Analyzing Pollutant Concentrations in Two Main Greek Urban Centers

Cristiana Tudor[(✉)]

International Business and Economics Department, The Bucharest University of Economic Studies, 010374 Bucharest, Romania
`cristiana.tudor@net.ase.ro`

Abstract. The main aim of the paper is to analyze the temporal behavior of air pollutant concentrations in two different Greek urban areas, Piraeus and Volos. Results indicate that the daily mean concentrations of PM10 exceeded the EU standards in both cities on a significant number of days over the most recent calendar years. Further, the Theil-Sen estimations indicate that the overall trend for PM2.5 in Piraeus is negative and statistically significant over the analysis period, whereas the trend analysis for PM10 in Piraeus, as well as for both PM2.5 and PM10 in Volos reflects only modest decreases that lack statistical significance, suggesting that more effective control measures and policies are needed to tackle this global challenge. Other results show that in Piraeus, CO and NO_x exhibit similar seasonal and daily variations, with the highest concentrations in winter and the lowest in summer, and also with the highest concentrations on Fridays and the lowest over weekend days. Particulate matter (PM10 and PM2.5) shows similar temporal behavior in both urban areas, also registering higher concentrations in winter months, suggesting that the main culprit might be the use of unsustainable energy sources for heating. On the other hand, the O_3 concentration in Piraeus is highest in the summer months, reflecting strong solar radiation.

Keywords: Air pollutants · Time variation · Theil-Sen trend · Piraes · Volos

1 Introduction

The European Union is often regarded as a world leader in environmental and health policies and regulations (Jephcote and Mah 2019; Tudor and Sova 2022). However, the World Health Organization (WHO) has recently adjusted its recommendations for acceptable levels of air pollution after recognizing evidence of harm to human health at lower levels than previously anticipated, which leaves the current EU standards well above the WHO's recommendations (Euronews 2021). Table 1 reflects the EU standards for air pollutants that must be met by all member states.

A considerable part of Europe's urban population lives in cities where EU air quality criteria for human health protection are routinely breached (EEA 2021). Consequently, air pollution continues to have a substantial influence on Europeans' health, particularly the population living in urban areas. In turn, these health consequences have economic implications, such as shortened lives, increased medical costs, and decreased productivity

Table 1. Ambient air quality standards for the European Union.

Air pollutant	Averaging period	EU standard
PM10	Daily Annual	$50\ \mu g/m^3$ $40\ \mu g/m^3$
PM2.5	Annual	$25\ \mu g/m^3$
SO$_2$	Hourly Daily	$350\ \mu g/m^3$ $125\ \mu g/m^3$
NO$_2$	Hourly Annual	$200\ \mu g/m^3$ $40\ \mu g/m^3$
O$_3$	8-h	$120\ \mu g/m^3$
CO	8-h	$10\ mg/m^3$
Benzene (C$_6$H$_6$)[a]	Annual	$5\ mg/m^3$

Source European Environment Agency (EEA), 2021: https://www.eea.europa.eu/themes/air/air-quality-concentrations/air-quality-standards
[a] For benzene, the source of information is EEA (2014): https://www.eea.europa.eu/data-and-maps/figures/benzene-annual-limit-value-for-the-protection-of-human-health

due to lost working days (EEA 2021). Greece is the most recent EU member state to be accused of failing to satisfy air quality criteria. Air pollution has become one of the most prominent environmental issues in Greece, with many cities still experiencing severe air pollution that surpasses EU standards. Hence, due to the high levels of nitrogen dioxide created by traffic and industry, the European Commission has put it on a list of nations risking legal action (CGTN 2022). Among the main factors impacting air pollution in urban and industrial areas in Greece, we encounter fast urbanization, chaotic housing development lacking basic infrastructure, and growth in motor vehicle fleet in urban areas (Athanasios et al. 2015). Moustris et al. (2016) demonstrate the health impact of air pollution in the case of the Greek city of Volos, showing that when the average annual PM10 concentration exceeds the EU guideline, the number of hospital admissions for respiratory disease is on average 25% higher. This finding, in turn, highlights the stringent urgency that the country faces to decrease air pollution and mitigate the health risk for its population. In this context, analyzing longer-term air pollution data with high temporal and spatial resolutions is paramount to inform on the local air pollution situation and to ultimately assist the issuers of policy in the stringent global climate combat.

In this paper, we aim to analyze the temporal behavior of air pollutant concentrations in two different Greek urban areas, Piraeus and Volos, by sourcing hourly data for air pollutants spanning 2018–2022 and measured by automatic air monitoring stations located in the two cities.

2 Data

Hourly observations of air pollutants were obtained from automatic air quality monitoring stations located in two Greek urban centers, Piraeus and Volos, respectively. For Piraeus, data is available for multiple air pollutants (i.e., PM10, PM2.5, SO_2, NO_2, O_3, CO, and benzene), whereas for Volos, only particulate matter data (i.e., PM10 and PM2.5) is available. Both stations are classified as urban traffic measurement stations. Figure 1 highlights their exact location, while Table 2 provides more details on the two stations.

Next, Table 3 summarizes the data and includes the observation period and the air pollutants measured by the two stations.

3 Method

The time series of air pollutants concentrations are first plotted through the "timePlot" function in the "openair" package in R software. Subsequently, through the same function, the "normalize" option is employed, which enables the direct comparison of variables using the same scale.

Additionally, the temporal variation of air pollutants is assessed through the Theil-Sen estimator (Theil 1950; Sen 1968), which, by being a non-parametric median-based estimator, carries the important advantage of providing accurate confidence intervals even with non-normal data and heteroscedasticity, while also being resistant to outliers, characteristics that can be particularly important in analyzing air pollution (Carslaw 2020). In addition, in terms of statistical power, the estimator is capable of competing well against least squares also for normally distributed data (Wilcox 2001). Thus, the Theil–Sen estimator, sometimes known as the Kendall robust line-fit method, is a method for robust linear regression that finds the median slope among all lines through pairs of two-dimensional sample points (Tilgenkamp 2022).

As per Chervenkov and Slavov (2019), the estimation is accomplished by estimating the slopes of all possible $\binom{n}{2} = \frac{n(n-1)}{2}$ combinations of pairs of points. Then, the non-parametric slope is defined as the spatial median of these slopes, such that:

$$\hat{\beta}_1 = median\left\{\tilde{B}\right\}, \tilde{B} = \left\{b_{ij}|b_{ij} = \frac{y_j - y_i}{x_j - x_i}, x_i \neq x_j, 1 \leq i < j < n\right\} \qquad (1)$$

Moreover, the estimates of parameters are made more robust through bootstrap-resampling, which is accomplished by calling the TheilSen function in the openair package. As such, the function performs multiple simulations to assess the uncertainty in the slope. Moreover, the option "slope.percent" can be employed within the function to express slope parameters as an annual percentage change, which is valuable when comparing the trend for sites with different pollutant concentration levels. In this research, we estimate the trend with and without the "slope.percent" option.

(a) Location of the air quality monitoring station in Piraeus
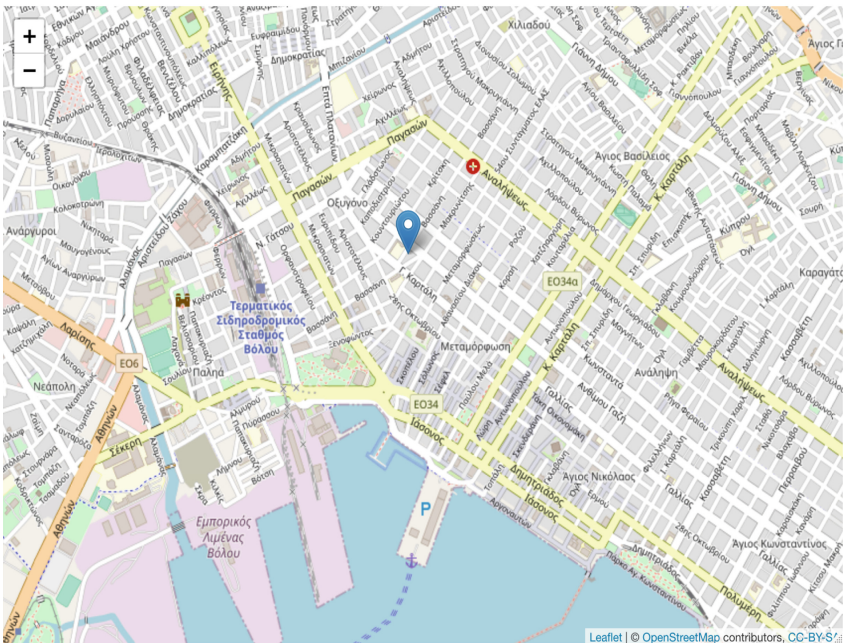
(b) Location of the air quality monitoring station in Volos

Fig. 1. The location of the two urban traffic air quality measurement stations.

Finally, the Inter-Annual Variation in Air Pollutants is explored through calendar plots, also in R's "openair" package. Hence, the "calendarPlot" function embedded

Table 2. Details of the two automatic air-monitoring stations in Greece.

Name	Code	Latitude	Longitude	Elevation	Type	Area	Network
gr0030a	PIREAUS-1	37.94329	23.647511	20	Traffic	Urban	NET-GR016A
gr0001a	VOLOS	39.36639	22.94306	31	Traffic	Urban	NET-GR014A

Table 3. Data

Station location	Observation period	Number of observations	Air pollutants
Piraeus	2018-01-01 (00:00:00) to 2022-06-14 (00:00:00)	38,780	PM10, PM2.5, SO_2, NO, NO_2, O_3, and CO
Volos	2018-01-01 (00:00:00) to 2022-01-03 (10:00:00)	33,414	PM10, PM2.5

within the package allows visualizing data by reflecting daily concentrations of air pollutants laid out in a calendar format and is also capable to highlight the days when air pollutants surpass a particular limit (i.e. PM10 > 50 μg m^{-3}). Subsequently, the hourly, daily, and monthly behavior of air pollutants concentration is uncovered through the "timeVariation" function.

4   Results and Discussion

4.1   Visual Inspection of Time Trends of Air Pollutants in the Two Greek Urban Areas

First, Fig. 2 reflects the evolution of the main air pollutants (PM10, PM2.5, SO_2, NO_2, O_3, CO, and benzene) in Piraeus over the period spanning 2018–2022.

Next, Fig. 3 reflects the evolution of the normalized data and helps to clarify that concentration of benzene, PM10, CO, and SO_2 has increased in Piraeus over the period 2018–2022, whereas NO_2 and PM2.5 have shown reductions of more than 20% over the same period.

On the other hand, the air quality evolution (i.e., PM2.5 and PM10) in Volos is reflected in Fig. 4 (time plot of original data) and Fig. 5 (normalized series), showing that, while the PM10 levels have registered a rather modest decrease of a little over 10% over the 2018–2022 period, the levels of PM2.5 show a worrying increase rate of more than 20% in the city (Fig. 5).

4.2   Inter-annual Variation in Air Pollutants in the Two Greek Urban Areas

We are next interested in detecting the inter-annual variations in air quality in the two Greek cities. For this task, we take a closer look at the PM10 daily variations over the
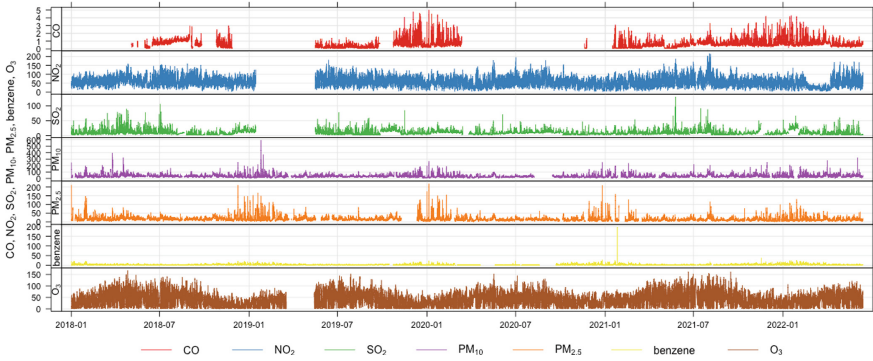
Fig. 2. Time evolution of main air pollutants in Piraeus (hourly data, 2018–2022)
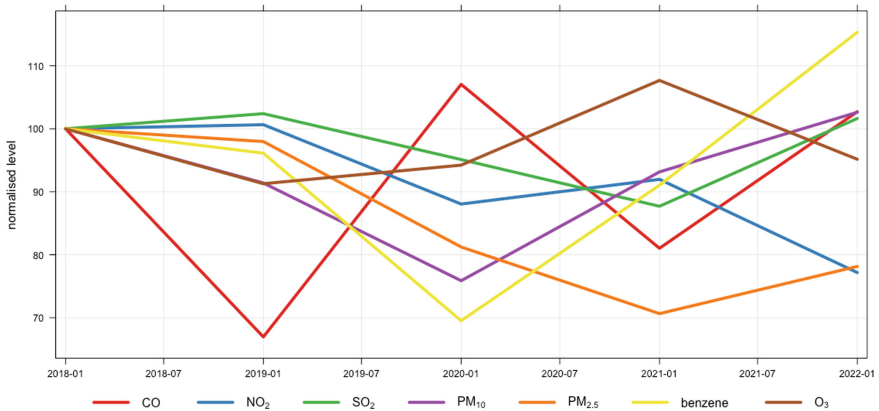

Fig. 3. Time evolution of main air pollutants in Piraeus (hourly data, normalized, 2018–2022)

most recent calendar years (i.e. 2021 and the first half of 2022 for Piraeus, and only 2021 for Volos, for which the monitoring stations do not currently report data for 2022).

Hence, Fig. 6 highlights days in 2021 (a) and 2022 (b) where PM10 concentrations in Piraeus surpass the 50 µg m^{-3} EU guideline, whereas Fig. 7 accomplishes the same task for Volos for the year 2021, clearly indicating the days where PM10 > 50 µg m^{-3} in the city.

Subsequently, Fig. 8 shows the results of R's openair "TimeVariation" function applied to normalized concentrations of PM10 and PM2.5 in Piraeus. The chart clearly indicates that the temporal trends in concentration are distinct. For O$_3$, there is a pronounced increase in concentrations in the afternoon of each weekday. This was expected, as ozone is the main component of the mix of air pollutants known as "smog" that emerges from the action of sunlight on air contaminants from automobile exhausts and other sources (NY Department of Health: https://www.health.ny.gov/environmental/out doors/air/ozone.htm). Another significant difference is noticed on Sundays when NO$_x$ concentrations are lower, indicating that there is less heavy-duty diesel truck traffic on
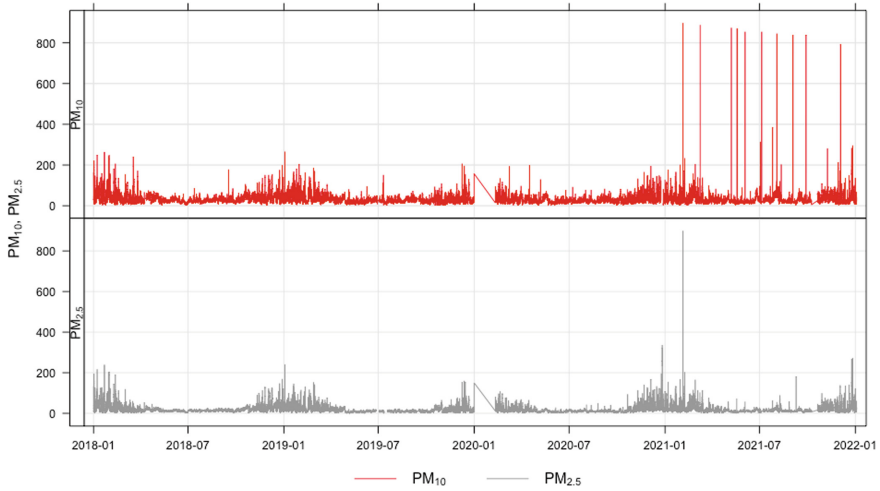
Fig. 4. Time evolution of particulate matter in Volos (hourly data, 2018–2022)
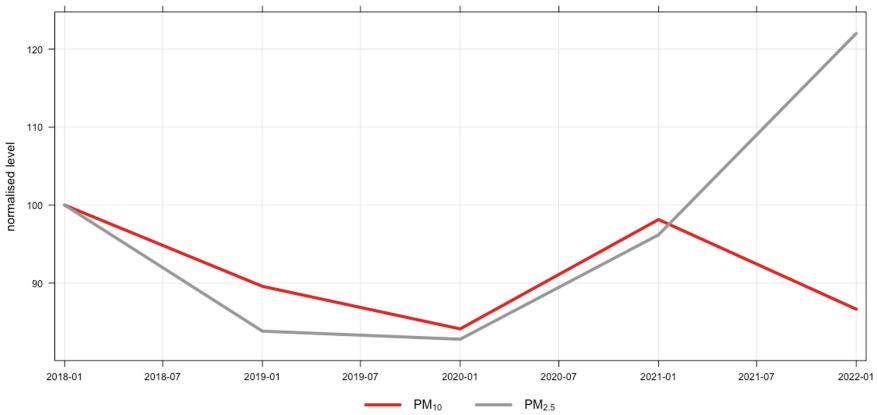

Fig. 5. Time evolution of particulate matter in Volos (hourly data, normalized, 2018–2022)

those days (Marr and Harley 2002), whereas peak levels are encountered on Fridays. Moreover, we notice that the monthly trend for most pollutants is quite distinct, which might indicate different origin sources. Additionally, it is important to mention that traffic emissions (CO and NO_x) dominate this area (i.e., Piraeus), and concentrations are higher in the winter months, particularly in December. However, a significant difference in how these emissions vary by hour of day and day of the week is encountered in Piraeus, which is important for local authorities to consider issuing efficient and effective policies. As per Dobson et al. (2021), the ramifications of these temporal fluctuations in pollutant concentrations throughout the course of the day, week, and month for health services, particularly those related to cardio-respiratory health, may be significant.
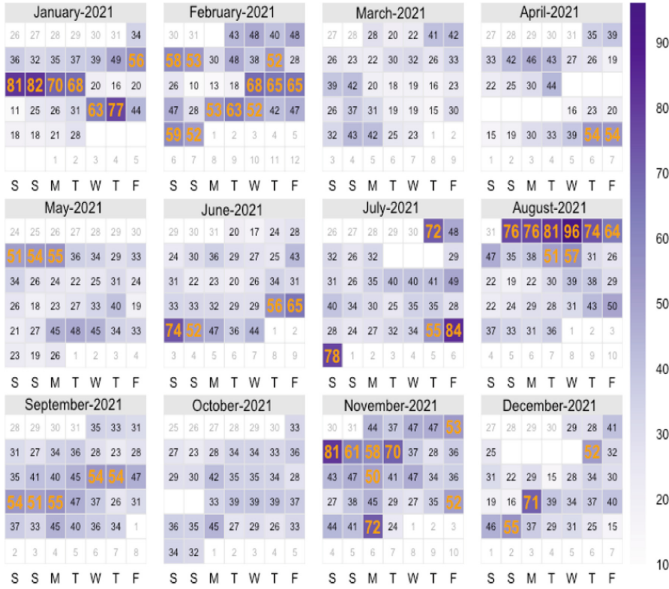
(a)
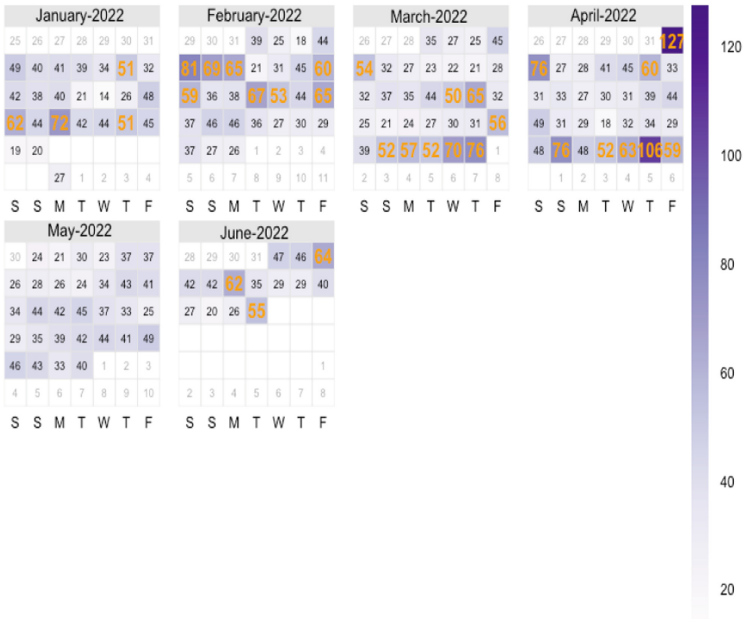
(b)

Fig. 6. Calendar plot for PM10 concentrations in Piraeus: year 2021 (panel a), year 2022 (panel b); with highlight, days with PM10 exceeding standard levels
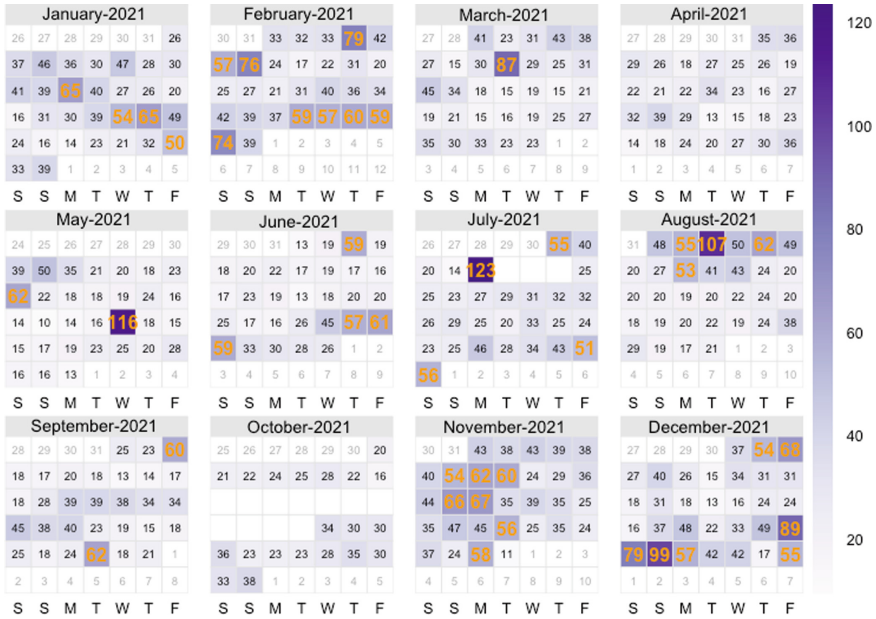
Fig. 7. Calendar plot for PM10 concentrations in Volos (2021); with highlight, days with PM10 exceeding standard levels
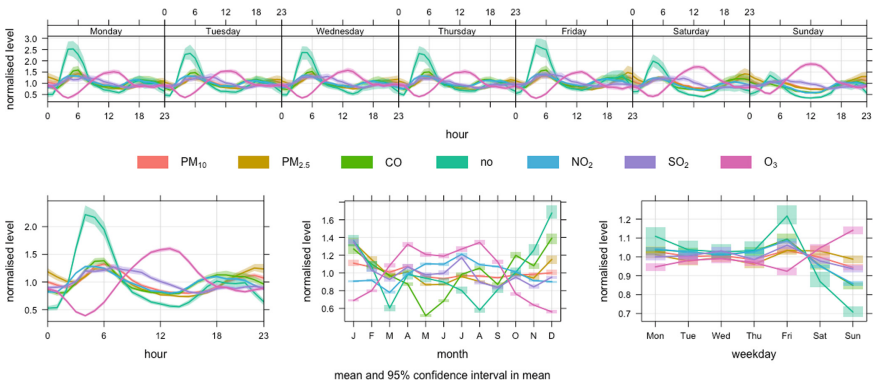

Fig. 8. Hourly, daily, and monthly variation of air pollutants in Piraeus (2018–2022)

Due to a lack of available data in the case of Volos, Fig. 9 is limited to showing the time variation in particulate matter (i.e., PM10 and PM2.5) over the 2018–2022 period. The chart indicates that particulate matter concentrations increase during weekend days, evening hours, and winter months. This temporal behavior is extremely relevant for regulators and policymakers, having important implications for public health and climate policies.
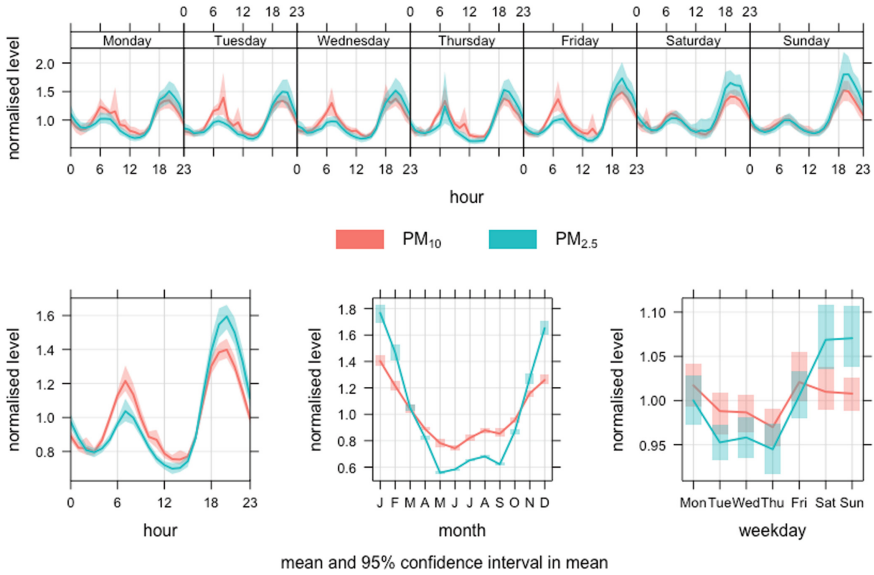

Fig. 9. Hourly, daily, and monthly variation of particulate matters (PM10 and PM2.5) in Volos (2018–2022)

4.3 Trend Estimates for PM10 and PM2.5 in Piraeus and Volos with the Theil Sen Estimator

Figure 10 plots the deseasonalized monthly mean concentrations of PM2.5 in Piraeus, while Fig. 11 shows the deseasonalized monthly mean concentrations of PM10 in the same area and over the same period (i.e., 2018–2022). The 95% confidence intervals based on resampling methods are also indicated by the dotted lines. The overall trend for PM2.5 in Piraeus is negative and statistically significant, indicating that the city has managed to register important decreases in PM2.5 levels over the last few years (i.e., an average annual decrease of more than -8%). On the contrary, the trend for PM10 shows a modest decrease that lacks statistical significance (i.e., -0.17%), suggesting that improving air quality should continue to be a priority for local authorities.

In Volos, estimation results (reflected in Figs. 12 and 13) show that air quality, as proxied by the concentrations of particulate matter, did not register a significant
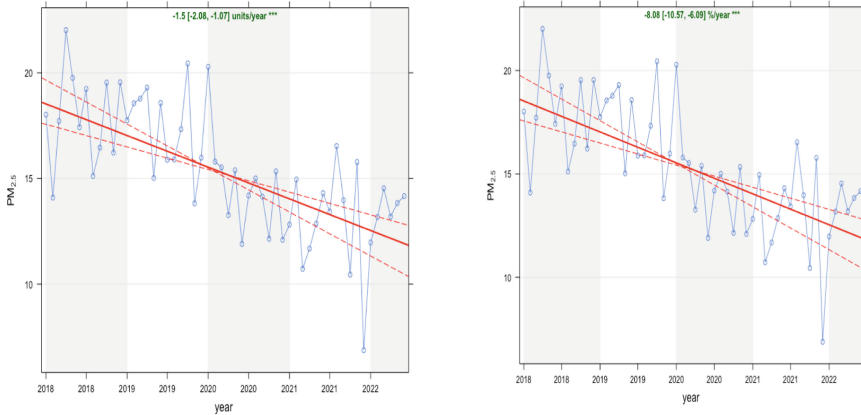
Fig. 10. Trends in PM2.5 in Piraeus (2018–2022); (a) absolute change; (b) percentage change
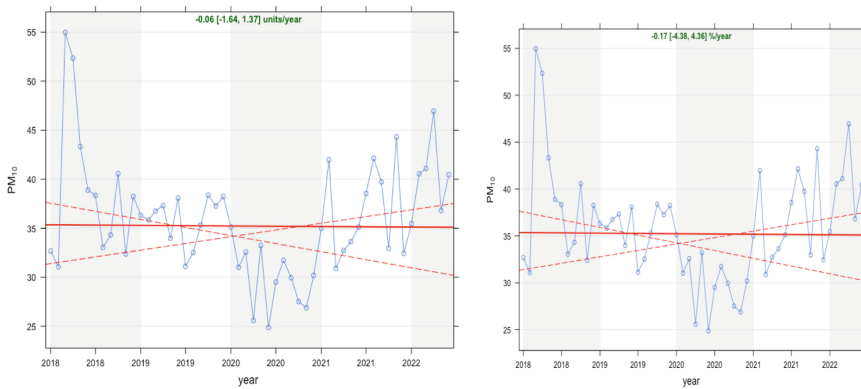

Fig. 11. Trends in PM10 in Piraeus (2018–2022); (a) absolute change; (b) percentage change

improvement over the 2018–2022 period. Consequently, the slope coefficient is −2.01% for PM2.5 and −1.47% for PM10, lacking statistical significance in both cases. As such, more efficient policies are needed to significantly reduce pollution levels to EU standards. In this respect, the time variation of air pollutants depicted in Fig. 9 can provide important information for policymakers.

5   Conclusions

Greece still registers air pollution levels that surpass EU standards, with important health consequences for its population. In this context, long-term air pollution data with a high temporal and spatial resolution is extremely helpful for informing the issuers of policies and assisting them in adopting effective policies and control measures.

This research sources data for main air pollutants levels registered in two Greek cities (i.e., Piraeus and Volos) and provides an analysis of the air pollutants' evolution over
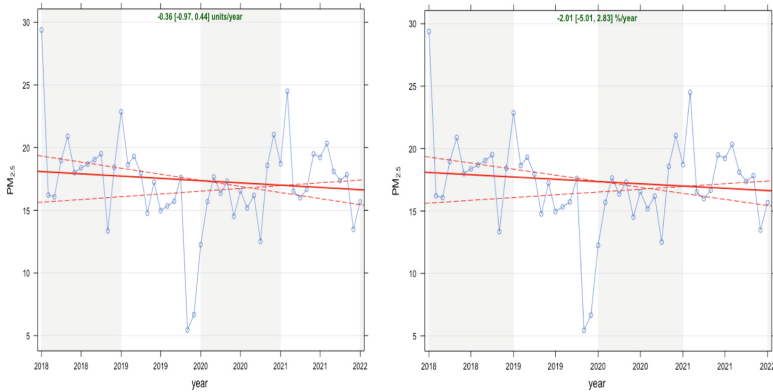
Fig. 12. Trends in in PM2.5 in Volos (2018–2022); (a) absolute change; (b) percentage change
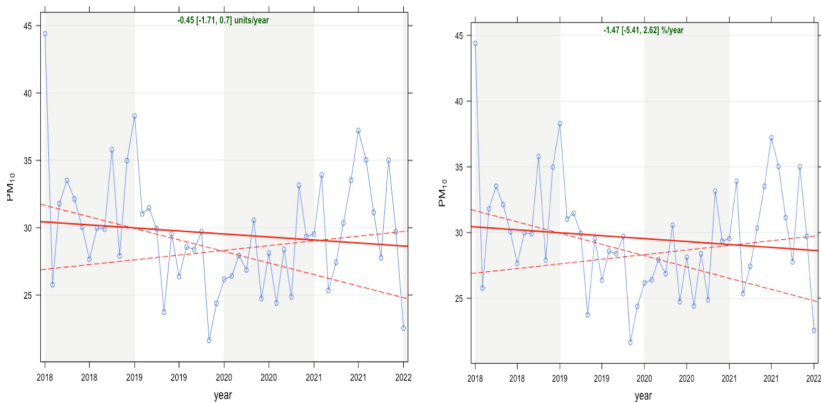

Fig. 13. Trends in in PM10 in Volos (2018–2022); (a) absolute change; (b) percentage change

the 2018–2022 period. Thus, hourly data spanning the 2018–2022 period for various air pollutants concentrations is extracted for air monitoring stations classified as urban traffic measurement stations and located in the two Greek cities. Overall, 38,780 hourly observations are sourced for Piraeus for multiple air pollutants (i.e., PM10, PM2.5, SO_2, NO_2, O_3, CO, and benzene), whereas for Volos, 33,414 valid hourly observations for PM10 and PM2.5 are used in the analysis. The Theil-Sen trend is also estimated for particulate matter concentrations over the 2018–2022 period in the two Greek cities.

Some of the main findings indicate that the daily mean concentrations of PM2.5 and PM10 exceeded the EU standards in both cities on a significant number of days over the most recent calendar years. The Theil-Sen estimations indicate that the overall trend for PM2.5 in Piraeus is negative and statistically significant over the analysis period, indicating that the city has managed to register an average annual decrease of more than −8% in its PM2.5 levels. On the contrary, the trend analysis for PM10 in Piraeus, as well as for both PM2.5 and PM10 in Volos, reflects only modest decreases that lack statistical significance.

Other results show that in Piraeus, CO and NO$_x$ exhibit similar seasonal and daily variations, with the highest concentrations in winter and the lowest in summer, and also with the highest concentrations on Fridays and the lowest over weekend days.

Particulate matter shows a similar evolution in both urban areas, registering higher concentrations in the winter months. This further indicates that the use of unsustainable fossil fuel combustion sources for heating in winter might contribute to increased pollution (Zhang et al. 2009; Xiao et al. 2018).

On the other hand, the O$_3$ concentration in Piraeus is highest in the summer months, reflecting strong solar radiation.

Overall, the results suggest that air pollution in Greece is caused by multiple air pollutants and that the air pollution exhibits significant hourly, daily, and seasonal divergence. In turn, these findings highlight the need for more efficient and targeted measures to bring the air quality in Greece within EU standards and mitigate the devastating health and economic consequences of this global issue.

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