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Comparison analysis of the effect of high and low port-activity season on air quality in the port of Heraklion†

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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. Its impact on operation affects the socio-economic life and development because Heraklion is not just a tourist destination, but also a significant trade and transportation center over 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 conducted from 02.08.2018 to 08.08.2018, while the second one between 11.05.2018 and 16.05.2018. For the air quality measurements, a low-cost sensor is used while the recordings are 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, the mean differences between high and low period 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. In both seasons studied, the air pollution level increases during hours of high port-activity indicating the impact of the 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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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 over the world, with a rapidly growing trade activity due to globalization and socio-economic development [1]. Even if the port activity is a key feature of economic development, its impact on the environment and human health concerns the scientific community [2]. Increased shipping and port operation affect on the air quality degradation, and it also contributes to the increase of coastal climate risk [3, 4]. The Mediterranean region is recognized by the United Nations Environmental Programme [1] as one of the most prominent and vulnerable climate change hot-spots [5, 6, 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 have an important impact on human health [3, 11], as global shipping emission mortality for 2020 was estimated at 250,000 per year [12].

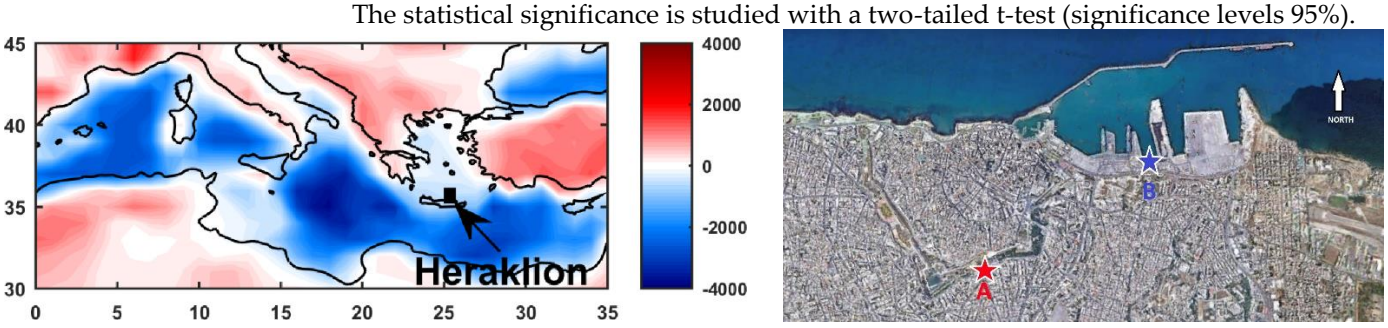
Emissions from navigation, ships on berth and port operation are a significant component of pollution including gases (NOx, SOx, CO, O3), particulate matter (PM) and GHGs [13]. Excluding emissions, air quality is affected by weather [14], while additionally the concentration of pollutants is sensitive to climate and meteorological parameters [15, 16]. The emissions from port operation and shipping are projected to increase in the future. In particular, the economic development is projected to increase the CO2 between50% to 250% by 2050 [17], if mitigation measures are not taken by policy makers. Generally, the emissions from transport have been decreased since 1900 except for shipping, where PM, SO2 and NOx emissions have been increased [8, 18] representing about10% 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 shown that maritime emissions contribute to the SO2 concentration more significantly than the road traffic. However, the shipping contributes to the concentration of PM and NOx in 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]. 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 the shipping [24]. During the period from 2013 to 2016, Civitavecchia port activity in Italy contributes significantly to the concentration of NO2 (33%), PM10 (43%) and SO2 (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 over eastern Mediterranean [25]. There are not previous studies which investigate the impact of shipping and port activity over the ports of south Aegean Sea. This study investigates the impact of port operation and ship emissions in order to characterize the air quality, based on conducted air measurement campaigns in the Heraklion port, that compared a high and a low port activity season during 2018. Moreover, the effect of meteorological conditions on the air quality is investigated for the two studied periods.

2. Methods and Data

The Heraklion city (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 over eastern Mediterranean (Figure 1a). Heraklion is the capital of Crete and the fourth largest city of 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, NO2; ppb, O3; ppb, CO; ppm, SO2; ppb), particle matters (PM1, PM2.5, PM4, PM10, PM_tot; μg/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 the period from 02.08.2018 to 08.08.2018, and the second, the low port and shipping activity period, is considered the period from 11.05.2018 to 16.05.2018. In order to evaluate the variability of the LCS recordings, the regression between the LCS anomalies with 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 pollutants concentration and the meteorological parameters are studied to better understand the impact of port operation and shipping on the air quality of Heraklion port. For the analysis, the hours with strong (weak) wind speed are considered the hours with wind speed higher (lower) to the 90% (10%) of 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 (significance levels 95%).



(a) **(b)**

Figure 1. (a) Location of Heraklion on Crete Island over 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

3. Results

In order to evaluate the variability of recordings from the LCS the regression coefficient of the anomalies of the available recordings (PM10) from the monitoring station of Ministry of Environment and Energy (MEEN) regarding the anomalies of PM10 recordings of 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. in order 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 from WNW to NW (~300°) directions and during the low port activity season, the wind speed blows from SSW (~200°; with high variability) directions, respectively. The dominant pattern of wind speed and direction during high season possibly reduce the impact of the port activity on central west area of Heraklion. To compare the PM10 recordings between 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 on the PM10 anomalies of LCS is about 2.0 (R=0.77, SE 0.15 and p-value <0.05). The wind direction (as recorded by LCS in the port) prevails mainly from 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 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 affects more significantly the air quality of Heraklion compared to the low port activity season.

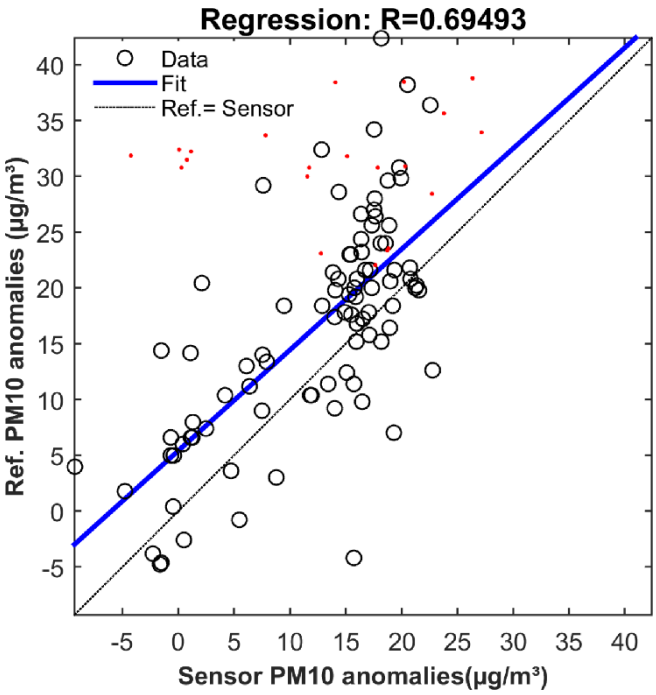


Figure 2. Scatter plot and linear regression of PM10 anomalies of the monitoring station of MEEN (Ref. PM10) recordings on LCS PM10 anomalies during the high port activity season. Red points indicate the recordings that are excluded from the regression analysis during the high shipping hours.

The correlation coefficients between air quality (gases and PM) and meteorological parameters for both high (left panel) and low (right panel) port activity season are shown in Figure 3. This analysis shows that wind speed (WS) is associated with the reduction of gases pollutants except for ozone (O3). The concentration of O3 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 (PM1 excluded). 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 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.

The ratio of PM2.5/PM10 usually is associated with the sources. The highest ratio shows the largest contribution of PM2.5 indicating primarily pollution for 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 stronger wind speed compared to the hours with 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 stronger wind speed are considered the hours with wind speed greater than 90% of wind speed distribution of high season and the hours with weak wind speed are considered the hours with wind speed less than 10% of wind speed distribution of 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.

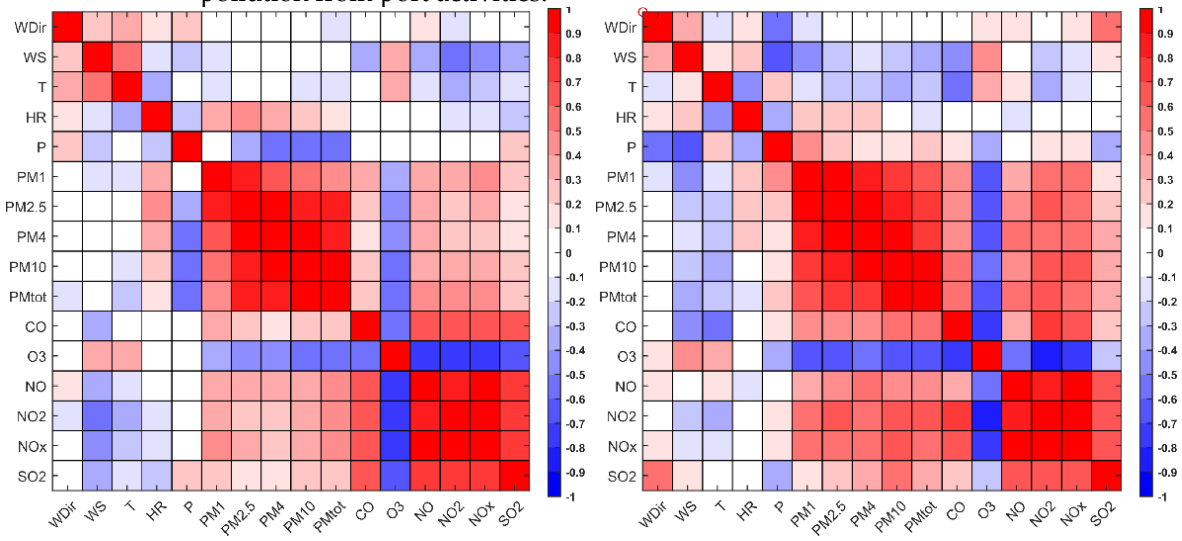


Figure 3. Correlation coefficients for air quality (pollutants) and meteorological parameters **(a)** for High port activity and **(b)** for Low port activity season.

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 season (Figure 4) is calculated. During the high port activity season, the winds prevail from NWW (~300°) direction having low variability (Figure 4a) and the wind speed is stronger about 1.34m/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, the one around 6:00-12:00 LT and the other around 20:00-23:00 LT. These are the two time periods during the day with 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 O3 and NO2 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 4.5mg/m^3 between the two studied seasons. Additionally, the difference between the concentrations for NO, NO2 and SO2 is higher by about 14ppb, 8ppb and 5ppb, respectively. The only exception is the CO which shows a slight increase. To sum up, the analysis of hourly evolution clearly shows the effect of the port activity on the local air quality. Additionally, wind speed (WS) and wind direction (WDir) play a significant role in the air quality by reducing the concentration of pollutants in port.

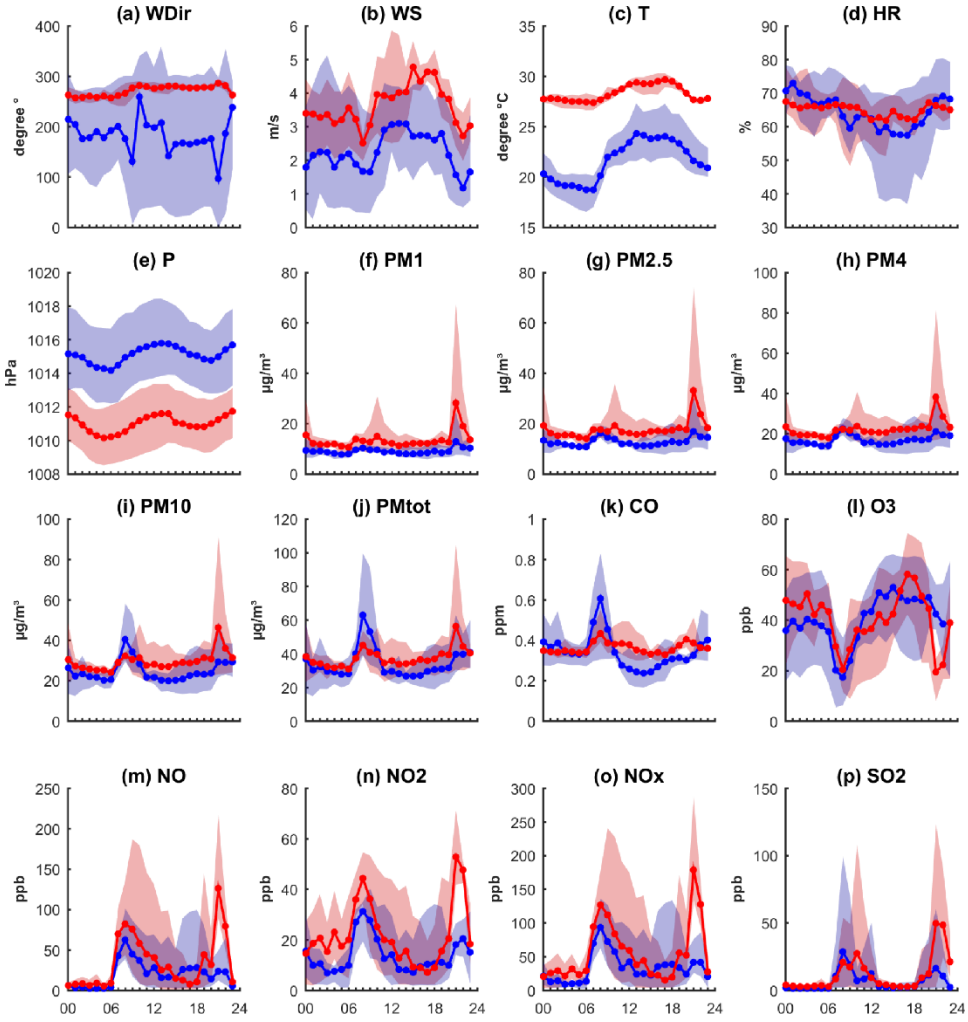


Figure 4. Hourly evolution of meteorology (a-e) and air quality parameters (f-p). The red/ blue lines indicate the high/ low port activity season. The shaded area indicates the range between lower and higher hourly variability during the two studied seasons (red for the high and blue for the low port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

4. Conclusion

This study investigates the impact of the 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 low season. In particular, the gases and PM are rising whereas the ozone presents insignificant changes due to the impact of low troposperic circulation over the eastern Mediterranean. The wind speed is significantly anti-correlated with gasses pollutants. Wind speed and wind direction are fundamental meteorological components which 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 Paris agreement [34], coastal climate risk and sustainable development.

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Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: https://ypen.gov.gr/

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

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