



Heat waves observed in 2007 in Athens, Greece: Synoptic conditions, bioclimatological assessment, air quality levels and health effects [☆]

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ARTICLE INFO

Article history:

Received 10 February 2009

Received in revised form

4 November 2009

Accepted 8 December 2009

Available online 8 January 2010

Keywords:

Heat wave

Heat load

Air quality

AQSI

Heatstroke

ABSTRACT

Heat waves are considered to be increasing in frequency and intensity whereas they comprise a significant weather-related cause of deaths in several countries. Two heat waves occurred in Greece in summer 2007. These severe heat waves are assessed by analyzing the prevailing synoptic conditions, evaluating human thermal discomfort, through the Heat Load Index (HL), as well as investigating its interrelation of air pollutant concentrations, and the daily air quality stress index (AQSI), in the greater region of Athens (Attica), Greece. Furthermore, the relation of HL values and the number of heatstroke and heat exhaustion events recorded in public hospitals operating within the Greek National Health System is examined. Data included radiosonde measurements from the Athens airport station (LGAT), NCEP/NCAR reanalysis data in order to obtain the position of the Subtropical Jet Stream (STJ), GDAS meteorological data for back-trajectory calculation, 10-min meteorological data from 10 Hydro-Meteorological stations and mean hourly values of nitric dioxide (NO₂), sulphur dioxide (SO₂) and ozone (O₃) concentrations, measured at 7 different sites, for the last 10-day period of June and July 2007. Spearman's rank correlation test was used to observe any possible correlation between HL values and air pollutant concentrations, and AQSI values. The results demonstrated different synoptic characteristics for the heat waves of June and July. In the heat wave of June, higher ambient temperatures were recorded and greater HL values were calculated. Extreme discomfort conditions were identified in both heat waves during both day-time and night-time hours. The air pollution analysis showed poor air quality conditions for the heat wave of July, while a significant correlation was found between HL values and average hourly concentrations of O₃, NO₂ and SO₂. The number of heat-affected patients reported during the June heat wave was larger.

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1. Introduction

A heat wave is an extended period of excessively hot weather condition, which may be accompanied by high levels of humidity and it is considered to be linked to the synoptic-scale circulation of the atmosphere (Kysely, 2002; Meehl and Tebaldi, 2004). There is no universal definition of the heat wave (Meehl and Tebaldi, 2004); the term is related to the average atmospheric conditions of an area. Temperatures that inhabitants of hot climate zones consider normal, can be extremely high for those living in cooler areas.

Scientific interest has been expressed for heat waves and other extreme phenomena as they affect ecosystems and human society

[☆] There were no funding sources to support the work described in the manuscript.

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owing to adverse impacts in agriculture, water resources, energy demand, regional economies and human health (Meehl et al., 2000; WHO, 2004). Moreover, the impact of global warming on the frequency, duration and intensity of heat waves has been examined (Meehl and Tebaldi, 2004; WHO, 2004). Studies of heat waves have analyzed thermal and air quality conditions (Giles and Balafoutis, 1990; Giles et al., 1990; Matzarakis and Mayer, 1991), investigated the relation between heat waves and atmospheric circulation (Kysely, 2002; Makrogiannis et al., 2008), calculated discomfort indices (based on combinations of various meteorological and personal parameters such as clothing, activity as well as human physiology) so as to estimate human thermal discomfort (Giles et al., 1990; Matzarakis and Mayer, 1997) and tackle heat-related mortality and morbidity (Pantavou et al., 2008; Dolney and Sheridan, 2006; Fouillet et al., 2006; Basu and Samet, 2002).

Heat waves are not very rare in Greece as a consequence of the warm climate. Several scientists have studied the conditions leading to the occurrence of this phenomenon over Greece as well

as its implications (Metaxas and Kallos, 1980; Giles et al., 1990; Karakostas and Gawith, 1994; Karakostas and Downing, 1996; Gawith et al., 1999; Brikas et al., 2006; Pakalidou and Karakostas, 2004) whereas others have focused on the more severe heat waves that were observed during the past twenty years or so (Katsouyanni et al., 1988; Prezerakos, 1989; Matzarakis and Mayer, 1991; Giles and Balafoutis, 1990; Balafoutis and Makrogiannis, 2001; Makrogiannis et al., 2008; Founda and Giannakopoulos, 2009).

According to the World Meteorological Organization (WMO) a heat wave is defined as the phenomenon during which the daily maximum temperature for at least five consecutive days exceeds the average maximum temperature by 5 °C, considering the period between 1961 and 1990 as the normal measuring period (Frich et al., 2002). In the case of Greece, according to Metaxas and Kallos (1980), a heat wave occurs when the following criteria are met:

- The maximum temperature at the station of the National Observatory of Athens (NOA) located in Thission in the center of Athens, is at least 37 °C.
- The average daily temperature is at least 31 °C, at the aforementioned station.
- The maximum temperature at Larissa station (Central Greece) is at least 38 °C on that day.
- The temperatures is at least 5° above normal in parts of this area for a period of at least two days or more (USA norms).

The key synoptic feature for the occurrence of a heat wave over Greece is the position of the Subtropical Jet Stream (STJ) in the upper troposphere (Balafoutis and Makrogiannis, 2001). Under normal meteorological conditions the main position of the STJ is observed over SW Spain, Sicily, south of the Greek peninsula, Central Aegean Sea and SW Turkey (Prezerakos, 1989). The maximum wind speed is observed at the 200 mb level. When the STJ moves to the North of the Greek area, abnormal meteorological conditions are formed over Greece which result in very high values of surface air temperature. As the STJ moves away from Greece, towards the North, heat waves become more intense.

This northward displacement of the STJ can be effected by low-pressure systems over the SW of England—Northern Biscayan Gulf, combined with ridges protruding from Africa towards the Mediterranean. This type of mechanism causes powerful heat invasions to the SE Balkan region, with the climaxing to befall 3–4 days afterwards (Prezerakos, 1989; Katsouyanni et al., 1993; Brikas et al., 2006). Moreover, the physical process that takes place under these synoptic conditions is the large-scale subsidence within the tropospheric air below and to the south of the STJ which leads to: (a) Raising air temperature due to adiabatic compression, (b) surface horizontal divergence of the vertical flux, and (c) increase of the Sea Level Pressure, enhancing the anticyclonic circulation and the concurrent hot weather.

In conclusion, the combination of large-scale subsidence and horizontal movement of air masses from southern parts is the typical cause of the heat wave phenomenon over Greece.

During the last ten days of June and July 2007, Athens experienced two extreme heat events, defined as such according to both the WMO and Metaxas and Kallos' definitions. At that time, these heat waves became front page news in all Greek newspapers and the Public Authorities took preventive measures. Air temperatures reached the highest levels recorded in the past 100 years, breaking the previous records with temperatures exceeding 45 °C at the meteorological station of Philadelphia in Athens. Air pollution exceeded the World Health Organization air

quality guidelines on 42% of the days in the center of Athens (Patisson St.), where the highest levels of air pollutants concentrations were observed. The highest ambient temperature for the summer of 2007 was recorded on June 26. That day the maximum temperature at NOA (Thission station) was 44.8 °C (Founda and Giannakopoulos, 2009). The previous record maximum temperature recorded at NOA was 43 °C on June 21, 1916 and July 2, 1998. On June 28th, a wild fire broke out in the National Park of Greece, Parnitha, due to the combination of strong westerly winds and high temperatures. This was the most severe heat wave ever recorded and the second longest heat wave of significant intensity after that of 1987 (Katsouyanni et al., 1988; Matzarakis and Mayer, 1991). These parameters resulted in possibly the worst heat wave event recorded in Greece. In July 2007, the daily maximum temperature remained above 40 °C for four consecutive days. According to the records of NOA, since 1897 only twice has Athens experienced two heat waves the same summer period: in the years 2000 and 2007.

The main target of this paper is to describe and analyze the synoptic situation, the resulting meteorological conditions and the consequences of this relatively rare phenomenon on the life of inhabitants in greater region of Athens, Attica, through the induced thermal stress and its possible association to air pollution (Katsouyanni et al., 1997; Giles et al., 1990; Giles and Balafoutis, 1990; Katsouyanni et al., 1993; Philandras et al., 1999; Paliatsos and Nastos, 1999; Balafoutis and Makrogiannis 2001; Kassomenos et al., 2001; Makra et al., 2003). The greater urban zone of Athens was chosen for this paper, as it is the largest city of Greece, with a population of 3,761,810 people—about 34.31% of the population of Greece—according to the 2001 census carried out by the General Secretariat of National Statistical Service in Greece (ESYE, 2001) and it is also a popular tourist destination for people coming from northern Europe who are more vulnerable to the heat (WHO, 2004). Moreover, individuals living in large cities probably have greater risk for mortality or morbidity attributable to elevated ambient temperatures since urban environments are considerably warmer than the surrounding suburban areas due to the so-called 'urban heat island effect'. Athens has a reliable network of urban and suburban meteorological stations recording various meteorological parameters for a long period of time.

2. Materials and methods

2.1. Study area

The Greater Athens area is situated in a small peninsula located in the south-eastern end of the Greek mainland. It covers about 450 km² and the built-up area is mainly located in a basin surrounded by high and rather stony mountains from three sides and open to the sea from the south (Fig. 1). There are small openings connecting the metropolitan area of Athens with the Greek mainland to the north, northwest, and northeast of the basin. In Athens, more than 2,000,000 vehicles are registered; industrial activities are mainly located in the western part of the basin (Thriassion Plain).

2.2. Meteorological data

In order to investigate the vertical temperature distribution from the surface to the 10 mb pressure level, radiosonde data were gathered from the station of Athens airport (LGAT) at 00 and 12 UTC, from 22nd to the 27th of June and from 23rd to the 27th of July 2007 (University of Wyoming, 2008). For detailed information on the synoptic structure and an analysis of atmospheric circulation, we used the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data to obtain the position of the Subtropical Jet Stream (STJ) at the 300 mb level, and additionally at the 700 mb and 500 mb levels for the two heat wave incidents (June 22nd to 27th and July 23rd to 27th, 2007), respectively, (Kalnay et al., 1996; Brikas et al., 2006; Earth System Research Laboratory, 2008). Finally, the HISPLYT model from the READY system of the NOAA Air Resources Laboratory (ARL) (Draxler and Rolph, 2003; Rolph, 2003; ARL, 2008) was used to generate isentropic back-trajectories at three

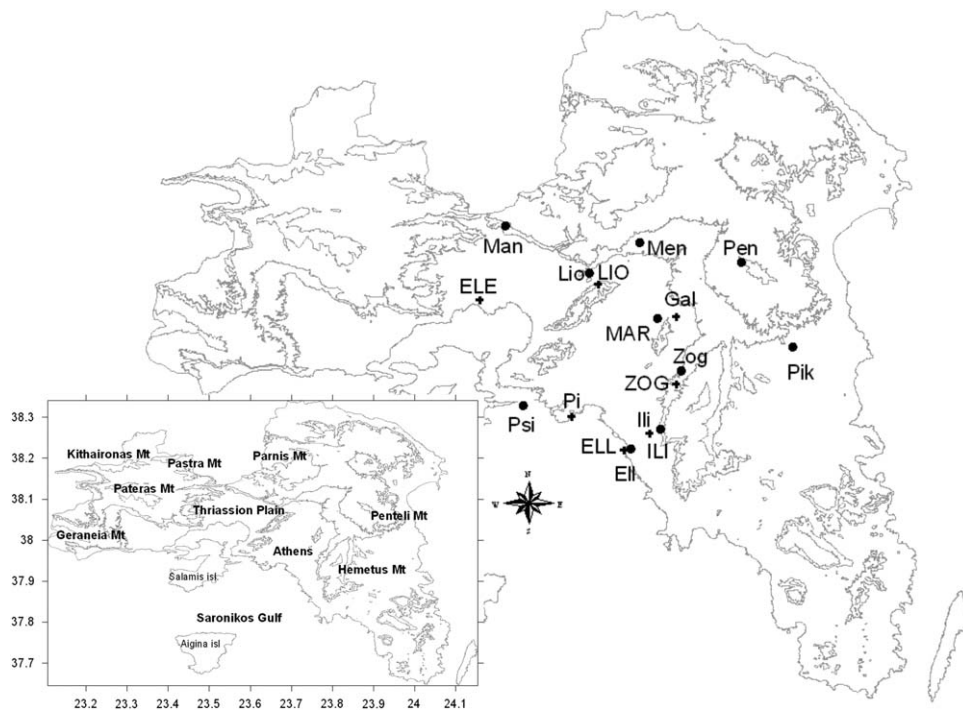


Fig. 1. Map showing the Attica region and the air quality (diamonds) and hydro-meteorological (dots) stations.

heights (1000, 3000, and 5000 m) at 12 UTC on June 26th and on July 25th, 2007. Back-trajectories were based on Global Data Assimilation System (GDAS) meteorological data.

In the urban area of Athens, a monitoring network of ten Hydro-Meteorological surface stations has been operated by the National Technical University of Athens (NTUA). Seven of these stations (Agios Kosmas_m, Ano Liosia_m, Galatsi_m, Zografou_m, Ilioupoli_m, Menidi_m and Penteli_m) are located within the basin of Athens. One is located in the east, in the Messogia plain (Pikermi_m station), and another one in the west, in the neighboring Thriassion plain (Mandra_m station). The last station is located south, on the small rocky island of Psitalia_m (Fig. 1). Meteorological measurements were obtained from the NTUA network including air temperature (T_{air}), relative humidity (RH), horizontal wind speed (WS) and global solar radiation (SR) in intervals of 10 min, for the periods from 22 to 30 June and from 22 to 30 of July 2007 (NTUA, 2008). Sun altitude data were obtained from the Astronomical Applications Department of the US Naval Observatory (USNO) in intervals of 10 min (USNO, 2008).

Assessment of the thermal environment was obtained through the thermo-physiological index Heat Load (HL). Based on the Man-ENvironment heat EXchange model (MENEX model), meteorological conditions as well as physiological parameters establish the heat gain or loss of the human body by radiation, convection, conduction, evaporation and respiration. According to the MENEX model, the general equation of the heat balance has the following form (Blazejczyk, 2001):

$$M + mR + mL + mC + mE + mRes = mS, \quad (1)$$

where M is the metabolic heat production, mR the absorbed solar radiation, mL the net long-wave radiation, mC the turbulent exchange of sensible heat, mE the turbulent exchange of latent heat, $mRes$ the respiratory heat loss and mS stands for the net heat storage. All parameters in $W m^{-2}$. The HL index represents the load of the thermoregulatory system due to the intensity of adaptation processes of a human body, on a seven-step scale according to Table 1. The HL index is estimated as the combination of the three principal heat fluxes of the human heat balance equation, as follows:

$$\text{At } mS < 0 \text{ W m}^{-2} \text{ and } mE \geq -50 \text{ W m}^{-2},$$

$$HL = [(mS + 1000)/(1000)]^{(5/(1+mR))} \quad (2)$$

$$\text{At } mS \geq 0 \text{ W m}^{-2} \text{ and } mE \geq -50 \text{ W m}^{-2},$$

$$HL = [(mS + 1000)/(1000)]^{(2-1/(1+mR))} \quad (3)$$

$$\text{At } mS < 0 \text{ W m}^{-2} \text{ and } mE < -50 \text{ W m}^{-2},$$

$$HL = [mE/(-50)][(mS + 1000)/1000]^{(5/(1+mR))} \quad (4)$$

$$\text{At } mS \geq 0 \text{ W m}^{-2} \text{ and } mE < -50 \text{ W m}^{-2},$$

$$HL = [mE/(-50)][(mS + 1000)/1000]^{(2-1/(1+mR))} \quad (5)$$

Table 1

Correspondence between (A) Heat Load index values and thermal stress levels (B) AQSI values and air quality related stress conditions.

A	HL	Thermal sensation	B	AQSI	Assessment
	≤ 0.25	Extreme cold stress		0.0–0.5	Barely stressed
	0.251–0.820	Great cold stress		0.5–1.0	Slightly stressed
	0.821–0.975	Slight cold stress		1.0–1.5	Moderately stressed
	0.976–1.025	Thermoneutral		1.5–2.0	Distinctly stressed
	1.026–1.180	Slight hot stress		> 2.0	Heavily stressed
	1.181–1.750	Great hot stress			
	≥ 1.715	Extreme hot stress			

In this paper, the HL index was estimated for a walking young male person, walking with a speed of 1.1 ms^{-1} and a metabolic heat production of 135 W m^{-2} , according to ISO 8996.

2.3. Air quality data

Air pollution data encompassed mean hourly values of nitric dioxide (NO_2), sulphur dioxide (SO_2) and ozone (O_3) concentrations, measured at 7 different locations within the Attica region covering the study area and are representative of the population exposure. These include the suburban station of Elliniko_{ap}, the suburban industrial station of Elefsina_p, the suburban background stations of Ano Liosia_{ap} and Zografou_{ap} and the urban, urban background and urban traffic stations of Ilioupoli_{ap}, Marousi_{ap} and Piraeus_{ap}, respectively. The data cover a 21-day period (June 21st to 30th 2007 and July, 21st to 31st 2007) and were obtained from the Directory of Air and Noise Pollution Control (DANPC) of the Ministry of the Environment. Statistical analysis was performed using the statistical software SPSS, Version 12 (SPSS Inc., Chicago, Illinois, USA).

For the assessment of the urban air environment, the air quality stress index AQSI was calculated on a daily basis. AQSI₂₄ is stated based on the average daily concentrations of air pollutants, by the formula (Matzarakis and Mayer, 1991):

$$AQSI_{24} = \sum_{i=1}^3 \frac{\text{average daily value}}{MI_{24h \text{ value}}} \quad (6)$$

i indicating the three air pollutants, NO_2 , SO_2 and O_3 during heat waves and $MI_{24h \text{ value}}$ indicating the threshold values of air pollutants according to the European Community standards (NO_2 : $100 \mu\text{g}/\text{m}^3$; O_3 : $50 \mu\text{g}/\text{m}^3$; SO_2 : $125 \mu\text{g}/\text{m}^3$). Table 1 displays the AQSI₂₄ values with the suggested description of human biometeorological stress conditions.

In order to examine a possible link between human biometeorological conditions and air quality, the linear cross-correlation and lagged cross-correlation between mean hourly HL values and mean hourly values of air pollutants concentrations, as well as AQSI₂₄ values were estimated using the Spearman's rank correlation test. The confidence level was set at 0.05.

2.4. Data on human health effects

In summer 2007, the National Health's Operational Center (NHOC) declared a state of national alert from June 22 to June 28 and from July 23 to 27. During these periods, all patients diagnosed with heat exhaustion and heatstroke in the emergency department units, as well as mortality data of heatstroke, were recorded in all public hospitals operating within the Greek National Health System in the region of Attica, and were obtained from the NHOC. Heat exhaustion is a milder form of heat-related illness, the symptoms of which may include increased body temperature (not above 40 °C). The signs that could indicate a heat exhaustion are fatigue, dizziness, nausea, vomiting, tachycardia and hypotension. Heatstroke is the most dangerous condition, in which the human body is unable to regulate its temperature due to excessive heat and it is defined by elevated body temperature (above 40 °C) and dehydration. A heatstroke can cause death or permanent disability if emergency treatment is not provided.

3. Results

3.1. Synoptic situation and atmospheric circulation analysis

During the studied periods, a deep low-pressure system rotated in the region of Britain for several days and then moved north–northeast. At the same time, there was a shallow ridge over the central Mediterranean. The result was temperatures that by far exceeded the previous maximum temperature records.

The radiosonde data at 00 and 12 UTC for Athens airport (LGAT), for the period from 24 to 27 June and from 24 to 27 July 2007, demonstrate high air temperature values between 950 mb and 850 mb, which overrun the values of air temperature at the surface and a temperature drop at the level of 700 mb, for the majority of radiosondes (for detailed information see Supplementary Material). On June 25th, a strong adiabatic heating can be observed, accompanied by a small drop of temperature on the surface. However, during the heat wave of July, there is no such phenomenon observed, except for the 12 UTC radiosonde on July 25, which was also the hottest day of this second heat wave. Radiosonde measurements of wind velocity indicated that STJ was higher at day than at night, at the level of 300 mb. A temperature decrement is observed at 500 mb. Furthermore, an important variation observed in surface RH between day and night for both heat waves. Radiosondes show that RH decreased up to 37% and 30% during the day in June and July heat waves, respectively.

The reanalysis data of NCEP/NCAR model suggest that during the heat wave of June, maximum air velocities of STJ were located northeast of Balkans, over central Europe, with average wind velocity of 30 ms^{−1} at 00 UTC, at the level of 300 mb. Moreover, average wind velocity was 10 ms^{−1} at 700 mb and maximum values of wind speed were recorded in northwest Greece and in the west of Balkans. During the heat wave of July, the maximum wind speed at 00 UTC at the 300 mb level was 25 ms^{−1}. At 500 mb, the mean air velocity was 20 ms^{−1} and the maximum values of wind speed were observed northwest of Balkans, at a distance long enough from Greece. These characteristics, during the heat wave of July, comply with those reported in previously published studies so they can be considered as typical of a heat wave over Greece (Metaxas and Kallos, 1980; Prezerakos, 1989; Giles and Balafoutis, 1990; Balafoutis and Makrogiannis, 2001; Brikas et al., 2006) (see Supplementary Material).

According to the analysis of the back trajectories, the origin of air masses for the two heat wave episodes differs (see Supplementary Material). We observed that in the heat wave of June, air masses originated from the Northern African desert. Dry and hot

air masses, enriched in water vapor above the Mediterranean and reached Greece with increased amounts of humidity. At the 1000 m level the air mass departs from Northern Africa with RH less than 10% and arrives at Athens with an average RH value of 30%. A similar increase is observed at the 5000 m with an RH value of 40% at the point of origin and an RH value of 60% over Athens, whereas the situation is inverted at the 3000 m level with higher RH values observed over Africa compared to the RH values over Athens. This movement of air masses during the heat wave of June does not comply with the usual characteristics of heat waves observed over Greece. By contrast, the heat wave of July had typical characteristics. Low and middle level masses, starting from the Balkan Peninsula, moved southward, reaching the surface layer over Greece with increased temperature and relatively reduced humidity. At the lower level (1000 m) the decrease in RH reaches 25%, at the 3000 m there is a 40% RH increase, while at the higher level (5000 m) there is a small decrease, around 10%.

The two heat waves had markedly different thermohygrometric characteristics at the surface level that could be characterized as hot and damp for the event of June and hot and dry for the event of July. Evidently the hot and wet characteristics of the June event lead to extremely high values of the HL index.

3.2. Thermal discomfort assessment

In the first heat wave, the worst incident of thermal discomfort was recorded on June 26th for all the stations studied (see Supplementary Material). During that day, between 08 and 20 LST, all stations except Pikermi_m indicated conditions of extreme thermal stress. Absolute maximum HL values were estimated for the station of Ano Liosia_m between 15 and 16 LST. The daily minimum values of the HL index were computed during night-time hours for all measurement locations. The lowest daily HL minimum values were estimated for the stations of Agios Kosmas_m and Psitalia_m illustrating 'slight hot stress' conditions. It is worth noting that HL values suggest extreme thermal conditions throughout the day at the stations of Ilioupoli_m and Mandra_m. Diurnal variation of the HL index at Ano Liosia_m station for the June heat wave is presented in Fig. 2a. It can be noticed that the maximum and minimum values of HL were estimated on June 26th and 23rd respectively. The highest percentage frequency of HL values indicating extreme hot stress was observed on the 26th (78%), 27th (97%) and 28th (75%), whereas the maximum frequency of HL values showing 'slight hot stress' was recorded on the 22nd (25%), 23rd (22%) and 30th (18%) of June.

In the July heat wave, the peak of thermal discomfort was recorded for all stations on the 25th (see Supplementary Material). That day, between 08 and 20 LST, all stations except Agios Kosmas_m and Psitalia_m indicated extreme discomfort conditions. Absolute maximum HL values were recorded at Ano Liosia_m station between 13 and 14 LST. For all the measurement sites, the lower HL values occurred during night-time hours. The lowest minimum HL values were estimated at the station of Agios Kosmas_m illustrating 'slight hot stress' conditions. In addition, HL values display extreme thermal conditions throughout the day at the stations of Ilioupoli_m and Mandra_m. Fig. 2b presents the diurnal variation of HL at Ano Liosia_m station. Maximum HL values were estimated on July 25th and minimum on July 22nd. Furthermore, the maximum frequency of HL values indicating extreme hot stress was recorded on the 23rd, 24th and 25th with 93, 89 and 82% respectively, whereas the maximum frequency of HL values referring to 'slight hot stress' was observed on the 22nd with 10%.

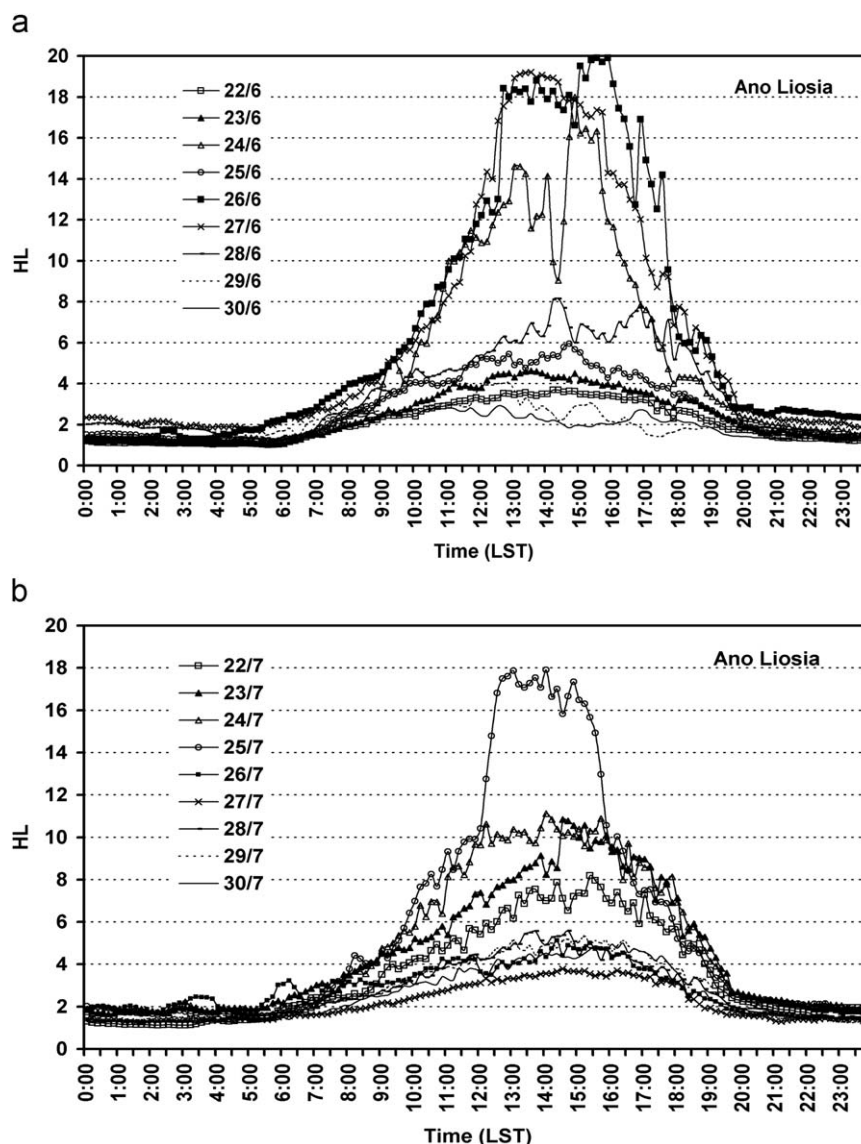


Fig. 2. Diurnal variation of Heat Load index at Ano Liosia_m station for: (a) June and (b) July heat wave event.

The frequency distribution of the HL index classes for all stations at the peak of both heat waves is presented in Fig. 3. 'Extreme hot stress' conditions were reported for 79% of the cases on June 26th and 80% on July 25th. On the other hand, 'slight hot stress' conditions were estimated for less than 2% of the cases for both days. It should be noted that 10% on June 26th and 4% on July 25th of HL values were greater than 13.5. In addition, a greater number of HL values corresponding to 'extreme hot stress' was recorded in June (64%) compared to July heat wave (71%) at Ano Liosia_m station (Fig. 3). Moreover, 'slight hot stress' conditions were estimated for less than 8% and 1% of the cases of heat wave periods during June–July, respectively.

The assessment of thermal discomfort during June and July heat wave episodes revealed extremely uncomfortable conditions during both day and night-time hours across the entire Greater Athens area.

3.3. Air quality analysis

The linear cross and lagged cross-correlation coefficients between HL values and average hourly concentrations of O₃,

NO₂ and SO₂ were estimated for the last ten day periods of June and July 2007 and are summarized in Table 2. Empty cells indicate unavailable information.

The statistical analysis demonstrated that mean hourly HL values were positively correlated with average hourly O₃ concentrations, for both June and July heat waves. Spearman's rank correlation coefficients range from 0.72 to 0.92 ($p < 0.05$) at all the stations considered, as expected since solar radiation determines to a large extent both the diurnal O₃ and temperature (hence also HL) variations. A non-significant correlation was observed between concurrent HL values and both NO₂ and SO₂ concentrations, thus the potential effect of lagged values was examined. NO₂ reached the minimum value 3 h (June) and 1 h (July) after the estimated HL peak value. An exception was Elliniko_{ap} station, where the lowest NO₂ concentration was recorded 7 h after the maximum HL value. The estimated coefficients varied between -0.52 and -0.90 ($p < 0.05$). This result complies with the yearly report of DANPC (2007) and other study findings (Kassomenos et al., 1995; Kassomenos et al., 1998) based on which maximum NO₂ concentration occurs around 09:00 LST and minimum pollutant concentration is measured during midday hours, indicating that NO₂ promotes O₃ formation.

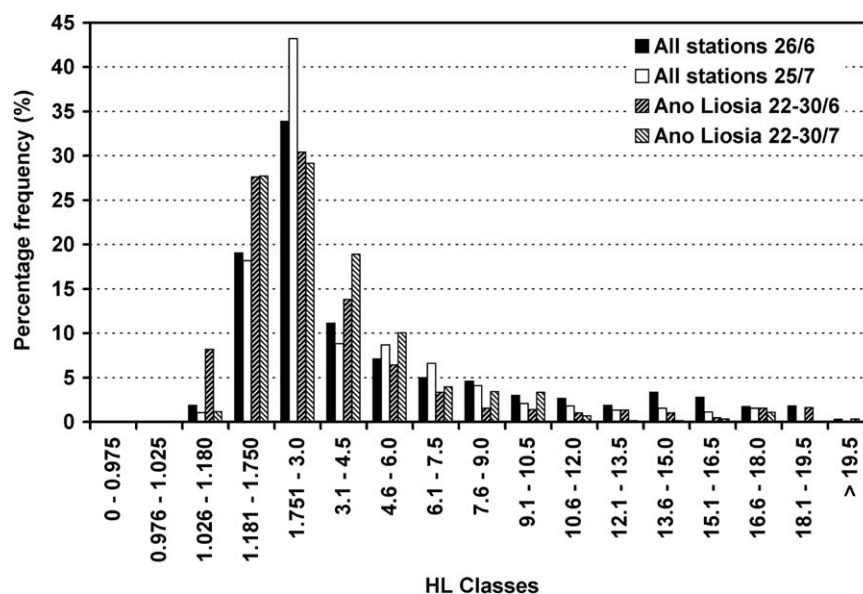


Fig. 3. Frequency distribution for the classes of Heat Load index between all stations at the peak of each heat wave event and during each heat wave event at Ano Liosia_{ap} station.

Table 2

Linear cross and lagged cross-correlation coefficient between HL values and concentrations of air pollutants during the summer of 2007 heat wave.

Station	Linear cross coefficient (HL–O ₃)		Lag cross coefficient (HL–NO ₂)		(HL–SO ₂)	
	June	July	June	July	June	July
Elefsina _{ap}	0.77	0.87	R3 ^a = −0.83	R1 ^a = −0.85	R1 ^a = 0.81	R2 ^a = 0.65
Elliniko _{ap}	0.84	0.92	R7 ^a = −0.78	–	R3 = 0.81	R6 ^a = 0.67
Ilioupoli _{ap}	0.77	0.91	R3 = −0.71	–	R6 ^a = 0.48	R6 = 0.65
Ano Liosia _{ap}	0.79	0.85	R3 = −0.76	R1 = −0.81	R3 = 0.86	R7 ^a = 0.6
Marousi _{ap}	0.86	0.87	R3 = −0.90	–	–	–
Piraeus _{ap}	0.46	0.88	R3 = −0.78	R1 = −0.81	R3 = 0.93	R6 = 0.73
Zografou _{ap}	0.72	0.76	R3 = −0.77	R1 = −0.52	–	–

^a R1: value of 1 h time lag, R3: value of 3 h time lag, R6 value of 6 h time lag, R6 value of 6 h time lag, R7: value of 7 h time lag.

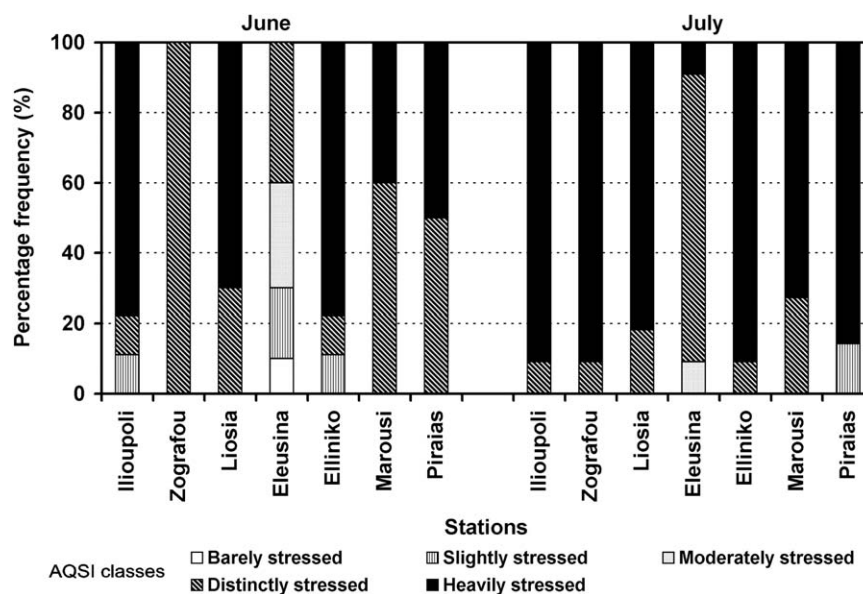


Fig. 4. Frequency distribution of the AQSI₂₄ index for each heat wave event, June, 21st to 30th and July, 21st to 31st.

Significant results ($p < 0.05$) with positive coefficients, from 0.48 to 0.93, were obtained when the relationship between HL and hourly SO_2 concentrations was investigated, using lagged cross-correlation analysis. Maximum SO_2 concentrations were measured about 3 h (June) and 6 h (July) after maximum HL values were recorded. These results can be attributed to the topography of Attica and transport phenomena. The locations of the air quality stations and the land use distribution have also affected the measured concentration of SO_2 .

In order to estimate the air quality in the greater region of Athens during the two heat waves, the AQSI_{24} index was estimated on a daily basis separately for each station (for detailed information see Supplementary Material). The results display poor air quality conditions for the June heat wave period. AQSI_{24} values range from 0.38 (Elefsina_{ap} station) on June 21st to 2.56 (Ilioupoli_{ap} station) on June 30th. In most stations AQSI_{24} values exceeded the threshold value of 2.0, indicating 'heavily stressful' air pollution conditions. In fact, for more than 50% of the days Elliniko_{ap}, Ano Liosia_{ap}, Piraeus_{ap} and Ilioupoli_{ap} stations the classes were identified as 'heavily stressed', whereas 40% of the days were classified as 'distinctly stressed' in Elefsina_{ap}, Marousi_{ap} and Zografou_{ap} stations (Fig. 4). Analysis of air pollution data for the July heat wave demonstrated higher daily AQSI_{24} values than in June. The lowest value of AQSI_{24} is 0.94 (Piraeus_{ap} station) on July 27th and the highest is 3.09 (Zografou_{ap} station) on July 24th. In six out of the seven measurement locations, 73% of the days were classified as 'heavily stressed'. The Elefsina_{ap} station showed

lower daily AQSI_{24} values, with 82% of the days classified as 'distinctly stressed' (Fig. 4).

Spearman's rank correlation test was applied at a 0.05 level of significance, to detect the possible relation of HL values and AQSI_{24} values. The estimated correlation coefficients differ from site to site as well as between June and July heat waves (Table 3). A significant negative correlation was found for the Elefsina_{ap} station for both heat waves, whereas positive correlation coefficients were obtained for Elliniko_{ap}, Ilioupoli_{ap} and Zografou_{ap} sites. The analysis for Ano Liosia_{ap}, Marousi_{ap} and Piraeus_{ap} yielded coefficients ranging from -0.30 to -0.78 ($p < 0.05$) for June and from 0.24 to 0.73 ($p < 0.05$) for July. The strongest inverse correlation was found in Piraeus_{ap} (Fig. 5), whereas the strongest positive correlation was identified in Zografou_{ap}. The variation of the observed correlations between HL and AQSI_{24} is probably related to the dependence of AQSI_{24} on the concentration levels of O_3 , NO_2 and SO_2 that vary inconsistently among the stations.

3.4. Human health effects

During the first summer heat alert, on the June heat wave, NHOC reported 146 emergency department visits for heat exhaustion and heatstroke in Attica region, of which 62 were men and 84 women. Also 6 deaths (4 males and 2 females) from excessive heat exposure were reported. In July there was a limited number of patients affected by the heat wave. According to the NHOC, 46 patients visited emergency departments, the majority of which were females (25 females). One death of a female was also recorded. This corresponds to a drop in emergency department visits by 68.5%, indicating that a heat wave has a more significant impact on heat-related events when it occurs earlier in summer than later (Kysely, 2004; Hajat et al., 2002; Laschewski and Jendritzky, 2002) and that heat wave duration and intensity can be important factors, since the heat wave in June lasted longer and was characterized by greater HL values than that of July. However, the reduction in the number of emergency visits could also be linked to the psychological adaptation since high temperatures are expected in July (Nikolopoulou and Lykoudis, 2006) and to the fact that July 20–August 20 is the most popular vacation period in Greece.

Table 3
Linear cross-correlation between Heat Load index (HL) & Air Quality Stress Index (AQSI_{24}) at seven different sites in Athens in the heat wave periods of June and July 2007.

Stations	HL vs AQSI_{24} June 2007	July 2007
Elefsina _{ap}	−0.43	−0.18
Elliniko _{ap}	0.19	0.24
Ilioupoli _{ap}	0	0.52
Ano Liosia _{ap}	−0.3	0.73
Marousi _{ap}	−0.6	0.56
Piraeus _{ap}	−0.78	0.24
Zografou _{ap}	0.06	0.94

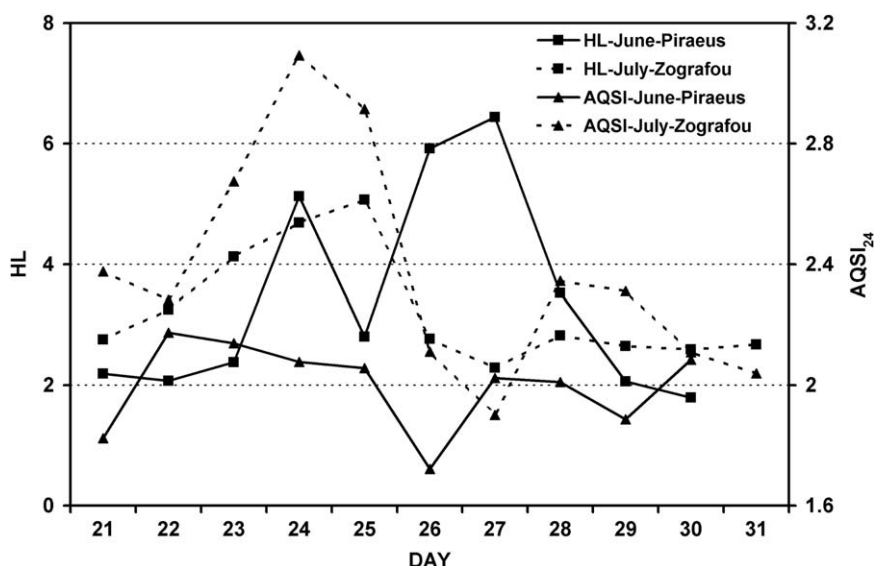


Fig. 5. Variation of Heat Load index and AQSI_{24} index for each heat wave event at Piraeus_{ap} station and Zografou_{ap} station.

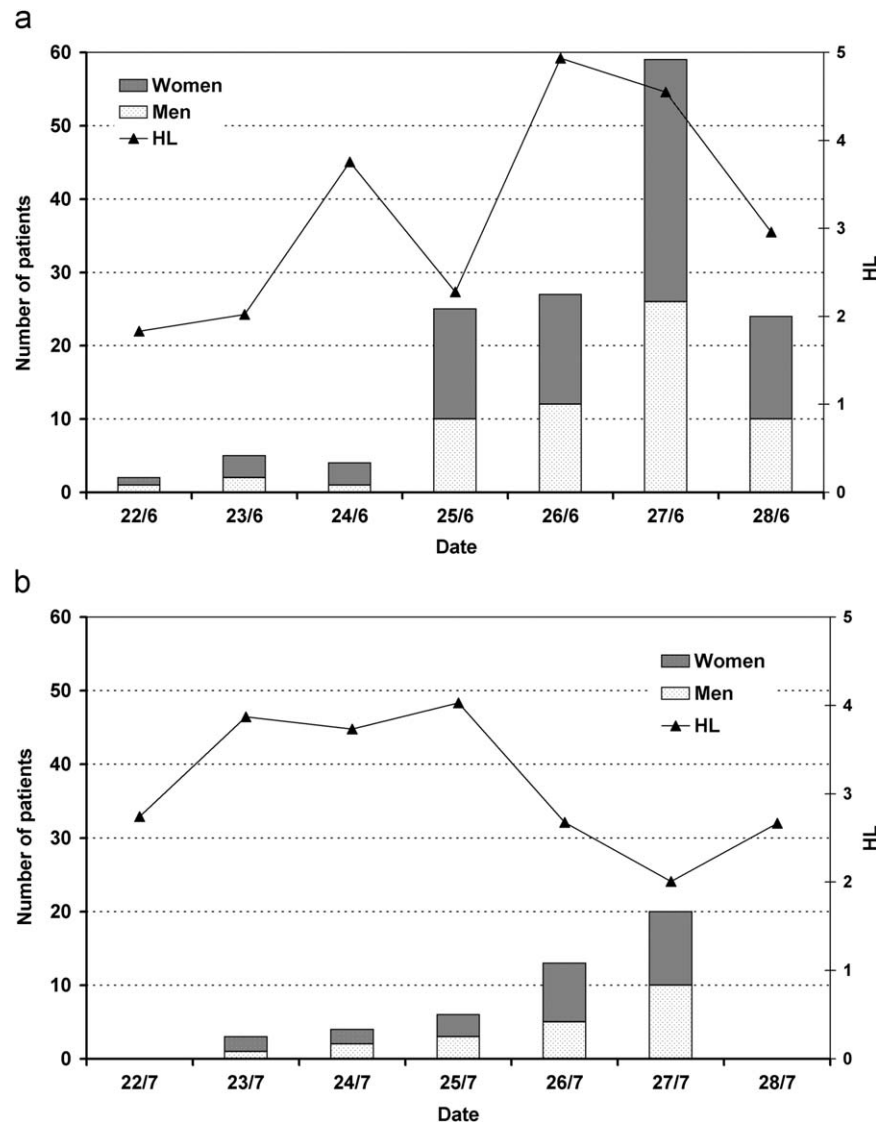


Fig. 6. Daily number of heat exhaustion and heatstroke patients affected during (a) June and (b) July 2007 heat wave events.

The daily variation of heat exhaustion and heatstroke cases for June and July heat waves are presented in Figs. 6a and b, respectively. In the first heat wave, a relatively moderate maximum of HL values occurred on June 24th and the peak maximum value of HL was measured on the 26th, while a gradual increment in heat-affected patients is observed between June 25th and 27th. In July, the maximum thermal discomfort was estimated on the 25th, whereas a smooth increase of heat exhaustion and heatstroke incidents was recorded from July 26th to July 27th. In both cases, the maximum numbers of patients were observed 1 or 2 days after the hottest day of the heat wave, suggesting a potential lagged effect of HL values on patient's number. Based on this, the possibility of extending the heat alert duration to 3 or 4 days (instead of 2) after maximum HL values are observed should be considered.

4. Conclusions

Athens experienced two severe heat waves in summer 2007. In this study we examined associations of daily synoptic conditions

with the surface weather conditions and we assessed human thermal stress during these extreme events using the HL index. We also investigated the possible correlation between HL values and air pollutants concentrations as well as the AQSI index. Finally, we evaluated the consequences of a hot thermal environment on human health.

During the June heat wave, the prevailing synoptic circulation facilitated North-African air masses to move over the Balkans. These hot air masses were enriched in water vapor when passing over the Mediterranean and at the time they arrived over the Attica were trapped below the pressure level of 700 mb, generating extreme HL values in Athens. On the contrary, the synoptic conditions during the July heat wave, comply with those reported in previously published studies as being typical of heat waves over the region of Attica (Prezerakos, 1989; Balafoutis and Makrogiannis, 2001; Katsouyanni et al., 1993; Brikas et al., 2006) and can be considered as typical for the region of Attica.

The minimum estimated HL values indicated 'slight hot stress' conditions during night-time hours whereas during day-time hours HL values overrun the threshold of 16.6 on the warmest days of the studied periods. The June heat wave appeared more

intense compared to that of July. HL values reached the maximum permitted values of the index and stayed in high levels for more consecutive days in June than in the July heat wave.

Statistical analysis showed a positive correlation and a positive lagged correlation between HL values and hourly concentrations of O₃ and SO₂, respectively, in both heat waves periods. A negative lagged correlation was obtained for HL and NO₂ concentrations. These results can be justified considering the formation mechanisms of the pollutants (primary and secondary pollutants). AQSI₂₄ values suggested worse air quality conditions for the heat wave period of June.

The analysis of patient data demonstrated a relatively low number of heat exhaustion and heatstroke incidents, especially during the July heat wave, probably due to the adoption of preventive measures by the NHOC. The maximum number of patients with heat exhaustion or heatstroke was recorded within 2 days after the daily peak value of HL. The number of heat-affected patients is certainly underestimated, as excessive heat is also related to increased morbidity and mortality from a number of causes other than heat exhaustion and heatstroke, respectively (Shen et al., 1998).

The present research probably has limitations. An apparent issue is the short period of observation since a heat wave is usually a relatively short period of time. Another important issue is the lack of measurements on important air pollutants such as particulate matter. Finally the nature of human health effects data did not permit a sophisticated statistical analysis. Additional data related to the variety of factors affecting human response to heat stress, such as exposure conditions or demographic information on the reported medical incidents were unavailable due to the lack of targeted and detailed recording. Nevertheless, this study is one of few applying a multidisciplinary approach on the heat waves in Attica and it could be a starting point for a better understanding of the physical processes creating extreme heat phenomena, aiming to update the heat wave forecast and improve the preventative measures of the central administration.

Acknowledgment

The authors wish to thank Mr. K. Gogosis, MSc, Director of NHOC and Mr. M.Grivas, Officer of NHOC, for assisting in the collection of health effects data. Also, the authors would like to acknowledge the provision of Air Quality data for Athens by the Directory of Air and Noise Pollution Control (DANPC) of the Ministry of the Environment, Greece.

Appendix A. Supplementary Material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envres.2009.12.002.

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