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The Air Quality and Influence of Etesians on Pollution Levels in the City of Rhodes: The Case of July 2022 †

Ioannis Logothetis *, Christina Antonopoulou, Georgios Zisopoulos, Adamantios Mitsotakis and Panagiotis Grammelis

Centre for Research and Technology Hellas, Chemical Process and Energy Resources Institute, 57001 Thermi, Greece
* Correspondence: logothetis@certh.gr
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Abstract: In July 2022, strong and high-frequency northern sector winds blew over the Aegean Sea. The low tropospheric circulation in combination with air quality and human comfort is of great importance for the climate and human health. This study investigates the variation in pollutants' concentrations (PM_{10}, NO_2, O_3 and SO_2), meteorological factors (temperature, relative humidity, wind speed and direction) and the discomfort index in the city of Rhodes during July 2022. Additionally, the impact of Etesians on pollution levels is studied. The strength of the Etesian flow is quantified by calculating a statistical index that takes the July pressure gradient (ΔP) over the Aegean Sea into consideration. For the analysis, pollutants' concentration recordings from a mobile air-quality-monitoring system during July 2022 and mean sea level pressure (MSLP) data from ERA5 reanalysis during July for the period from 1980 to 2022 are analyzed. The results indicate that traffic affects the pollution level although the pollution limits, according to the European directive for air quality (2008/50/EC), are not exceeded. The findings also reveal an increase in ΔP, about 1.8 hPa, during 2022 compared to the period from 1980 to 2022 and the dipole of high (over Balkans) and low (over eastern Mediterranean) pressure centers also strengthens, leading to stronger winds over the Aegean Sea. The ΔP is strongly correlated (0.8) to the first principal component of MSLP over the eastern Mediterranean. Finally, this study shows that the Etesian flow tends to reduce the concentration of PM_{10}, NO_2 and O_3, and improving the air quality in the city of Rhodes.

Keywords: air quality; pollutants; discomfort index; Etesian flow; low tropospheric circulation; eastern Mediterranean; Aegean Sea; pressure gradient (ΔP); PC analysis; EOF analysis

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1. Introduction

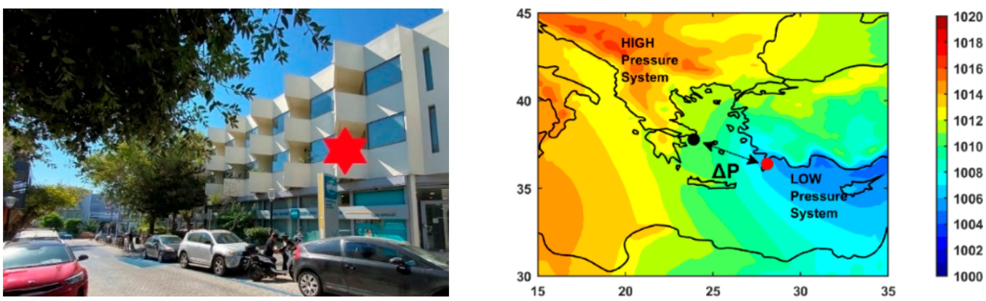
In July 2022, strong northern sector winds blew over the Aegean Sea, affecting tourism activities and sailing over the Aegean basin. Generally, the northern sector wind speed system during the summer period is the dominant atmospheric circulation over the southeastern Mediterranean [1–4]. This annual permanent wind system has been known since ancient times. Aristotle gave these winds the name "Etesians" because they blow every year in the summer period and peak in July and August. The cause of this wind system is a pressure gradient that is created over the Aegean Sea [2,4]. In particular, a dipole of a high-pressure center located in the Balkans-central Europe and a low-pressure center located over southeast Mediterranean (as part of thermal low extending from the Indian Monsoon through the Middle East to southeastern Mediterranean [2,5]) leads to the formation of a pressure gradient over the Aegean Sea during the summer months [2,4,6]. The pressure gradient, in combination with the topography of eastern Mediterranean, establishes the Etesian regime that transfers cool air masses from the Caspian Sea and Russia to southeastern Europe, acting as a "ventilation" system for the southeastern Mediterranean [7,8].

Poor air quality is a factor that increases environmental danger and negatively affects human health [9]. Rhodes Island, located in the southeastern Mediterranean, is a desirable tourist destination. The increasing tourism industry (the high rate of tourist arrivals, the increased marine traffic and cruise shipping) leads to the deterioration of air quality in this climate-prone region, affecting sustainable development [9–11]. Air quality over coastal regions is affected by traffic emissions, human activities and meteorological factors [10,12]. Logothetis et al. [10] have already shown that the urban region of Rhodes is affected by traffic emissions and pollution episodes that are related to the transfer of particle matter and gaseous pollutants from wildfire regions to the southeast Aegean Sea. The Etesian wind system is related to the improvement in air quality over the Aegean Sea by dispersing the concentration of pollutants over the southeastern Mediterranean [5,8], whereas Etesians are associated with high wildfire risk during the summer season [13].

The current work investigates the variability in pollutant concentrations (PM_{10}, NO_2, O_3 and SO_2) and the impact of low tropospheric circulation on the pollution level of the city of Rhodes during the heart of the summer of 2022. It is important to highlight that the variation in the concentration of pollutants is sensitive to the impact of street planning due to its influence on local air mass circulation. In this context, the present study aims to investigate the impact of the tropospheric circulation of Etesians, which is the dominant summer circulation in the area, on the pollution level and variation in the pollutant concentration. Finally, this study could form the basis for the development of an air-quality-management plan that would provide data regarding summer atmospheric circulation indices and pollution levels associated with environmental and health risk.

2. Materials and Methods

In this work, recordings from the Haz-Scanner™ HIM-6000 model, air-quality-monitoring station (AQMS) are used to analyze pollutant concentration variation. The recordings include (a) the concentrations of particulate matter with a diameter less/equal to 10 μm (PM_{10}), nitrogen dioxide (NO_2), ozone (O_3) and sulphur dioxide (SO_2), as well as (b) the meteorological factors of temperature (T), relative humidity (RH), wind speed (WS) and direction (WDir). The air-quality-monitoring station is located on a high-traffic road in the city center of Rhodes (Figure 1a). To investigate the impact of Etesian wind system on the pollutants concentrations, MSLP data available from the ERA5 reanalysis, in the frame of European Centre for Medium-Range Weather Forecasts (ECMWF), are analyzed in a spatial window over the eastern Mediterranean (15°–35° E, 30°–45° N).



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

Figure 1. (**a**) Red star shows the location of the air quality monitoring system in the city center of Rhodes. (**b**) Map of the composite mean July MSLP (hPa) for the period from 1980 to 2022. The black/red points show the location of Elliniko (Attica)/Rhodes. The locations of the high- and low-pressure systems are also shown.

In order to investigate the sense of comfort of the population during July 2022 in the city center of Rhodes, the Thoms's discomfort index (DI) [14,15] is calculated. DI is considered as the most common bioclimatic index to express human experience under modified meteorological conditions using the following equation:

$$DI\ (^{\circ}C) = T - 0.55 \times (1 - 0.01 \times RH) \times (T - 14.5) \quad (1)$$

To study the frequency and quantify the strength of the Etesian flow over the Aegean Sea, the methodology of Dafka et al. [2] is followed, where the pressure gradient over the Aegean Sea is used to classify a day as an Etesian day. In our analysis, the July pressure gradient (ΔP) is defined by the difference between the pressure in the region of Elliniko (Attica) and Rhodes Island using MSLP data from ERA5 (Figure 1b). ERA 5 is a reanalysis dataset available in the frame of ECMWF that provides hourly estimates of a large number of climate parameters (atmospheric, land and oceanic variables). ERA5 combines historical observations into global estimates using modelling and data assimilation techniques. Its spatial resolution is 31 km (grid), and the atmosphere is resolved by 137 levels (from surface up to 80 km) [16]. Regarding the analysis, a day is classified as an Etesian day when ΔP is greater than/equal to the median of the positive values of the ΔP distribution. Note that, in this work, the analysis is focused on July 2022 because this period presents a climatic interest (high frequency of Etesians and high diurnal wind speed compared to the period from 1980 to 2022). To investigate the concentration of pollutants, during the studied period, the diurnal variation and the evolution of the daily mean concentration of pollutants for July 2022 are calculated. Additionally, the Spearman correlation coefficients among pollutants concentration, meteorological factors and DI are calculated to investigate the possible association among these variables. Additionally, in order to identify the impact of Etesian flow on the pollution level in the city of Rhodes, the composite difference map of MSLP over the spatial window 15°–35° E, 30°–45° N is constructed. This analysis shows the changes in the high- and low-pressure system over the Balkans and the eastern Mediterranean, respectively. This dipole leads to the establishment of a pressure gradient over the Aegean Sea during summer months causing the Etesian flow. Furthermore, the difference in diurnal variation of (July) ΔP between 2022 and the period from 1980 to 2022 is calculated to investigate the diurnal changes in ΔP between two periods.

In climate studies, the empirical orthogonal function analysis (EOF) is commonly used to investigate the spatiotemporal variability of climate variables and to identify patterns [17]. In this study, the three dominant modes of EOFs and PCs that explain 79.1%, 14.1% and 6.1% of MSLP over the eastern Mediterranean are estimated, respectively. Additionally, the EOF maps with the corresponding PCs (normalized) are constructed. Finally, the two-tailed t-test with 95% significance levels is used for statistical significance [18].

3. Results

Figure 2 shows the diurnal variation in the pollutant concentrations, meteorological factors and discomfort index. This analysis shows that the concentration of pollutants is maximized during the hours with high traffic activity. The maximum concentrations of NO_2 and O_3 occur during the afternoon and midnight hours (Figure 2b,c). This change is probably explained by the combined effect of traffic emissions, photochemical and photolysis reactions as well as the diurnal wind speed variation (Etesian regime) [2,10]. The recordings show that the wind speed increases by about 30% during the hours 11:00 to 18:00 as compared to the other hours in an average day in July 2022. The concentration of PM_{10} presents the maximum hourly values (about 30 to 40 $\mu g/m^3$) during afternoon and early morning hours. A peak concentration (about 46 $\mu g/m^3$) is presented about 12:00–13:00 (EEST), possibly due to the maximization of human activities and traffic emissions during this time (Figure 2a). Additionally, during daytime hours, the shipping and port activities are maximized. The activity of passenger and cruise ships in combination with traffic emissions in the city center of Rhodes possibly explains the variability of the concentration of PM_{10}. The common diurnal variation in SO_2 and PM_{10} possibly indicates the common origin of these pollutants (possibly shipping). DI values vary between 22 and 25, which means that a significant percentage of the population feels discomfort (Figure 2g). Generally, high concentrations of pollutants and high DI increase the risk to human health [5,10].

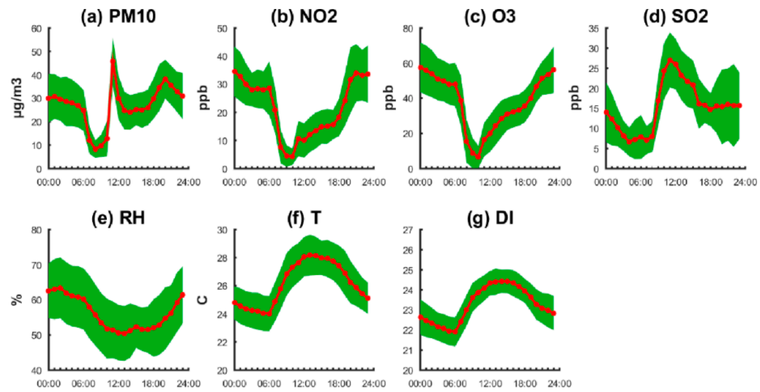


Figure 2. Diurnal variation for (**a**–**d**) the concentration of PM_{10}, NO_2, O_3 and SO_2, (**e**,**f**) meteorological factors (RH,T) and (**g**) discomfort index (DI) for the city center of Rhodes during July 2022. The red line shows the daily mean value, and the green area denotes the mean value plus/minus one standard deviation.

The daily mean evolution of the pollutants concentration during July 2022 does not present any daily mean exceedance of the threshold limit according to the European Air Quality Directive (2008/50/EC; Figure 3). Rizos et al. [8] and Logothetis et al. [10] have shown that strong wind speeds are related to a reduction in pollutant concentrations. It is likely that the strong winds that blow during July 2022 significantly affect the level of pollution in the city center of Rhodes.

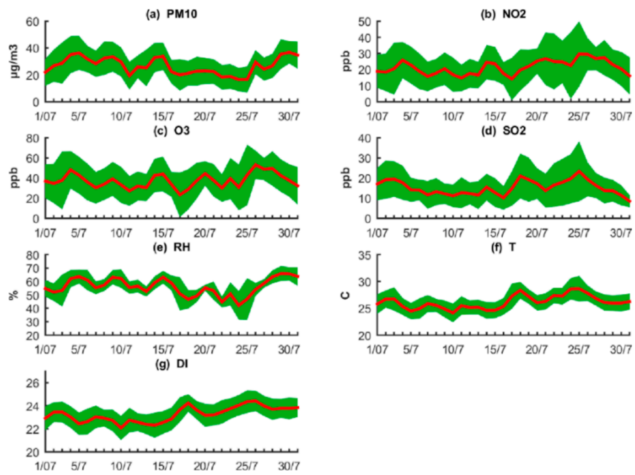
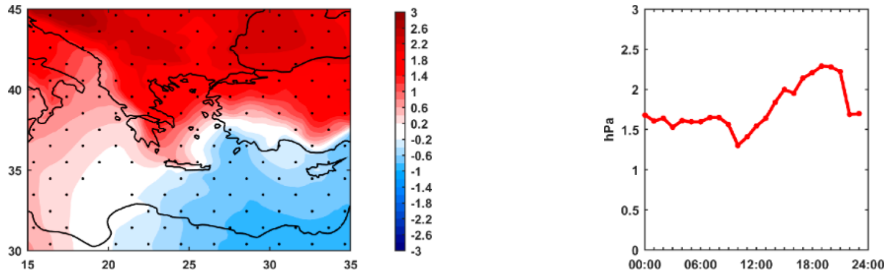


Figure 3. Daily mean variation for (**a**–**d**) the concentration of PM_{10}, NO_2, O_3 and SO_2, (**e**,**f**) meteorological factors (RH,T) and (**g**) discomfort index (DI) for the city center of Rhodes during July 2022. The red line shows the daily mean value, and the green area denotes the mean value plus/minus one standard deviation.

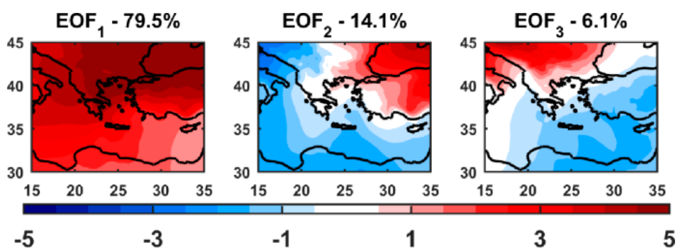
The July mean pressure gradient (July ΔP) over the Aegean Sea during 2022 was stronger, about 1.8 hPa, compared to the July mean ΔP from 1980 to 2022 (recent, past-July period). This indicates the intensification of the Etesian regime in July 2022. The difference between the composite mean (July) MSLP for 2022 and that of the period from 1980 to 2022 shows that the high-pressure center over the Balkan Peninsula increased and that the low-pressure center over the southeastern Mediterranean deepened (Figure 4a). The change in this dipole (defined by the two pressure centers) leads to the strengthening of ΔP and the wind speed over the Aegean Sea. In addition, the diurnal variation in the difference of ΔP over the Aegean Sea between 2022 and the period from 1980 to 2022 shows that the ΔP is stronger in the afternoon and early evening (Figure 4b). This finding emphasizes that, during July 2022, the diurnal variation in the Etesian winds shows high wind speeds during the afternoon and night hours as well. According to the recordings, during the summer 2021, there are days with moderate air quality above the city center of Rhodes (in terms of CAQI index [10]). The improved air quality during the summer of 2022 is likely influenced by the intensifying Etesian regime. The analysis shows that the frequency of Etesian days for July for the period from 1980 to 2022 is about 48% and, for 2022, is about 81%, respectively (a relative increase of about 68%).



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

Figure 4. (**a**) Map of the difference between composite mean (July) MSLP (hPa) of 2022 and the period from 1980 to 2022. (**b**) Diurnal variation in the difference in (July) pressure gradient over the Aegean Sea between 2022 and the (July) 1980–2022 period.

In order to further investigate whether changes in MSLP contribute to the increase in Etesians during July 2022, the three dominant modes of empirical orthogonal function (EOFs) and the corresponding principal component timeseries (PCs) of MSLP variability are calculated (Figure 5). The variation in the EOF1 shows an increase in MSLP over the east Mediterranean (Figure 5a). EOF2 and EOF3 show north–south dipoles that intensify the pressure gradient over the Aegean basin (Figure 5b,c). The analysis shows that ΔP is strongly associated with the PC1 (correlation coefficient ~0.8). Furthermore, ΔP is (significantly) negatively related to the concentration of PM_{10}, NO_2 and O_3, with correlation coefficients −0.45, −0.25 and −0.4. This result indicates that, when the Etesian flow increases, in terms of ΔP, the pollutant concentrations show a decrease. In line with previous works [8,19], the findings of this study possibly indicate the influence of Etesian winds variability on pollution level.



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

Figure 5. The three dominant EOF modes of MSLP between 15°–35° E and 30°–45° N for July 2022. The percentage of total variance explaining the pattern appears in the title of each subplot.

4. Conclusions

Our investigation into the air quality and influence of Etesians on pollutant concentrations in the city of Rhodes in July 2022 results in the following points:

- Traffic and human activity affect air quality, although the pollution limits do not exceed the thresholds according to 2008/50/EC.

- The discomfort index indicates that, in some cases, half of the population feels discomfort in the city center of Rhodes. The combination of high DI values and increased pollutant concentrations negatively affects human health.
- ΔP is negatively associated with the concentration of PM_{10}, NO_2 and O_3, providing evidence that the strong and high-frequency Etesians of July 2022 are related to improved air quality over the southeastern Aegean Sea.

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