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Short-Term Effects of Air Pollution on Mortality in the Urban Area of Thessaloniki, Greece

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Abstract: This study examines the effects of short-term exposure to PM_{10} and O_3 on all-cause, cardiorespiratory, and cerebrovascular mortality in the urban area of Thessaloniki, Greece. An analysis was performed on the vulnerable subgroup (the elderly population). The primary effect estimates employed were the relative risks for every 10 μg/m^3 increase in air pollutant concentrations. Strong associations between PM_{10} and O_3 levels on mortality were reported, with the elderly people becoming frailer. An increase of 10 μgr/m^3 in PM_{10} concentration resulted in a 2.3% (95% CI: 0.8–3.8) and 2% (95% CI: 0.1–4.5) increase in total and cardiorespiratory mortality, respectively. O_3 concentrations showed even stronger associations for all-cause (3.9%, 95% CI: 2.5–5.3) and cardiorespiratory deaths (5.3%, 95% CI: 3.1–7.7) with 10 μgr/m^3 increases; no statistically significant associations were found for cerebrovascular causes, while both pollutants presented stronger impacts on health between day 0 and 3. Concerning the elderly, the total mortality rose by 3.2% (95% CI: 1.5–5) due to PM_{10} concentrations and by 4.4% (95% CI: 2.9–6) due to O_3 concentrations. In total, 242 (170) all-cause deaths were annually attributed to the PM_{10} (O_3) level in Thessaloniki. In the efforts towards achieving a sustainable environment for humanity, health benefits resulting from two air pollution abatement scenarios (a 20% reduction in PM_{10} levels and full compliance to the European Union PM_{10} limits) were quantified. The analysis led to a respective decrease in total excess mortality by 0.4% and 1.8%, respectively. This outcome stresses the necessity of appropriate civil protection actions and provides valuable scientific knowledge to national and regional administrations in order to develop proper health and air quality plans.

Keywords: air pollution; PM_{10}; ozone; cardiorespiratory mortality; cerebrovascular mortality; elderly; Thessaloniki; Greece

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1. Introduction

In recent years, poor air quality, both ambient and indoor, has become a pressing issue, with more frequent and intense episodes of high pollution levels being prevalent in cities across the globe. Currently, it is considered the biggest environmental risk to human health and the second-greatest environmental concern among Europeans, second only to climate change [1].

According to the WHO [2], 3 million deaths were solely attributable to outdoor air pollution globally in 2012, an estimation which Fuller et al. [3] has raised to 4.5 million, particularly for ambient particulate matter (4.14 million) and ambient ozone (0.37 million). This not only impacts mortality but morbidity as well. The most compelling evidence regarding the health consequences of air pollution relates to cardiovascular and respiratory ailments; nevertheless, studies exploring other health impacts are also increasing [4,5]. Older adults are more susceptible to the negative health impacts of air pollution due to their decreased aability to adapt to stressors on their physiological, metabolic, and compensatory processes, as well as their higher likelihood of having cardiovascular and respiratory diseases [6,7]. Elderly mortality has been found to be particularly affected by PM_{10} and O_3, with higher excess risks than other age groups [8–11].

PM_{10} and O_3 are considered to represent a major part of the problem [12]. Ozone exposure has significantly increased worldwide, leading to a 46% increase in ozone-attributable mortality from 2000 to 2019 [13]. PM_{10} and O_3 are linked to a rise in all-cause, cardiovascular, and respiratory mortalities [11,14–18]. The WHO has also emphasized $PM_{2.5}$ [19] as they are found to be associated with the premature mortality of several age groups [15,20,21]. In 2020, approximately 238,000 premature deaths in the European population were caused by exposure to PM_{10} concentrations above the WHO's 2021 guideline level of 45 μgr/m^3 [22]. Additionally, the European Environment Agency attributed 16,800 premature deaths to acute ozone exposure in 2019 [23]. Despite EU and national policies, the pollutant levels in many areas exceed the recommended guidelines (European Council Directive 2008/50/EC), and although significant improvements are evident, the impacts of serious air pollution in Europe still persist. Approximately 11% and 12% of the EU urban population is exposed to PM_{10} and O_3 concentrations above EU standards, a percentage that rises to 71% and 95%, respectively, when taking into account the WHO guidelines of 2021 [24].

Threshold violations take place at several locations throughout Europe [25]. However, the problem appears to be more pronounced in Southern and Eastern Europe [26], especially with respect to the PM and ozone concentrations in Greece, Spain, and Italy [27–29]. These areas are characterized as climate change hotspots; thus, the collective impacts of climate change and air pollution variables should be taken into consideration [30] under the specific topographical and meteorological conditions of each region [31]. With respect to the latter air pollutant, the ground-level ozone concentrations in Southern Mediterranean countries are often alarmingly high and are comparable to the highest levels of places that are located in the most contaminated parts of Central Europe [32].

When focusing on Greece, the country has been found to be in violation of the three most commonly exceeded EU air quality standards for PM_{10}, O_3, and NO_2, according to [33]. Using 2019 data, it was estimated that 75 deaths per 100,000 population in Greece could be attributed to air pollution, where the deaths were primarily caused by ischemic heart disease, stroke, and respiratory infections [4]; this corresponds to 1,101 attributable DALYS (Disability-adjusted life years) per 100,000 citizens [34], or 104,000 YLLs (Years of life lost) for the entire Greek population [35]. As expected, the two largest cities of the country suffer the most from the acute air quality problems because of the dense population and build-up of air pollutants caused by the topography and adverse meteorological conditions, e.g., the urban heat island effect [36]. The EU air quality standards are significantly surpassed by the PM_{10} concentrations observed in Athens and Thessaloniki [37], and the YLLs are primarily affected by PM_{10} exposure as well as O_3 to a lesser extent [38].

Thessaloniki in particular is one of the most polluted cities in Europe, especially with respect to the PM level [39] but also with respect to the O_3, VOCs, and noise pollution levels [40]. O_3 limit values are mostly exceeded during the summer months, while winter is the most favorable season for PM_{10} violations [32]. Nevertheless, Thessaloniki's major air quality problem consists of PM_{10} concentration levels. As a result, in December 2020, the European Commission decided to take legal action against Greece by referring the country to the European Court of Justice for the substandard PM_{10} air quality of Thessaloniki [41].

To address the issue, effective and enduring air pollution mitigation plans must be identified and put into action [42,43]. Such measures and policies to combat particulate air pollution were tested in a recent study [44], which resulted in a more than 20% reduction in the PM_{10} concentrations in Thessaloniki, Greece. Moreover, it is necessary to assess the health benefits of the abatement measures by quantifying the impact of air pollution on human health.

However, majority of the literature focuses almost entirely on Athens (e.g., [38,45,46]); only recently has a study by [47] discovered that brief exposure to $PM_{2.5}$ and PM_{10} in Thessaloniki is connected to an amplified risk of all-cause and cardiovascular mortality.

In addition to the above, there is a significant lack of studies specifically examining the suitability of mitigation measures in terms of health benefits for the area of Thessaloniki.

In this study, we utilized advanced statistical tools to investigate the associations between short-term exposure to PM_{10} and O_3 and daily all-cause (natural, non-accidental), cardiorespiratory, and cerebrovascular mortality from 2006 to 2016 in the urban area of Thessaloniki. We also examined the effect of air pollution on the elderly (all-causes, 65+ years) as it is crucial to understand the specified response of frail subgroups to environmental stressors.

Most importantly, to assist air quality planning, we estimated for the first time the impact of the modification of PM_{10} levels on Thessaloniki's population mortality under two air pollution abatement scenarios: (1) full compliance to EU levels, thus eliminating the exceedances of PM_{10} daily values; and (2) a 20% horizontal reduction in the PM_{10} concentration in order to assist air quality planning. These scenarios were based on the most cost-efficient measures identified by the recent study of [44] to combat PM_{10} pollution in the urban area of Thessaloniki.

Thus, the main goal of the current work was to present evidence on the air pollution–mortality relationship in the Thessaloniki urban area, accounting for the cause-specific deaths, lag structure, elderly mortality, and potential mitigation measures that can be of utmost importance for environmental stakeholders and local policy makers.

2. Materials and Methods

2.1. Study Area

This research centered on the urban area of Thessaloniki (Figure 1), which includes seven municipalities (Thessaloniki, Kordelio-Evosmos, Pavlos Melas, Kalamaria, Neapoli-Sikies, Ampelokipoi-Menemeni, Pylaia). Thessaloniki, the second largest city in Greece and an important economic and industrial center in the Balkans, is situated in the northern part of the country and has a population of about 1,000,000, representing 20% of the country's industrial activity [32]. The city is located on the northeastern coast of the Thermaikos Gulf and is close to Hortiatis mountain (1200 m) on the eastern side. The western side is characterized by a large flat area, which houses the industrial zone of Sindos. The city's location to the south means that it is greatly affected by the nearby sea, which contributes to its Mediterranean climate [48]. Vehicular traffic, residential heating [44], biomass burning [49], and industrial emissions [32] are the main origins of air pollutants in Thessaloniki [50], resulting in the deteriorated air quality in the area, especially during years of economic crisis [51]. Dust storms originating from North Africa also significantly contribute to particle pollution in the area [47,52,53].

2.2. Air Quality and Mortality Data

The hourly values of PM_{10} and O_3 concentrations ($\mu gr/m^3$) for the period of 2006–2016 were acquired by 5 air quality monitoring stations that cover the urban area of Thessaloniki and are operated by the Ministry of the Environment and Energy. The highest PM_{10} value and maximum 8-hour moving average for O_3 over each station were used in the present study, which represented the daily concentrations for the datasets.

The Hellenic Statistical Authority (ELSTAT) provided the daily mortality data, consisting of age and cause of death, for all municipalities in the urban region of Thessaloniki (2006–2016); the causes of death were categorized into all-cause (natural, non-accidental), cardiorespiratory, and cerebrovascular according to the ICD-10. Emphasis was placed on studying the overall mortality rate among the elderly, specifically for deaths that occurred among individuals aged 65 years and older.

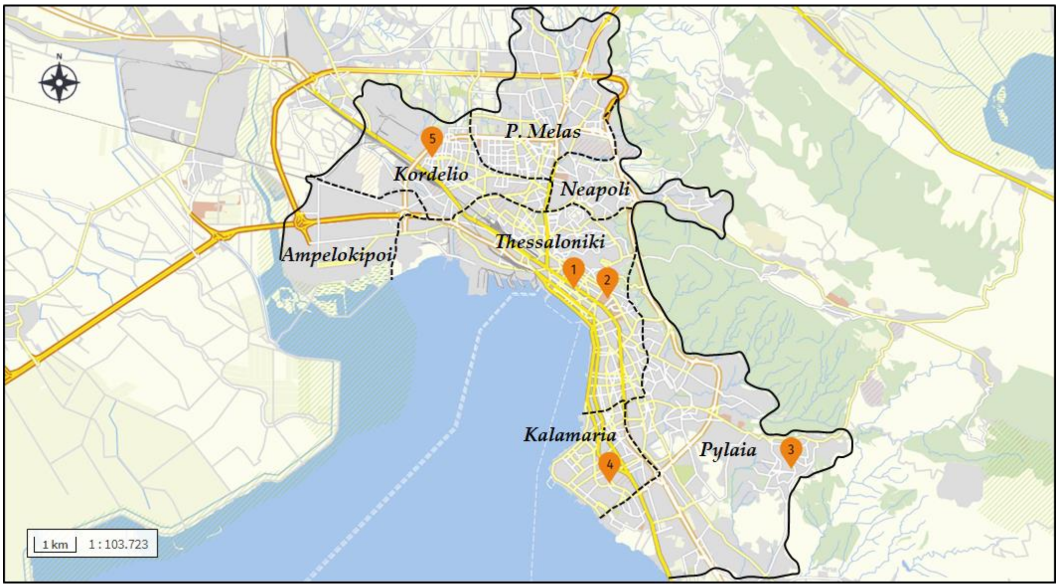


Figure 1. The study area with the locations of air quality stations (1: Agias Sofias, 40.63° N 22.94° E; 2: AUTh, 40.63° N 22.95° E; 3: Panorama, 40.58° N 23.03° E; 4: Kalamaria, 40.57° N 22.96° E; 5: Kordelio, 40.67° N 22.89° E). Dotted lines represent municipalities.

2.3. Data Analysis

We applied a DLNM to our data in order to show the impact of air pollution on mortality with delay in time, in accordance to previous studies [18,54,55]. DLNMs are a powerful modeling tool that are capable of simultaneously capturing both non-linear exposure–response dependencies and delayed effects. Unlike conventional distributed lag models, which struggle with non-linear relationships, the DLNM methodology utilizes a 'cross-basis', a two-dimensional function space that depicts the connection between predictor variables and the lag dimension of their occurrence. This approach offers a comprehensive portrayal of the exposure–response relationship's time course, making it possible to estimate the overall effect with precision, even in the presence of delayed contributions. In order to describe the air pollution–mortality associations in the present study, we applied generalized non-linear models with a quasi-Poisson family based on the quasi Akaike information criterion. The DLNM package [56] in R programming language (R version 4.1.1; R Foundation for Statistical Computing) was used to implement the family of applied models.

There are differences in the literature regarding the lag structure used to best describe the association between air pollution and mortality; in some cases, short lags of 0–1 days [21,57–61] or up to 3 days [15] are deemed to be the most appropriate, while in other studies, a week is chosen [62–64]. There are also examples in the literature suggesting that the adverse response to pollution persists for more than a month [65–67]. To this end, we investigated the correlation between short-term exposure to PM_{10} and O_3 and specific causes of death at various lags in order to decide the effect estimates for the present analysis.

In order to investigate the efficiency of mitigation measures in terms of health benefits, we not only applied the DLNM analysis for the original PM_{10} dataset, but also for 2 mitigation scenarios:

(1) Complete compliance with the EU limits (daily PM_{10} value < 50 μgr/m^3),
(2) 20% reduction in the PM_{10} concentration.

Table 1 shows the percentage of days in which the daily EU limits were exceeded during the range of 2006–2016. The EU air quality guidelines were surpassed on 1894 (47%) days of the 4018-day study period for PM_{10} (>50 μg/m^3) and on 1124 (28%) days for O_3

(>120 μg/m^3). Under the 20% PM_{10} reduction scenario, only 27% of days surpassed EU limits, resulting in 1119 exceedances.

Table 1. Mean annual values of pollutants (μgr/m^3) during the study period and during PM_{10} reduction scenario 2. Numbers in parentheses denote the percentage of annual violations of the EU daily limits.

Year	O_3 Mean Annual Value (%—Days Over 120 μgr/m^3)	PM_{10} Mean Annual Value (%—Days Over 50 μgr/m^3)	PM_{10} 20% Reduction Scenario (%—Days Over 50 μgr/m^3)
2006	85.8 (6.5%)	58.9 (53%)	47.1 (34%)
2007	95.3 (18%)	70.5 (79%)	56.4 (53%)
2008	118.7 (48%)	66.9 (76%)	53.5 (51%)
2009	112.7 (45%)	56.1 (57%)	44.9 (28%)
2010	99.1 (26%)	51.2 (39%)	41 (20%)
2011	114 (50%)	56.8 (45%)	45.5 (25%)
2012	115.2 (47%)	52.6 (43%)	42 (24%)
2013	101 (30%)	48.7 (35%)	39 (21%)
2014	82.2 (2.5%)	46.6 (30%)	37.3 (14%)
2015	99.5 (25%)	49.7 (33%)	39.8 (17%)
2016	92.3 (9%)	47 (31%)	37.6 (15%)

3. Results

3.1. Mortality Data Analysis

During the study period, we analyzed 73,990 natural deaths that occurred from all causes, 28,945 from cardiorespiratory diseases, and 10,007 from cerebrovascular causes. The number of deaths among the elderly population amounted to 62,482. The descriptive statistics of the pollution and daily mortality for the reference period are provided in Table 2.

Table 2. Statistics of the daily mortality (number of deaths, top) and pollution (μgr/m^3, bottom).

Daily Mortality		
	Mean	**St. dev.**
All-cause	18.4	4.7
Cardiorespiratory	7.2	2.9
Cerebrovascular	2.5	1.6
Elderly	15.5	4.4

PM_{10}					
Median	Mean	Min	25th perc.	75th perc.	Max
49	55	11.6	38	65	256.6

O_3					
Median	Mean	Min	25th perc.	75th perc.	Max
99	101	14	76	123	232

The data on deaths show that cardiorespiratory mortality accounts for over 40% of all natural deaths, making it a crucial group to examine in terms of susceptibility; the authors of [68] have reported that stroke and ischemic heart disease are the primary causes of mortality in Greece, which supports the claim. Elderly mortality reflects 84% of all-cause mortality for all ages, as Greece has one of the highest percentages of individuals aged over 65 years in Europe [69]. The daily mean and median pollutant concentrations are generally higher in Thessaloniki than those reported in other metropolitan areas [15,70] and resemble the values of large cities with important air quality issues [62,63,71]. Similar values of mean daily mortality and summary statistics of PM_{10} in Thessaloniki are also verified in [72].

3.2. Lag Effect Analysis

Table 3 displays the correlation between short-term exposure to PM_{10} and O_3 and specific causes of death at various lags. The lag structure here yields a prolonged effect of PM_{10} and O_3 on all mortalities from the current day to day 6 in Thessaloniki. As a result, the relative risk per 10 $\mu g/m^3$ increase in PM_{10} and O_3 concentrations over lag 0–6 is used hereinafter as the effect estimates.

Table 3. Associations between cause-specific mortality and short-term exposure to PM_{10} and O_3 at various time intervals (0–1, 1–6, and 0–6 days). Results are presented as a percentage increase of risk (RR%) and as 95% confidence intervals (95% CI) per 10 $\mu g/m^3$.

	PM_{10}		
Mortality	**RR%, Lag 0–1**	**RR%, Lag 1–6**	**RR%, Lag 0–6**
All-cause	2.2 (0.6–3.3)	0.8 (−1.9–3.2)	2.3 (0.8–3.8)
Cardiorespiratory	1.9 (0.5–3.6)	0.7 (−2–3.5)	2 (0.1–4.5)
Cerebrovascular	1.5 (−1.8–5.2)	1.1 (−1.9–4.9)	1.8 (−2–6.1)
Elderly	2.7 (1–3.5)	1.5 (−0.4–2.9)	3.2 (1.5–5)
	O_3		
Mortality	**RR%, Lag 0–1**	**RR%, Lag 1–6**	**RR%, Lag 0–6**
All-cause	1.9 (0.9–3)	2.7 (0.2–5.3)	3.9 (2.5–5.3)
Cardiorespiratory	2.8 (1.06–4.5)	3.5 (−0.54–4)	5.3 (3.1–7.7)
Cerebrovascular	−0.7 (−3.5–2.23)	2.8 (−4–9.9)	3 (−7–11)
Elderly	2.2 (1.55–3.4)	3 (0–5.86)	4.4 (2.9–6)

The estimated associations between the PM_{10}, O_3, and mortality in Thessaloniki are illustrated in Figure 2. The diagrams show the relationship among the air pollutants concentrations, excess risk, and lag values as a three-dimensional surface. The associations of PM_{10}, all-cause, and cardiorespiratory mortalities are non-linear. An immediate increase in deaths is evident for exposures to high levels of pollutants at lag days 0–2; however, for cardiorespiratory causes, a secondary maximum is present at lag 6. Concerning O_3, a lag of up to 3 days depicts a large increase in excess risk, which results in higher values of cardiorespiratory deaths. At days 5–6, a smaller increase is evident for both causes of death, indicating a prolonged impact.

The dose–response relationships for the natural and cardiorespiratory mortalities for PM_{10} and O_3 (not shown here) were found to be linear, as noted in previous studies [46,47,73].

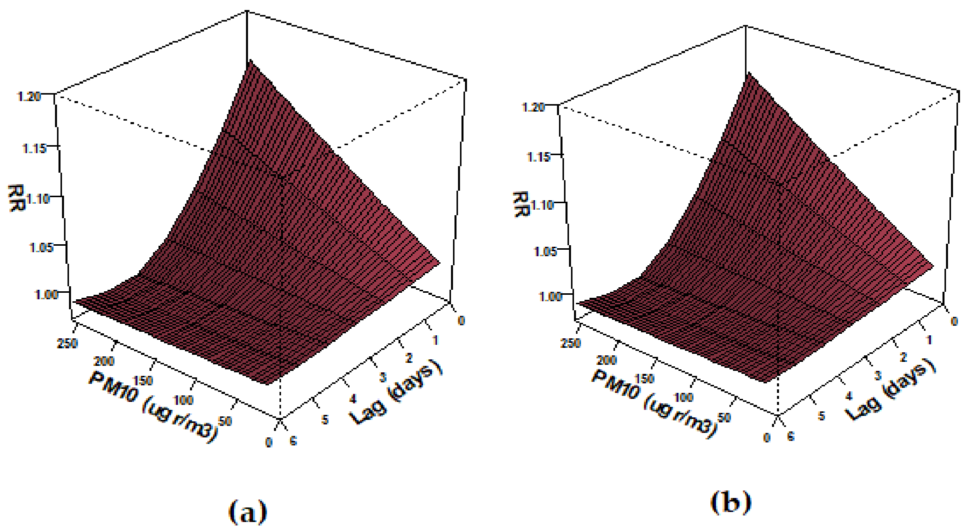
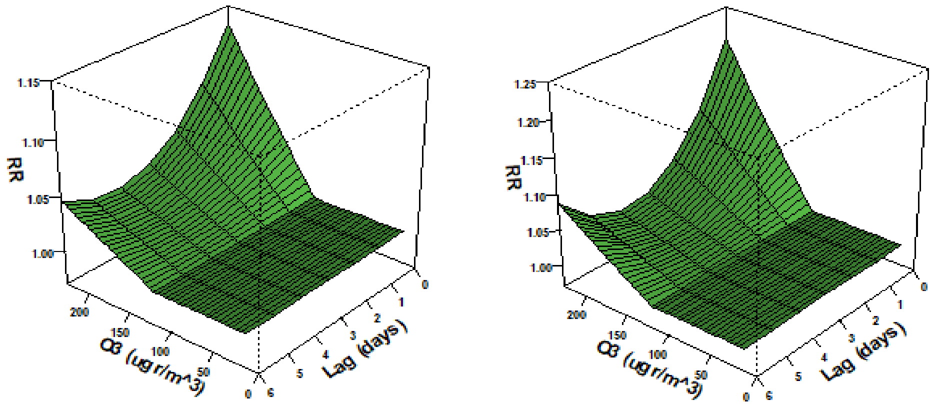


Figure 2. *Cont.*



(c) **(d)**

Figure 2. Overall effect of PM_{10} on all-cause mortality (**a**) and cardiorespiratory mortality (**b**); overall effect of O_3 on all-cause mortality (**c**) and cardiorespiratory mortality (**d**) for Thessaloniki in the years 2006–2016.

3.3. Total Effect Analysis

We present the evidence of the positive association of natural all-cause and cardiorespiratory deaths with PM_{10} and O_3 in Table 3.

A 10 unit increase in PM_{10} is associated with a 2.3% (95% CI: 0.8–3.8) increase in natural all-cause mortality and a 2% (95% CI: 0.1–4.5) increase in cardiorespiratory mortality; O_3 causes a 3.9% (95% CI: 2.5–5.3) increase in all-cause mortality and a 5.4% (95% CI: 3.1–7.7) increase in cardiorespiratory mortality. Neither of the two air pollutants are associated with cerebrovascular outcomes, as confirmed in similar studies [62,70].

Due to the significant differentiation of the lag selection, there is no uniformed way to compare our results with other studies. PM_{10} levels are generally associated with increases of 0.8–4.3% in all-cause mortality, 0.12–6.6% in cardiovascular mortality, and 0.47–4.2% in respiratory mortality, respectively [21,57–61,65,66,74]; the RR estimations in the present study are found to be within the range demonstrated above. Thessaloniki is underrepresented in similar publications; ref. [47] linked exposure to PM_{10} to a 1.75% increase in cardiovascular deaths (lag 0–6) but found no link to respiratory mortality.

Many studies [15,16,46,60,62,63,75] have reported positive associations between O_3 and increases in all-cause (0.33–2%), cardiovascular (0.45–2.5%), and respiratory mortalities (0.6–2.8%.), and correlations are evident in the present analysis. In particular, ref. [62] indicated higher impacts of O_3 on respiratory and cardiac mortality than on all-cause mortality, which is also confirmed by our results. However, the excess risks estimated here are higher compared with those obtained in other studies.

It is worth noticing, however, that the estimates from single-city studies tend to be higher compared with pooled multi-city results as the model specification utilized in the studies focused on individual cities could result in an overestimation of the outcome [59,76].

When comparing the effect of O_3 and PM_{10} on different causes of mortality, we document more severe impacts from the former than the latter. This consistent behavior is evident in similar studies covering various areas worldwide and various time spans, e.g., South Africa (2006–2015) [75], Russia (2003–2005) [77], and China [78].

Susceptible population subgroups are often separately considered in order to account for the specified behavior of these groups to environmental stressors. In the present work, we developed a dedicated DLNM model for assessing the impact of PM_{10} and O_3 on the elderly.

Elderly mortality is affected by both PM_{10} and ozone; a 3.2% RR increase (95% CI: 1.5–5) per 10 unit increase of PM_{10} and a 4.4% raise (95% CI: 2.9–6) per 10 unit increase of O_3 are evident. Similar results are verified in [11,15,62,77]. The air pollution in Thessaloniki has been found to demonstrate a more intense impact on elderly mortality than on the all-cause mortality for all ages, as found in [77].

Additionally, 5% of elderly deaths are attributed to PM_{10} and 2.6% are attributed to O_3 (a total of 4750 deaths out of 62,482). This corresponds to 284 and 146 annual deaths due to PM_{10} and O_3, respectively, for people aged 65 years and older.

Table 4 presents the attributable mortality and attributable fraction of mortality based on the PM_{10}–mortality and O_3–mortality relationships. We estimate that 3.6% of total mortalities and 3.2% of cardiorespiratory causes were attributed to PM_{10}, while the respective percentages for O_3 are 2.3% and 3%. These estimates correspond to 242 annual premature all-cause mortalities from PM_{10} and 170 from O_3, respectively. On an annual basis, 82 cardiorespiratory deaths are related to elevated PM_{10} levels, and another 80 cardiorespiratory deaths are related to O_3 levels. Overall, in Thessaloniki, 412 deaths are recorded annually due to PM_{10} and O_3 pollution, out of which 162 are attributed to cardiorespiratory causes.

Table 4. Attributable mortality (AM, number of deaths) and attributable mortality fraction (AF, %) for different causes of mortality.

	PM_{10}			O_3		
Mortality	**AM**	**AF**	**Average Annual Deaths**	**AM**	**AF**	**Average Annual Deaths**
All-cause	2664	3.6	242	1865	2.3	170
Cardiorespiratory	914	3.2	82	876	3	80
Elderly	3146	5	284	1604	2.6	146

Our results are similar to previous studies, where the attributable fraction of natural mortality fluctuated between 1.35% and 6% and cardiovascular mortality fluctuated between 1.63% and 6.89% due to PM_{10} pollution [71,74]. Ref. [60] reported that 1.96% of cardiovascular mortality is attributed to O_3 and 6.6% to PM_{10}, while [79] found that 3.2% of cardiovascular and 6.2% of respiratory mortality is attributed to O_3. According to [80], 2% of cardiovascular mortality, 5.6% of respiratory, and 1.5% of total mortality is attributed to O_3 levels.

3.4. Suitability of Studied Scenarios in Terms of Health Benefits

We present an examination of the suitability of two mitigation measures in terms of their health benefits for the urban area of Thessaloniki. The first case study (scenario 1) corresponds to a full abidance to EU limits concerning daily PM_{10} values (<50 μgr/m^3), whereas the second case study (scenario 2) horizontally reduces PM_{10} concentrations by 20%, a case that is more realistically applicable as shown in [44].

Table 5 displays the RR, AF, and AM for scenarios 1 and 2, respectively. Reducing PM_{10} concentrations by 20% would result in 2368 deaths and a 3.2% AF value with respect to total mortality. Full compliance with EU environmental legislation leads to a 1.8% attributable all-cause mortality, which corresponds to 710 deaths. When comparing the scenarios, the RR increases from 1.7% (scenario 1) to 2.1% (scenario 2). It is obvious that radical measures positively affect human health to a larger degree than moderate ones.

Table 5. RR (%), AM (number of deaths), and AF (%) of total mortality for different PM_{10} scenarios.

Scenarios	RR	AM	AF
1—Full EU compliance	1.7	710	1.8
2—20% reduction	2.1	2368	3.2

When comparing the results of Tables 3 and 4, the mortality burden decreases when mitigation measures are implemented. The AF is reduced by 0.4% and 1.8% compared with the original PM_{10} dataset for the 20% reduction and full compliance scenarios, respectively.

Thessaloniki would count 27 less deaths on an annual basis if the PM_{10} concentration were reduced by 20% and 177 less annual deaths if under full EU compliance.

Thus, even with the more moderate abatement scenario, the health impact of PM_{10} concentration on the local population could be significantly lower.

4. Discussion

In the international literature, the interaction between human health and air quality is well-defined [81] with respect to morbidity and mortality [82]. The adverse impact of deteriorated air quality has also raised international concern with respect to the natural environment [30] and economy [83]. Cities in the Mediterranean area are frequently experiencing elevated levels of air pollution [29] under the additional pressure of the climate crisis. Thessaloniki, Greece, is particularly impaired with respect to the air pollution, especially due to PM_{10} and O_3 levels [28,39]. Although some recent studies have quantified the impact of temperature on mortality [84,85], there is insufficient evidence concerning air quality, thus pointing a gap in relevant knowledge.

The present study aimed to address this vacancy by presenting an evaluation of the short-term changes in daily mortality counts as associated with the concentrations of daily air pollutants from 2006 to 2016 in the urban area of Thessaloniki. We analyzed the associations between the daily maximum values of PM_{10} and O_3 levels and cause-specific mortality, and we investigated this effect on the susceptible elderly subgroup with the use of DLNMs. To quantify the mortality burden, we used relative risk changes for every 10 $\mu g/m^3$ increase in air pollution concentrations as the primary effect estimates [86,87]. After conducting a specific analysis using a lag structure, which has great heterogeneity among literature, we determined thes most suitable lag for this work to be defined at days 0–6, similar to other studies [62,64].

Based on our results, a 10 unit increase ($\mu gr/m^3$) in PM_{10} concentration is associated with a 2.3% (95% CI: 0.8–3.8) increase in natural all-cause mortality and 2% (95% CI: 0.1–4.5) increase in cardiorespiratory mortality. O_3 causes increases of 3.9% (95% CI: 2.5–5.3) in all-cause mortality and increases of 5.4% (95% CI: 3.1–7.7) in cardiorespiratory mortality. Meanwhile, neither of the two air pollutants is associated with cerebrovascular outcomes. Considering the assigned attributable fraction of mortality for the various investigated causes, it is noted that overall, 3.6% of total mortalities are attributable to PM_{10} and 2.3% are attributable to O_3. PM_{10} levels are responsible for 3.2% of cardiorespiratory mortality (3% for O_3). These estimations correspond to 242 annual premature all-cause casualties due to PM_{10} and 170 due to O_3.

The direct comparison of our findings with similar studies in this field is particularly challenging due to the differentiation of the lag selection and underrepresentation of the specific area. Nevertheless, both RR estimates and attributable mortalities are in agreement with comparable research [15,61,62,66,74]. It is worth noting that [47] linked exposure to PM_{10} to a 1.75% increase in cardiovascular deaths (lag 0–6) but found no link to respiratory mortality in the Thessaloniki area.

Elderly mortality is also affected by the 10 unit increase in the air pollutants to an even larger degree than the mortality accounting for all ages, which was also confirmed in [77]. We report that excess risks increase by 4.4% and 3.2% due to O_3 and PM_{10}, respectively, while 284 annual deaths are attributed to PM_{10} and 146 are attributed to O_3, corresponding to a 5% and 2.6% attributable mortality, respectively. Studies on elderly people, such as [11,15], report sismilar results.

The need to abide by EU environmental legislation is crucial for reducing the negative impact of air pollutants on public health [44]; thus, high-resolution, location-specific information on the association of human morbidity and mortality to environmental stressors is of utter importance. Appropriate mitigation actions should be taken to decrease the population's exposure to pollutants and to further explore how location-specific factors contribute to this vulnerability. An innovative aspect of this work is the quantification of the health benefits as a result of two PM_{10} abatement scenarios, which was conducted for the first time in the study's urban area. The first case study (scenario 1—full abidance to EU limits, 50 $\mu gr/m^3$) yields 177 less annual deaths, and the second case study (scenario 2—horizontal reduction by 20%) results in 27 less casualties compared with the baseline.

The above findings of the present study clearly indicate that local residents are at risk from the current levels of PM_{10} and ozone. O_3 is found to have a more severe impact than PM_{10}, and the elderly are particularly frail to poor air quality in the area. If the two proposed mitigation measures were implemented, the attributed mortality fraction would decrease by 0.4% and 1.8%, respectively.

It should be noted that this study is limited by the fact that no confounding effects (e.g., temperature and humidity) were considered during the modeling process.

Future work should be conducted to include more air pollutants such as $PM_{2.5}$ and to further study the synergy between thermal stress and air pollution on health so as to draw decisive conclusions. Examining the impact of climate change and projected air quality conditions on mortality patterns could be a crucial next step.

5. Conclusions

While there is considerable literature on the impact of air pollution on human health, the case of Thessaloniki, Greece, is considerably under-studied, despite it being a city with significantly deteriorated air quality. By exploring the link between short-term exposure to air pollutants and cause-specific mortality, the current study offers proof of a positive association between daily mortality from natural and cardiorespiratory causes and exposure to PM_{10} and O_3. However, no connections were identified between these pollutants and cerebrovascular mortality. The study indicates that the elderly population is particularly vulnerable to the effects of PM_{10} and O_3. To further contribute to policy-making-associated knowledge for a sustainable environment for humans, the study quantified the health benefits that resulted from two air pollution abatement scenarios and found a significant reduction in total excess mortality. The respective results demonstrate significant decreases in air quality-related mortality, highlighting the importance of appropriate civil protection actions based on scientific expertise tailored to local populations for the development of proper health and air quality plans.

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Abbreviations

AF	Attributable fraction
AM	Attributable mortality
DLNM	Distributed lag non-linear model
ICD-10	International Classification of Diseases, 10th Revision
O3	Ozone
PM10	Particulate matter with aerodynamic diameter less than or equal to 10 μm
RR	Relative risk

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