

# The Air Quality of a Mediterranean Urban Environment Area and Its Relation to Major Meteorological Parameters

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**Abstract** The paper presents a comprehensive analysis of the most basic features of the air quality of a Mediterranean urban environment area. The impact of meteorology on the air quality is also examined. Observational surface concentrations of the most important air pollutants, recorded at two measuring stations in Patras, Greece, are used. The Weather Research and Forecasting (WRF) meteorological model was employed to produce a series of surface and upper air data and local circulation and ventilation indices. These modeled data along with selected surface meteorological observational data comprise a substantial data set that was used to assess the effect of meteorology on the air quality. Mostly during the summer period, a significant proportion of the particulate matter is transported from sources away from the measuring sites. The synoptic setting of winter and summer seasons represented primarily by the local ventilation and recirculation, the wind, the boundary layer height, and the precipitation has a very strong impact in the overall formation of the air quality status.

**Keywords** Urban environment · Boundary layer · Air quality · Meteorology

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## 1 Introduction

Atmospheric pollution is one of the most significant environmental problems of the modern world. Its adverse effects are associated with the degradation of the quality of life and the alteration of the characteristics of the biosphere, forcing governments and international organizations to dedicate economic and human resources for the improvement of air quality in order to protect the biosphere. Atmospheric pollution is not a simple problem of control of the emission sources. The complexity of the air quality management is amplified by the inducement of uncontrollable key factors in the process. The most important of these factors is meteorology. The prevailing meteorological conditions on local and synoptic scales are very important. The identification of the relations between meteorology and air quality is necessary and can help authorities to develop effective environmental strategies aiming to the improvement of the quality of life.

The city of Patras, Greece, is a typical medium-size Mediterranean coastal city of over 200,000 inhabitants. It is surrounded by a number of industrial facilities, including a large cement factory on the northeastern side of the city. Middle and low-elevation mountains and hills are located on the southeastern side. As a modern semi-industrial city, Patras is prone to all the air quality problems that such cities may present. Increased vehicular traffic, central heating, residential activities, and

industrial operations release significant amounts of gaseous and particulate matter pollutants in the urban atmosphere, increasing their surface concentrations (Markakis et al. 2010a and b). Moreover, the presence of a heavy-load port inside the urban area adds a considerable amount of port-related emissions and has a negative impact on the atmospheric quality.

Significant work has been done around the globe regarding air pollution characteristics and its relations to meteorology. Rodríguez et al. (2002) examined the origin of high summer PM<sub>10</sub> and total suspended particulate (TSP) concentrations at rural sites in Eastern Spain, concluding, among others, that breeze circulations are partly responsible for these extreme events. The dependence of urban air pollutants on meteorology in the area of Cairo was analyzed by Elminir (2005). It was shown that wind and humidity affected the concentration and speciation of the pollutants. Barmpadimos et al. (2011) examined the influence of meteorology on PM<sub>10</sub> trends and variability in Switzerland from 1991 to 2008 and indicated that wind and temperature are two of the most significant factors. Gadzhev et al. (2013), in a study which includes the whole Bulgarian region, also concluded that NO<sub>2</sub>, SO<sub>2</sub>, primary organic aerosol, coarse particulate matter, and fine particulate matter present higher concentrations during the cold period (autumn, winter) and lower during the warm period (spring, summer). Ozone concentrations, on the other hand, are higher during the warmer part of the year. Regarding Greece, Lalas et al. (1987) studied the influence of the complicated land-sea interactions and the diverse geomorphology of specific areas on atmospheric pollutants and showed that the sea breeze circulation is affecting the diurnal variation of surface O<sub>3</sub> in the city of Athens. Kallos et al. (1993) studied a series of air pollution episodes in Athens during the period 1983–1990 concluding that the “days with critical balance between synoptic and mesoscale circulations and/or days of warm advection in the lower troposphere” favor such episodes. Ziomas et al. (1995) showed that the use of simple meteorological variables like temperature and surface wind, combined with pollution measurements, can give rather good forecasts of peak pollutant levels for the city of Athens. The air quality in the Athens basin during sea breeze and non-sea breeze days was examined by Kambezidis et al. (1998) too. They showed that during sea-breeze conditions, O<sub>3</sub> is convected to rather high altitudes. NO<sub>2</sub> does

not show the same pattern, presenting low concentrations aloft. During the Etesian days, the O<sub>3</sub> field is rather homogeneous with maximum values at altitudes lower than those on sea-breeze days. Kassomenos et al. (1998a) examined the relationship between specific air quality indices and the atmospheric circulation over the Athens area and showed, among others, that the most favorable synoptic pattern for the accumulation of high pollutant concentrations is the open anticyclonic circulation. They also showed that the occurrence of extreme events is favored by the synoptic pattern of the closed anticyclone. Melas et al. (2005), using a 3D, higher-order turbulence model, showed that during days of sea-breeze, the Athens basin suffered horizontal recirculation that often resulted in increased pollutants levels. Papanastasiou et al. (2007) developed multiple regression and neural network (NN) prediction models, using, among others, meteorological parameters as predictors and estimated average daily PM<sub>10</sub> concentration values for the Greek city of Volos with satisfactory results. According to Poupkou et al. (2009), the urban plume of Athens is transported to the south by the north winds prevailing during summertime in the Eastern Mediterranean basin and allows elevated ozone levels to appear over the maritime areas a few hundreds of kilometers south of Athens given also the low deposition velocity of ozone over the sea. Im et al. (2011) investigated the impact of temperature changes on summer time ozone and its precursors in the Eastern Mediterranean and found that ozone mixing ratios increase almost linearly with ambient temperature. Tsiotas and Argiriou (2011) modeled with satisfactory results the air pollution over the Athens area using statistical approaches. Karagiannidis et al. (2013), analyzing the meteorological setting of a particulate air pollution episode in the Amyntaio-Ptolemais-Kozani basin, showed that the weak horizontal wind field near the surface and the reduced mixing height combined with the lack of synoptic forcing resulted in the trapping of the pollutants in the lower troposphere and in the increase of observed airborne particulate matter concentrations.

Specific aspects of the air quality problems of the city of Patras have already been analyzed. Danalatos and Glavas (1999), examining gaseous nitric acid, ammonia, and related particulate matter, found a distinct seasonality with higher concentration during summer and evidence of long-range transport for particulate sulfate. Riga-Karandinos and Saitanis (2005), assessing the air

quality of Volos and Patras, Greece, concluded that both these cities experience high levels of  $\text{NO}_x$ . Yannopoulos (2007) found that the mixing height is inversely related to the surface  $\text{SO}_2$  concentration. Finally, Maraziotis et al. (2008) found a strong negative correlation between inhalable and fine particles ( $\text{PM}_{10}$  and  $\text{PM}_{2.5}$ ) and the horizontal wind speed in Patras.

In the present paper, a general assessment of the air quality of a medium-size Mediterranean coastal city like Patras is attempted and the impact of meteorology on it is elucidated. Firstly, the general picture of the air quality of the city of Patras is illustrated. The interannual, seasonal, and weekly variations of pollutant surface concentrations are presented. The impact of meteorology on the air quality is then examined using observed and modeled meteorological data and calculated indices. The correlation coefficients between the meteorological parameters and indices and the surface pollution concentrations are calculated and discussed. Pollution roses are also created in order to further investigate the relation of air quality to surface wind field. The impact of precipitation is analyzed through the comparison between rainy days and days without rain. Finally, a synthesis of the results is attempted in the conclusion section.

## 2 Data and Methodology

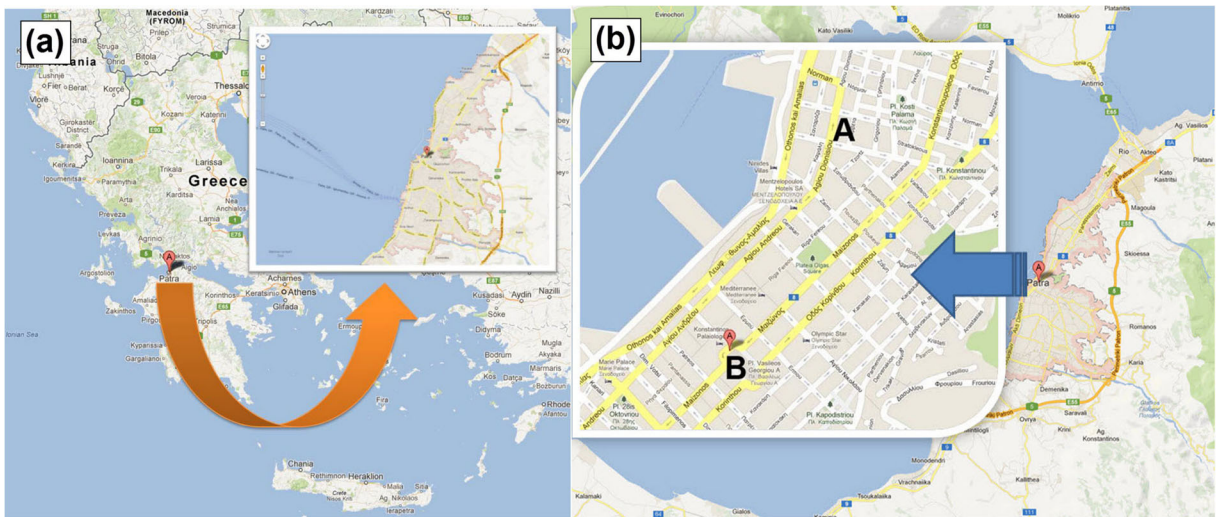
Daily values of  $\text{CO}$ ,  $\text{NO}$ ,  $\text{NO}_2$ , and  $\text{PM}_{10}$  concentration data, recorded at two monitoring stations operating inside the city, are used in this study.  $\text{O}_3$  concentrations are also measured at one of the two stations. The two stations provided hourly records of the pollutant concentrations from 2008 to 2011 that were used to compute the average daily values for the same period. Table 1 provides the location information and the main characteristics of the two measuring sites, while Fig. 1 illustrates the position of the two stations. As it can be seen, the monitoring stations are located very close to the city center and are expected to be influenced by the

pollutants emitted from the enhanced anthropogenic activities that take place in it. The proximity to the port is also expected to have an important impact on the measurements of the two stations.

Very close to those two stations, inside the port area, a meteorological station is operated by the National Observatory of Athens. It records hourly data of main surface parameters, like wind speed (WS), temperature ( $T$ ), mean sea level pressure (MSLP), and precipitation amount ( $P$ ). These data were used to compute average daily values for the parameters mentioned above for the period 2008–2011. In order to examine the impact of a series of dynamic meteorological parameters and indices that are not be measured by the surface meteorological station, the numerical model Weather Research and Forecast-Advanced Research Weather (WRF-ARW), version 3.2.1, was also employed in this study. WRF is a next-generation numerical weather prediction (NWP) modeling system developed to serve both operational forecasting and atmospheric research needs. The model's dynamics solver integrates the compressible non-hydrostatic Euler equations (Ooyama 1990), which are formulated on the Arakawa C grid using a terrain following mass vertical coordinate system (Laprise 1992). Microphysics processes were parameterized using the WRF single-moment six-class scheme (Hong and Lim 2006), whereas convection in the two coarse domains (d01, d02) was parameterized with the Kain-Fritsch scheme (Kain 2004). For the innermost domain (d03), no convective parameterization was used. Shortwave and longwave radiation processes were handled with the Dudhia (1989) scheme and the Goddard Fluid Dynamics Laboratory (GFDL) parameterization (Schwarzkopf and Fels 1991), respectively. The surface layer was parameterized using the MM5 similarity scheme (Skamarock et al. 2008), while for the planetary boundary layer, the Yonsei University (YSU) parameterization (Hong et al. 2006) was used. Land surface processes were handled with the Noah land surface model (Chen and Dudhia 2001). A detailed description of the model can be found in Skamarock et al. (2008).

**Table 1** Characteristics of the monitoring stations (AirBase v7 Database, (EEA 2013))

Location	Lat/Lon	Site Name	Type of station	Type of area	Characteristics of zone	Measured pollutants
Square Drosopoulou	38.253 N/21.738 E	Sta A	Traffic	Urban	Residential/commercial	$\text{CO}$ , $\text{PM}_{10}$ , $\text{NO}$ , $\text{NO}_2$ , $\text{O}_3$
Square King George	38.246 N/21.736 E	Sta B	Traffic	Urban	Residential/commercial	$\text{CO}$ , $\text{PM}_{10}$ , $\text{NO}$ , $\text{NO}_2$



**Fig. 1** a The city of Patras. b Locations of monitoring stations in the urban area (*sta A*: Square Drosopoulou, and *sta B*: Square King George)

The model develops initial and boundary conditions based on the operational 12:00 UTC forecast of ECMWF in 0.5° spatial resolution. The domain of the WRF modeling system is the South-East Europe/Eastern Mediterranean region from 18° N to 30° N and from 34.9° E to 44.5° E. The projection is the Lambert Conformal Conic, while the model runs are performed in two domains, the greater Balkan domain, having a grid of 10×10-km grid, and the Patras domain (37.8°–38.7° N/20.9°–22.5° E) which has a finer 2×2-km grid.

Model output consists of both 2D and 3D gridded fields. The 2D gridded fields used include 10-m horizontal wind components, 2-m dew point and air temperature, mean sea level pressure, sea surface temperature, skin temperature, and four-layer soil temperature and soil moisture (specified at 10, 30, 60, and 100 cm below ground).

The 3D fields used include geopotential height, relative and specific humidity, temperature, and horizontal and vertical wind components. Hourly values of boundary layer depth and horizontal wind speed and direction at 10 m above ground are estimated by the WRF model for the city center of Patras (38.252° N, 21.738° E). These parameters are then used to calculate the average daily values of the boundary layer depth ( $PBL_{ave}$ ); the geopotential height at the 500 hPa isobaric surface ( $Geop_{500}$ ); and also the ventilation factor ( $V$ ), wind run ( $S$ ), and recirculation factor ( $R$ ) for January, February, July, and August of 2010.

The circulation indices (ventilation factor, wind run, and recirculation factor) are defined and computed

according to Allwine and Whiteman (1994) and Melas et al. (2005) as:

$$V_i = T \sum_{j=1}^{i+p} (\langle U \rangle_j \cdot h_j) \tag{1}$$

$$S_i = T \sum_{j=1}^{i+p} \langle U \rangle_j \tag{2}$$

and

$$R_i = 1 - \frac{L_i}{S_i} \tag{3}$$

where  $U$  is the wind speed at 10 m above ground level (AGL),  $u$  and  $v$  are the west-east and south-north components of wind,  $h$  is the boundary layer depth,  $i=1,2,\dots,N-p$ ,  $N$  is the total number of series data points and  $p = \lceil T-1 \rceil$ ,  $\tau$  the selected transport time, and  $L_i$  the resultant transport distance, defined as follows:

$$L_i = \sqrt{X_i^2 + Y_i^2} \tag{4}$$

with

$$X_i = T \sum_{j=i}^{i+p} \langle u \rangle_j \tag{5}$$



and

$$Y_i = T \sum_{j=i}^{i+p} \langle v \rangle_j \quad (6)$$

$V$  values close to zero indicate stagnant conditions while values close to unit suggest strong horizontal ventilation.  $S$  is a measure of a straight line transport of an air parcel. Values close to zero are associated to almost stagnant conditions.  $R$  values approaching 0 indicate straight line transport, while values approaching 1 means negligible net transport and extended local horizontal recirculation. By definition, a value of 1 means that a complete recirculation has occurred and the air parcel returned to its origin.

After the preparation of the datasets presented earlier, the interannual, seasonal, and weekly variations of the pollutant concentrations are computed and discussed. Regarding the weekly variations, the analysis is carried out separately for winter and summer due to the different concentration levels of pollutants on these two seasons.

The impact of meteorology on the air quality is then examined. Correlation coefficients between the observational meteorological data ( $WS$ ,  $T$ , and  $MSLP$ ) and  $CO$ ,  $PM_{10}$ ,  $NO$ ,  $NO_2$ , and  $O_3$  concentrations are calculated for winter and summer. The 95 % level of significance is also calculated in order to identify the statistically significant coefficients. The relation between surface wind and air quality is more thoroughly investigated through the inspection of pollution roses that are created using observational wind and air quality data. Average concentrations are calculated for rain and no rain days separately, in order to assess the impact of precipitation. Finally, the WRF dynamic parameters and indices ( $Geop_{500}$ ,  $PBL_{ave}$ ,  $V$ ,  $S$ , and  $R$ ) are also correlated to the pollutant concentrations and the statistically significant correlations are identified and discussed.

### 3 Results and Discussion

#### 3.1 Interannual, Seasonal, and Weekly Variations

Figure 2 illustrates the interannual variation of the average annual concentration of each pollutant. A clear decrease is found for  $CO$ ,  $PM_{10}$ ,  $NO$ , and  $NO_2$  during the 4-year period examined. For example,  $NO_2$  at sta B decreases from  $40.3 \mu\text{g}/\text{m}^3$  during 2008 to  $20.2 \mu\text{g}/\text{m}^3$

during 2011 (almost  $-50\%$ ). During the same period,  $O_3$  concentrations increase from  $42.6$  to  $80.3 \mu\text{g}/\text{m}^3$ , probably due to the gradual decrease of  $NO_x$  levels resulting in reduced  $O_3$  titration. This remarkable differentiation is the probable outcome of two important changes. The first one is the Greek economic crisis which resulted in some cases in reduced anthropogenic activity, e.g., in the road transport sector. The second change is associated to the operational start of the Patras suburban railway station on the summer of 2010. Daily usage of the suburban railway by a significant part of the population reduced the vehicular traffic and associated emissions inside the urban area.

The seasonal variation of the examined pollutants is illustrated in Fig. 3.  $CO$  and  $NO_x$  present a clear seasonality with lower concentrations during summer and higher concentrations during winter as expected by the increased anthropogenic emissions on the cold period of the year. It should also be noted that  $CO$  and  $NO_x$  surface concentrations are lower on warm part of the year due to the most frequent cases of unstable atmosphere that result in more intensive mixing and transport to the higher atmospheric levels.  $O_3$  variation is the opposite of that for  $NO_x$ , presenting higher concentrations during summer. This is the result of the increased incoming solar radiation which enhances the formation of  $O_3$ , and the reduced availability of  $NO_x$  during summer, ending to reduced  $O_3$  titration by  $NO_x$ .

The present results are in good agreement with those of the available literature regarding various cities around the world. For example, Bigi and Harrison (2010) have found lower levels of  $CO$ ,  $PM_{10}$ ,  $NO$ , and  $NO_2$  and higher  $O_3$  levels at a background site of central London during the summer months. Kalobokas et al. (2012), studying the atmospheric concentrations of  $SO_2$ ,  $NO_2$ , and  $O_3$  in the Athens basin, found that  $SO_2$  and  $NO_2$  showed highest values during winter (cold period), while ozone showed a maximum in summer.

The finding that particulate matter concentration is slightly higher during winter and autumn but the amplitude of the variation is much smaller than the other pollutants is of special interest. This weak seasonality of the average  $PM_{10}$  concentrations is primarily attributed to significant transport of particulate matter from sources outside the urban area during the summer period which compensate for the lower local traffic and the absence of central heating emissions.

This suggestion is supported by literature and the results of the EU-funded "Contribution of Emission

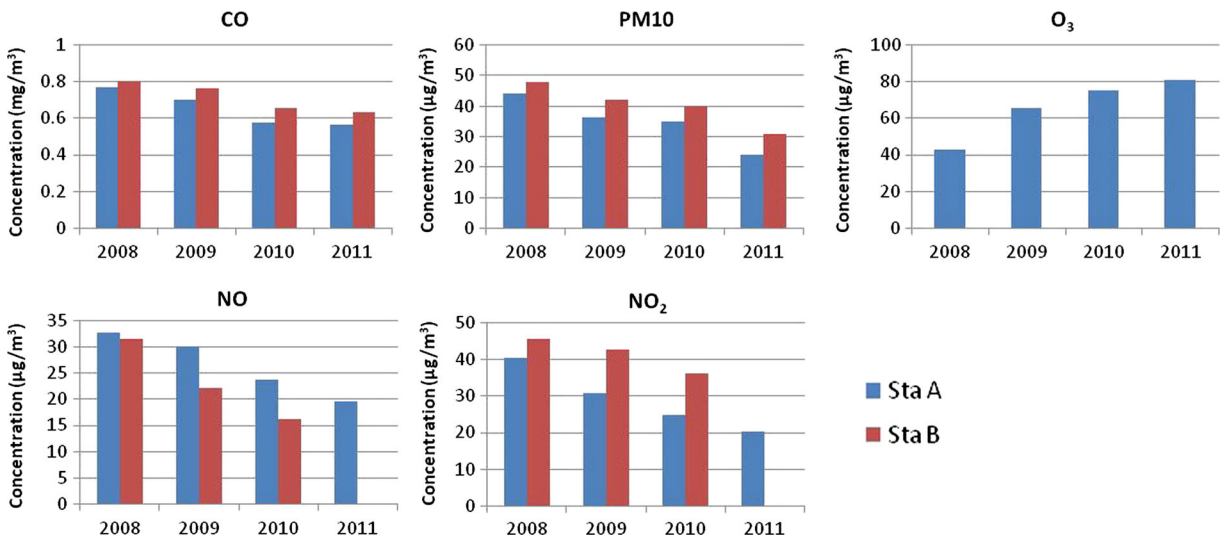


Fig. 2 Interannual variation of CO, PM10, NO, NO<sub>2</sub>, and O<sub>3</sub> average annual concentrations

Sources on the Air quality of the Port-cities in Greece and Italy” (CESAPO) project (UP 2014). Dimitriou and Kassomenos (2013) had already showed that Mediterranean cities can be significantly affected by “dust intrusions from the Sahara desert and transportation of Mediterranean/Atlantic sea spray,” while Pikridas et al. (2013) in an attempt to characterize the origin of the particulate matter in the city of Patras showed a seasonal variation for PM10 of almost the same amplitude with the present study. Moreover, they also showed that the transported particulate matter during winter accounts for a lower percentage of the total

concentration than during summer. Maraziotis et al. (2008) has found similar results for PM10 during winter-spring of 2005–2006. They showed that the March PM10 concentrations are not lower than those of December to February on two of the three examined stations. Finally, in the frame of the CESAPO project (UP 2014), winter and summer runs of the photochemical model CAMx were performed for the greater Patras area with a spatial resolution of 2 km. The source apportionment results of CAMx showed that the contribution of the pollution sources outside the city to the urban levels of PM almost doubles during summer,

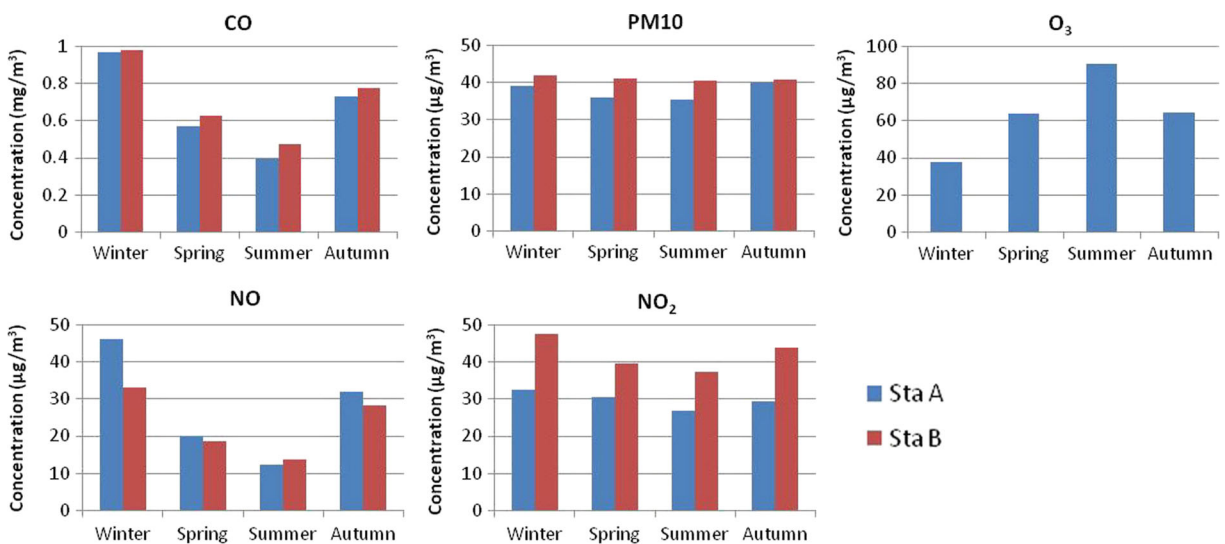


Fig. 3 Seasonal variation of CO, PM10, NO, NO<sub>2</sub>, and O<sub>3</sub> average concentrations

indicating that the impact of remote pollution sources is quite higher during summer than winter.

The weekly variation of the pollutant levels was examined separately for summer and winter because of the considerable differences in the seasonal values for some of the pollutants, as illustrated in Fig. 3. As shown in Fig. 4, all pollutants present a clear weekly variation in wintertime. Ozone values are slightly increased during weekends, while all the other pollutants are higher during weekdays. Especially, the primary gaseous pollutants (CO and NO) may be reduced by a factor of 42 % during weekends (e.g., in sta B, NO is 38.1  $\mu\text{g}/\text{m}^3$  on Tuesday and 21.8  $\mu\text{g}/\text{m}^3$  on Sunday). The weekly variation is smaller for PM10 with a percentage difference that is not exceeding 26 % for sta A and 10 % for sta B. The reduction of traffic and central heating during the weekends (mostly on Sunday) in the city center is the main reason for the reduction of concentrations of CO, PM10 NO, and NO<sub>2</sub>. Ozone is increased during weekends because the NO<sub>x</sub> levels are lower.

Summer weekly variation is also evident for all pollutants (Fig. 4). O<sub>3</sub> levels are higher during weekends while CO, NO, and NO<sub>2</sub> levels are higher during weekdays. PM10 levels do not fluctuate significantly, a finding which supports the suggestion for a significant contribution of remote pollution sources on the particulate matter atmospheric loading of the city.

The comparison of the present findings with the available literature indicates that the weekly variation of pollutant concentrations in Patras is similar to that for other sites in earlier studies. Riga-Karandinos and Saitanis (2005) found elevated O<sub>3</sub> levels and lower NO<sub>x</sub> levels in Patras during weekends. Stephens et al. (2008) examining the weekly patters of Mexico City found that CO, NO<sub>x</sub>, and PM10 are lower on weekends. Finally, Bigi and Harrison (2010), analyzing the air quality climate of a background site of central London,

reported a profound weekly variation for CO, NO, and NO<sub>2</sub>, with lower concentrations on weekends while the PM10 variation presented smaller amplitude.

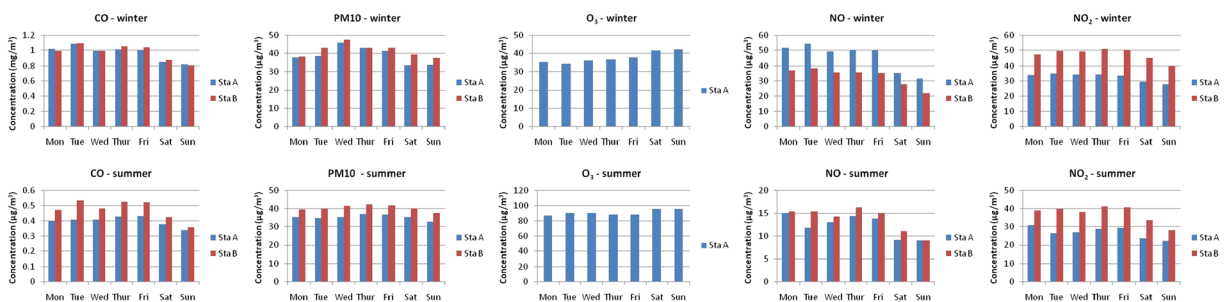
### 3.2 The Impact of Meteorology on Air Quality

#### 3.2.1 Observational Meteorological Data

Daily averages of surface wind, temperature, and mean sea level pressure observed values are used in this section along with CO, PM10, NO, NO<sub>2</sub>, and O<sub>3</sub> average daily surface concentration values.

The interannual trends of the pollutant levels as presented in Fig. 2 cannot be attributed to a climate regime change, as no such radical change is known. In order to avoid artificial correlations with the meteorological parameters, the trends of the pollutant time series have to be eliminated. To do so, the 15-day running mean was estimated for each pollutant and the deviations of the daily concentrations from the 15-day running mean were computed. These deviations were used instead of the raw values since they are free of long-term trends and thus more representative of the short-term component of air pollution variation.

The correlation coefficients between CO, PM10, NO, NO<sub>2</sub>, and O<sub>3</sub> and the surface WS, *T*, and MSLP for winter and summer are presented in Table 2. The most important characteristic for the winter is that WS is significantly affecting the surface concentration of every pollutant. All the pollutants except O<sub>3</sub> are reduced during days of strong surface winds as they are transported away from the emission sources in the urban center. On the contrary, O<sub>3</sub> is increased during days of strong winds, indicating that the transport of NO<sub>x</sub> away from the urban area reduces the destruction of O<sub>3</sub>. MSLP is positively correlated with all the pollutants except O<sub>3</sub>. MSLP is increased on days of anticyclonic circulation,



**Fig. 4** Weekly variation of CO, PM10, NO, NO<sub>2</sub>, and O<sub>3</sub> during winter (*top panel*) and summer (*bottom panel*)

**Table 2** Correlation coefficients between the pollutants and the observational and WRF output meteorology parameters for winter and summer

	Observational Data			WRF output Data				
	WS (m/s)	<i>T</i> (deg)	MSLP (hPa)	Geop <sub>500</sub> (gpm)	PBL (m)	<i>V</i> (m <sup>2</sup> /s)	<i>S</i> (m)	<i>R</i> (-)
Winter								
CO I (mg/m <sup>3</sup> )	<i>-0.46</i>	<i>0.11</i>	<i>0.17</i>	0.07	<i>-0.53</i>	<i>-0.48</i>	<i>-0.28</i>	0.19
CO II (mg/m <sup>3</sup> )	<i>-0.43</i>	0.09	<i>0.24</i>	0.21	<i>-0.67</i>	<i>-0.62</i>	<i>-0.38</i>	<i>0.44</i>
PM10 I (μg/m <sup>3</sup> )	<i>-0.23</i>	<i>0.30</i>	0.09	0.25	0.08	0.01	<i>-0.15</i>	0.13
PM10 II (μg/m <sup>3</sup> )	<i>-0.18</i>	<i>0.29</i>	0.06	<i>0.31</i>	<i>-0.03</i>	<i>-0.03</i>	<i>-0.17</i>	0.27
NO I (μg/m <sup>3</sup> )	<i>-0.42</i>	<i>0.15</i>	0.11	<i>-0.07</i>	<i>-0.34</i>	<i>-0.35</i>	<i>-0.22</i>	0.06
NO II (μg/m <sup>3</sup> )	<i>-0.27</i>	0.13	0.12	0.01	<i>-0.50</i>	<i>-0.36</i>	<i>-0.07</i>	0.18
NO <sub>2</sub> I (μg/m <sup>3</sup> )	<i>-0.48</i>	<i>0.12</i>	<i>0.16</i>	0.13	<i>-0.30</i>	<i>-0.44</i>	<i>-0.46</i>	0.15
NO <sub>2</sub> II (μg/m <sup>3</sup> )	<i>-0.34</i>	0.05	<i>0.22</i>	0.06	<i>-0.65</i>	<i>-0.56</i>	<i>-0.31</i>	<i>0.34</i>
O <sub>3</sub> I (μg/m <sup>3</sup> )	<i>0.63</i>	<i>-0.01</i>	<i>-0.27</i>	<i>-0.17</i>	<i>0.71</i>	<i>0.68</i>	<i>0.41</i>	<i>-0.27</i>
Summer								
CO I (mg/m <sup>3</sup> )	<i>-0.26</i>	<i>0.23</i>	<i>0.23</i>	<i>0.47</i>	0.16	<i>-0.38</i>	0.00	0.03
CO II (mg/m <sup>3</sup> )	<i>-0.03</i>	<i>0.19</i>	<i>0.17</i>	0.18	0.26	<i>-0.26</i>	0.12	<i>-0.10</i>
PM10 I (μg/m <sup>3</sup> )	<i>-0.22</i>	<i>0.36</i>	<i>-0.03</i>	<i>0.57</i>	0.12	<i>-0.41</i>	0.22	<i>-0.07</i>
PM10 II (μg/m <sup>3</sup> )	<i>-0.18</i>	<i>0.33</i>	<i>-0.02</i>	<i>0.61</i>	0.05	<i>-0.40</i>	0.00	<i>-0.01</i>
NO I (μg/m <sup>3</sup> )	<i>-0.22</i>	<i>-0.01</i>	0.05	<i>-0.13</i>	<i>-0.07</i>	<i>-0.07</i>	<i>-0.28</i>	0.12
NO II (μg/m <sup>3</sup> )	0.02	<i>0.19</i>	<i>0.27</i>	0.13	0.22	<i>-0.26</i>	0.12	0.03
NO <sub>2</sub> I (μg/m <sup>3</sup> )	<i>-0.46</i>	0.08	<i>0.16</i>	<i>0.36</i>	0.03	<i>-0.40</i>	<i>-0.41</i>	0.20
NO <sub>2</sub> II (μg/m <sup>3</sup> )	<i>-0.06</i>	<i>0.29</i>	<i>0.27</i>	<i>0.41</i>	0.21	<i>-0.52</i>	<i>-0.03</i>	0.05
O <sub>3</sub> I (μg/m <sup>3</sup> )	<i>0.30</i>	<i>-0.04</i>	<i>-0.30</i>	<i>-0.09</i>	<i>-0.27</i>	<i>0.38</i>	0.16	<i>-0.25</i>

Coefficients that are statistically significant at the 95 % significance level are noted in italics

when the surface wind field is weak. Therefore, high MSLP values are linked to higher levels for CO, PM10, NO, and NO<sub>2</sub> and lower O<sub>3</sub> levels, because during these days the average wind is weaker. The correlation between WS and the pollutants during summer is weaker than during winter but maintains its sign in almost all cases. During summer, the cyclonic systems that affect the area are much less frequent and the prevailing winds are weaker on average. The weak winds that prevail during summer in the area do not help in the distinction between windy and calm days, and therefore, the variability of the wind time-series is decreased. This has a direct impact on the correlation coefficients between pollutants' concentrations and wind speed that are also decreased. In general, stronger summer winds lead to lower CO, PM10, NO, and NO<sub>2</sub> and higher O<sub>3</sub> levels, in the same manner as they do during winter. The MSLP is also positively correlated to most of the pollutants and negatively correlated to O<sub>3</sub>, indicating that on days of anticyclonic circulation, when the surface wind field is

weak, the levels of all the examined pollutants, except ozone, are higher. Finally, for most of the cases, air temperature is positively correlated to pollutant concentrations because during the warm part of the year in the city, temperature is usually increased on days of weak zonal or anticyclonic circulation when the surface winds are very weak.

The profound relation between the wind direction and the average concentration of the pollutants can be more thoroughly examined with the use of pollution roses. These roses illustrate the average concentration of each pollutant for the 16 basic wind directions plus the average concentration during calm wind days (i.e., days when the daily average wind speed is under 0.5 m/s regardless of the direction).

Before the analysis of the pollution roses of each pollutant, the average winter and summer wind field of the city should be reviewed. Wind roses for the winter and summer were created and examined (not shown here). It was found that two specific directions dominate



the wind field in Patras. Northeastern and southwestern section winds prevail on both seasons while the other directions are almost absent. Every conclusion regarding these directions should be taken into account only as a suggestion and not as a sound fact. A second useful conclusion is that the average wind field is weaker during the warm season.

Figure 5 depicts the pollution roses for station A (station B roses are similar) for winter and summer. Regarding winter, the most striking feature is that pollutants having significant primary sources inside the urban area (like CO, PM10, and NO) tend to present higher concentrations during calm wind days. NO<sub>2</sub> concentrations, a pollutant which is produced by both local sources and secondary atmospheric chemistry processes, seem to be unaffected by the wind direction. Finally, O<sub>3</sub> which is a secondary pollutant is not favored by calm winds because its lower levels are recorded during calm wind days.

The pollution roses for summer are also depicted in Fig. 5. CO, PM10, and NO levels are increased during calm wind days. NO<sub>2</sub> levels are higher during the dominance of northeastern winds, while O<sub>3</sub> levels seem to be invariable to the wind direction change. The 0 values that are found in some directions and specific pollutants (e.g., for the PM10 of the ESE direction) are the result of missing observations during the few days that these winds prevailed.

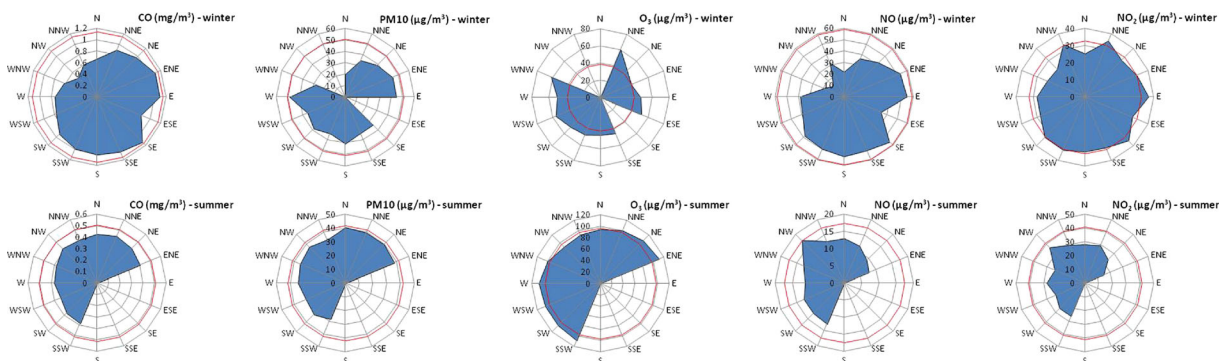
The impact of precipitation on air quality is assessed by the examination of the bar-charts of Fig. 6, where the average deviation of the daily concentration from the 15-days running mean is compared between rainy days and days with no rain. As rainy days are defined those that receive any amount of precipitation. CO is almost unaffected by the precipitation for both winter and

summer. CO is not dissolvable by water and so the scavenging of the pollutant by precipitation is very limited. PM10 concentrations are significantly lower on rainy days due to the wash-off effect. NO and NO<sub>2</sub> levels are also negatively affected by rain. Finally, O<sub>3</sub> levels are lower on no rain days, most possibly due to the reduction of NO<sub>x</sub> during these days.

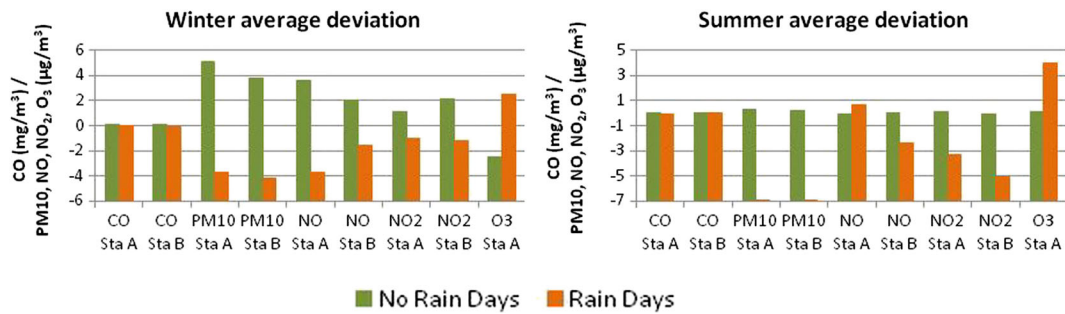
### 3.2.2 WRF Output Data

Daily averages of WRF geopotential height at the 500 hPa isobaric surface and planetary boundary layer depth, daily ventilation factor, wind run, and recirculation factor values and also daily CO, PM10, NO, NO<sub>2</sub>, and O<sub>3</sub> surface concentration averages are used in this section. The correlation coefficients between the five selected dynamic meteorology parameters and indices estimated by the WRF model results and the observed concentrations of pollutants for winter and summer are shown in Table 2.

During winter, the average geopotential height at the 500 hPa isobaric surface (Geop<sub>500</sub>) is not clearly correlated to any of the pollutants. PBL is negatively correlated to CO, NO, and NO<sub>2</sub>, implying that a deep boundary layer helps on the dispersion of the pollutants, reducing the concentrations near the surface. The Ventilation factor (*V*) is also negatively correlated to CO, NO, and NO<sub>2</sub>, indicating that besides vertical mixing, strong horizontal ventilation helps the dispersion of these pollutants. Wind run (*S*) is negatively correlated to CO and NO<sub>2</sub> because significant straight line transport carries the pollutants outside the city, reducing the local concentrations. The recirculation factor (*R*) is not clearly correlated to any of the pollutants, suggesting that the local scale recirculation does not



**Fig. 5** Pollution roses for CO, PM10, NO, NO<sub>2</sub>, and O<sub>3</sub> for winter (*top panel*) and summer (*bottom panel*). The red line shows the average concentration during calm wind days ( $WS \leq 0.5$  m/s)



**Fig. 6** Average value of the deviation of the daily concentration from the 15-day running mean of each pollutant on rain and no rain days for winter and summer

affect positively or negatively the surface concentrations.  $O_3$  is a pollutant with very different behavior with respect to the meteorological parameters examined, as it is positively correlated to PBL,  $V$ , and  $S$ . This is considered to be the result of a relatively complex mechanism of combined reduced local destruction of  $O_3$  and possible transport from sources outside the city. According to this mechanism, the increase of PBL decreases the  $NO_x$  concentrations due to increased volume for dispersion. The increase of  $V$  and  $S$  also leads to increased dispersion of  $NO_x$ . Since  $NO_x$  acts as  $O_3$  sink, lower  $NO_x$  concentrations result to higher  $O_3$  concentrations. On the same time, a deep boundary layer may allow  $O_3$  that was produced outside the city to be more easily transported inside the city and increase the local concentrations.

Summer average Geop<sub>500</sub> is positively correlated to PM10,  $NO_2$ , and possibly CO. Increased geopotential height is related to anticyclonic circulation in the area and to weak surface synoptic wind field. The stagnant conditions that prevail on such days favor the accumulation of pollutants near the surface and increase concentrations. Strong ventilation also reduces CO, PM10,  $NO_2$ , and possibly NO because it enhances dispersion. Finally, horizontal ventilation has a positive impact on surface ozone concentration as it leads to significant reduction of  $NO_2$ .

The results of the present study in Sect. 3.2.1 and Sect. 3.2.2, regarding the relationships between the examined meteorological parameters and the pollutants, are in good agreement when compared with the results of previous studies. For example, Kassomenos et al. (1998b) showed that weak surface flow, sea breezes, and calm conditions degrade the air quality of the city of Athens. Regarding  $O_3$ , however, it was found that the transport from non-urban areas and from sea, especially during summer, leads to elevated concentrations. Aldrin

and Haff (2005), developing additive models of air pollution, showed that wind speed and precipitation play important roles on the diurnal variation of PM10 and  $NO_x$ . Wise and Comrie (2005) found that PM10 concentrations are positively correlated to the maximum daily temperature and that  $O_3$  is also positively correlated to mixing height in the southwestern USA. Aküz and Çabuk (2009) showed that the increase of wind speed and precipitation leads to PM10 concentration decrease. The positive correlation between the weak synoptic field and the pollutants (mostly CO and PM10) concentrations was pointed out by Flocas et al. (2009) for Thessaloniki, Greece. Tai et al. (2010) found a positive correlation between airborne particulate matter and temperature for the USA and they also showed a definite increase during stagnant days. Unal et al. (2011), examining the influence of meteorological factors and emission sources on spatial and temporal variations of PM10 concentrations in Istanbul metropolitan area, reported that low and calm winds that are associated to anticyclonic conditions favor the accumulation of PM10 near the surface. Especially for the city of Patras, Maraziotis et al. (2008) have already showed that strong winds reduce PM10 levels.

#### 4 Conclusions

A general assessment of the air pollution problem of the medium-size Mediterranean city of Patras was performed in the present study. Some aspects of the impact of meteorology on the air quality were also examined. The most important conclusions of this analysis can be summarized in the following.

CO, PM10, NO, and  $NO_2$  concentrations in the city are decreasing during the period 2008–2011, while  $O_3$  is significantly increasing during the same period. These

findings are considered to be associated to the reduction of anthropogenic activities in the urban area induced by the economic crisis in Greece and by the changes of the local transport system in Patras.

CO and NO<sub>x</sub> present lower concentrations during summer and higher during winter due to the increased emissions and the decreased atmospheric instability on the cold part of the year. O<sub>3</sub> is lower during winter and higher during summer as a result of the reduced titration from NO<sub>x</sub> during summer and the increased incoming solar radiation which enhances the formation of O<sub>3</sub>. Particulate matter seasonality is present, with higher concentrations during winter, but it is rather limited, a finding primarily attributed to the significant contribution of remote emission sources to the determination of PM levels mostly during summertime. These results imply that the wintertime PM pollution in Patras can be possibly more effectively controlled while focusing on emission mitigation strategies for the local emission sources. During summertime, the PM pollution is more complicated and can be addressed probably while considering the need for decrease of PM levels in regional scale in the Eastern Mediterranean.

All pollutants except O<sub>3</sub> are reduced during weekends due to reduced emissions. On the contrary, O<sub>3</sub> levels are higher during weekends because NO<sub>x</sub> levels are lower. PM10 summer weekly variation is rather limited due to the significant contribution of remote sources.

The meteorological conditions have a significant impact on the air quality of the city during winter. Days of anticyclonic or weak zonal circulation are characterized by high MSLP, shallow boundary layers, weak surface winds, poor ventilation, and limited straight line transport of air parcels. As shown by the analysis, such conditions favor the increase of surface concentrations of CO, PM10, NO, and NO<sub>2</sub>, due to the limited dispersion of the pollutants. O<sub>3</sub> is also affected by the synoptic setting, but in a reversed pattern, as it is increased during days of cyclonic circulation. On such days, when the boundary layer is deeper and the surface wind and ventilation are stronger, the decrease of NO<sub>x</sub> concentrations leads to O<sub>3</sub> increase because NO<sub>x</sub> acts as O<sub>3</sub> sink. Moreover, the deep boundary layer may allow O<sub>3</sub> that was produced by sources outside the urban area to be more easily transported inside the city.

During summer, the impact of meteorology presents similar characteristics to winter. Weak zonal and anticyclonic circulation, which leads to weaker winds,

increased temperature, and poor horizontal ventilation and transport, is associated with higher levels of CO, PM10, NO, and NO<sub>2</sub> and lower levels of O<sub>3</sub>. The limited dispersion increases CO, PM10, NO, and NO<sub>2</sub> and decreases O<sub>3</sub> surface concentrations in the same manner that was described for winter.

Finally, precipitation has a positive effect on air quality during winter and summer season as it removes important amounts of PM10, NO, and NO<sub>2</sub>.

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