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Air pollution and health impacts during the COVID-19 lockdowns in Grenoble, France

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A R T I C L E   I N F O

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A B S T R A C T

It is undeniable that exposure to outdoor air pollution impacts the health of populations and therefore constitutes a public health problem. Any actions or events causing variations in air quality have repercussions on populations’ health. Faced with the worldwide COVID-19 health crisis that began at the end of 2019, governments of several countries were forced, in the beginning of 2020, to put in place very strict containment measures that could have led to changes in air quality. While many works in the literature have studied the issue of changes in the levels of air pollutants during the confinements in different countries, very few have focused on the impact of these changes on health risks. In this work, we compare the 2020 period, which includes two lockdowns (March 16 - May 10 and a partial shutdown Oct. 30 - Dec. 15) to a reference period 2015 -2019 to determine how these government-mandated lockdowns affected concentrations of NO₂, O₃, PM₂.₅, and PM₁₀, and how that affected human health factors, including low birth weight, lung cancer, mortality, asthma, non-accidental mortality, respiratory, and cardiovascular illnesses. To this end, we structured 2020 into four periods, alternating phases of freedom and lockdowns characterized by a stringency index. For each period, we calculated (1) the differences in pollutant levels between 2020 and a reference period (2015–2019) at both background and traffic stations; and (2) the resulting variations in the epidemiological based relative risks of health outcomes. As a result, we found that relative changes in pollutant levels during the 2020 restriction period were as follows: NO₂ (~32%), PM₂.₅ (~22%), PM₁₀ (~15%), and O₃ (~10.6%). The pollutants associated with the highest health risk reductions in 2020 were PM₂.₅ and NO₂, while PM₁₀ and O₃ changes had almost no effect on health outcomes. Reductions in short-term risks were related to reductions in PM₂.₅ (~3.2% in child emergency room visits for asthma during the second lockdown) and NO₂ (~1.5% in hospitalizations for respiratory causes). Long-term risk reductions related to PM₂.₅ were low birth weight (~8%), mortality (~3.3%), and lung cancer (~2%), and to NO₂ for mortality (~0.96%). Overall, our findings indicate that the confinement period in 2020 resulted in a substantial improvement in air quality in the Grenoble area.

1. Introduction

Outdoor air pollution has a major influence on the health of populations, and has been of utmost concern for many years. Air pollution is classified as carcinogenic to humans by the International Agency for Research on Cancer (IARC) and is estimated to be responsible for approximately 3.1 million premature deaths worldwide every year and 3.2% of the global burden of disease (Babatola, 2018; Loomis et al., 2013, 2014). In addition to the associated mortality, the inhalation of such air pollution leads to a series of problems for human health: while short-term exposures can trigger or aggravate existing respiratory and/or cardiovascular problems and increase cases associated hospitalizations, long-term exposures are linked in particular to lung cancer and a greater susceptibility to respiratory tract infections. Anthropogenic sources, such as road traffic, fossil-fuel combustion and households, are the main sources of outdoor air pollution. However, the COVID-19 pandemic has caused a significant reduction in anthropogenic activities (prominent sources of air pollution) at certain times. Indeed, the global spread of SARS-COV-2 (COVID-19) has led governments to implement unprecedented restrictive and preventive measures to slow down COVID-19 outbreaks. Some of these actions (e.g., stay-at-home or national lockdown, curfew) which restricted vehicle

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traffic and other activities, had a direct impact on air quality and therefore on public health.

1.1. Changes in air pollution during lockdowns

Shortly after the start of the COVID-19 pandemic, a few studies reported that there was a significant drop in air pollutants during the lockdown period (Duthieil et al., 2020; Venter et al., 2020). Although there were still high air pollution events like in northern China (Wang et al., 2020), most publications found decreased background concentrations of pollutants (Bhat et al., 2021; Singh et al., 2020) and improved air quality indices (Bao and Zhang, 2020; He et al., 2020; Mahato et al., 2020; Naqvi et al., 2021; Sahraei et al., 2021) during lockdowns. The decrease in pollutant concentrations at background stations was also confirmed by satellite measurements, especially for nitrogen dioxide (Duthieil et al., 2020; Naqvi et al., 2021; Shehzad et al., 2020; Venter et al., 2020). Currently, more than 200 studies worldwide have assessed the effects of lockdown measures on air quality. Most of them go in the same direction and agree in concluding that the levels of fine particulate matter (PM) and nitrogen dioxide (NO₂) generally decreased, whereas ozone (O₃) concentrations increased during lockdowns (Gkatzelis et al., 2021). O₃ levels remained a challenge in some parts of the world as they showed dramatic increases (Grange et al., 2021; Huang et al., 2021). In this context, some works attempted to understand the role of meteorological conditions in the recorded pollution levels and observed reductions (He et al., 2020; Petetin et al., 2020; Ropkins and Tate, 2021). To study the associations between restrictive measures and air pollution, Gkatzelis et al. (2021) and Schneider et al. (2022) used the stringency index (Ihle et al., 2021), an indicator to characterize the strictness of government measures. They found significant negative correlations between the stringency index and pollutant concentration changes, especially for NO₂.

1.2. Health impacts related to changes in air pollution during lockdowns

One of the main consequences of the changes in air quality is to be sought on the health of populations. Although epidemiological studies have highlighted the relationship between mortality records or hospital admissions and changes in air quality during COVID-19 restrictions (Bozack et al., 2021; Hameed et al., 2021; Naqvi et al., 2021), little work has been done on the health impacts resulting from these changes in air pollutant levels compared to the number of studies on air quality during lockdowns. Table 1 summarizes the result of the comprehensive literature review on health risks related to changes in air pollution during lockdowns. Most of these studies focus only on short-term health effects and mortality risks. It appears from these works that the occurrence of all these health effects has declined during the lockdowns due to decreasing levels of air pollutant.

Regarding other health impacts, several studies found that outdoor air pollution had an impact on the incidence, prevalence or mortality of COVID-19, as exposure to pollutants can impair immune responses and affect the host’s immunity from respiratory virus infections (Katoto et al., 2021). For instance, Zhu et al. (2020), using a generalized additive model, found associations between PM₂.₅, PM₁₀, CO, NO₂, and O₃ levels and COVID-19 cases. Similarly, using artificial neural networks, Magazzino et al. (2020) identified PM thresholds related to COVID-19 deaths. And according to a meta-analysis by Katoto et al. (2021), it appears that COVID-19 cases are most consistently associated with PM₂.₅ and NO₂ exposures. Other work has investigated mechanistic aspects of COVID-19 virus infection. Frontera et al. (2020), established a relationship between pollutant exposure and overexpression of the pulmonary ACE-2 receptor associated with severe COVID-19 infections. Frontera et al. (2020), established a relationship between pollutant exposure and overexpression of the pulmonary ACE-2 receptor associated with severe COVID-19 infections. A large cohort study associated NO₂ and PM₂.₅ with high titres of anti-COVID-19 IgG antibodies (Kogevinas et al., 2021), likely reflecting high viral exposure. However, pollutant levels were not implicated in the prevalence of COVID-19 which led Hansell and Villeneuve, 2021 to state that reducing air pollution during the pandemic could not be considered a COVID-19 mitigation measure.

In this context, we can legitimately ask whether the restrictive measures implemented to counter COVID-19 outbreaks could have been beneficial not only for air quality, but also for the health of populations regularly exposed to these pollutants, or is there rather a double penalty, i.e., poor air quality plus the COVID-19 health crisis. Concomitant with COVID-19, several surveillance systems observed a decline in infectious diseases such as influenza or gastroenteritis (Kuo et al., 2020; Hatoun et al., 2020; Soo et al., 2020), suggesting that social distancing or other measures taken during the pandemic could have helped to prevent some contagious diseases. From the French Public Health Agency (Santé Publique France (Geodes), 2020), in the Isère department, where the city of Grenoble is located, the number of home emergency acts for influenza and gastroenteritis, and the rate of emergency room visits for gastroenteritis, declined in 2020 compared to 2010–2019.

1.3. Study objectives

In this study, we therefore propose taking stock of whether 2020, due to the health crisis, was less heavy in terms of exposure to air pollutants compared to past years. We do not intend to explain the mechanisms and factors that could lead to the changes and drop in air pollution levels, but rather to obtain an idea of the magnitude of variation in exposure levels, regardless of the origin during 2020 in the city of Grenoble, France.

Table 1
Studies associating air pollution with health risks during lockdowns.

| Pollutant | Health outcome | Effect | Reference |
|-----------|----------------|--------|-----------|
| NO₂, O₃  | Non-accidental mortality | ST | Achebak et al. (2020) |
| PM₂.₅, NO₂ | Non-accidental & cardiovascular mortality, mortality for hypertensive disease, coronary heart disease, stroke & chronic obstructive pulmonary disease | ST | Chen et al., 2020 |
| PM₂.₅, O₃ | Mortality all causes, cardiovascular & respiratory | ST, LT | Cole et al. (2020) |
| NO₂      | Mortality | ST, LT | Giani et al. (2020) |
| PM₂      | Mortality | ST | Han and Hong (2020) |
| PM₁₀     | Mortality | LT | Hao et al. (2021) |
| PM₁₀, NO₂, O₃, SO₂ | Hospital admission for respiratory & cardiovascular diseases | ST | Housain et al. (2021) |
| PM₂.₅, O₃ | Mortality | ST | Maji et al. (2021) |
| PM₂.₅, PM₁₀, NO₂ | Mortality | ST, LT | Medina et al. (2021) |
| PM₂.₅, PM₁₀, NO₂, O₃, SO₂, CO | Mortality | ST | Nie et al. (2021) |
| PM₂.₅, PM₁₀, NO₂, O₃ | Mortality | ST | Schneider et al. (2022) |
| PM₂.₅, NO₂, O₃ | Mortality, paediatric asthma emergency room visits | ST | Venter et al. (2021) |
| NO₂, O₂, CO | Mortality | ST | Xu et al. (2021) |

*Abbreviations: ST = short-term, LT = long-term.
Subsequently, we will determine whether these reductions in pollution levels were sufficient to induce a reduction in risks to human health. Concretely, we aim to answer the following two questions:

- To what extent did outdoor air pollution decrease in Grenoble during the lockdown period in 2020 compared to previous years?
- What would have been the impact of such a reduction in air pollution on the short- and long-term risks to human health?

2. Methods

2.1. Study area

This study focuses on Grenoble, the largest city in the French Alps. This metropolis has approximately 450,000 inhabitants, spread over an area of 545 km². Located in a flat, Y-shaped valley at an altitude of approximately 215 m, Grenoble is surrounded by three large mountain ranges reaching almost 3000 m in height. The local weather is temperate with a continental influence and an effect of the mountainous region. Hot summers and cold winters generate an important thermal amplitude between day and night. Rainfall is relatively high. The surrounding mountains make the city prone to episodes of heavy air pollution. The topography makes it difficult for pollutants to be evacuated horizontally, and the temperature inversion (a meteorological phenomenon in which a layer of hot air overlies the cold air in a given layer of the atmosphere) often worsens the situation by creating an obstacle to vertical dispersion. The major part of the urbanization is located in the valley.

2.2. Study period

In December 2019, a coronavirus disease epidemic started in Wuhan, China. In March 2020, the World Health Organization (WHO) qualified this outbreak as a pandemic. On March 16th, the President of France announced a full lockdown starting the day after. People were ordered to stay at home unless they needed to satisfy essential needs (e.g., buying food, medical appointments, etc.). This mandatory lockdown ended on May 10th. After a relaxed summer, France launched another series of measures starting on October 17th. A curfew was imposed in Grenoble, followed by a second nationwide lockdown, which started on October 30th and ended on December 15th. This lockdown was much softer than the first one, schools remained open, and many people were still working, although many did so remotely.

To structure the comparison of air pollution before, during and after government pandemic measures, we divided 2020 into four periods, and computed a mean daily stringency index for each period (Table 2). The stringency index, ranging from 0 (free and no restrictions at all) to 100 (strictest), allows for the quantification of the severity of measures taken by governments to mitigate the effects of COVID-19 (Hale et al., 2021). This composite index uses nine governmental response indicators, including school, workplace and transport closures, as well as restrictions on gathering. Fig. 1 displays the stringency index trajectory of France in 2020. Clearly, mean stringencies were very high for lockdowns L1 and L2, moderate during the free period F2, and low but different from zero in F1 as the measures gradually settled in at the beginning of the health crisis. By definition, all the years before 2020 were characterized by a zero-stringency index.

2.3. Air pollution data

We considered four airborne pollutants: NO\textsubscript{2}, O\textsubscript{3}, and PM of sizes less than 2.5 μm (PM\textsubscript{2.5}) and 10 μm (PM\textsubscript{10}), respectively. We obtained pollutant concentrations from four background and three traffic monitoring stations, all managed by Atmo Auvergne Rhône-Alpes (the regional non-profit organization accredited by the French authorities to measure and assess air quality). We collected hourly concentration data from January 1st: 2015 to December 31st 2020 thanks to an Application Programming Interface (https://api.atmo-aura.fr/). The use of hourly values over a 6-year reference period made the analysis more representative and smoothed interannual weather-induced fluctuations. There was a total of 3447 slightly negative values out of 839,493 pollutant levels (0.4%). For NO\textsubscript{2} and O\textsubscript{3}, negative values (0.5%) were replaced by half of the instrumental limit of detection (LOD) values equal to 1 ppb (1 ppb corresponding to 1.88 μg/m\textsuperscript{3} for NO\textsubscript{2} and 2 μg/m\textsuperscript{3} for O\textsubscript{3}). For PM, negative concentrations (0.3%) were replaced by zero as no LOD were available.

We compared pollutant levels monitored in 2020 to measurements made between 2015 and 2019 (hereafter referred to as the “historical” or “reference period”). The quantity of interest is the relative change in the daily mean pollutant levels, calculated as follows:

\[
\Delta P = \frac{P_{2020} - P_{2015-2019}}{P_{2015-2019}}
\]

where \(P_{2020}\) and \(P_{2015-2019}\) correspond to daily mean pollutant concentrations in 2020 and during the historical 2015–2019 period, respectively. As daily mean concentrations were distributions for the reference 2015–2019 period, we reported descriptive statistics for. We computed the \(\Delta P\) values for all pollutants considered: NO\textsubscript{2}, O\textsubscript{3}, PM\textsubscript{2.5}, and PM\textsubscript{10}. We performed all statistical analyses using R software 4.0.5 (R Core Team, 2018) for Windows 10©.

2.4. Health risk assessment

To assess the health impacts of lockdowns, we followed guidelines from a quantitative health impact assessment tool developed by Santé Publique France together with the WHO (Blanchard et al., 2019). For such an assessment, we used the pollutant concentrations measured at background stations because they are more representative of population exposure than traffic stations (Corso et al., 2019). The health effect caused by exposure to a pollutant for a given period is determined using the relative risk formula, as follows:

\[
RR = e^{(\beta(C-C_o))}
\]

where \(C\) is the pollutant concentration, \(C_o\) is the low concentration threshold below which there is no risk of health effects, and the coefficient \(\beta\) is obtained as follows:

\[
\beta = \frac{\ln(RR)}{\delta}
\]

where \(RR\) is the relative risk of health effects obtained from epidemiological studies, and \(\delta\) is the associated concentration increment (see

| Timeframe          | Period | Description         | Average stringency index |
|--------------------|--------|---------------------|--------------------------|
| 01.01.20 (01:00) – 17.03.20 (11:00) | F1     | No measures         | 15                       |
| 17.03.20 (12:00) – 10.05.20 (00:00) | L1     | Strict lockdown     | 88                       |
| 11.05.20 (01:00) – 17.10.20 (00:00) | F2     | Relaxation of measures | 55                       |
| 18.10.20 (01:00) – 31.12.20 (00:00) | L2     | Soft lockdown       | 70                       |

Note: L1 and L2 represent the 1st and 2nd lockdowns, and F1 and F2 represent the 1st and 2nd “free” periods.
The quantity of interest is the relative change in relative risks: 

\[ \Delta RR = \frac{RR_{2020} - RR_{2015-2019}}{RR_{2015-2019}} = e^\delta (C_{2020} - C_{2015-2019}) \]  

(4)

where \( C_{2020} \) and \( C_{2015-2019} \) are the pollutant concentrations in 2020 and during the 2015–2019 period, respectively, averaged over the appropriate timeframe, and “daily” and “yearly” are the bases for short- and long-term risks, respectively. Since both daily and yearly means were distributions for the reference period of 2015–2019, we reported descriptive statistics (median [95% CI]) for distributions for the reference period of 2015.

Table 3. Pollutant associated health outcomes and relative risks.

| Pollutant | Exposure/ timeframe | Age group | Health outcome | RR, [CI 95%] per 10 μg/m³ | Reference |
|-----------|---------------------|-----------|----------------|----------------------------|-----------|
| \( \text{O}_3 \) | Short-term/8h-maximum daily mean | all | Mortality, all causes | 1.0019 [1.0006–1.0031] | Vicedo-Cabrera et al. (2020) |
| | | ≥ 65 | Hospitalizations for respiratory causes | 1.0044 [1.0007–1.0083] | WHO (2013) |
| | | | Hospitalizations for cardiovascular causes (excluding strokes) | 1.0089 [1.0050–1.0127] | WHO (2013) |
| \( \text{NO}_2 \) | Short-term/daily mean | all | Non-accidental mortality | 1.0075 [1.0040–1.0110] | Corso et al. (2019) |
| | | ≤ 17 | Hospitalizations for respiratory causes | 1.0180 [1.0115–1.0245] | WHO (2013) |
| | | | Emergency room visits for asthma | 1.0101 [0.9900–1.0200] | Host et al. (2018) |
| \( \text{PM}_{2.5} \) | all | Non-accidental mortality | 1.0030 [1.0013–1.0047] | Liu et al. (2019) |
| | | ≤ 17 | Hospitalizations for respiratory causes | 1.0063 [1.0025–1.0101] | Liu et al. (2019) |
| | | | Emergency room visits for asthma | 1.0190 [0.9882–1.0402] | WHO (2013) |
| | | all | Hospitalizations for cardiovascular causes (including strokes) | 1.0091 [1.0017–1.0166] | WHO (2013) |
| Long-term/annual mean | ≥ 30 | Mortality, all causes | 1.1500 [1.0500–1.2500] | Pascale et al. (2016) |
| | Adults | Lung cancer incidence | 1.0900 [1.0400–1.1400] | Hamra et al. (2014) |
| | Infants | Low birthweight at full term | 1.2900 [1.1200–1.7700] | Pedersen et al. (2013) |
| \( \text{NO}_2 \) | ≥ 30 | Mortality, all causes | 1.0230 [1.0080–1.0370] | Committee on the Medical Effects of Air Pollutants, 2018 |

Fig. 1. Evolution of the COVID-19 stringency index in France in 2020.
There was no clear trend during L2, but we observed two peaks above the seasonal norms. We witnessed a large 2020 PM increase at the beginning of L1 at background stations, with levels above the seasonal norms. Another positive anomaly was recorded at the end of November 2020. PM$_{2.5}$ concentration changes (compared to seasonal norms) appeared more important during winter than during summer. Traffic values tended to be lower in 2020 than in 2015–2019, and slightly lower than background values. Time series profiles of PM$_{2.5}$ concentrations were similar at the background and traffic stations. The peak seen in 2020 at the beginning of L1 in background stations was less pronounced at traffic stations.

In 2020, the general trend of PM$_{10}$ levels was very similar to that of PM$_{2.5}$, except that PM$_{10}$ levels were more frequently within the seasonal norms, even during L1. However, similar anomalies were noted for both PMs.

3.2. Changes in air pollutant levels

To quantify differences in concentration between 2020 and the period of 2015–2019, we used the descriptive statistics of the relative change in pollutant concentrations, $\Delta P$, defined in Eq. (1), as summarized in Figs. 3 and 4. First, Fig. 3 shows that with high Pearson and Spearman correlation coefficients ($r, \rho \geq 0.8$), the general trend is a decrease (increase) in NO$_2$, O$_3$, and PM$_{2.5}$ as a function of the average stringency index and no changes ($r, \rho < 0.35$) for PM$_{10}$. We found significant ($p < 0.05$) negative correlations between the 2020 concentrations of NO$_2$ and the average stringency index of the F1, L1, F2, and L2 periods, but no such correlations for O$_3$ and PM (see Fig. 3). That is, high stringency indices were associated with low concentrations of NO$_2$ and vice versa.

Next, in Fig. 4, at background stations, there was a substantial decrease ($-48\%$) in daily mean NO$_2$ levels during L1 when compared to 2015–2019. The release of the measures in F2 showed an increase in NO$_2$ levels (see Fig. 2), but daily mean NO$_2$ levels were still lower than that in 2015–2019 ($-19\%$ and $-18\%$ at background and traffic stations, respectively). During L2, NO$_2$ levels declined by about $-25\%$. The NO$_2$ level decrease was $25\%$ higher at traffic stations than for background stations during L1, but almost the same during F2 and L2.

For O$_3$ at background stations (O$_3$ not measured at traffic stations), concentration levels increased during L1 and L2 in 2020, and the situation returned to normal during F2. During L1 in 2020, daily mean PM$_{10}$ concentrations increased ($+3\%$) at background stations, but the maximum level was reduced by $46\%$ and the 97.5th percentile by $14\%$ thus indicating a change in the profile of the distribution. There was no clear trend for PM$_{10}$ during L1. After L1, the daily mean PM$_{10}$ levels at background stations stayed well below the historical values until the end of the year ($-15\%$ in F2 and $-22\%$ in L2). The general pattern for PM$_{2.5}$ was similar to that of PM$_{10}$. Overall, positive or negative concentration changes appeared more pronounced for PM$_{2.5}$ than for PM$_{10}$ during L1, F2, and L2. In contrast to background stations, PM concentrations were reduced (e.g., a mean of $-19\%$ and $-17\%$ for PM$_{2.5}$ and PM$_{10}$, respectively) during L1 at traffic stations.
3.3. Changes in health risks

We assessed the impact of air pollution changes in 2020 on health outcomes using the relative change in relative risks, $\Delta RR$, defined in Eq. (4), as reported in Fig. 5. The long-term (average of the entire year) impacts of air pollution changes turned out to be larger than short-term impacts.

Long-term decreases in PM$_{2.5}$ levels would result in 2%, 3%, and 8% reductions in the risk of lung cancer, mortality, and low birth weight, respectively. Likewise, the decline in NO$_2$ levels could result in a 0.95% reduction in the associated long-term mortality risk.

Regarding short-term outcomes, the most important reductions occurred after the health crisis began (in L1, F2, and L2), except for the PM$_{2.5}$-related child emergency room visits for asthma (−1% in F1). During L1, the drop in NO$_2$ levels would result in 0.63%, 0.86%, and 1.5% reductions in non-accidental mortality, emergency admissions for asthma, and hospitalizations for respiratory causes, respectively. During F2, the most important risk reduction was related to PM$_{2.5}$ for emergency room visits for asthma (−1.8%). The decline in O$_3$ concentrations during F2 would lead to a 0.6% reduction in hospitalizations for cardiovascular causes. During L2, the decrease in NO$_2$ concentrations reduced the risk of emergency room visits for asthma by 0.8%, non-accidental mortality by 0.6%, and hospitalizations for respiratory causes by 1.5%.

4. Discussion

Our main objectives were to assess the magnitude of changes in outdoor air pollution levels in Grenoble during 2020 (structured in stringency periods) compared to previous years (of zero stringency), and to examine the associated potential impacts on short- and long-term human health risks.

Over the entire restriction period of 2020 (i.e., from March 17th to the end of December), the overall level (average of the mean values in Fig. 4 over the periods L1, F2 and L2 on the two stations) decreased compared to previous years for NO$_2$ (−32%), PM$_{2.5}$, (−22%), and PM$_{10}$ (−15%) at both background and traffic monitoring stations, but there was an increase of O$_3$ (+10.6%) at background stations. Unexpectedly, PM levels rose at background stations during L1. Similar observations have been noted in several studies (Le et al., 2020; Seo et al., 2020; Ropkins and Tate, 2021). Seo et al. (2020) reported PM$_{2.5}$ concentration decreases of 36% and 31% in Seoul and Daegu, respectively. In the UK, Ropkins and Tate (2021) revealed a rise at both traffic and background stations in contrast to Grenoble, where traffic PM levels fell. In Beijing, Le et al. (2020) stated that PM$_{2.5}$ levels rose significantly, as did O$_3$. In our study, we witnessed an important O$_3$ increase during lockdowns, as in other European studies (Collivignarelli et al., 2020; Sicard et al., 2020). In Barcelona, for example, Tobías et al. (2020) also observed a significant increase in O$_3$ (about +50%) during the lockdown from March 14 to 30 which they attribute to the chemical mechanisms of the decrease in NOx causing an increase in O$_3$ and a decrease in NO reducing O$_3$ titration. At background stations, they found large relative changes for NO$_2$ (−47%), PM$_{10}$ (−27.8%) and O$_3$ (+28.5%) between pre-lockdown (from February 16 to March 13) and during confinement (March 14 to 30). We also observed the most critical concentration reduction in Grenoble for NO$_2$, with levels significantly ($p < 0.01$) and negatively correlated with the average Oxford stringency index ($r^2 = 0.9$). Likewise, Gkatzelis et al. (2021) stated in a worldwide analysis that NO$_2$ level decreases were due to the stringency of lockdown measures. Reductions in traffic-related NO$_2$ levels were also reported in the UK (Brown et al., 2021).

Recall that we are looking here at the differences in the monitored...
pollutant concentrations (i.e., outdoor exposure) over several years without investigating the mechanisms and/or factors (e.g., meteorological conditions, changes in the behavior of population displacement, pollutant transportation, etc.) that could have contributed to these changes in pollutant levels in 2020. For instance, according to Airparif (2021), meteorology accounted for one-third of the NO$_2$ concentration decrease in 2020.

Currently, it is well known that exposure to air pollution may result in a variety of acute or chronic health effects. Short-term outcomes occur within a few days after acute exposure. Thus, air pollution peaks increase the risks of emergency room visits for asthma, mortality, and hospitalizations for cardiovascular or respiratory causes and mortality. Such acute effects impact vulnerable people including children, the elderly, and patients with respiratory or cardiovascular diseases. Long-term health effects, originating from persistent exposure to air pollutants, are much greater because they lead to the development of chronic pathologies. In this study, we found that the most important health risk reductions in 2020 were related to PM$_{2.5}$ and NO$_2$, while PM$_{10}$ and O$_3$
changes had almost no effect on health outcomes.

For long-term health outcomes, the reduction of PM$_{2.5}$ levels in 2020 could lower the risk of low birthweight (from $-1.3\%$ up to $-30\%$), mortality ($-3.3\%$), and lung cancer ($-2\%$). In an Irish study, Philip et al. (2020) indicated a $-73\%$ reduction in very low birthweight between January and April 2020 compared with the preceding 20 years. Kim et al. (2021) observed that during the COVID-19 period in South Korea, the low birthweight rate was 2.2 times lower than that during the pre-COVID-19 period (2011–2019). For France, in a study by Medina et al. (2021), the long-term mortality decrease was estimated to be approximately $-0.4\%$ for metropolitan France, which was lower than that in Grenoble. Likewise, we found a risk reduction of $-0.95\%$ in mortality associated with a decrease in long-term NO$_2$ levels in Grenoble, whereas Medina et al.’s (2021) estimation showed a $-0.2\%$ decline for all of France. Although going in the same direction, differences in values between the findings of Medina et al. (2021) and those of our research mainly reflect the heterogeneity of exposure to air pollutants across France. Like most urban cities, Grenoble is very connected to major intercity transport networks and therefore very prone to NO$_2$ pollution. The drop in pollutants would have been more pronounced in Grenoble than the average across the whole country.

Among all short-term effects, those concerning PM$_{2.5}$ and childhood asthma would be the most impacted, with $-1\%$, $-1.8\%$, and $-3.22\%$ risk reductions during F1, F2 and L2, respectively. Other European studies reported larger decreases. In Slovenia, Krivec et al. (2020) indicated a $-71\%$ to $-78\%$ decline in paediatric asthma admissions from March 16th to April 20th, 2020 compared to 2017–2019. Shah et al. (2021) found a statistically significant change in the level ($-0.196$; $p = 0.008$) of the asthma exacerbation rate in England after March 23rd 2020. According to Davies et al. (2021), the lockdown in Scotland and Wales was associated with a $-36\%$ pooled reduction in emergency admissions for asthma.

For short-term effects on non-accidental mortality, NO$_2$ turned out to be more critical than PM$_{2.5}$ in contrast to what was seen for long-term effects. We found a short-term risk reduction of $-0.6\%$ in mortality related to NO$_2$ levels in Grenoble during L1, consistent with Medina et al.’s (2021) estimation of $-0.3\%$ for the entire country. Because of the high NO$_2$ concentration decreases, hospitalizations for respiratory causes could have been reduced by $-1.5\%$ during L1 and L2 in Grenoble. In a cohort study in Greece, Kyriakopoulos et al. (2021) reported that the incidence rate for respiratory diseases between March and April 2020 was 21.4 admissions per day, compared to 40.8 in 2018 or 39.9 in 2019 (i.e., an approximately 47% reduction). The risk reduction ($-0.63\%$) of hospitalizations for cardiovascular causes was mainly associated with O$_3$ levels during F2 in Grenoble. Bhatt et al. (2020) observed a significant daily decline in ($-5.9\%$) hospitalizations for primary acute cardiovascular reasons in March 2020 across a large American tertiary care health system.

Beyond the differences in values that can be attributed to differences in methods, epidemiological and environmental contexts, there is a concordance between all these observations and ours in the reduction of the health risks associated with air quality during the entire lockdown period. Other things to consider include hospital avoidance behavior during the COVID-19 crisis and indoor air. Indeed, many patients may have delayed treatment for fear of catching the COVID-19 virus in hospitals. Czeisler et al. (2020) estimated that 41% of American adults delayed or avoided health care during the pandemic because of concerns about COVID-19. In addition, the quality of indoor air would certainly have had an impact on health (perhaps contrasted with outdoor air) during lockdowns, particularly during L1, when a large proportion of the population was housebound. All estimates presented in this study are based only on outdoor air pollutant exposure.

In sum, pollutants with major health impacts in 2020 were NO$_2$ and PM$_{2.5}$ for both short- and long-term risks. Although O$_3$ was the only pollutant that underwent an increase during that period, those changes were not sufficient to induce major health risk increases. The most impacted short-term outcomes during lockdowns were asthma and hospitalizations for respiratory ailments. This is consistent with several
studies showing greater decreases during lockdowns for respiratory illnesses than for cardiovascular diseases. Impacted long-term outcomes include low birthweight, mortality, and lung cancer. The mortality in question here would be the delta of deaths to be subtracted from the large number of deaths caused by COVID-19.

As mentioned above, the experience of lockdowns in 2020 has shown that the main health impacts were related to NO₂ and PM₂.₅. In Grenoble area, 56% of NOx emissions can be attributed to transport while 63% of PM₂.₅ emissions originate from wood heating (Atmo, 2020). This therefore indicates that both emission sectors need to be considered when designing effective policies to reduce pollution levels. Interestingly, Boucassse et al. (2022) have recently developed an inverse approach for the Grenoble urban area, starting from public health objectives to define urban policies compatible with these objectives. They report that replacing all inefficient wood-burning appliances with pellet stoves and reducing private vehicle traffic by 36% would result in a two-thirds reduction in fine particulate mortality by 2030.

5. Conclusion

As expected, the lockdowns in Grenoble resulted in a substantial drop in PM and NO₂ levels. While the NO₂ concentration decrease could be significantly statistically associated with the stringency of governmental mitigation measures, no such clear trend could be drawn for PM concentration changes, especially during the first lockdown (L1). The most pronounced health effects were found to be associated with PM₂.₅ with long-term outcomes such as low birthweight, mortality, or lung cancer, but also with short-term effects such as childhood asthma. A decrease in NO₂ levels was associated, to a lesser extent than a decrease in PM₂.₅, with a drop in long-term mortality risk and a short-term decline in hospitalizations for respiratory causes. During the restrictions, levels of O₃ or PM₁₀ did not induce an important change in health risk compared to the other pollutants. Now that all kinds of activities are on the rise, it would be instructive to redo this analysis with data from 2021 and years to come to learn more about how the trends outlined in this study will evolve.

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Author contributions

Marie-Laure Aix: data curation, formal analysis, investigation, software, visualization, writing (original draft and reviewing). Pascal Petit: formal analysis, investigation, visualization, writing (review and editing). Dominique J Bisout: conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, software, supervision, validation, visualization, writing (review and editing).

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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