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Temporal Evolution of $PM_{2.5}$ Levels and COVID-19 Mortality in Europe for the 2020–2022 Period

Jean-Baptiste Renard [1,*], Jérémy Surcin [2], Isabella Annesi-Maesano [3] and Eric Poincelet [2]

[1] LPC2E-CNRS, 3A Avenue de la Recherche Scientifique, CEDEX 2, F-45071 Orléans, France
[2] Pollutrack, 5 rue Lespagnol, F-75020 Paris, France; jeremysurcin.pollutrack@protonmail.com (J.S.); e.poincelet@gmail.com (E.P.)
[3] Institute Desbrest of Epidemiology and Public Health, University of Montpellier and INSERM, Allergic and Respiratory Diseases Department, Montpellier University Hospital, Montpellier, IDESP IURC, 641 Avenue du Doyen Gaston Giraud, F-34093 Montpellier, France; isabella.annesi-maesano@inserm.fr
* Correspondence: jean-baptiste.renard@cnrs-orleans.fr

Abstract: Air pollution has a strong impact on human health, from respiratory and severe pulmonary diseases to heart attack and cancer. During the 3 years of the COVID-19 pandemic, several peaks of mortality occurred, which could be related to particulate matter (PM) pollution events. The possible effects of PM (PM_{10} and $PM_{2.5}$, with diameters less than 10 and 2.5 µm, respectively) on COVID-19 mortality have now been established. To better understand this relationship at the European level for the period 2020–2022, data from 16 representative locations in Europe (81 million people) with $PM_{2.5}$ levels ($\mu g \cdot m^{-3}$) ranging from low to high values were analyzed using statistical methods. The analysis confirms a temporal relation between the peaks of $PM_{2.5}$ exposure and COVID-19 mortality. The best correlation was obtained considering the history of exposure to PM2.5 pollution during a 2-month integration time coupled with a one-week delay for the COVID-19 mortality. Although the trend of COVID-19 mortality vs. $PM_{2.5}$ levels varies among locations, the global trend was similar, giving an estimated mean value of a 40 ± 20% mortality increase per $\mu g \cdot m^{-3}$ $PM_{2.5}$ increase. The stronger the positive (negative) gradient of the PM peak, the stronger the positive (negative) gradient of the COVID-19 mortality. These results indicate that a succession of PM pollution peaks could be more dangerous than permanent exposure to moderate pollution levels. Finally, PM number concentrations should be used in the future rather than the $PM_{2.5}$ mass concentrations ($\mu g \cdot m^{-3}$), with the consideration of PM composition to better evaluate the effect of submicron particles on human health, particularly for other respiratory diseases. These results must be considered in the management of future pandemics.

Keywords: COVID-19; mortality; $PM_{2.5}$; air pollution; Europe

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Citation: Renard, J.-B.; Surcin, J.; Annesi-Maesano, I.; Poincelet, E. Temporal Evolution of $PM_{2.5}$ Levels and COVID-19 Mortality in Europe for the 2020–2022 Period. *Atmosphere* **2023**, *14*, 1222. https://doi.org/10.3390/atmos14081222

Academic Editors: Mario Coccia and Yu Zhao

Received: 16 June 2023
Revised: 19 July 2023
Accepted: 25 July 2023
Published: 29 July 2023

1. Introduction

Ambient air pollution has a large range of negative impacts on human health [1–4], mainly increasing the number and severity of respiratory and pulmonary diseases [5], including infections [6] and the risk of heart attacks and strokes [7,8]. Also, long-term exposure to polluted air can cause perturbations in the immune system [9]. Air pollution mainly concerns airborne particulate matter (PM) with particles smaller than 10 µm (PM_{10}), and more precisely, smaller than 2.5 and 1 µm ($PM_{2.5}$ and PM_1).

The spread and transmission of the virus could be due to several parameters, such as weather conditions, population density, local sanitary conditions, and air pollution. During the 3 years of the COVID-19 pandemic, several peaks of mortality occurred during particulate matter (PM) pollution events. The PM concentration peaks are the final consequence of human activities combined with weather parameters, with the highest pollution peaks occurring during low winds due to stable anticyclonic conditions. Thus, the possible effects of PM_{10} and $PM_{2.5}$ pollution on the new cases and mortality of COVID-19

(SARS-CoV-2) pandemic were intensively studied less than a year after the pandemic began, mainly based on the situation in the Lombardy region (Italy), where air pollution levels and mortality were among the highest in Europe. These studies presented a statistical relation between PM levels and COVID-19 morbidity and mortality during the first phase of the pandemic [10–17], and a significant mortality variability appears between polluted and unpolluted locations. These conditions first consisted of respiratory and cardiovascular distresses [18] and were indeed related to the immune system [19,20]. Nevertheless, only a few studies have investigated the link between PM and COVID-19 mortality at the European level [21].

Although a large number of papers support the existence of a relation between air pollution exposure and COVID-19, one can argue that this correlation could be an artifact due to, for example, weather parameters. The number of COVID-19 cases was found to be lower during periods of high-speed wind, which dissipates the PM pollution. The authors of [22,23] studied the correlation between COVID-19 and weather conditions during the first phase of the pandemic and concluded that, as far as local meteorology is concerned, temperature and humidity are negatively correlated with the number of cases. In winter conditions, PM pollution often increases when temperature decreases due to heating that produces fine particulates, thus making it difficult to decorrelate the various parameters. Nevertheless, the absence of a relationship between COVID-19 outbreaks and temperature and UV radiation [24] suggests that air pollution is indeed the main contributor to COVID-19 impact. In addition, during a long series of observations conducted in France, abatement from rain precipitation was observed for particles larger than 10 µm but not for particles 0.2–10 µm [25], thus supporting an intervention of fine PM independent of meteorological factors. The proper role of air pollution was further confirmed by studies in which air pollution and COVID-19 morbidity and mortality were statistically related after adjusting for meteorological variables [18].

All measurements from 32 cities and districts of 6 countries in Western Europe have been combined to show a statistical trend between $PM_{2.5}$ levels and COVID-19 mortality for a period longer than all previous studies from early 2020 to early 2022 [26]. The authors found that an increase in COVID-19 mortality aligned with an increase in $PM_{2.5}$ mass concentration, leading to a factor 5.5 ± 1.0% increase in mortality when the pollution increased from 5 to 45 $\mu g \cdot m^{-3}$. This corresponds to a mean increase of 10.5 ± 2.5% in mortality per $PM_{2.5}$ 1 $\mu g \cdot m^{-3}$. More precisely, the trend, similar for the 6 countries analyzed, depended on the analysis period and decreased with time from the first spread of the pandemic in early 2020 to the vaccinal race after mid-2021. This mean result is close to that of previous studies showing that a $PM_{2.5}$ increase of 1 $\mu g \cdot m^{-3}$ can lead to at least an increase of 11% in COVID-19 mortality in the United States [27]. Similar values were found in England [28], the Netherlands [29], Northern Italy [30], Brazil [31], and in a meta-analysis of 35 observational studies [32]. All these studies suggest that the relative effect of PM pollution on COVID-19 mortality is not country-dependent.

A Spearman correlation coefficient of 0.44 was found when analyzing the data in the US up to mid-2021 [33]. The Spearman correlation was between 0.45 and 0.61 for the most affected part of Italy during the first semester of 2020 [14]. A low but positive correlation of 0.29 was also found in Poland in Spring 2020 [34]. Finally, it has been shown that for the 3 months of 2020 in Wuhan City (China), the Pearson correlation rose to 0.4 considering a lag time of about 20 days between $PM_{2.5}$ spikes and COVID-19 mortality [35]. These positive correlation values support the hypothesis of a statistical link between $PM_{2.5}$ pollution and COVID-19 mortality.

The various processes of virus transmission that can produce the background mortality levels are not considered here. The aim of this paper is to focus on how strong PM pollution events, regardless of their origin, may possibly accelerate the COVID-19 mortality rate. To better understand such a relation, 16 representative locations in Europe are considered with mean $PM_{2.5}$ levels, ranging from low to high, for a total of 81 million people. This study is motivated by the interest to first better evaluate the time evolution of the relationship between $PM_{2.5}$ and COVID-19 mortality at different locations in Europe, and second, to provide new results on the possible lag time between the pollution events and COVID-19 mortality and on the effect of the strength and duration of the events.

2. Materials and Methods

The main period of the pandemic is considered here to be from early 2020 till the end of 2022. As explained before [36], the comparison of the temporal evolution of $PM_{2.5}$ spikes and COVID-19 mortality needs reliable data in order to minimize the statistical bias that irregularly sampled data may generate (such as missing mortality data for several days followed by sudden data adjustment).

2.1. $PM_{2.5}$ and COVID-19 Data

$PM_{2.5}$ mass concentration data were available from different sources. The initial sources were the national air quality monitoring networks; however, because of their operational cost, only a few reference stations were available per city or region. The other sources were non-official sources with a higher resolution. The Pollutrack networks in several cities of Europe are considered, where measurements are gathered using mobile light optical aerosol counters deployed on rooftops of hundreds of electric vehicles, providing a better spatial coverage of the cities than using just a few reference fixed stations [36]. Thus, all available $PM_{2.5}$ daily measurements are averaged in a given location from the air quality networks, and, when available, from the Pollutrack data that provides a better integration of the hyperlocal $PM_{2.5}$ variability. Such measurement heterogeneity can complicate the analysis when conducting a direct comparison of the $PM_{2.5}$ pollution levels from different locations in Europe. Then, the relation between $PM_{2.5}$ levels and COVID-19 mortality will be considered separately for the different locations. Also, working on the relative variations of $PM_{2.5}$ levels, instead of absolute values, could minimize the effect of such heterogeneity.

For each location, COVID-19 mortality daily data are retrieved from the John Hopkins University website [37].

To go further than in previous works [26], the results from 16 locations (cities, regions, or countries) are considered for a total of almost 81 million people (Table 1), almost equally representing the most polluted regions in Europe (where reliable COVID-19 data are available) and the regions with medium and low pollution levels, to facilitate direct comparisons. The “low pollution level” is defined as when $PM_{2.5}$ mean mass concentration during the considered period is below 10 $\mu g \cdot m^{-3}$ (twice the new annual mean value recommended by the World Health Organization as of September 2021), “medium pollution level” when the mean value is between 10 and 15 $\mu g \cdot m^{-3}$, and “high pollution level” when the mean value is higher than 15 $\mu g \cdot m^{-3}$ (three times the WHO-recommended annual average). Information on the locations analyzed is presented in Table 1.

The analysis stops at the end of 2022 because the mean COVID-19 mortality decreased in Europe due to vaccination, herd immunity, and the return of the classical seasonal flu and respiratory diseases. However, the date of the beginning of the analysis depends on the availability of COVID-19 data and on the spread of the pandemic. To be able to compare similar effects of the $PM_{2.5}$ level on COVID-19 mortality for the various locations, the period when the pandemic was locally not well managed was sometimes excluded, as well as when the lockdowns had significantly affected the mortality trend for short time periods. The starting dates of the time period considered for the 16 locations are provided in Table 1.

Table 1. Regions, departments, or studied cities, population, source of $PM_{2.5}$ pollution data, and level of pollution peaks, considering the time period.

Location Name	Population (10^6 Inhabitants)	Source of $PM_{2.5}$ Data	Mean $PM_{2.5}$ Level	Starting Date
Bouche du Rhone (France)	2.0	Pollutrack	Medium	Mid-December 2020
Emilia-Romagna (Italia)	4.5	Air quality network	High	Mid-April 2020
Estonia	1.3	Air quality network	Low	Mid-December 2020
Gironde (France)	1.6	Air quality network	Low	Mid-March 2020
Hungary	9.7	Air quality network	Medium	Mid-April 2020
Lazio (Italia)	5.9	Air quality network	Medium	Mid-December 2020
Lombardy (Italia)	10.1	Air quality network	High	Mid-December 2020
London (Great Britain)	9.0	Pollutrack	Medium	End May 2020
Nord (France)	2.6	Pollutrack	Medium	Early January 2021
Nordrhein-Westfalen (Germany)	17.9	Air quality network	Low	Mid-April 2020
Paris (France)	2.2	Pollutrack	High	Mid-December 2020
Rhone (France)	1.9	Air quality network	Medium	Mid-December 2020
Seine Saint-Denis (France)	1.7	Air quality network	Medium	Mid-December 2020
Toscana (Italia)	3.7	Air quality network	Medium	Mid-December 2020
Yorkshire and the Humber (Great Britain)	5.5	Air quality network	Low	Early July 2020
Zuid-Holland (The Netherlands)	3.7	Pollutrack	Medium	End July 2020

2.2. Data Analysis Procedure

As previously proposed [26], mortality data were divided by the population of the location. Then, both mortality and air pollution data were integrated over one week to limit the scatter of daily pollution values and daily variations in the collection process of the mortality data. A sliding smoothing procedure was applied to three consecutive points to reduce the remaining short-term variations in the data. It was then necessary to adjust the time scale of the two curves by researching a better time resolution of the pollution trend when compared to the COVID-19 mortality trend. Tests and trial procedures showed that applying a sliding smoothing procedure to the pollution curve was not enough to increase the correlation between the two curves. Thus, a more complex procedure is proposed by using two freedom parameters. The first one assumes that the effect of pollution on COVID-19 mortality is not direct but requires an integration time; a given exposure time to pollution peaks could be needed to significantly irritate the pulmonary system, which will consequently become more sensitive to COVID-19. Mathematically speaking, each value of $PM_{2.5}$ pollution was replaced by the mean of the previous $PM_{2.5}$ values during a given time period, acting as an integration procedure (Equation (1)), while the COVID-19 mortality values remain unchanged.

$$MC_{\mathrm{n}} = \left(\frac{1}{A}\right) * \sum_{i=n-A}^{n} MC_{\mathrm{i}} \tag{1}$$

where MC is the weekly mean mass concentration and A is the number of weekly MC considered.

The second parameter is a possible positive lag time (i.e., a shift) between this new $PM_{2.5}$ curve and the mortality curve, which could be related to the lethality of COVID-19 after invading the pulmonary system. These two parameters are adjusted to search for a higher correlation between the two curves.

All the results and the proposed conclusions in this paper result from different analyses. First, the Pearson correlation coefficient was used for the temporal evolution of COVID-19 mortality with $PM_{2.5}$ pollution levels; lag times between the two sets of data were also considered as a possibility to increase the correlation. Then, we introduced the notion of gradients for the temporal evolution of $PM_{2.5}$ and COVID-19 mortally by calculating at a given time the difference between each value and the value just before, and dividing the results by a temporal window (Equations (2) and (3)).

$$GM_{\mathrm{n}} = (MC_{\mathrm{n}} - MC_{\mathrm{n}-1})/\Delta t \tag{2}$$

$$GC_{\mathrm{n}} = (MO_{\mathrm{n}} - MO_{\mathrm{n}-1})/\Delta t \tag{3}$$

where *GM* is the gradient for the mass concentrations, *GC* is the gradient for the COVID-19 mortality, *MC* is the mass concentrations, *MO* is the COVID-19 mortality, and Δt is the time variation equal to 1 week. This calculation was used to establish a relationship between the slope of the time evolution of $PM_{2.5}$ and COVID-19 mortality, considering relative variations rather than absolute values. Finally, for all locations, the relationship between these parameters was established by applying linear fits (the data were integrated over dedicated windows to reduce the scatter of the individual values). As the data could be scattered at a given location mainly because of the mortality-reporting uncertainties, in each location, air pollution data and their corresponding mortality data at the corresponding time were averaged with steps of about 0.5 $\mu g \cdot m^{-3}$; then, the linear fit was applied.

3. Results

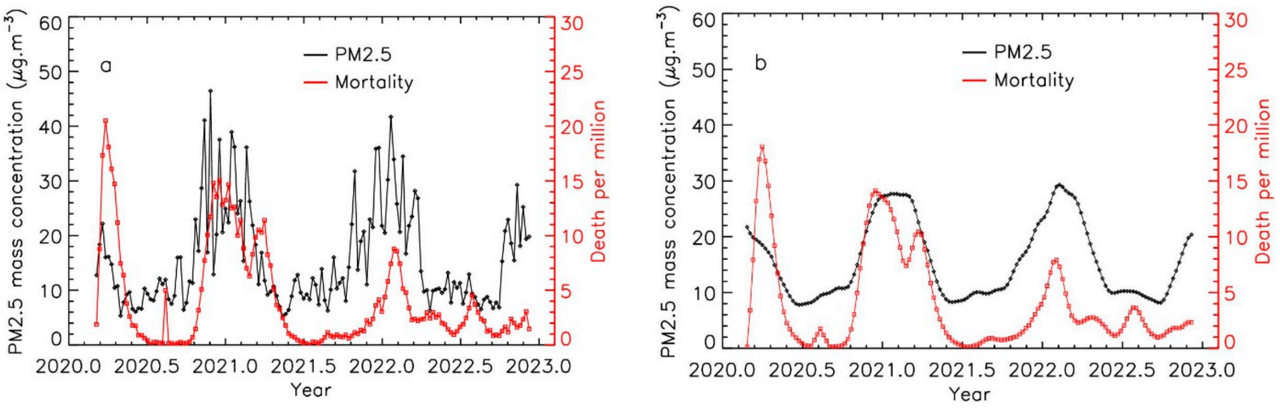
3.1. Time Evolution of $PM_{2.5}$ Levels and COVID-19 Mortality

Figures 1a and 2a present examples of $PM_{2.5}$ pollution and COVID-19 mortality for one of the most polluted regions in Italia (Emilia-Romagna) and for a low-pollution region in France (Gironde). The curves do not present the same behavior; the air pollution curve oscillates more than the mortality curve. It can be suggested that the mortality evolution is a slower phenomenon than the air pollution evolution, which is strongly linked to the short time-scale variations in the meteorological parameters (mainly wind speed).

Figure 1b shows the time evolution of $PM_{2.5}$ levels and COVID-19 mortality for the Emilia-Romagna region, exposed to high levels of pollution, using weekly integrated data after applying the integration procedure for $PM_{2.5}$ data. This procedure was applied to increase the correlation between the curves, even for regions with low pollution levels like the Gironde region, as shown in Figure 2b and for regions with medium pollution levels like Zuid-Holland (Figure 3).

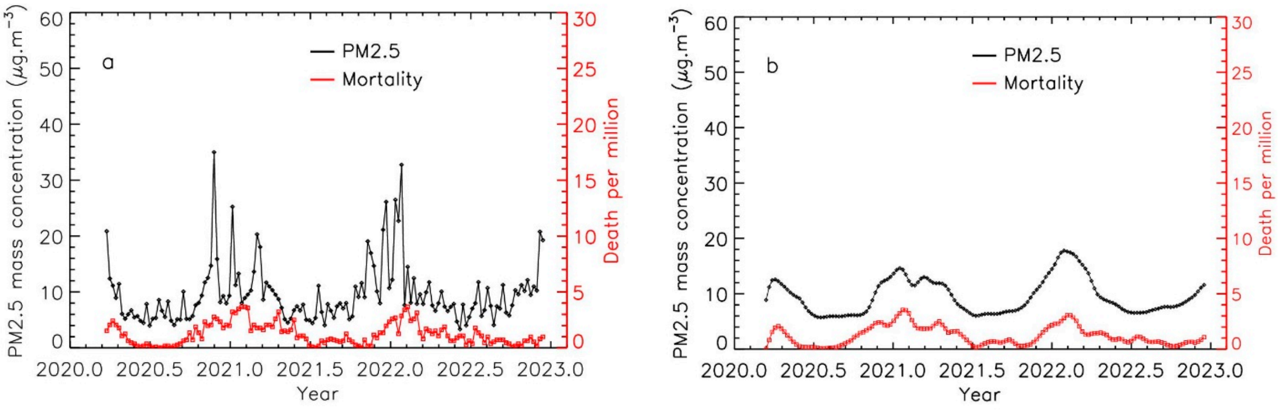
Pearson correlation coefficients are calculated for the raw measurements and PM2.5 measurements after applying the first sliding smoothing and the two-parameter adjustments, as given in Table 2. The mean value for the integration is 8.8 ± 2.5 weeks, and the mean value for the shift (lag-time) is 0.7 ± 0.8 weeks. These results could indicate that an exposure of about 2 months to significant pollution peaks is needed to sufficiently irritate the pulmonary system before impacting COVID-19 mortality. These deleterious effects are reversible and are similar to the negative trends (decrease in mortality with pollution dispersion). On the other hand, about a one-week shift may indicate the swiftness of virus lethality.

The proposed procedure strongly improved the Pearson correlations for most cases, reaching correlations of up to 0.8. Considering the strength of the $PM_{2.5}$ spikes and COVID-19 mortality rates that differ from one county to another, the convergence to similar values seems to indicate that these correlations are real and that the proposed procedure can reveal the time effect of pollution on COVID-19 mortality.



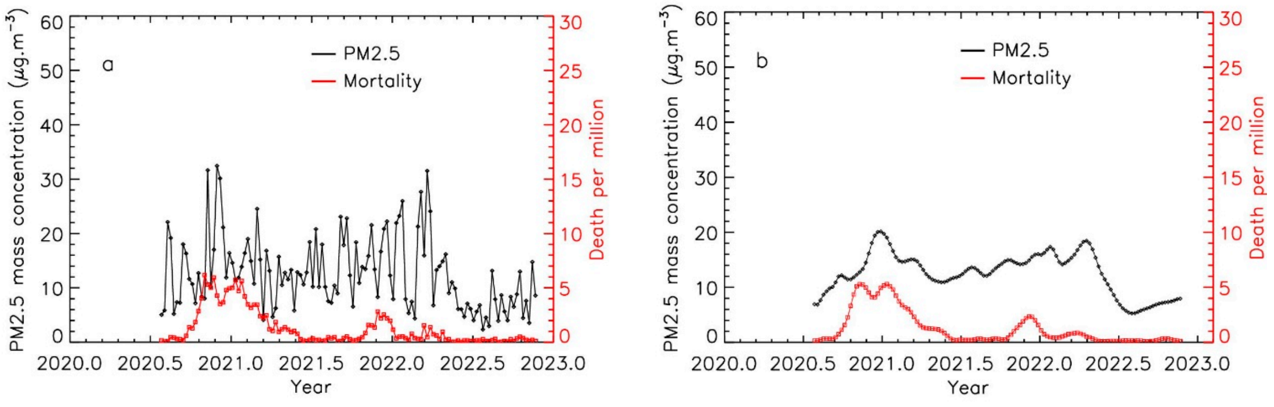
(**a**) (**b**)

Figure 1. Time evolution of $PM_{2.5}$ levels and COVID-19 mortality for the Emilia-Romagna region exposed to high levels of pollution; (**a**) weekly integrated data; (**b**) weekly integrated data after applying the smoothing, integration, and shift procedure.



(**a**) (**b**)

Figure 2. Time evolution of $PM_{2.5}$ levels and COVID-19 mortality for the Gironde region exposed to low levels of pollution; (**a**) weekly integrated data; (**b**) weekly integrated data after applying the smoothing, integration, and shift procedure.



(**a**) (**b**)

Figure 3. Time evolution of $PM_{2.5}$ levels and COVID-19 mortality for the Zuid-Holland region exposed to low levels of pollution; (**a**) weekly integrated data; (**b**) weekly integrated data after applying the smoothing, integration, and shift procedure.

Table 2. Regions, departments, or cities studied: population, length of the integration (in weeks) for PM2.5 level data, and the shift (in weeks) of the COVID-19 mortality curve; Pearson correlation coefficient without and with the sliding smoothing.

Location Name (Country)	Integration Width (Weeks)	Shift (Weeks)	Correlation without Applying the Adjustments	Correlation When Applying the Adjustments
Bouche du Rhone (FR)	7	2	0.56	0.82
Emilia-Romagna (IT)	9	0	0.52	0.76
Estonia (EE)	14	0	0.28	0.60
Gironde (FR)	11	0	0.36	0.81
Hungary (HU)	7	1	0.56	0.83
Lazio (IT)	9	2	0.37	0.79
Lombardia (IT)	9	0	0.47	0.78
London (GB)	8	0	0.25	0.45
Nord (FR)	14	1	0.41	0.78
Nordrhein-Westfalen (DE)	7	0	0.17	0.42
Paris (FR)	8	1	0.33	0.62
Rhone (FR)	7	1	0.40	0.73
Seine Saint-Denis (FR)	10	0	0.41	0.64
Toscana (IT)	8	3	0.53	0.80
Yorkshire (GB)	5	0	0.25	0.41
Zuid-Holland (NL)	8	0	0.29	0.51

3.2. Linear Relation between $PM_{2.5}$ Levels and COVID-19 Mortality

The relationship between COVID-19 mortality and $PM_{2.5}$ exposure seems to follow a linear relationship, although individual measurements were scattered from one location to another. This could be due to the possible heterogeneity of the population density (for example variations between large towns and rural zones), to the health status of the populations that can influence mortality, and to the local management of the pandemic [26]. Then, at each location, COVID-19 mortality per million inhabitants is averaged to produce 5 or 6 integrated values for $PM_{2.5}$ mass concentration intervals of 5 to 10 $\mu g \cdot m^{-3}$. The error bars are calculated by considering the standard error of the mean. Since the evolution of the mortality values per $\mu g \cdot m^{-3}$ follows a linear trend at each location, at least in the first order, a linear fit is applied to these data.

Figure 4 presents the linear fit for the 16 locations (mean correlation of 0.9 per fit), obtained using between 100 and 150 points per location. The same trend is systematically observed with an increase in mortality with increasing $PM_{2.5}$ levels, even for locations with low air pollution levels. The difference in the slope and the value at origin ($PM_{2.5}$ value for zero mortality) slightly differed from one location to another because of the population heterogeneity and pandemic management variations. The mean value of the slope is 0.39 ± 0.22, meaning a mortality increase of about 40 ± 20% per 1 $\mu g \cdot m^{-3}$ $PM_{2.5}$ increase.

The shape of the curves for the time evolution of $PM_{2.5}$ levels and COVID-19 mortality suggests that a relationship exists between the slope of the curves. The gradient values had similar magnitudes for COVID-19 mortality and $PM_{2.5}$ spikes. Figures 5 and 6 present examples of the Emilia Romagna and the Gironde regions, respectively. The mean features are well correlated between the two curves; nevertheless, the agreement between the two curves seems lower after 2022, which could be due to the effect of the vaccine that decreases the amplitude of mortality, and the progress of herd immunity.

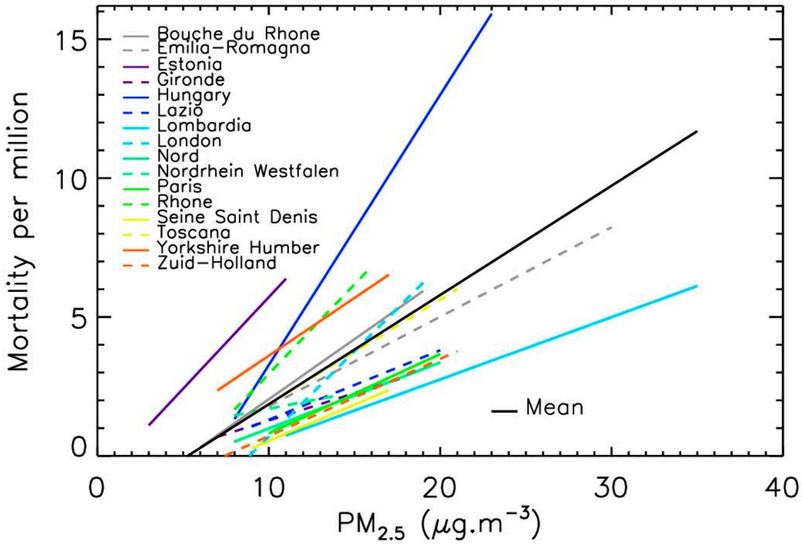
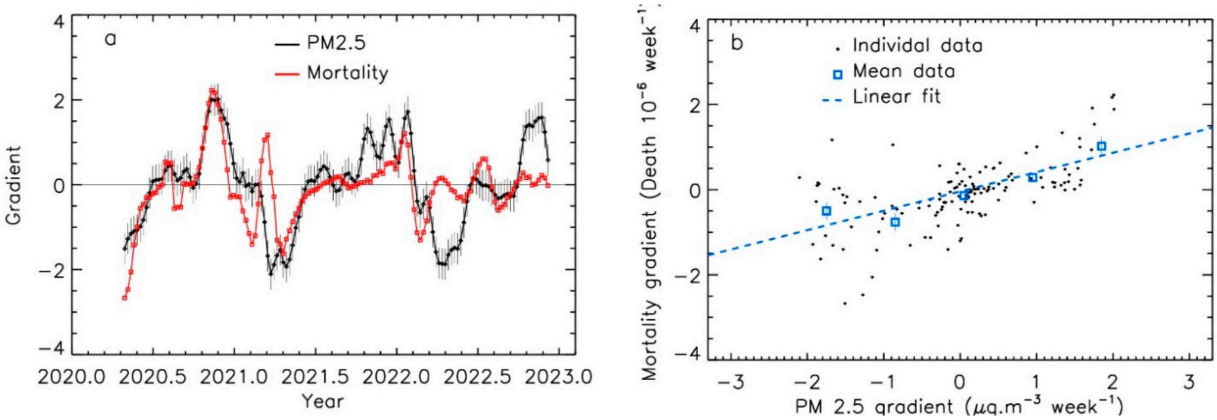
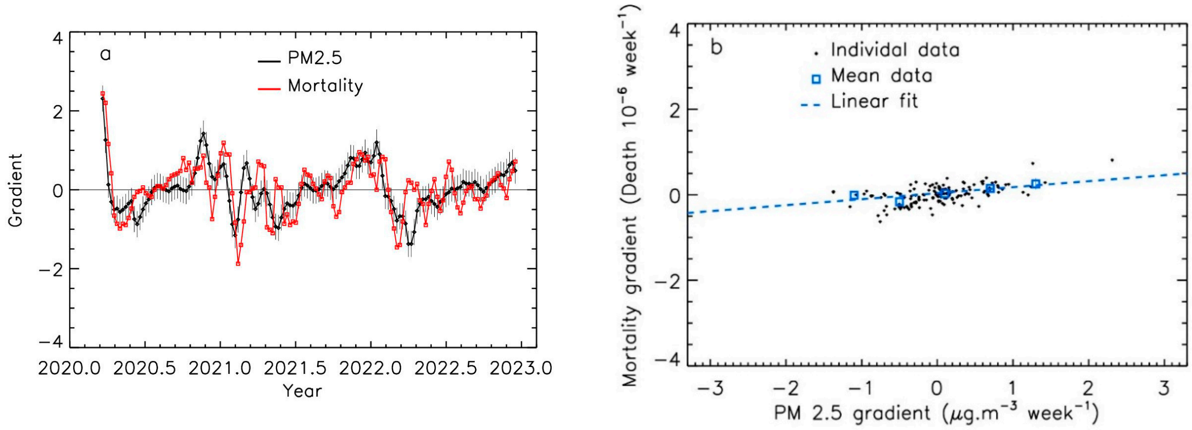


Figure 4. Trend evolution of COVID-19 mortality per million inhabitants vs. $PM_{2.5}$ for the 16 locations. The lines represent the linear fits in the domain range where $PM_{2.5}$ and mortality values are available.



(**a**) (**b**)

Figure 5. Gradient evolution of $PM_{2.5}$ levels and COVID-19 mortality per million inhabitants for the Emilia-Romagna region; (**a**) time evolution; (**b**) data and linear fit.



(**a**) (**b**)

Figure 6. Gradient evolution of $PM_{2.5}$ levels and COVID-19 mortality per million inhabitants for the Gironde region; (**a**) time evolution; (**b**) data and linear fit.

The synthesis of the linear fits for the gradients at the 16 locations is presented in Figure 7 (mean correlation of 0.9 per fit). Globally, COVID-19 mortality gradients also linearly increased with increasing $PM_{2.5}$ gradients, and the mean slope was 0.36 ± 0.25. These results indicate that the strength of the $PM_{2.5}$ peak is also an increasing factor contributing to COVID-19 mortality.

In fact, three groups can be itemized: the locations presenting a strong slope (Hungary and Estonia), the locations with a close-to-zero slope while having a medium mean level of pollution (Zuid-Holland, London, UK), and the other cities. The difference between the first and the third group could once again be due to the varying management of the pandemic and population densities. Although only two cases have been identified, the second group could indicate that cities with almost constant pollution levels, or without successive relatively short-lasting peaks of $PM_{2.5}$ and low values in between, could limit pulmonary inflammation. Thus, steep variations in $PM_{2.5}$ exposure rather than permanent exposure to medium pollution levels could be an aggravating factor of COVID-19 mortality.

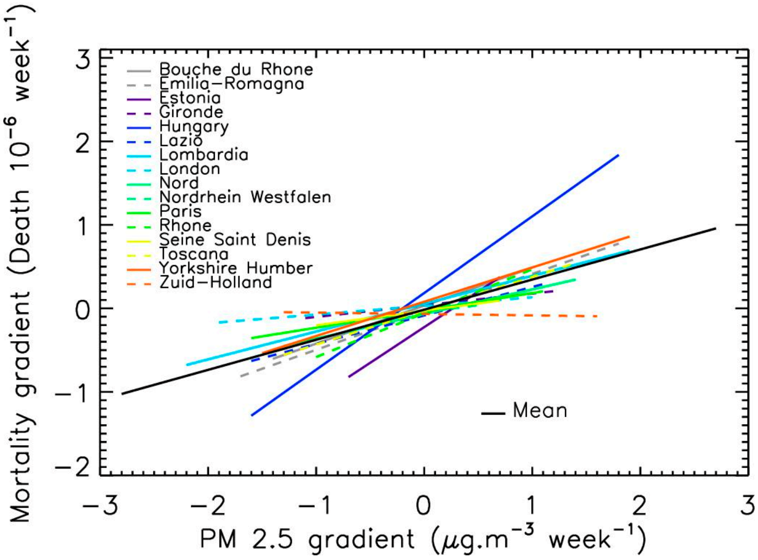


Figure 7. Trend evolution of the gradients of COVID-19 mortality per million inhabitants vs. $PM_{2.5}$ levels for the 16 locations. The lines represent the linear fits in the domain range where $PM_{2.5}$ gradients and mortality gradients are available.

4. Discussion

This study conducted a more in-depth investigation of the time relation between $PM_{2.5}$ levels and COVID-19 mortality using data from 16 representative European locations. The results are summarized in Table 3.

The COVID-19 mortality increase of about 40 ± 20% per each 1 $\mu g \cdot m^{-3}$ $PM_{2.5}$ increase is strongly higher than the 10% value previously reported [26,28–32] and can be explained by two different reasons. The first reason is that the mean value is dominated by the locations with high values, as for Hungary, although most of the locations remain in the 10–40% increase range. The second reason is that the proposed method of data analysis reduces the scatter of the data and increases the correlation between $PM_{2.5}$ levels and COVID-19 mortality time evolution, thus increasing the trend.

Furthermore, exposure to several PM peaks during a 2-month period constituted the main factor for mortality increase, rather than permanent exposure to (medium) pollution levels. The stronger the positive gradient of the pollution peak, the stronger the positive gradient of COVID-19 mortality; this effect is reversible, with a faster decrease in COVID-19 mortality observed during a faster decrease in $PM_{2.5}$ peaks. Thus, the lag time combined with the strength and the duration of the pollution peaks should be considered by health policies for the management of new and seasonal pandemics.

Table 3. Synthesis of the results.

Integration Time for PM2.5 Mean Level (Week)	Shift between COVID-19 Mortality and $PM_{2.5}$ Peaks (Week)	Rate of Mortality Increase per $\mu g \cdot m^{-3}$ of $PM_{2.5}$ Increase
8.8 ± 2.5	0.7 ± 0.8	$40 \pm 20\%$

To explain the observed relation between $PM_{2.5}$ levels and COVID-19 mortality, it has been proposed [18] that fine PM and overall ultra-fine particles (UFP) increase airway permeability by reducing tight junction proteins, which facilitates virus penetration, as well as the fact that PM boosts the action of the angiotensin-converting enzyme 2 (ACE2). This explanation was confirmed in a review of the process of lung inflammation resulting from PM exposure, and thus the impact on COVID-19 mortality following a cytokinic storm [38]. In particular, the authors studied the role of the angiotensin-converting enzyme 2 (ACE2), a receptor that is involved in the entry of the virus into pulmonary cells. Indeed, ACE-2 is a receptor for coronaviruses, including severe acute respiratory syndrome coronavirus 1 and 2 (SARS-CoV), and ACE-2 is overexpressed under chronic exposure to air pollution such as NO_2 and $PM_{2.5}$. ACE-2 is overexpressed in the case of medical comorbidities that contribute to the development of severe COVID-19.

Different natures of PM are present in ambient air [20]. Apart from dust episodes in Europe mainly coming from Sahara [39], the main PM peaks are due to anthropogenic activities. The peaks occur during periods of anticyclonic conditions when pollutants accumulate and cannot be dispersed by winds [36,40]. The primary and secondary PM originate from vehicular traffic throughout the year (mainly carbonaceous particles), industrial activities (all kinds of particles), heating in winter (mainly carbonaceous particles), and agricultural activities in autumn and spring (mainly ammonium). Other kinds of particles can also be present, like plastic, mineral, and metal particles, originating from tyres, cars, and train brakes. In fact, no seasonal effect was linked to the origin, and thus the main nature of the particles was scrutinized during our analysis. The PM composition is complex; thus, it is difficult to estimate the kind of particles to which the population is exposed. Consequently, it cannot be concluded if COVID-19 mortality is due to all kinds of particles or specific ones.

Another parameter to be considered is the size distribution of particles. The mass concentration of $PM_{2.5}$ corresponds to all particles smaller than 2.5 µm, although the largest ones mainly contribute to the values. Obviously, the smaller the particles, the deeper they penetrate into the human body. It has been reported [4] that $PM_{0.1}$ (particles smaller than 100 nm) cause more pulmonary inflammation. Thus, it is better to consider the PM size distribution rather than the integrated mass concentrations since the size distribution depends on the origin of the pollution events [38]. The lower limit of scientific optical aerosol counters is about 200nm (and 300nm for Pollutrack sensors used in this study); thus, they cannot detect such ultrafine particles. Expensive instruments could be used, such as the scanning mobility particle sizer systems [41], but they are not routinely operated by air monitoring networks; they are mainly used during dedicated field campaigns. Thus, one solution for future studies should be to use the smallest size classes of Pollutrack sensors in cities where they are already deployed (33 European capitals and major cities to date) to tentatively improve COVID-19 mortality analysis (or other respiratory illnesses) as a function of the number concentrations of particles of a few hundred nm in size.

5. Conclusions

To better understand the relation between the time evolution curves of $PM_{2.5}$ spikes and COVID-19 mortality, it is proposed to consider the historic population exposure to pollution peaks rather than instantaneous measurements in 16 representative European cities. This was conducted by applying an integration procedure of ~2 months on the $PM_{2.5}$ data and a ~1-week positive shift of the COVID-19 mortality data to better correlate the peaks and their gradients. The related increase in COVID-19 mortality and $PM_{2.5}$ levels was linear for both increasing and decreasing periods. Probably due to vaccination campaigns and the collective immunity progression, the correlation decreased at the end of 2022 in Europe. As an example, in France, flu and bronchiolitis mortalities increased at the end of 2022 to the detriment of COVID-19 (although still present), occurring a few weeks after a strong $PM_{2.5}$ pollution peak, that led to a significant excess mortality by year end.

The proposed two-month exposure period to $PM_{2.5}$ is probably just a first step and should be adjusted through a more complex equation, for example, by considering a decreasing memory effect on PM exposure over time. The first analysis presented in this study has shown an interest in considering $PM_{2.5}$ peaks for COVID-19 mortality rather than permanent exposure to a mean level. It will be of interest to see if this approach is specific to this coronavirus or could also be applied to other respiratory diseases like the flu. Finally, data other than $PM_{2.5}$ mass concentrations must be considered, and in particular, the number concentration and size distribution of particles smaller than 1 µm obtained with counters used during research campaigns and/or operated by private networks searching way beyond WHO recommendations.

Such results on the effect of PM on respiratory pandemic mortality should be considered by political authorities, especially in regions where high pollution peaks occur frequently due to specific weather conditions and geographical constraints [42]. To better manage future pandemics, the authorities should reduce all polluting industrial, transportation, and agricultural activities during the most critical days of (winter) anticyclonic conditions to limit the population's exposure to fine particulate matter.

Author Contributions: Conceptualization, J.-B.R. and E.P.; methodology, J.-B.R.; software, J.S.; validation, E.P. and I.A.-M. formal analysis, J.-B.R., E.P., I.A.-M. and J.S.; investigation, J.-B.R.; resources, E.P. and J.S.; data curation, E.P.; writing—original draft preparation, J.-B.R.; writing—review and editing, E.P., I.A.-M. and J.S.; visualization, J.-B.R.; supervision, J.-B.R.; project administration, E.P.; funding acquisition, E.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The pollutrack data are available on request.

Acknowledgments: The authors thank the Pollutrack team for the deployment of hundreds of mobile PM sensors in Paris and across Europe, the ENEDIS and DPD groups for offering their fleets of electric vehicles and financing the sensors, and Scott Stonham for his most efficient proofreading.

Conflicts of Interest: The authors declare no conflict of interest.

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