

HEAT WAVES CHARACTERISTICS AND THEIR RELATION TO AIR QUALITY IN ATHENS

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ABSTRACT

This paper studies the characteristics of the heat waves that were observed in Athens, Greece since 1951. A heat wave is detected when two temperature criteria are fulfilled at the city centre: the daily maximum temperature value is at least 37 °C and the daily average temperature value is at least 31 °C. Information about the intensity, duration, timing in season and annual frequency of occurrence of heat waves were extracted. The slope of the linear fit of the annual number of heat wave days indicated that 1.30 more heat wave days per year were observed after 1992. The intensity and the duration of heat waves have also increased since 90s, while heat wave days have been detected during the whole summer since then, even during the first days of September. Additionally, air quality at the centre and at a suburb of Athens during the heat wave days that were identified during the last decade is examined. The daily average value of PM₁₀ concentration exceeded 50 µg m⁻³ in 65% and 59% of the heat wave days at the urban and the suburban site, respectively, while the information and the alert O₃ threshold were exceeded in 17% and 5% of the heat wave days, respectively, at the suburban site. The degradation of air quality during heat wave days is also verified by the means of the common air quality index. Moreover, it was found that O₃ levels decrease when heat waves last more than 6 days.

Keywords: Heat wave, temperature, air quality, air pollution

1. Introduction

Heat waves are related to serious environmental and medical problems, generating also serious economic consequences (Matzarakis and Nastos, 2011). High temperatures can cause thermal stress and can worsen air quality. These conditions can trigger adverse health effects especially to the more vulnerable groups that include individuals suffering from cardiovascular or respiratory diseases and the elderly (Stafoggia *et al.*, 2006). Nastos and Matzarakis (2008a) suggested that a considerable increase in sleep disturbances existed in 1994 compared to 1989, due to the many consecutive days with heavy thermal load in 1994 compared to the lack of such days in 1989. Additionally, heat waves can affect various other sectors including agriculture, livestock, fisheries, forests, construction and transportation

(Fuhrer *et al.*, 2006; Smoyer-Tomic *et al.*, 2003). Moreover, the combination of high temperatures and drought can result in forest fires that contribute to the degradation of air quality and the reduction of carbon stocks (Vautard *et al.*, 2007). Furthermore, heat waves induce significant increases in electricity demand for air conditioning (Miller *et al.*, 2008), as the access to cool environments contributes to the reduction of heat related mortality (O'Neill *et al.*, 2005).

Many studies that have been conducted worldwide underlined the relation between thermal stress and mortality. Giles *et al.*, (1990) stated that more than 1,000 people died in Greece during the July 1987 heat wave. Nastos and Matzarakis (2009) analyzed the daily maximum and minimum air temperature, the daily temperature range and the daily values of thermal indices observed in Athens during the period 1992 – 2001 and found that very hot conditions are risk factors for the daily mortality. Fouillet *et al.*, (2006) reported that 15,000 excess deaths were observed during the August 2003 heat wave in France. Tan *et al.* (2007) reported that the maximum number of daily deaths during the July 2003 heat wave in Shanghai was 42% more than the non-heat day average. Vaneckova *et al.*, (2008) reviewed some physiological and social factors that have also been found to contribute to higher incidence of heat-related deaths.

Air quality is worsened when high temperatures prevail (Papanastasiou *et al.*, 2010; Struzewska and Kaminski, 2008; Theoharatos *et al.*, 2010). O₃ levels increase as photochemical processes are enhanced, the emission of biogenic organic compounds that may also affect ozone's chemistry is favoured and the production of secondary aerosols is also supported (Seinfeld and Pandis, 1998). Additionally, pollution levels can be further increased if atmospheric conditions that favour the accumulation of pollutants prevail during a heat wave (Tressol *et al.*, 2008). Stagnation of air masses allows the accumulation of pollutants in the atmospheric boundary layer and in the residual layer during the night (Solberg *et al.*, 2008). The combination of high pollution levels and high temperatures has been implicated to increase discomfort conditions and health risks. Paliatsos and Nastos (1999) found that during the days of the warm period of the year when pollution levels were high, more than 50% of the population in the greater Athens area feels discomfort from 10:00 to 19:00 LST. Fischer *et al.* (2004) showed that 400 – 600 deaths occurred during the 2003 heat wave in the Netherlands could be attributed to O₃ and PM₁₀ exposure. Filleul *et al.*, (2006) found that the excess risk of deaths linked to O₃ and temperature together during the August 2003 heat wave in France ranged from 10.6% in Le Havre to 174.7% in Paris. Stafoggia *et al.*, (2008) estimated that a 10 µg m⁻³ increase in PM₁₀ concentration results in a 2.54% and 0.20% rise in risk of death in summer and winter, respectively.

As the adverse health effects of heat waves are largely preventable, heat-health action plans could be developed and implemented at national and regional levels in Europe to prevent, react upon and contain heat related risks to health (Matthies and Menne 2009; Michelozzi *et al.*, 2007). These plans could exploit meteorological and air quality early warning systems (Moustris *et al.*, 2010; Vouterakos *et al.*, 2012).

The objective of this paper is to identify the characteristics of the heat waves that have been observed in Greece since 1951 and to assess the air quality in Athens during the heat waves that occurred in the last decade.

2. Materials and methods

Temperature data recorded at the centre of Athens (Thissio, National Observatory of Athens) and air pollution data (PM₁₀, NO₂, O₃) recorded at the city centre (Aristotelous station) and at a suburban site (Lykovrisi station) were used in this study. Both air pollution stations are members of the national network of air pollution monitoring. PM₁₀ and NO₂ concentrations were monitored in both sites, while O₃ was observed only at Lykovrisi. The temperature archive includes daily maximum and daily minimum temperature values recorded during the period 1951 – 2010, while the air pollution archive includes hourly pollutants' concentrations monitored during the period 2001 – 2010.

The identification of a heat wave day was based on two temperature criteria that have been suggested by Metaxas and Kallos (1980): the daily maximum and the daily average temperature value at the city centre are at least 37°C and 31°C, respectively. The daily average temperature value for each day was set equal to the average of the daily maximum and the daily minimum temperature value. The number of the identified heat wave days could be slightly different if the daily average temperature value was calculated using the hourly temperature values.

Air quality (PM₁₀ and O₃ concentration levels) during heat wave days was assessed (i) taking into account the European Union's regulations in force (Directive 2008/50) and (ii) by the means of the common air quality index (CAQI). Directive 2008/50 states that the daily average value of PM₁₀ concentration should not exceed 50 µg m⁻³ on more than 35 days per year and also sets information (180 µg m⁻³) and alert (240 µg m⁻³) thresholds for hourly O₃ concentration. CAQI was developed under CITEAIR project (Van den Elshout *et al.*, 2008) and has also been applied in other relevant studies (Poupkou *et al.*, 2011). It is calculated according to a grid (Table 1), by linear interpolation between the class borders. The final index is the highest value of the sub-indices for each component. Two CAQIs have been proposed: one for traffic monitoring sites that comprises PM₁₀ and NO₂ concentrations and one for urban background sites that comprises PM₁₀, NO₂ and O₃ concentrations. Both indices were used in this study. As CAQI was used for a daily index, the daily average value of PM₁₀ concentration and the daily maximum hourly value of NO₂ and O₃ concentration were used in this study.

Table 1. Calculation grid for the CAQI

Index class	Grid	Concentration class (µg m ⁻³)		
		PM ₁₀	NO ₂	O ₃
Very low	0 – 25	0 – 12	0 – 50	0 – 60
Low	26 – 50	13 – 25	51 – 100	61 – 120
Medium	51 – 75	26 – 50	101 – 200	121 – 180
High	76 – 100	51 – 100	201 – 400	181 – 240
Very high	>100	>100	>400	>240

3. Results and discussion

3.1 Characteristics of heat waves

The number of heat wave days and the number of heat wave events that were identified per year during the period 1951 – 2010 are shown in figure 1. This figure reveals that few heat wave days were identified until the mid 60s. Their higher annual number was observed in 1958 (i.e. 5 heat wave days). Taking also into account the number of the heat wave events that were identified until the mid 60s, it is revealed that the heat wave days were observed isolated or in two consecutive days. Exceptions are years 1957 and 1958 when 4 and 5 heat waves days, respectively, were observed consecutively, all detected in 1 heat wave event per year. Afterwards and until 1984, a negligible number of heat wave days were detected. The most significant heat wave event since 1951 was observed in 1987 when the heat wave day selection criteria were met during 8 consecutive days, while 4 consecutive heat wave days were also detected in years 1985 and 1988 (Giles and Balafoutis, 1990). No heat wave days were identified in years 1990 – 1992. The situation is totally reversed after 1992 as a clear increasing trend is detected afterwards. The slope of the linear fit denotes that 1.30 more heat wave days per year were observed. The higher number of heat wave days during the examined period was observed in 2007, when 39 heat wave days were detected. The summer of 2007 was very likely the warmest summer at NOAA's instrumental history (Founda and Giannakopoulos, 2009) and was exceptionally hot for south-eastern Europe (Cheval *et al.*, 2009). An upward trend is also detected in the annual number of the heat wave events after 1992 (figure 1), the slope being 0.45. This fact indicates that the number of consecutive heat wave days has increased year by year, a conclusion that is also verified by figure 2b. Similar results regarding the temporal variation of the heat waves in Mediterranean during the last

decades are reported by two other studies. Baldi *et al.* (2006) analyzed surface temperature data collected in fifty stations in Italy. They found that the heat waves are almost absent in the 70s, while they detected an impressive warming in the last decade of the 20th century. They identified 187 heat wave days in the period 1991 – 2000, which account for the 46% of the total number of heat wave days identified in the last half century. Nastos and Matzarakis (2008b) studied the variability of the tropical days (i.e. days with a maximum air temperature greater than 30.0 °C) over Greece within the second half of the twentieth century. The time series of the annual number of tropical days for the NOA revealed that the fewer tropical days were observed in 1976 and that a significant positive trend appeared after 1976 until the end of the examined period.

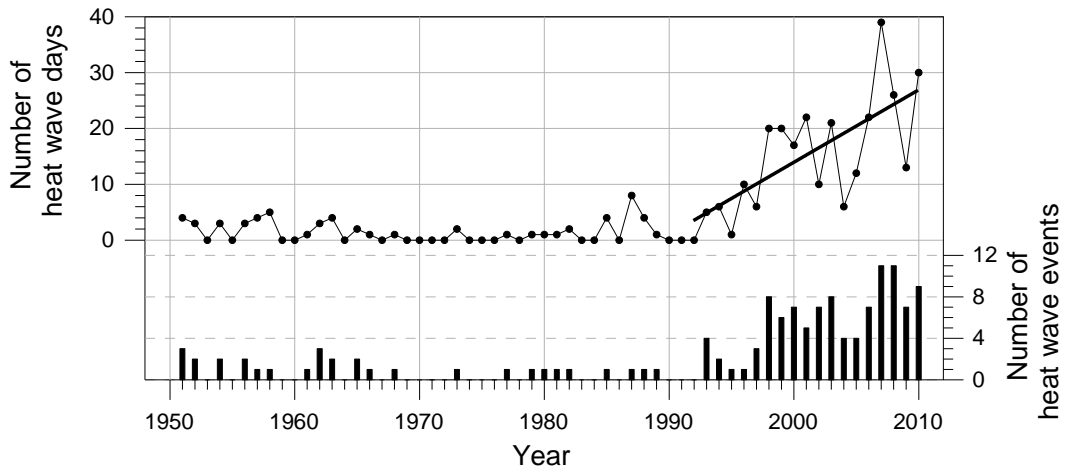


Figure 1. Number of identified heat wave days (solid curve with black circles) and heat wave events (bars) during the period 1951 – 2010. Black line: linear fit

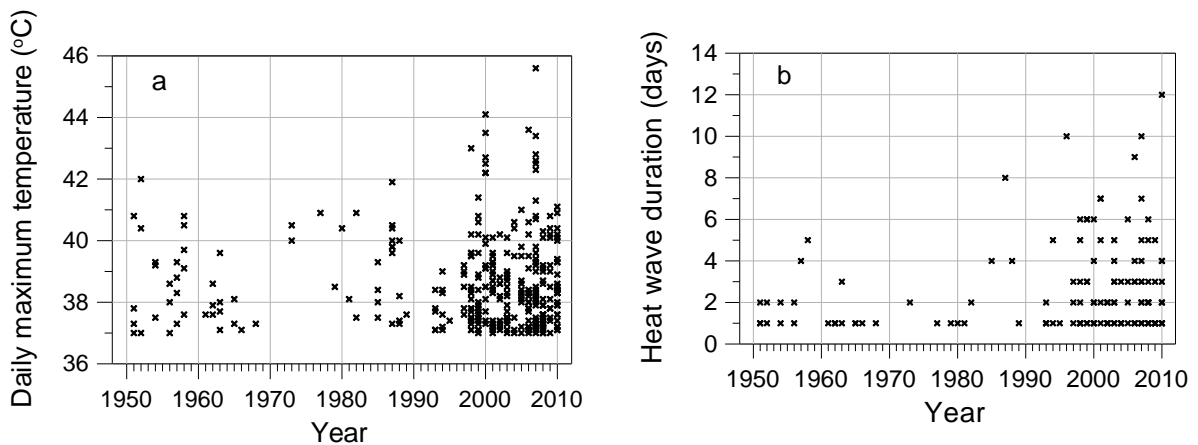


Figure 2. Intensity (a) and duration (b) of the heat waves observed during the period 1951 – 2010

The daily maximum temperature values that were recorded during the identified heat wave days are plotted in figure 2a. It is shown that peak temperatures higher than 42 °C were observed after year 1998. Abaurrea *et al.*, (2007) analyzed temperature data collected during the period 1951–2004 at the northeast of Spain and also found that the increase of the daily maximum temperature became more important after 1994. However, high temperatures, for example higher than 40 °C were observed in Athens during the whole examined period. On the contrary, the duration of the heat wave events started to increase in 90s (figure 2b). The most prolonged heat wave event was observed in 2010, when 12 consecutive days were identified as heat wave days. The first long heat wave event was observed in 1987 and lasted 8 days. An increase of the heat wave duration, as well as an increase of the heat wave

frequency of occurrence, was also detected by Unkašević and Tošić (2011) during the period 1999 – 2007, who studied the characteristics of the heat waves that were observed in central Serbia during the period 1949 – 2007.

Figure 3 shows that during the last two decades summer is more uniformly hotter than before and the period prone to heat wave occurrence is longer. The heat wave days until the mid 60s were observed in July and August, the longer events being observed in August. The more important events during 80s were observed in July. During the last two decades, heat wave days were spread in the whole summer. Similar results are presented by Abaurrea *et al.*, (2007). Based on summer data, they reported that July is the month most prone to have heat waves at the north-eastern Spain, followed by August and, finally, June. However, they underlined that this pattern disappears in 90s due to the increase of the temperature in June. It is noticeable that the present study reveals that heat wave days have also been observed during the first days of September since 2003.

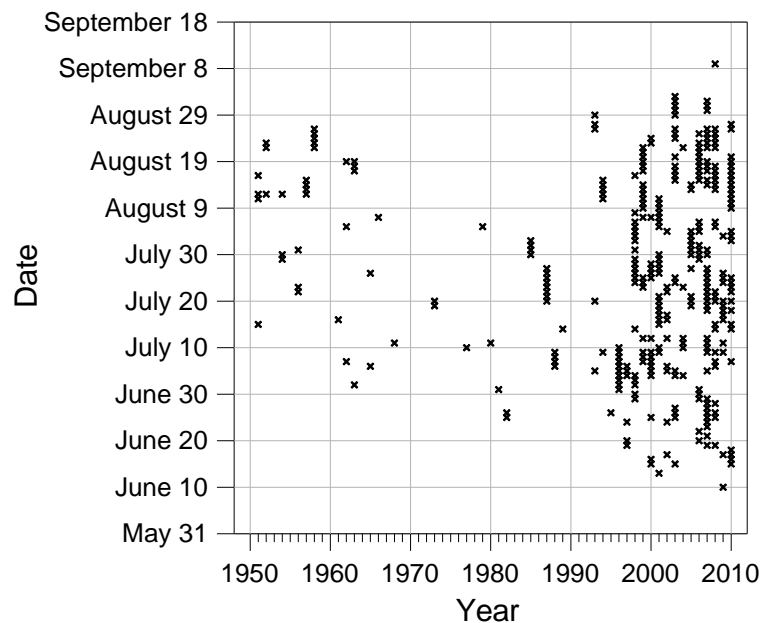


Figure 3. Dates during the period 1951 – 2010 when the heat wave days occurred

3.2 Assessment of air quality during heat waves

Air pollution levels during the heat wave days that were identified during the last decade were studied. Air quality at the city centre and at a city suburb was assessed taking into account the European Union's regulations in force (Directive 2008/50) and by the means of CAQI. Table 2 presents the number of heat wave days per year when the air quality standards established for PM_{10} and O_3 were exceeded. 201 heat wave days were identified during the period 2001 – 2010. PM_{10} air quality standard was exceeded in 130 and 118 of them at Aristotelous and Lykovrisi, respectively, while the information and the alert O_3 threshold were exceeded in 35 and 10 heat wave days, respectively, at Lykovrisi. These days correspond to the 65%, 59%, 17% and 5% of the total number of heat wave days. The higher number of exceedances was observed in 2007, when the higher number of heat wave days was also identified. In 2007, the daily average value of PM_{10} concentration remained over $50 \mu g m^{-3}$ during 27 and 28 heat wave days at Aristotelous and Lykovrisi, respectively, and the daily maximum hourly value of O_3 concentration surpassed the information threshold during 8 heat wave days at Lykovrisi. Consequently, the air quality standard for PM_{10} concentration was violated in 69% and 72% of the total heat wave days at the urban and the suburban site, respectively, while the air quality standard for O_3 concentration was violated in 21% of the total heat wave days at the suburban site.

The annual number of the exceedances of the air quality standards correlates well with the annual number of heat wave days. This fact could be attributed to the atmospheric conditions that usually

prevail during heat wave days. Stagnation of air masses is usually observed during heat waves (Tressol *et al.*, 2008; Vautard *et al.*, 2007), favouring the accumulation of particles and O₃ precursors. Additionally, as heat waves usually occur under anticyclonic conditions (Katsoulis and Hatzianastassiou, 2005), the development of sea breeze is favoured. Sea breeze is considered to increase near surface pollution levels in Athens (Kambezidis *et al.*, 1998; Larissi *et al.*, 2010; Melas and Kambezidis, 1992). Moreover, hot weather in Mediterranean could be sometimes induced by the transport of hot air masses from North Africa (Theoharatos *et al.*, 2010) that are rich in dust. Dust transport events frequently occur in Greece during summer (Papanastasiou *et al.*, 2010; Papayannis *et al.*, 2005), triggering an increase in PM₁₀ levels (Kaskaoutis *et al.*, 2008; Katragkou *et al.*, 2009). The correlation coefficient between the annual number of heat wave days and the annual number of the exceedances of PM₁₀ air quality standard at Aristotelous and Lykovrisi during heat wave days and the annual number of the exceedances of ozone's information threshold at Lykovrisi during heat wave days was found equal to 0.92, 0.73 and 0.62, respectively. The correlation coefficient becomes lower at Lykovrisi compared to Aristotelous, as the impact of background pollution levels, which are less influenced by weather changes, is more pronounced there than at the city centre (Kalabokas and Repapis, 2004; Kalabokas *et al.*, 2010).

Table 2. Annual exceedances of the PM₁₀ and O₃ air quality standards and air quality assessment by the means of CAQI during heat wave days at the urban and the suburban site

Year	Air quality standard				CAQI class		
	Daily average value of PM ₁₀ concentration		O ₃ threshold		High	Very High	
			information	alert			
	ARI	LYK	LYK	LYK	ARI	LYK	LYK
2001	19	19	4	3	19	16	3
2002	1	7	1	0	1	5	2
2003	14	18	4	0	14	17	0
2004	3	5	0	0	3	4	1
2005	10	9	4	3	9	6	3
2006	17	11	1	0	17	10	1
2007	27	28	8	1	20	19	10
2008	19	12	6	2	19	14	2
2009	5	2	5	1	5	5	1
2010	15	7	2	0	15	8	0

The degradation of air quality during heat wave days is also verified by the CAQI values (table 2). Air pollution was "high" during 122 and 104 heat wave days at Aristotelous and Lykovrisi, respectively, and "very high" during 23 heat wave days at Lykovrisi. These values correspond to the 61%, 52% and 11% of the total heat wave days. Air pollution was "very high" during 7 heat wave days at Aristotelous, all of them detected in 2007. The annual frequency of occurrence of CAQI classes during heat wave days also correlates well with the annual number of heat wave days. The correlation coefficient between the annual number of heat wave days and the annual frequency of occurrence of class "high" during heat wave days at Aristotelous and Lykovrisi and the class "very high" during heat wave days at Lykovrisi was 0.86, 0.77 and 0.54, respectively.

The heat wave events were classified according to their duration. The mean value of the daily average PM₁₀ concentrations and the mean value of the daily maximum O₃ concentrations that were recorded during the heat wave days included in every duration class were calculated. The results are presented in figure 4. This figure shows that pollution levels are not monotonous increasing as heat wave duration increases. A unimodal distribution is detected that is clearer for O₃. It is revealed that mean O₃ levels

decrease when the heat wave event lasts more than 6 consecutive days. This reduction could be attributed to ozone's destruction and deposition processes, as well as to changes of the synoptic atmospheric conditions. Rao *et al.* (2003) analyzed O₃ data observed in summer 1995 at two elevated platforms (~400 m agl) in Garner, NC, and Chicago, IL, and found that O₃ can persist for about 2 – 3 days aloft before NO titration and deposition processes remove it. Additionally, Rao (1988) used surface O₃ data recorded during the summer months of 1981 and 1983 in New Jersey and Connecticut and showed that once the surface O₃ level exceeds 80 ppb, the probability of that exceedance lasting for 2 – 3 days is very high. Moreover, Beaver *et al.* (2008) found that synoptic transitions can force changes of O₃ levels. It is obvious that the onset and the cessation of a heat wave event coincide with a change in the prevailing synoptic atmospheric regime (Katsoulis and Hatzianastassiou, 2005).

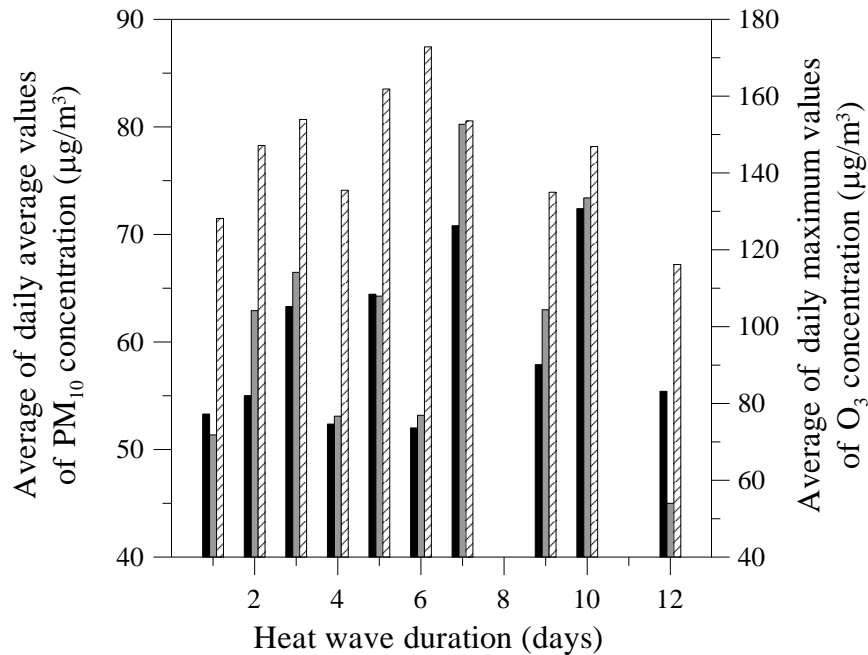


Figure 4. PM₁₀ and O₃ levels in relation to heat wave duration (black and grey bars: PM₁₀ at Aristotelous and Lykovrisi, respectively; hatched bars: O₃ at Lykovrisi).

4. Conclusions

The annual number of heat wave days and the annual number of heat wave events exhibit an upward trend after 1992 in Athens. A mean value of 1.30 more heat wave days per year was estimated. The more heat wave days during the period 1951 – 2010 were detected in 2007, a fact that verifies that the summer of 2007 was the warmest summer for Athens in the last century. The peak temperature values also increased after 90s, exceeding 42 °C. The duration of the heat waves started to increase in the beginning of 90s. The most prolonged heat wave was a 12-day event that was observed in 2010. During the last two decades, summer is more uniformly hotter than before and the period prone to heat wave occurrence is longer, extending from approximately the mid of June to the beginning of September.

Air quality was deteriorated during the heat wave days that were identified in the last decade. The air quality standards in force regarding the PM₁₀ and O₃ concentration were frequently violated. The annual number of exceedances correlates well to the annual number of heat wave days, a fact that could be attributed to the atmospheric conditions that usually prevail during heat wave days, which favour the increase of pollution levels. The application of CAQI showed that air pollution was high in 61% and 52% of the heat wave days at the urban and the suburban site, respectively and very high in 11% of the heat wave days at the suburban site. The variation of average pollution levels in relation with heat wave

duration exhibited a peak that is more pronounced for O₃. Mean O₃ levels were higher during 6-day events.

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