environmental sciences proceedings

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Proceeding Paper

Comparison Analysis of the Effect of High and Low Port Activity Seasons on Air Quality in the Port of Heraklion †

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† Presented at the 4th International Electronic Conference on Atmospheric Sciences, 16–31 July 2021; Available online https://ecas2021.sciforum.net/.

Abstract: Emissions from port operation and shipping have a significant impact on climate risk, affecting the environment and human health in coastal regions (UNEP). The port of Heraklion, located on the island of Crete over the eastern Mediterranean, plays a key role in the sustainability of Southeast Europe. The impact on its operation affects the socio-economic life and development of the region because Heraklion is not just a tourist destination but also a significant trade and transportation center for the eastern Mediterranean. This study investigates the impact of port operation on the air quality of Heraklion between two representative periods. The first, which is considered as the high port activity season, was from 02 August 2018 to 08 August 2018, while the second period was between 11 May 2018 and 16 May 2018. For the air quality measurements, a low-cost sensor was used, while the recordings were initially compared and finally evaluated based on the available data of the monitoring station of the Ministry of Environment and Energy. To investigate the air quality differences between the two studied periods, the correlation analysis, the hourly evolution of pollutants, and the mean differences between high and low periods for gaseous pollutants and particulate matter are studied. Moreover, the effect of meteorology on air quality is investigated. The results indicate that the high season is characterized by significantly higher concentrations of pollutants compared to the other period. In both seasons studied, the air pollution level increases during hours of high port-activity, indicating the impact of port activity on air quality in Heraklion. The analysis shows that meteorology affects the air quality. In particular, strong wind speeds are associated with lower concentrations of gaseous pollutants other than ozone, which is affected by atmospheric circulation. Finally, the analysis emphasizes the importance of further investigation of the impact of port operations on coastal air quality in the context of sustainable development.

Keywords: air quality; ships; port operation; eastern Mediterranean; climate risk; green and sustainable development

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Citation: Logothetis, I.; Antonopoulou, C.; Sfetsioris, K.; Mitsotakis, A.; Grammelis, P. Comparison Analysis of the Effect of High and Low Port Activity Seasons on Air Quality in the Port of Heraklion. *Environ. Sci. Proc.* **2021**, *8*, 3. https://doi.org/10.3390/ecas2021-10329

Academic Editor: Anthony R. Lupo

Published: 22 June 2021

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1. Introduction

The eastern Mediterranean is a crucial area for the economy and sustainable development, as it is located over the trade crossroads of three continents (Asia, Africa, and Europe). This region is one of the major marine routes of the world, with a rapidly growing trade activity due to globalization and socio-economic development [1]. Even if the activity of the port is a key feature of the region's economic development, its impact on the environment and human health concerns the scientific community [2]. Increased shipping and port operation result in air quality degradation and also contribute to the increase of the coastal climate risk [3,4]. The Mediterranean region is recognized by the United Nations Environmental Program [1] as one of the most prominent and vulnerable climate

change hot-spots [5–7] and a key area in terms of shipping, navigation, and human health consequences [8–10]. It is clear that port emissions are a small fraction of global shipping, but they have an important impact on human health [3,11], as global shipping emission mortality for 2020 was estimated at 250,000 per year [12].

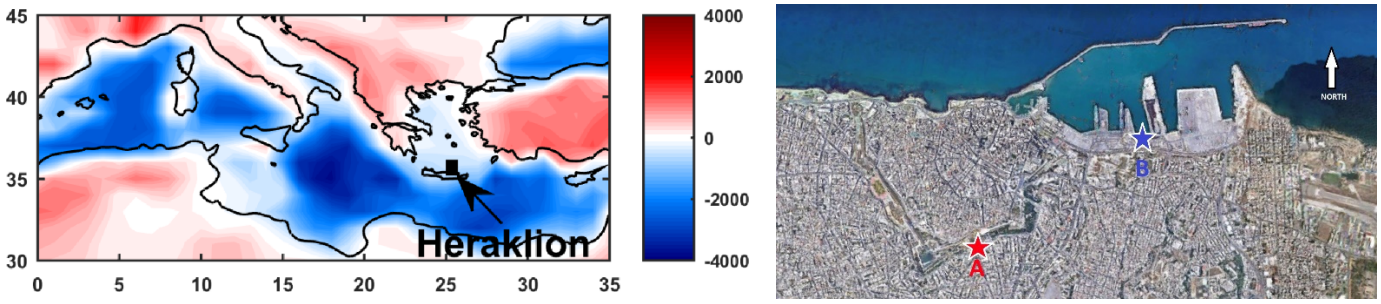
Emissions from navigation, ships at berth, and port operation are a significant component of pollution including gases (NOx, SOx, CO, O_3), particulate matter (PM), and GHGs [13]. Besides emissions, air quality is affected by weather [14], while additionally the concentration of pollutants is sensitive to climate and meteorological parameters [15,16]. The emissions from port operation and shipping are projected to increase in the future. In particular, economic development is projected to increase the level of CO_2 by between 50% to 250% by 2050 [17] if mitigation measures are not taken by policy makers. Generally, the emissions from transport have decreased since 1900 except for shipping, where PM, SO_2, and NOx emissions have increased [8,18], representing about 10% of GHG emissions by 2050 [17]. Previous studies have investigated the impact of port operation and shipping on urban coastal areas [19,20]. The impact of shipping on air quality in Adriatic and Ionian ports has already been studied using numerical models, measurements, and air emission estimations [21]. This analysis shows that maritime emissions contribute to the SO_2 concentration more significantly than road traffic. However, shipping contributes to the concentrations of PM and NOx at the same level as the road traffic. Furthermore, the meteorological conditions affect the concentration of pollutants and modulate the plume behavior, affecting the dispersion of pollution [22]. In total, 10% to 30% of PM2.5 in large coastal Mediterranean cities comes from shipping [23]. Additionally, the air quality of Istanbul and Athens is affected significantly by shipping [24]. During the period from 2013 to 2016, the port activity of Civitavecchia in Italy contributed significantly to the concentrations of NO_2 (33%), PM10 (43%), and SO_2 (60%), affecting the local air quality [8].

Heraklion is one of the most important Greek ports, and its economic activity is a significant factor for the socio-economic and sustainable development of the eastern Mediterranean. It attracts thousands of tourists annually, and it is also a significant partner for the transit, transportation, and trade network of the eastern Mediterranean [25]. There are no previous studies that investigate the impact of shipping and port activity on the ports of the south Aegean Sea. This study investigates the impact of port operation and ship emissions in order to characterize air quality, based on air measurement campaigns conducted in the Heraklion port that compared high and low port activity seasons during 2018. Moreover, the effect of meteorological conditions on the air quality is investigated for the two studied periods.

2. Methods and Data

The city of Heraklion (25°8′53.7144″ E, 35°20′30.6456″ N) is located on the north–central coast of Crete island, and it is one of the most important shipping ports and ferry docks of the eastern Mediterranean (Figure 1a). Heraklion is the capital of Crete and the fourth largest city in Greece (the urban area population is about 210,000). Moreover, it is one of the most popular tourist destinations during the summer months and an important trade hub for the eastern Mediterranean. The present analysis employs recordings from a low-cost sensor (LCS) operated at the port of Heraklion. The LCS recordings include gases (NOx; ppb, NO; ppb, NO_2; ppb, O_3; ppb, CO; ppm, SO_2; ppb), particle matters (PM1, PM2.5, PM4, PM10, PM_tot; $\mu g/m^3$) and meteorological parameters (wind speed—WS; m/s, wind direction—WDir; °, temperature—T; °C, pressure—P; hPa and relative humidity; RH—%). Some of the basic characteristics of the LCS used for the analysis are shown in Table 1. To investigate the impact of port operation and shipping emissions in the Heraklion port, two representative periods of 2018 are studied. In particular, the first period, with high port and shipping activity, is considered as the period from 02 August 2018 to 08 August 2018, and the second, the low port and shipping activity period, is considered the period from 11 May 2018 to 16 May 2018. In order to evaluate the variability of the LCS recordings, the regression between the LCS anomalies and the corresponding

available recordings anomalies (PM10) from the monitoring station of the Ministry of Environment and Energy (MEEN; Figure 2) is calculated. The Spearman correlation is performed in order to study the relation between the meteorological variables and the concentration of pollutants [26]. Finally, the hourly evolution of pollutant concentrations and the meteorological parameters are studied to understand the impact of port operation and shipping on the air quality of Heraklion port more thoroughly. For the analysis, the hours with strong (weak) wind speed are considered the hours with a wind speed higher (lower) than 90% (10%) of the wind speed distribution for the studied period (high or low port activity period, respectively). The statistical significance is studied with a two-tailed t-test (with significance levels of 95%).



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

Figure 1. (**a**) Location of Heraklion on Crete Island in the eastern Mediterranean (topography map). (**b**) Location of monitoring station of MEEN (red star; A) and LCS (blue star; B).

Table 1. The low-cost sensors (LCS) used for the analysis and the corresponding certificates.

Sensor	Certifications
PM10 and PM2.5 (HORIBA APDA-372	Certificate QAL 1 (TUV Rheinland Energie und Umwelt GmbH) VDI 4202-1 (2002), VDI 4203-3 (2004), EN14211 (2012), EN 15267-1 (2009), EN 15267-2 (2009)
CO (HORIBA APMA 370)	Certificate QAL 1 (TUV Rheinland Energie und Umwelt GmbH) VDI 4202-1 (2002), VDI 4203-3 (2004), EN14211 (2012), EN 15267-1 (2009), EN 15267-2 (2009)
O3 (HORIBA APOA 370)	Certificate QAL 1 (TUV Rheinland Energie und Umwelt GmbH) VDI 4202-1 (2002), VDI 4203-3 (2004), EN14211 (2012), EN 15267-1 (2009), EN 15267-2 (2009)
SO2 (HORIBA APSA 370)	Certificate QAL 1 (TUV Rheinland Energie und Umwelt GmbH) VDI 4202-1 (2002), VDI 4203-3 (2004), EN14211 (2012), EN 15267-1 (2009), EN 15267-2 (2009)
NOx (HORIBA APNA 370)	Certificate QAL 1 (TUV Rheinland Energie und Umwelt GmbH) VDI 4202-1 (2002), VDI 4203-3 (2004), EN14211 (2012), EN 15267-1 (2009), EN 15267-2 (2009)
Meteorological parameters	Theodor Friedrichs

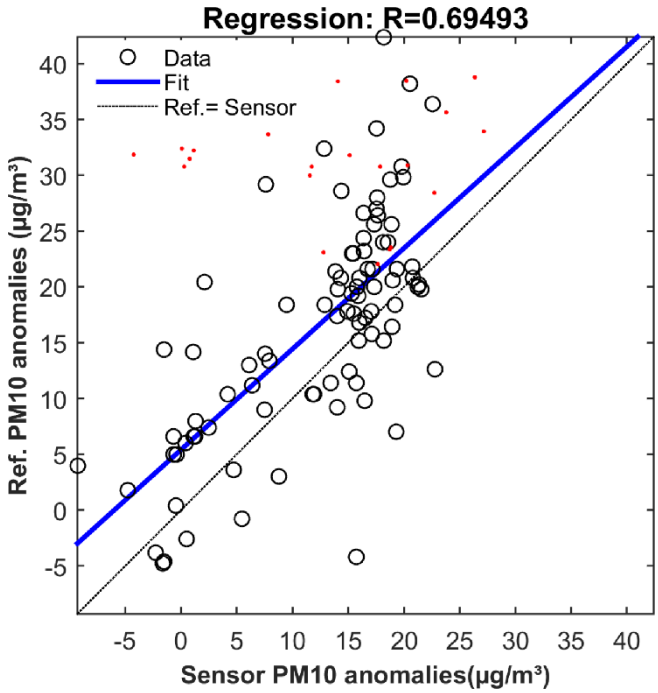


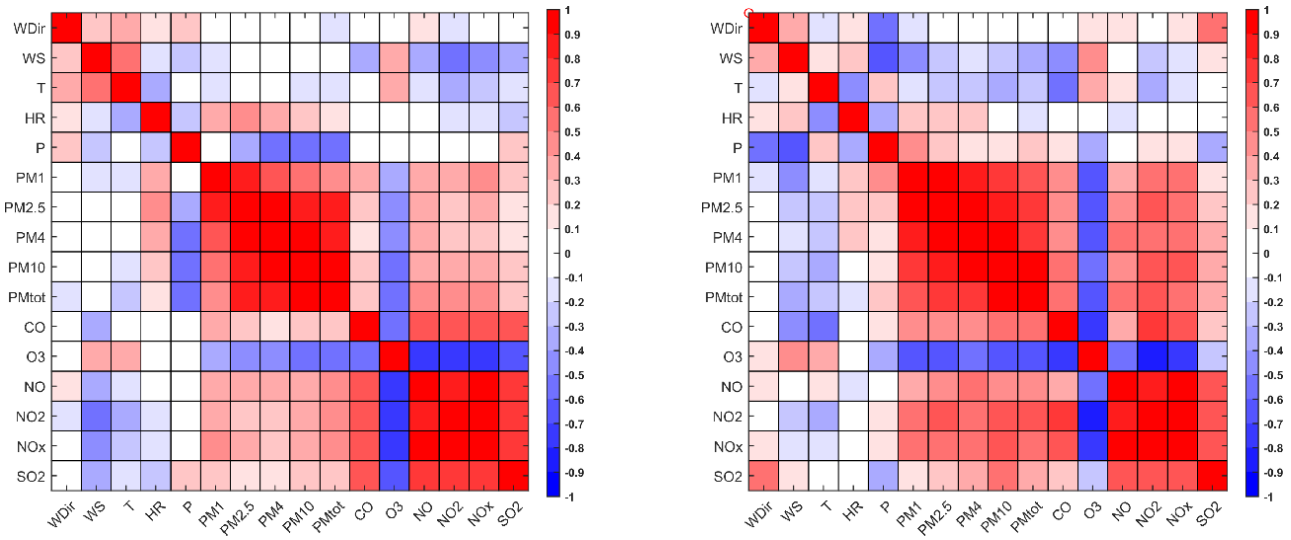
Figure 2. Scatter plot and linear regression of PM10 anomalies of the monitoring station of MEEN (PM10) recordings of LCS PM10 anomalies during the high port activity season. Red points indicate the recordings that are excluded from the regression analysis during the hours with high shipping.

3. Results

In order to evaluate the variability of recordings from the LCS, the regression coefficients of the anomalies of the available recordings (PM10) from the monitoring station of the Ministry of Environment and Energy (MEEN) regarding the anomalies of the PM10 recordings of the LCS are calculated. The LCS is located in a representative position for the air quality of the port of Heraklion (according to the indication of the Heraklion Port Authority S.A. to ensure the representative sampling of recordings). The official monitoring station (MEEN) is located southwest of the LCS location (Figure 1b). During the high port activity season, the dominant sector for the wind speed is in the direction from WNW to NW (~300°), and during the low port activity season, the wind speed blows from SSW (~200°; with high variability). The dominant pattern of the wind speed and direction during the high season possibly reduces the impact of the port activity on the central west area of Heraklion. To compare the PM10 recordings between the LCS and the MEEN station, the recordings during the hours with high port activity are excluded from the regression analysis (Figure 2; please note that the red points denote recordings during high port activity hours). This analysis, for the high season, shows a regression coefficient equal to 0.93 (R = 0.69, SE 0.1 and p-value < 0.05; Figure 2) between the LCS and MEEN station recordings. For the low port activity season, the regression coefficient of PM10 anomalies of MEEN recordings of the PM10 anomalies of the LCS is about 2.0 (R = 0.77, SE 0.15 and p-value < 0.05). The wind direction (as recorded by the LCS in the port) prevails mainly from the SSW direction. This may reduce the impact of port activity on the air quality, acting as a "ventilation system" for the central and western urban area of Heraklion during the low port activity season. The analysis shows that port operation and shipping affect the air quality of Heraklion. The impact of port operations during the high port activity season more significantly affects the air quality of Heraklion compared to the low port activity season.

The correlation coefficients between air quality (gases and PM) and meteorological parameters for both high (left panel) and low (right panel) port activity seasons are shown in Figure 3. This analysis shows that wind speed (WS) is associated with the reduction

of gaseous pollutants except for ozone (O_3). The concentration of O_3 and the wind speed show a positive correlation, possibly due to the impact of summer low tropospheric circulation [27–29]. The highest positive correlation coefficient during the high port activity season (compared to the low port activity one) is related to the dominant characteristics of atmospheric circulation during the summer period [27]. Moreover, during high season, the wind speed is not correlated with PM (excluding PM1). This is explained by the dominant mode of lower summer atmospheric circulation, the northerly winds over the eastern Mediterranean (the Etesians regime) [27,28,30], which contribute to the transfer of PM [31]. In particular, the weaker wind speed during the low port activity season (compared to the high port activity season) and the features of low troposphere circulation over the eastern Mediterranean illustrate the negative relation between wind speed and PM in the port. The positive correlation between gaseous pollutants and PM results from the chemical processes (photochemical reactions and photolysis during daytime hours) [32] and the impact of port activity (operation and shipping) on local air quality.



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

Figure 3. Correlation coefficients for air quality (pollutants) and meteorological parameters (**a)** for high port activity and (**b**) for low port activity seasons.

The ratio of PM2.5/PM10 is usually associated with the relevant sources. A higher ratio shows a larger contribution of PM2.5, primarily indicating pollution from anthropogenic activities [33]. During the high port activity season, the ratio is equal to 0.6 (with a standard deviation of 0.07), and during the low season, it is equal to 0.54 (with a standard deviation of 0.08). Moreover, the hours with a stronger wind speed compared to the hours with a weaker wind speed show a lower PM2.5/PM10 ratio (approximately 0.09). Please note that, for the high port activity season, the hours with a stronger wind speed are considered to be the hours with a wind speed greater than 90% of the wind speed distribution of the high season, and the hours with a weak wind speed are considered to be the hours with a wind speed less than 10% of the wind speed distribution of the high season, respectively. During the high season, the negative difference between PM2.5/PM10 ratios for the hours with high port activity and the hours with low port activity suggests that strong wind speed is associated with lower pollution from port activities.

To study the impact of port operation and shipping on the air quality of Heraklion port, the hourly evolution of the concentration of pollutants and meteorology parameters during high and low port activity seasons (Figure 4) is calculated. During the high port activity season, the winds prevail from a NWW (~300°) direction with low variability (Figure 4a), and the wind speed is stronger about 1.34 m/s compared to the low season (Figure 4b). The temperature (Figure 4c) shows less variability during the high season

compared to the low season. The hourly variation of the concentration of PM and gases (excluding O3) shows two peaks: one at around 6:00–12:00 LT and the other at around 20:00–23:00 LT. These are the two time periods during the day with the maximum port operation and shipping traffic. The hourly ozone concentration follows the hourly solar activity, and it is affected by the photochemical and photolysis reactions [32]. In particular, the correlation between O_3 and NO_2 is −0.81 and −0.8 during the high and the low season (Figure 3), respectively. During the high port activity season, the concentration of pollutants shows statistically significant higher values compared to the low season. The PMs show an increase of about 4.5 mg/m^3 between the two studied seasons. Additionally, the difference between the concentrations for NO, NO_2 and SO_2 is higher by about 14 ppb, 8 ppb, and 5 ppb, respectively. The only exception is CO, which shows a slight increase. In summary, the analysis of the hourly evolution clearly shows the effect of the port activity on the local air quality. Additionally, wind speed (WS) and wind direction (WDir) have a significant effect on air quality by reducing the concentration of pollutants in the port.

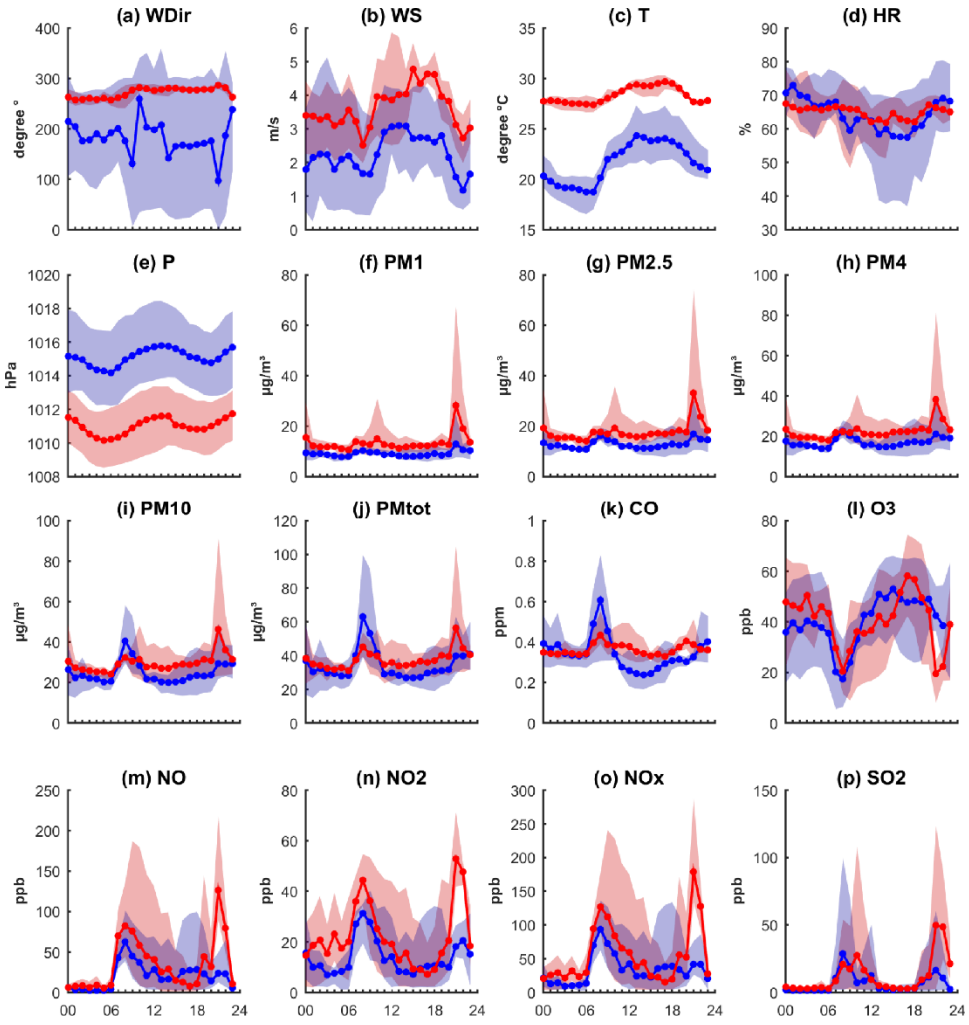


Figure 4. Hourly evolution of meteorology (**a**–**e**) and air quality parameters (**f**–**p**). The red/blue lines indicate the high/low port activity seasons. The shaded area indicates the range between lower and higher hourly variability during the two studied seasons (red for the high and blue for the low port activity season, respectively).

4. Conclusions

This study investigates the impact of port operation and shipping on the air quality of the port city of Heraklion. For the analysis, the comparison of a high and a low port activity season during 2018 is conducted. The results show that port activity and shipping

are associated with the degradation of the local air quality for both studied seasons. The impact of port activity is more significant during the high season compared to the low season. In particular, the gases and PM increase, whereas the ozone presents insignificant changes due to the impact of low tropospheric circulation over the eastern Mediterranean. The wind speed is significantly anti-correlated with gaseous pollutants. Wind speed and wind direction are fundamental meteorological components that affect the concentration of pollutants in Heraklion port. Moreover, the PM2.5/PM10 ratio increases during the high port activity season compared to the low season, indicating the impact of port operation and shipping on the local air quality. Finally, the analysis highlights the impact of port operations and shipping activities on coastal air quality in the context of the Paris agreement [34], coastal climate risk, and sustainable development.

Funding: This research was funded by the Connecting Europe Facility of the European Union, grant number 2014-EU-TM-0673-S. The APC was funded by Poseidon Med II Action No.2014-EU-TM-0673-S.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: https://ypen.gov.gr/ (accessed on 3 April 2021).

Acknowledgments: The study received support from the POSEIDON MEDII project, which is co-financed by the Connecting Europe Facility (CEF) Transport Sector of the European Union. The authors would like to thank DEPA Commercial S.A (project coordinator) and DESFA S.A. (project technical coordination). The authors acknowledge the Ministry of Environment and Energy (MEEN) for the available recordings of the Heraklion monitoring station (https://ypen.gov.gr/ (accessed on 3 April 2021). We wish to thank Heraklion Port Authority S.A. and personnel for providing information regarding the port activity to guarantee the representative sampling of recordings for the analysis. We would also like to thank Envirosys Ltd. Environmental Applications Technological Equipment, Athens, Greece, for the collaboration and the availability of the Horiba Ltd. Sensors.

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

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