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Trends of the Global Burden of Disease Linked to Ground-Level Ozone Pollution: A 30-Year Analysis for the Greater Athens Area, Greece

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Abstract: The Greater Athens Area (GAA), situated in the southern part of the European continent (in Greece), has a Mediterranean climate characterized by hot, dry summers and mild, wet winters. As a result of increased sunshine and high temperatures, exceedances in ozone concentrations are often recorded during the hot period. In the present study, the monthly as well as daily variations of O_3 concentrations at thirteen stations in the GAA were investigated for the period 1987–2019. Moreover, the impact of O_3 on the people's health in Greece was examined by using data from the Global Burden of Disease (GBD) study with the socio-economic conditions of the country. Ozone concentrations were found to be particularly high during the summer months, especially in suburban stations. Values ranged from 65 $\mu g/m^3$ to 90 $\mu g/m^3$ during the night, in contrast to urban areas and remain high for several hours. Comparing estimates from GBD, it was found that exposure to ozone can impair respiratory function, leading to death or susceptibility to respiratory diseases that reduce quality of life, especially for people over 55 years of age. Finally, since 2009, when the economic crisis began in Greece, an upward trend was observed for deaths and disability adjusted life years.

Keywords: ozone; Greece; Athens; Global Burden of Disease

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1. Introduction

The Global Burden of Disease (GBD) Study is described as the most comprehensive effort to date to measure epidemiological levels and trends worldwide. It was created over 30 years ago to provide timely health estimates. Researchers collaborate and study the incidence of hundreds of diseases and risk factors worldwide [1].

The new Global Burden of Disease (GBD) study (2019) ranked air pollution as the fourth ranked risk factor for mortality. It also includes Disability-Adjusted Life Years (DALYs) globally. In addition, the health effects attributable to exposure to $PM_{2.5}$ and ambient ozone are estimated and quantified, considering the morbidity and mortality of selected pollution-related diseases. These diseases are lower respiratory tract infections (LRI), chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), stroke, cancer, type 2 diabetes mellitus (T2DM), tracheal bronchial and pulmonary (TBL), premature birth, and decreased birth weight [2,3]. Air pollution was recognized by the World Health Organization (WHO) in 1958 as a health risk factor and with effects ranging from mild symptoms to premature death and decreased birthweight [4]. With the aim of proposing measures towards the reduction of ozone levels worldwide and their health effects, the WHO issues annual reports. The increase in O_3 levels has become a significant public health concern in EU-28 cities. The number of premature deaths related to O_3 has also increased by 0.55 deaths per 10^6 inhabitants annually [5]. Furthermore, ozone inhalation is responsible for 14,000 hospital admissions for respiratory diseases per year in the EU25. Public health is also affected, as evidenced by short activity days, use of respiratory drugs (especially in children), and coughing and lower respiratory symptoms [6]. Hospital admissions related to ozone exposure are expected to increase due to changes in the structure of the population, such as an increase in the at-risk elderly population. It should also be noted that current health impact assessments only address acute health effects, and do not consider the potential effects at short-term ozone exposure levels below 70 $\mu g/m^3$ or the potential effects of long-term exposures [7]. Although the premature mortality associated with ozone in the EU25 is significantly lower than that associated with particulate matter, ozone remains as one of the most important health-related air pollutants in Europe [4]. Among the consequences from the recording of ozone exceedances are (a) the increased school absences, emergency room visits, and hospital admissions. As a result, social institutions are burdened. In addition to people with pre-existing respiratory conditions such as asthma and COPD, children, the elderly, and outdoor workers should be included since they are the ones more vulnerable to ozone exceedances exposure. Therefore, ozone affects multiple sectors of the economy [8,9]. According to the WHO, there are many parameters of air pollution that need to be considered. There is a need to identify the sensitive subgroups of the population that need to be protected. Socio-economic status, nutrition, pregnancy, and health of the population should be considered, as well as child development and physical activity gymnastics. It is also useful to study neurological effects, including effects on brain morphology, in young children and the elderly. In addition, the short-term effects of exposure to pollutants leading to worsening symptoms of diseases such as allergic, cardiovascular and respiratory diseases should be investigated [6].

The Global Burden of Disease [10] survey publishes information on mortality and disability in all countries, by time, age, and sex. In order to improve health systems and address inequalities, it quantifies health loss from hundreds of diseases, injuries, and risk factors. Air pollution is considered one of the risk factors, and according to GBD 2019, is caused by two pollutants, particulate matter, and ozone. Concerning ground-level ozone, it should be mentioned that it is not emitted directly into the air. Instead, it forms when nitrogen oxides (Nox) and volatile organic compounds (VOCs) react in the presence of sunlight. These pollutants are often released by vehicles, industrial facilities, and certain natural processes. Ozone can react with other pollutants such as particulate matter (PM), sulfur dioxide (SO_2), and carbon monoxide (CO). These reactions can lead to the formation of secondary pollutants, which may exacerbate health issues. The redesigned GBD 2019 Results tool allows estimates due to ozone pollution in the environment for all causes of chronic respiratory diseases, for all ages and for both sexes causing deaths and DALYs [10]. In that way, the reduction of emissions of precursor pollutants like Nox and VOCs has proved to be essential for mitigating the formation of ground-level ozone and protecting public health.

2. Research in Context

Evidence before This Study

A comprehensive literature review concerning the application of GBD 2019 both worldwide and in Greece particularly was conducted by searching the terms “Greece” AND “Air quality” “Ozone” AND “Public Health” OR “Burden of Disease” from the beginning to 10 November 2023, using PubMed and Google Scholar.

More specifically, L. Murray explains that the latest edition of GBD 2019 provides assessments for diseases, injuries and risk factors in more than 200 countries and territories and at sub-national level in more than 20 countries [2]. The investigation of longitudinal changes in the disease burden of $PM_{2.5}$ and ambient ozone in Italy using estimates from the Global Burden of Disease Study 2019 revealed that the burden of ambient $PM_{2.5}$ (but not of ozone) significantly decreased, even with the concurrent population ageing. The results suggest a positive impact of air quality regulations, which should encourage further regulatory efforts [3]. Similarly, Motairek et al. through the investigation of CardioVascular Disease (CVD) trends associated with particulate matter ($PM_{2.5}$) in the Eastern Mediterranean from 1990 to 2019 found out that although there has been a significant reduction in overall air pollution, household exposure to poor air quality persists in this region. This has led to an increasing trend in mortality from CVD disease and DALYs [11]. In addition, researchers studied GBD data on chronic respiratory diseases in North Africa and the Middle East and China [12,13]. The information provided by the Global Burden of Disease Study helped the researchers to analyze health loss, risk factors, and health financing in different countries such as Greece, Pakistan, Spain, and Saudi Arabia, and compare the health levels among 15 countries in the European Union [12,14–18].

Concerning Greece, and in particular the region of Attica, the studies carried out by researchers about ozone air pollution are summarized in Table 1. Except for two researchers that used data from the EU air quality database, National Observatory of Athens and the Medcaphot-Trace project [19,20], at the majority of studies data provided by the Hellenic Ministry of Environment, Energy and Climate Change (HMEEC) were used [21–33]. This is to be expected because the ministry is responsible for operating a network of air pollution measuring stations certified according (HMEEC) to European standards. In some studies, measured O_3 concentrations from the HMEEC were combined with data from other measuring stations such as Bureau of Pollution Control and Environmental Quality (GERPPE) and the Environment and Quality Department of the new International Airport of Athens "Eleftherios Venizelos", as well as with the outputs from the Variable-grid Urban Airshed Model (UAM-V) [25,27–29,31]. However, no study has statistically analyzed the effects of O_3 in the wider Attica region, in urban and non-urban areas and has not considered the longitudinal patterns in the respective data. As a result, there is a gap in the literature, which this paper hopes to fill by conducting a time series analysis of O_3 pollution over a long period of time. To quantify the health impacts of O_3 on residents at various ages regarding chronic respiratory diseases due to O_3, an analysis was performed using data extracted from GBD 2019 Results Tools. GBD 2019 is a global tool that provides composite results related to the health sector.

Table 1. Studies about ground-level ozone over the Greater Athens Area.

	Paper-References	Data Source	O_3 * ($\mu g/m^3$)	Time Period of Study
1.	Butkovi et al. (1990) [34]	D-B	58–120	1984
2.	Ziomas et al. (1998) [19]	M-T	100	1994
3.	Varotsos et al. (2001) [35]	NAO	55–94	1901–1940/ 1987–1998
4.	Viras (2002) [23]	HMEEC	55–79	1995–1999
5.	Saitanis et al. (2003) [27]	AIA, HMEEC	147	2000
6.	Kassomenos et al. (2008) [21]	HMEEC	103	1992–2000
7.	Paschalidou et al. (2008) [26]	HMEEC	40–100	2001–2004
8.	Mavrakis et al. (2009) [25]	HMEE, GERPPE	90–100	2003
9.	Paschalidou et al. (2009) [28]	NOA, HMEEC	100	1994–2004
10.	Poupkou et al. (2009) [29]	UAM-V, HMEEC	120	2000
11.	Kassomenos et al. (2011) [30]	HMEEC	103	1992–2000
12.	Moustis et al. (2012) [22]	HMEEC	89–105	2001–2005
13.	Mavroidis et al. (2012) [32]	HMEEC	78–100	1984–2009
14.	Dimitriou et al. (2015) [20]	EEA, NAO	87	2009–2011

Table 1. *Cont.*

	Paper-References	Data Source	O_3 * ($\mu g/m^3$)	Time Period of Study
15.	Stergiopoulou et al. (2018) [33]	HMEEC	57–83	2013–2014
15.	Dimakopoulou et al. (2020) [24]	HMEEC	83–94	2001–2014
16.	Dimitriou et al. (2020) [31]	NOA, HMEEC	63–65	2014–2018

Hellenic Ministry of Environment, Energy and Climate Change (HMEEC); EU Air Quality Database (EEA); National Observatory of Athens (NOA); Bureau of Pollution Control and Environmental Quality (GERPPE); Variable-grid Urban Airshed Model (UAM-V); Medcaphot-Trace (M-T); Environment and Quality Department of International Airport of Athens (AIA); Dasibi AH 1003-Bendix 8002 (D-B); * They refer to the average O_3 concentrations for the years considered.

GBD 2019 assessments can directly inform long-term health planning in Greece. Due to the aging of the Greek population, investments and policies based on the best available evidence are needed to address both the health impacts of O_3 and ensure long-term wellbeing and economic growth. During winter and summer, the concentration of O_3 varies in the wider Attica region. The study of the variation of O_3 concentrations will be based on the cold and the warm periods of the year, as well as on its variation over 24 h.

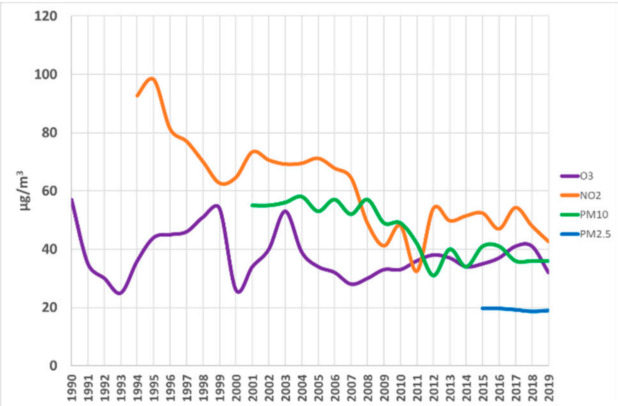
3. Materials and Methods

3.1. Area of Interest

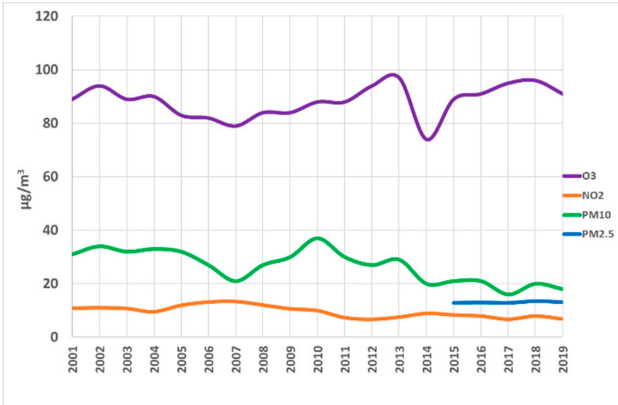
Attica occupies a strategic position in the middle of the Aegean Sea. It has an undulating morphology, with alternating coastal and inland plains. The largest plain is the "Attica Basin" where Athens is located. The Attica Basin is defined by mountains (Egaleo, Poikilo Oros, Parnitha, Penteli, Ymittos) that often exceed 1000 m in altitude, while in the south its boundary is the coastline of the Saronic Gulf. These mountains are naturally damming with small gaps between them. The winds that blow in Attica come from the northeast and find an outlet in the opening between Mount Parnitha and Penteli, or from the southwest towards the Saronic Gulf [36]. The dispersion of pollutants is mainly due to north-easterly winds, which are characterized by higher wind speeds and shorter duration than south-westerly winds, which are statistically quite rare. Since the area is in direct contact with the sea, the dispersion of pollutants is fully influenced by the meteorological conditions prevailing along the coast. South-westerly winds, caused by local traffic, such as sea breezes, favor the formation of secondary pollutants in the periphery of Attica. Southwesterly winds caused by local traffic, such as sea breezes, favor the dispersion of secondary pollutants in the Attica region. In the north of Attica, the sea breeze from the Saronic Gulf converges with the sea breeze blowing from the east of the Attica peninsula, a phenomenon that, as will be shown in detail in this study, causes the particularly high concentration of O_3 on the northern side of Attica [36–38].

Furthermore, another factor exacerbating pollution in the area of interest is the Saharan dust effect, so-called because of the transport of dust particles from North Africa. It occurs mainly in spring and autumn. The Arabian Peninsula sometimes produces similar dust phenomena [39,40]. Studies have linked the effects of Saharan dust events to the development of asthma in children and to an increase in the number of hospital admissions for bronchitis [40,41].

The present study focuses on the Greater Athens Area (GAA), located in the Attica basin, the most urbanized geographical area in Greece, and one of the most important in the Eastern Mediterranean in terms of air pollution. According to the Hellenic Statistical Authority, 1/3 of the country's population (3.09 million) resides in Attica. The main characteristic is the dense building density that dominates from one end to the other, while open spaces are scarce [42–45]. According to Chorianopoulos et al., the region of Attica is considered a typical example of traditional Mediterranean societies that exhibit an economic polarization [46]. The mean annual values for two characteristic monitoring stations are presented in Figure 1. Data were provided by the Hellenic Ministry of Environment, Energy and Climate Change (HMEEC). The Athinas station is located in the center of Athens while the Thrakomakedones station is about 25 km far from the center of Athens. In Greece, Directive 2008/50/EC of the European Parliament and of the European Council applies to pollutant concentrations. The target values for the protection of human health concerning annual average values for the following pollutants are: for O_3—120 μg/m^3, for NO_2—40 μg/m^3, for PM_{10}—40 μg/m^3 and for $PM_{2.5}$—25 μg/m^3 [47]. While the WHO sets more stringent long-term exposures (for O_3—100 μg/m^3, for NO_2—10 μg/m^3, for PM_{10}—20 μg/m^3 and $PM_{2.5}$—10 μg/m^3) [6]. Athinas station has all the characteristics of a big city. In the 1990s it had serious problems with NO_2 and particulate matter. As can be seen in Figure 1a, all pollutants show a significant decrease, especially NO_2, but O_3, PM_{10}, and $PM_{2.5}$, while decreasing from 1990 to 2009, have remained at a constant level in recent years.



(**a**) ATH-UT



(**b**) THR-SB

Figure 1. Annual average O_3, NO_2, PM_{10}, and $PM_{2.5}$ concentrations of ATH station ((**a**) Urban-Traffic 1990–2019) and THR station ((**b**) Suburban-Background 2001–2019).

The economic crisis since 2009 has had a particular impact, preventing further reductions in pollutants. The use of firewood for heating has returned to the center of Athens. In addition, climate change is causing African dust to occur more frequently and for longer periods of time. Similarly, summer heat waves are more frequent and longer in duration.

At the Thracomacedones station, the variation of pollutants is at a low level, except for O_3. The reduction of nitrogen oxides by the processes in which they are involved results in the increase of ozone concentration. This is why we observe the paradox that in the center of Athens, where there is a lot of traffic and primary pollutants are emitted, low ozone concentrations are measured. However, in the suburbs the ozone produced by the precursor pollutants is not destroyed and therefore increases. Mount Parnitha (height at about 1.400 m), which lies at the edges of Thrakomakedones suburb, combined with the north-easterly winds that disperse pollutants from the center of Athens, contribute to the area's high level of pollution compared to other suburbs.

Vinci et al. observed that the analysis of demographic data eventually recorded a trend towards an ageing population. The average age of the population increased by 6 years in Attica (1990–2020), according to what they have observed in the rest of Greece. The elderly dependency ratio shows similar dynamics. It is worth noting that the concentration of the elderly population is pronounced in the Greater Athens area, particularly in North and South Athens [42]. As a result of the global economic crisis, economic growth turned negative in 2009 and the Greek economy faced its worst crisis since 1993, with the highest public deficit and the second highest debt as a percentage of GDP in the EU. Unemployment, one of the most important economic indicators, increased as it is directly linked to the general state of the economy and, by extension, a country's society [43].

3.2. Air Pollution Data and Social Economic Population Status

In the present study, the monthly variation of O_3 concentrations and the 24 h variation of O_3 at thirteen stations in the Athens area was investigated. For this purpose, daily average O_3 concentrations for the period 1987–2019 were obtained from thirteen air-pollution-monitoring stations located in the greater GAA area (Figure 2, generated by utilizing Quantum GIS with background map data from F4_map Map WORK).

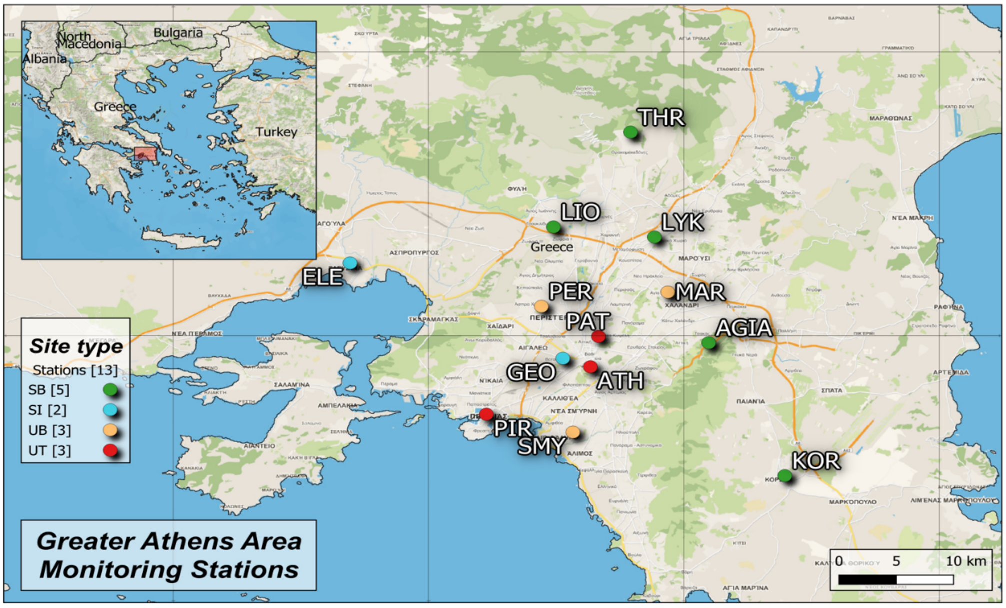


Figure 2. Map with the location of O_3-monitoring stations within the GAA.

All stations belong to the Attica Air Pollution Monitoring Network, which is part of the Climate Change and Air Quality Directorate (CAA) and operates under the supervision of the Greek Ministry of Environment and Energy (MEEE). Each station is classified as an Urban Traffic (UT): located within an urban area and about 10 m from the source of pollution which may be a busy road, such as a highway, an Urban Background (UB): located some kilometers from significant emission sources to fully capture the path of the pollutant concentrations they measure, Suburban Background (SB): installed near in urban centers and Suburban Industrial (SI): located within a radius of less than one kilometer from the city center. Detailed data for the thirteen monitoring stations are presented in Table 2. The completeness of data used in the present study was at least 80.0% [33]. The monthly analysis was performed for 8 h average O_3 concentrations, while the analysis of the 24 h period was based on hourly values. O_3 concentrations were processed according to Directive 2008/50/EC of the European Parliament and European Council. The target value for the protection of human health concerning the maximum daily 8 h mean is 120 μg/m^3 [46]. Additionally, the population figures for the surrounding area of each station are presented, provided by the Hellenic Statistical Authority (ELSTAT) according to the 2011 population census. Furthermore, data on the evolution of GDP and unemployment in Greece over time were provided by the Greek statistical authority (ELSTAT) [43].

Table 2. The characteristics of the examined air pollution monitoring stations within the GAA.

	Name	Abbr.	Site Type	Longitude	Latitude	Altitude (m)	Population
1	ATHINAS	ATH	UT	23.726845	37.978204	75	664,000
2	GEOPONIKI	GEO	SI	23.705153	37.984100	40	664,000
3	LYKOVRISI	LYK	SB	23.788986	38.067793	234	10,000
4	MAROUSI	MAR	UB	23.787372	38.030837	170	73,000
5	NEA SMYRNI	SMY	UB	23.713020	37.931998	50	72,853
6	PATISSION	PAT	UT	23.733053	37.999587	105	664,000
7	PIREAS	PIR	UT	23.645230	37.944656	4	163,688
8	PERISTERI	PER	UB	23.688361	38.020811	80	133,630
9	AGIA PARASKEYI	AGP	SB	23.819421	37.995110	290	62,147
10	LIOSIA	LIOS	SB	23.697781	38.076741	165	33,565
11	THRAKOMAKEDONES	THR	SB	23.758195	38.143521	550	6200
12	ELEYSINA	ELE	SI	23.538432	38.051322	20	24,910
13	KOROPI	KOR	SB	23.879026	37.901308	140	19,164

Urban-Traffic (UT); Urban-Background (UB); Suburban–Industrial (SI); Suburban-Background (SB).

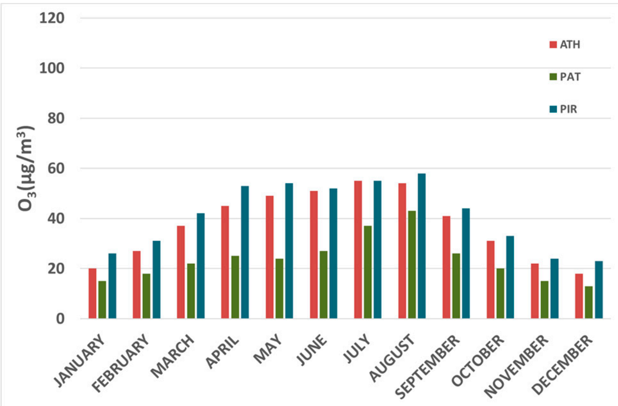
3.3. Global Burden of Diseases 2019 Study

The Global Burden of Disease Study (GBD) 2019 gives an overview of mortality and disability by country, period, age, and sex. To improve health systems and reduce inequalities, it quantifies the loss of health from hundreds of diseases, injuries, and risk factors. The GBD commenced three decades ago with the aim of offering timely, valid, and pertinent evaluations of crucial health outcomes. The latest edition of GBD 2019 provides assessments of thousands of outcomes for diseases, injuries, and risk factors in more than 200 countries and territories, and at the subnational level in more than 20 countries. Results are produced by an active collaboration of more than 8000 scientists and analysts from more than 150 countries around the world [1,2]. The GBD 2019 enables creating standard reports by location and time between 1990 and 2019, as well as by age and gender. These reports follow the guidelines of the World Health Organization (WHO) for reliable and open reporting of health evaluations. They comprise disease occurrence, frequency, death rates, and years of healthy life lost due to disability or early death (DALYs). DALYs are the sum of years of life lost due to premature death (YLL) and years of life lived with a disabling disease or injury (YLD). It is determined using life expectancy, estimates of disease occurrence, and the severity of the disability [10]. Our estimates are based on GBD 2019 [10] data for the population-weighted exposure to ozone in Greece, for all causes and all ages groups. The report refers to men, women, and the total population for the period 1990–2019 estimates of deaths, as well as DALYs, for 100,000 inhabitants were downloaded. Finally, regarding age groups, the highest incidence of O_3-related chronic respiratory diseases according to the GBD 2019 [10] was found for older age groups. For this reason, data relating to ozone pollution—chronic respiratory disease—DALYs for under +55 years, for 100,000 inhabitants were processed.

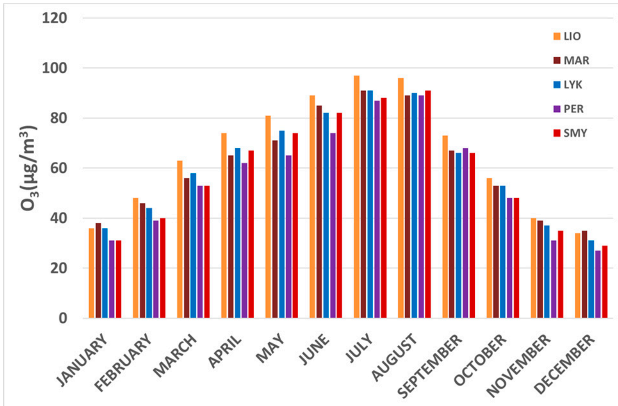
4. Results

4.1. Variation of Monthly and 24 h Ozone Concentrations

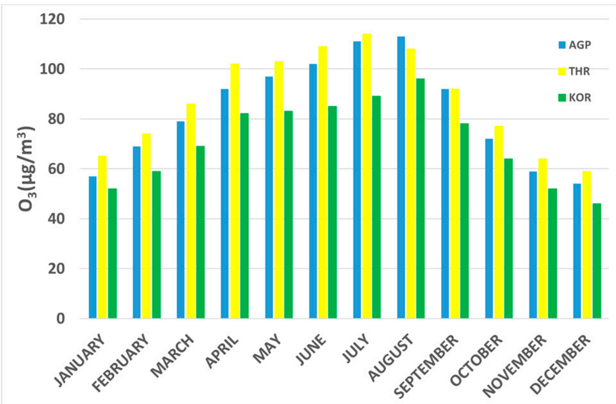
The monthly variation of 8 h O_3 concentrations at the thirteen stations of the region of Attica is shown in Figure 3, according to the period that measurements were made and each station's characterization. The analysis of monthly variations indicates that the pollutant exhibits seasonality at all stations. Photochemical cloud episodes are frequently observed and are characterized by high ozone concentrations, which are formed under the presence of precursors and favorable climatic conditions in the atmosphere. The highest ozone concentrations are usually measured during summer in many overpopulated city centers [47], such as the Greater Athens Area. In our case, lower concentrations are found at urban-traffic stations such as Athinas, Patision, and Piraeus, even during the summer period (Figure 3a). The World Health Organization (WHO) sets an eight-hour limit at 100 μg/m^3 [6]. This is probably due to the reduction of VOCs leading to lower ozone concentrations [48–50]. The concentrations of O_3 at the Elefsina and Geoponiki stations are similar (Figure 3d). As shown in Figure 3b,c, O_3 concentrations are high, especially in the summer months, while the highest concentrations are recorded at the suburban stations of Agia Paraskevi and Thrakomakedones.



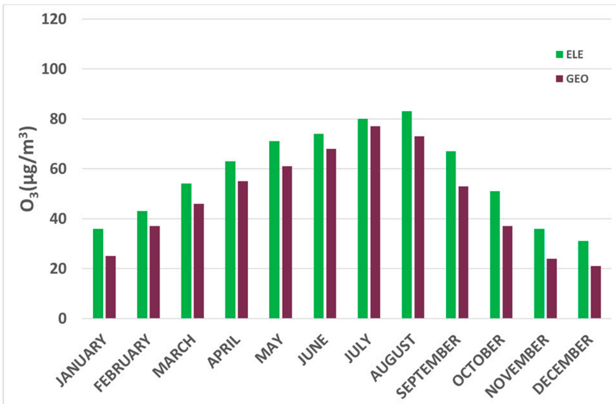
(**a**) UT



(**b**) UB



(**c**) SB



(**d**) SI

Figure 3. Monthly O_3 concentrations of the examined stations within the GAA. ((**a**) Urban-Traffic 2001–2019, (**b**) Urban-Background 1987–2019, (**c**) Suburban-Background 2001–2019, (**d**) Suburban–Industrial 2001–2019).

The area's topography and meteorological conditions, such as wind direction, speed, and intensity of sunshine, significantly affect the formation and dispersion of O_3. This is evident in the 24 h O_3 variation diagrams presented in Figure 4 as well as at the wind roses showing the distribution of ground-level ozone concentrations per wind direction at four selected stations (Figure 5).

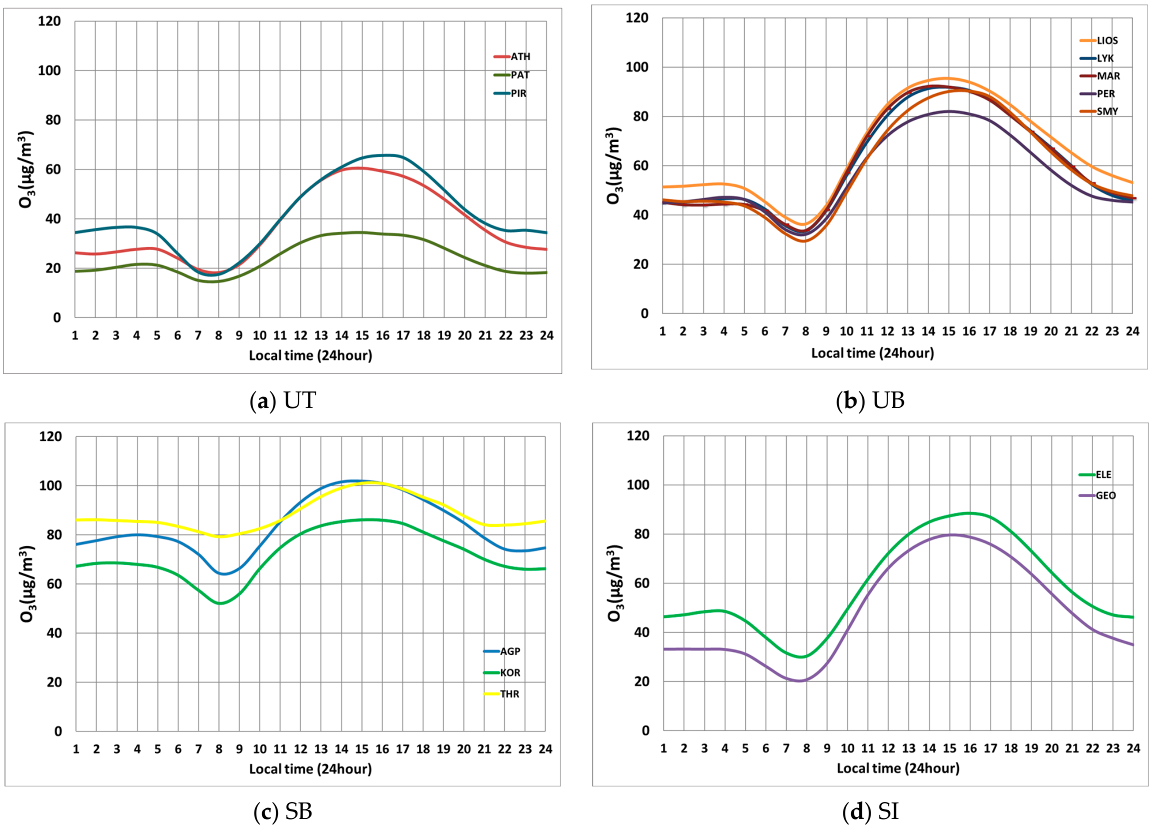


Figure 4. Local time (24 h) O_3 concentrations of all examined stations within the GAA. ((**a**) Urban-Traffic 2001–2019, (**b**) Urban-Background 1987–2019, (**c**) Suburban-Background 2001–2019, (**d**) Suburban–Industrial 2001–2019).

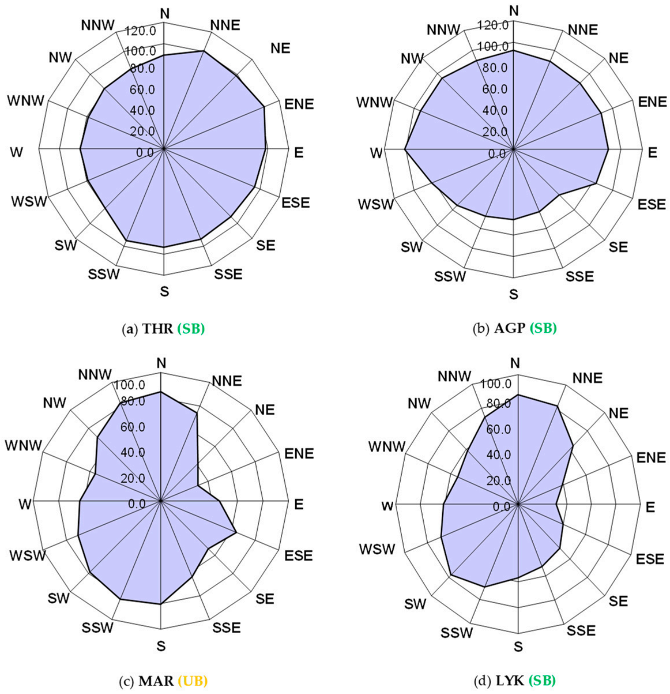


Figure 5. Average O_3 values (in $\mu g/m^3$, purple shading) at THR, AGP, MAR, and LYK stations for each wind direction (period: 2005–2019). Source: Hellenic Ministry of Environment and Energy Available online at https://ypen.gov.gr/ (accessed on 23 February 2024).

Examining the 24 h average variation of O_3 (Figure 4a), it is evident that at Urban-Traffic stations ATH, PAT, and PIR it is low in the morning hours (below 20 μg/m^3), while, during midday, the concentration reaches a maximum of 65 μg/m^3, with a short duration. At GEO and ELE Suburban-Industrial stations (Figure 3d) mean hourly concentrations are up to 20 μg/m^3. However, during midday, the concentration reaches a maximum of 85 μgr/m^3, lasting for approximately four hours before decreasing.

Figure 4b shows the 24 h average O_3 variation for Suburban-Traffic stations LIO, MAR, LYK, PER, and SMY. The data indicate higher pollutant values, with the lowest values occurring in the morning hours at above 30 μg/m^3. The concentration reaches a maximum of 98 μg/m^3 during midday, which lasts for about four hours before decreasing. The 24 h variation of ozone concentration at the three peripheral stations AGP, THR, and KOR revealed that concentrations remain at increased levels (from 65 μg/m^3 to 90 μg/m^3) during the night unlike in urban areas. Pollutant levels are high, with values exceeding 85 μg/m^3 from the morning hours at THR. The concentration peaks during midday (at 100 μg/m^3) and remains high for several hours. The topography of the Athens basin is closed, which makes ventilation difficult and the diffusion of pollutants challenging. This is due to the existence of mountainous areas. The prevailing wind direction is either northeast or southwest (Figure 5a), depending on the wind blowing from the north or south. This is because of the opening in the northeast between the Parnitha and Penteli mountains and in the south to the Saronic Gulf. In cases of weak or absent concordant flow, winds from the south sector may result from the development of a local circulation system known as a sea breeze. This can lead to high concentrations of photochemical pollutants in the periphery of the basin towards the north. These reasons explain why suburban stations record high O_3 episodes. In urban areas (e.g., MAR and LYK stations), north-easterly winds last for a short period of time and have a higher average speed compared to the southwest winds. This contributes decisively to the diffusion of pollutants [51,52] (Figure 5c,d). Further meteorological data at different regional units of the region of Attica (Monthly Average Temperature, Monthly Average Humidity, Prevailing Wind Direction, Monthly Average Wind Intensity) can be found as Supplementary Materials (Table S1).

4.2. Mortality and DALYs Due to O_3: An Analysis from the Global Burden of Disease Study 2019

Figure 6a,b presents estimates based on GBD 2019 data [10] for the weighted exposure of the Greek population to ambient ozone for all causes and age groups. The report covers both genders and the entire population for the period 1990–2019. Figure 6a shows the number of deaths, and Figure 6b shows the number of Disability-Adjusted Life Years—DALYs per 100,000 inhabitants. All graphs display identical variations. The curve rises from 1990 to 2005, followed by a decline and a steep increase until 2013. From 2013 to 2016, there was a slight decrease, followed by an increase until 2019. Continuous exposure to high levels of ozone can cause a range of health problems, including chest pains, coughing, throat irritation, and congestion, and can worsen heart problems, bronchitis, emphysema, and asthma. Epidemiological studies have demonstrated that regions with elevated pollution levels experience a rise in asthma cases, hospital admissions, and premature mortality. It has been found that high ozone concentrations can cause short-term lung dysfunction and irritation when inhaled [5]. The graphs were split into two parts: (a) showing all-cause deaths at all ages due to O_3 and (c) showing deaths caused by respiratory problems at ages over 55 years. Indeed, for all age groups—Ambient ozone pollution (Figure 6a), the maximum number of deaths is 6 per 100,000, while for those over 55 ages—Chronic respiratory diseases (Figure 6c), the maximum is 20 per 100,000, much greater. Also, the same picture can be observed in diagrams b and d. The impact of ozone on the lives of residents is significant, as it limits their daily activities and causes respiratory symptoms and coughing. One DALY represents one year of healthy life lost. Concerning all age groups—Disability-Adjusted Life Years (Figure 6b), the maximum number of DALYs is 80 per 100,000, while for the over-55 ages—Disability-Adjusted Life Years (Figure 6d), the maximum number of DALYs is 251 per 100,000, which is much higher. It has been confirmed that even low-level ozone exposure can impair respiratory function, leading to death or vulnerability to respiratory diseases that reduce quality of life. Finally, the graphs show the death rate and the DALYs for all ages and for the over-55s for both sexes and for both men and women. In all graphs, it can be observed that women exhibit less sensitivity to O_3 air pollution compared to both the general population and men. Men have a higher lifetime risk of respiratory problems or death from O_3 than women. This statement is in accordance with official data on deaths caused by respiratory issues in Greece, where the proportion of male deaths is higher than that of females [43].

(**a**) Deaths-all age-Ambient ozone pollution (**b**) Disability-Adjusted Life Years

(**c**) Deaths-+55 age-Chronic respiratory diseases (**d**) Disability-Adjusted Life Years

Figure 6. Time series of deaths and disability-adjusted life years (DALYs) per 100,000 inhabitants, due to ozone pollution from 1990 to 2019. (**a**) Deaths—all age Ambient ozone pollution (**b**) Disability-Adjusted Life Years, (**c**) Deaths—+55 age-Chronic respiratory diseases, (**d**) Disability-Adjusted Life Years (Global Burden of Disease Study, Greece, 1990–2019).

The mean annual ozone concentrations (O_3_mean, in $\mu g/m^3$) from all stations at the region of Attica from 1990 to 2009 as well as the annual values of DALYs and Deaths are presented in Figure 7. The trendlines for O_3 concentrations (grey equation), as well as for DALYs (orange equation), are shown revealing an increasing trend in both parameters. Moreover, it is obvious that they follow a similar pattern, especially from 1990 to 2002, indicating that there was a correlation between ground-level concentrations and health impacts. Afterwards, a decrease is observed in 2003 at O_3 concentrations and in DALYs and Deaths values for the period 2003—2004 followed by a subsequent increase of about 64% in DALYs values (41 in 2005 and 67 in 2012). For the same period, ozone concentrations ranged from 51 $\mu g/m^3$ (in 2007) to 64 $\mu g/m^3$ (in 2011). Apart from pollutants exceedances, health impacts are also related to the number of consecutive hours high concentrations are measured.

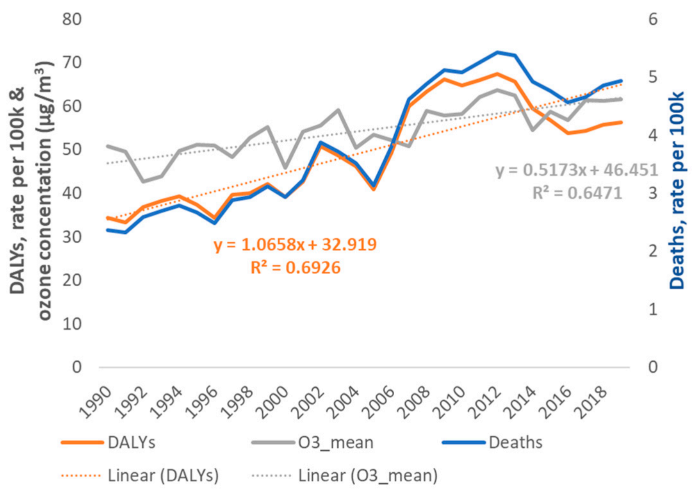
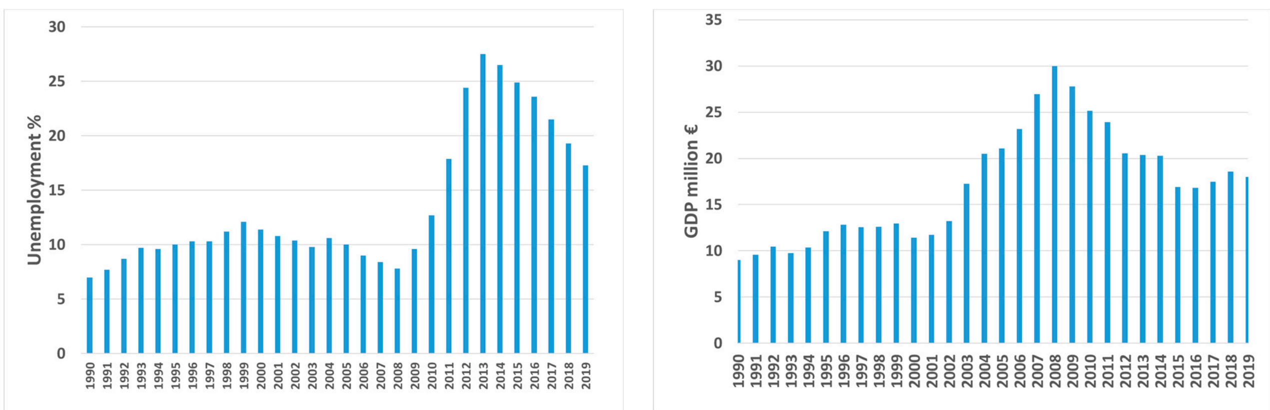


Figure 7. The variation of annual values for ozone concentration (in μg/m^3) at the region of Attica station, DALYs, and Deaths.

4.3. Socioeconomic Conditions in Greece during the Period 1990–2019

Figure 8 shows the evolution over time of unemployment (a) and national GDP (b) in Greece for the period 1990–2019. The graphs are divided into two periods: the first one refers to the time before the Greek economic crisis (until 2009), while the second to the period after the crisis (2009–2019). It is obvious that unemployment has been on the rise since 2008. It peaked in 2013 and has fallen afterwards, but not to the levels recorded before the economic crisis. Greece's GDP per capita follows a similar path, peaking in 2009 and declining slightly thereafter. The aim of this comparison is to demonstrate that there is a correlation between unemployment, GDP, and the effects of O_3 on public health. From 2009, when the economic crisis began, all charts related to deaths and Disability-Adjusted Life Years show an upward trend, similarly to the pattern presented in Figure 8. However, from 2013 to 2019, there was a decline, although pre-crisis values were not reached. Similar to these results, others have reported that in European countries, and especially in those most affected by the crisis (such as Spain and Iceland), general mortality decreased and the health of the population improved between 2008 and 2013 [53–55]. All this is related to the fact that during the Greek economic crisis (second reference period) there is a decreasing trend in the concentrations of the air pollutants SO_2, CO, and NO_2, in contrast to the increasing trend in the concentrations of O_3 [56].



(**a**) Unemployment (**b**) GDP

Figure 8. Temporal variation of unemployment and GDP in Greece for the period 1990–2019.

5. Conclusions

This study provides a comprehensive overview of the air quality in the Greater Athens Area, shedding light on the intricate interplay of geographical, topographical, and meteorological factors that define the timeseries of the ozone concentrations. A long timeseries of measurements from 13 air quality monitoring stations was studied (1990–2019) in combination with estimates based on GBD 2019 data about deaths and disability-adjusted life years (DALYs) per 100,000 inhabitants, due to ozone pollution. The concluding remarks can be summarized as follows:

- O_3 monthly concentrations exhibit seasonality at all stations with highest values to be recorded during summer when photochemical cloud episodes are frequent.
- The area's topography and meteorological conditions, such as wind direction, speed, and intensity of sunshine, significantly affect the formation and dispersion of O_3. So Higher monthly concentrations are shown at the suburban background concentrations (especially at Thrakomakedones).
- A typical daily pattern appears with the lowest values early in the morning (at 08:00 LT). Since ground-level ozone is a secondary pollutant, its formation is highly related to sunlight and complex, anthropogenically influenced processes. Emissions of nitrogen oxides (NOx) and volatile organic compounds (VOCs) from human activities lead to the production of ozone, having a peak from 14:00 LT to 16:00 LT. The duration as well as the extent of the peaked concentrations differ from station to station. At the suburban background stations concentrations remain increased for a longer period, ranging from 60 $\mu g/m^3$ to 100 $\mu g/m^3$ for about 20 h while at the urban background stations the curve of peak values (above 60 $\mu g/m^3$) lasts for about 10 h.
- The impact of ozone on the lives of residents is significant, as it limits their daily activities and causes respiratory symptoms and coughing. People over 55 years old are mostly affected by poor air quality due to ozone exceedances. Concerning all age groups, the maximum number of DALYs is 80 per 100,000, while for the over-55 ages, the maximum number of DALYs is 251 per 100,000, which is much higher.
- The link between the economic crisis and the quality of health care is illustrated by studying the relation between deaths and DALYs, as well as the unemployment rates and GDP annual variation.

The information presented in this work serves as a foundation for further research and practical applications, contributing to the sustainable development and resilience of Athens in the face of ongoing climate change, air quality deterioration and the possible burden on the public health.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/atmos15030380/s1, Table S1: Meteorological data of Attica 1990–2019.

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