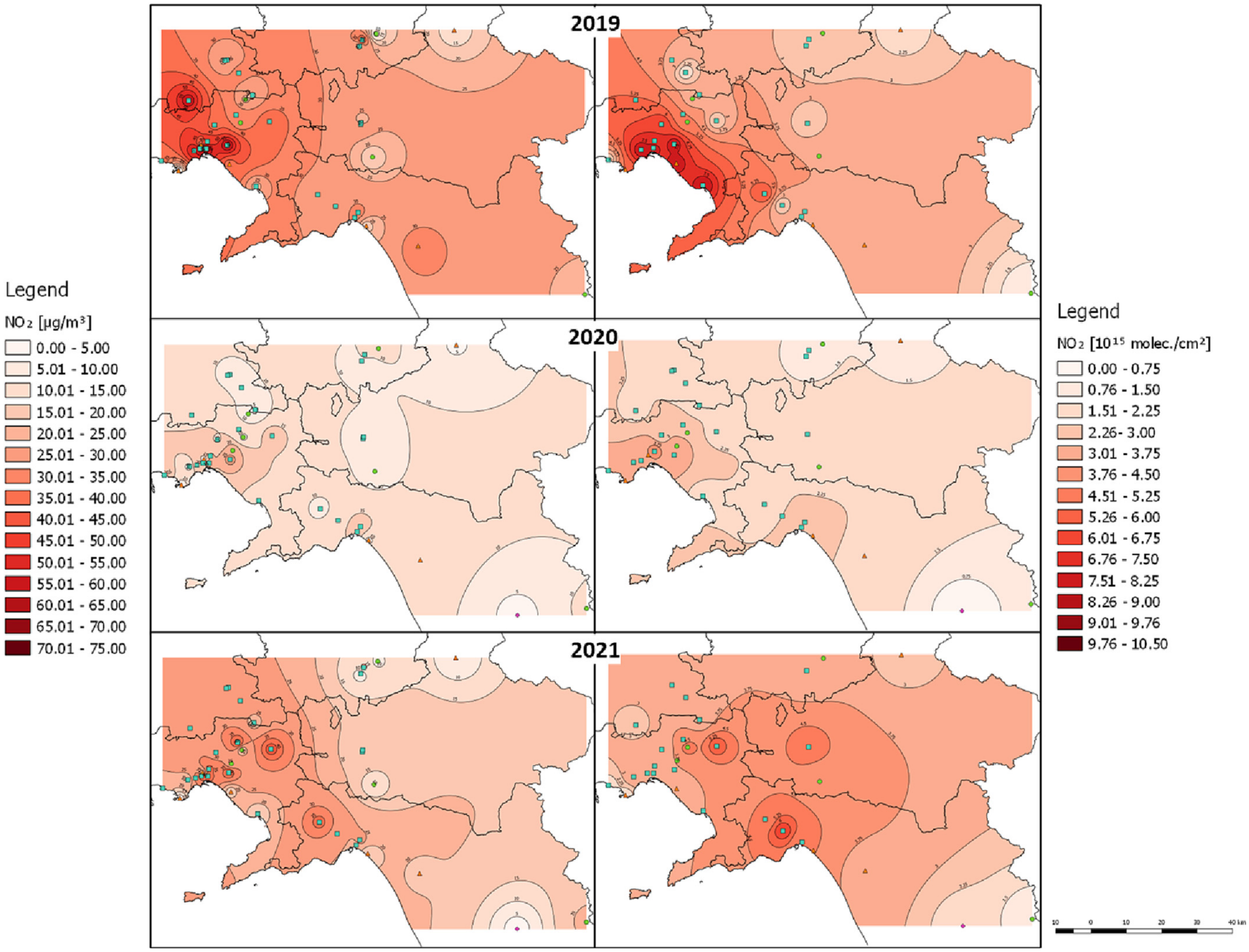

Fig. 6. Comparison between the interpolation of NO_2 ground level concentration (left) and of NO_2 tropospheric column concentration (right), for the selected days (30th March 2019, 7th April 2020, 11th March 2021).

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